GREAT SALT LAKE

a Scientific, Historical and Economic Overview

edited by J. Wallace Gwynn, Ph.D.

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INTRODUCTION

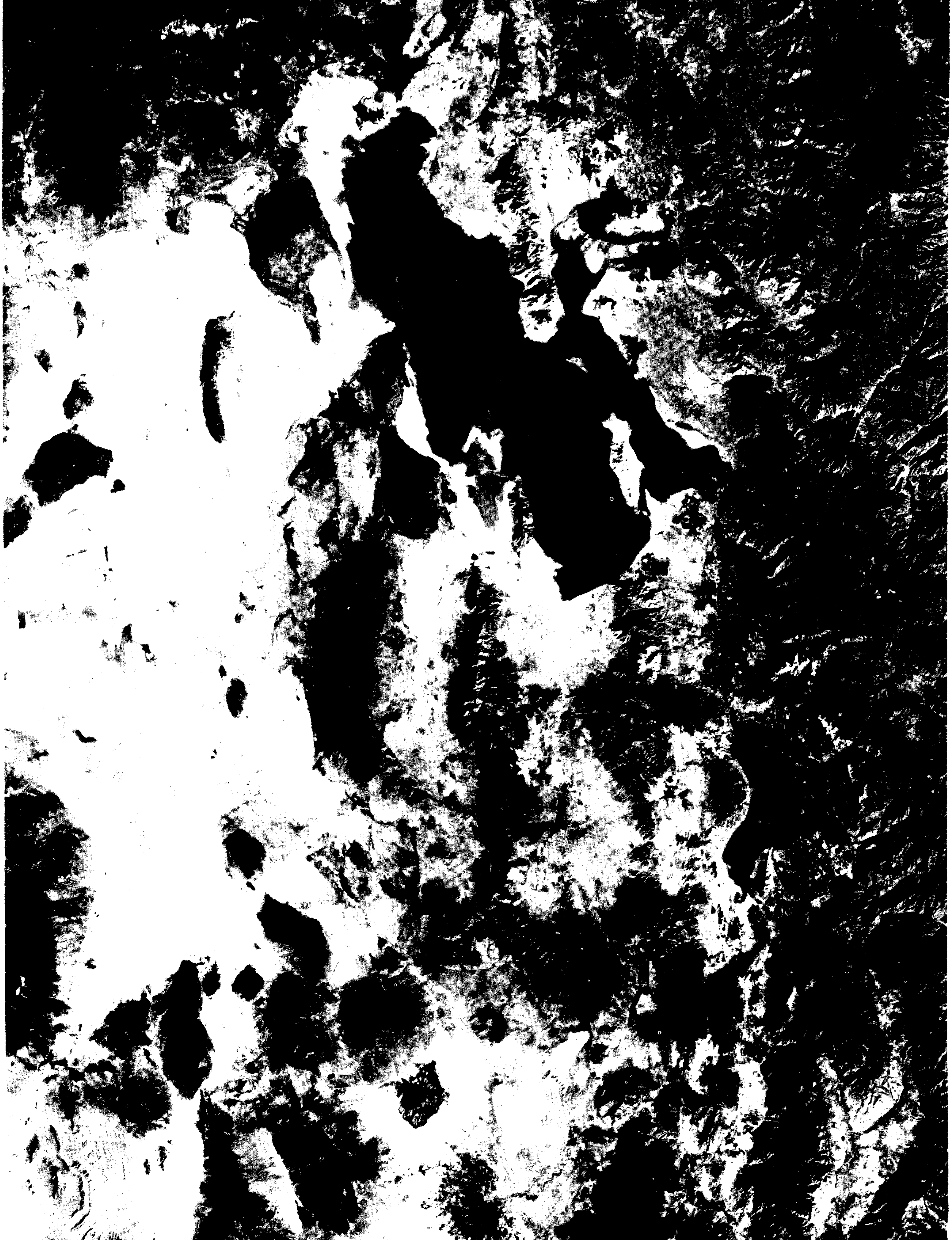
In 1966, Guidebook to the Geology of Utah number 20, entitled "The Great Salt Lake", was published by the Utah Geological Society. The book, edited by Dr. William Lee Stokes, contained ten informative articles, each dealing with a specific topic about the lake such as its history, biology, geologic setting and sediments. As this book became unavailable, the need for an update volume on the Great Salt Lake became apparent. To fill this need, the Utah Geological and Mineral Survey began to compile this volume in February of 1978. Some forty-seven individuals, each specialists in some aspect of the lake, or its environs, have contributed to the articles in this compilation. The resulting volume contains seven sections on the history and recreation, geology and geophysics, chemistry, lake industries, hydrology and climatology, biology, and engineering of the Great Salt Lake. It is hoped that this volume on one of the great wonders of the world, the Great Salt Lake, will be informative and of value to many people.

As more knowledge is gained about the Great Salt Lake through new or ongoing research programs, it is the present intent of the Utah Geological and Mineral Survey to publish periodic, though shorter, update volumes.

ACKNOWLEDGMENTS

The editor wishes to express a sincere thanks and appreciation to those individuals, and the corporations or agencies they represent, who have contributed to this volume on the Great Salt Lake.

The editor also wishes to express his appreciation to Paul A. Sturm, Research Geologist, Utah Geological and Mineral Survey, for his considerable assistance and insight in the editing of this volume.



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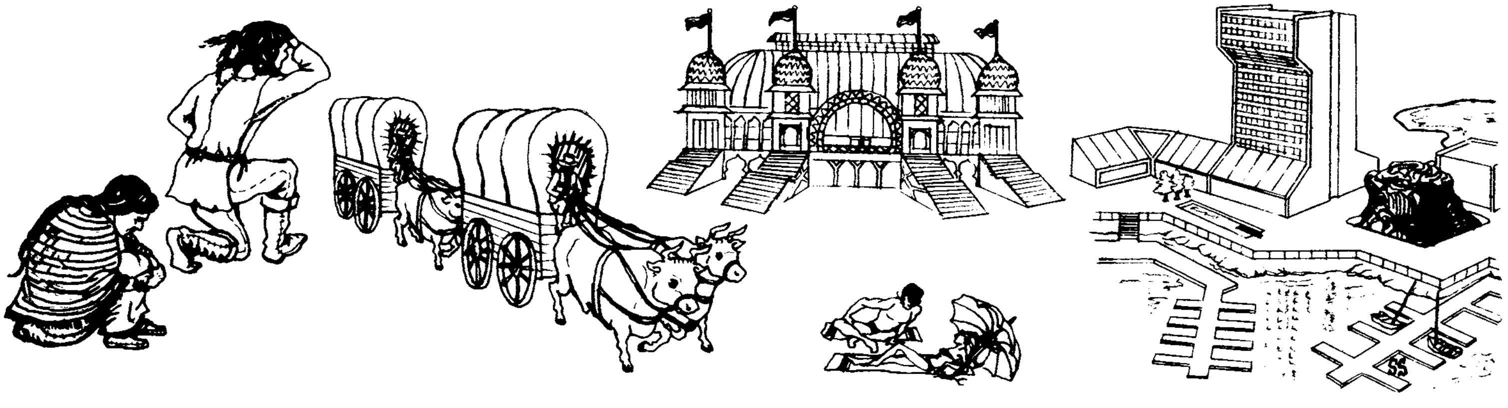
PAST PRESENT AND FUTURE



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I. PAST, PRESENT AND FUTURE

GREAT SALT LAKE: A HISTORICAL SKETCH

David E. Miller

Professor Emeritus of History, University of Utah

DISCOVERY, EXPLORATION AND SURVEYS

Reports and rumors of the existence of a huge salty lake somewhere in western America circulated quite freely for more than a century before any white man actually obtained authentic information about it or visited its shores. Numerous maps purporting to show such a lake appeared in print from time to time beginning as early as 1710 with the La Hontan map. One of the strongest and most prevalent traditions, based on information gained from native Americans, centered around Lake Copala. Since it seemed quite easy for cartographers to draw maps of a lake no white man had ever seen, it is not surprising to find these various maps showing lakes quite different from each other in size, shape and location.

The first authentic information regarding the actual existence of such a body of water came from the Dominquez-Escalante expedition of 1776 (Chavez and Warner, *The Dominquez-Escalante Journal*, B. Y. U. Press 1976). Attempting to open a line of communication between the missions of New Mexico and the Spanish capital of California at Monterey, the missionary explorers arrived near the present site of Provo, Utah on September 23, 1776. The expedition had penetrated the Great Basin by way of the Green, Duchesne, Strawberry and Spanish Fork rivers. Leaders of the group learned from the natives that the lake on whose shores they had arrived was connected with a larger body of water directly to the north, the water of which was extremely salty. The fathers did not choose to explore northward since their intended objective seemed to lie in the opposite direction. However, Miera y Pacheco, cartographer of the expedition, drew a map of the area reflecting the information obtained from the Indians. On the map he drew a huge two-armed lake labeled Lake Timpanogos (figure 1). The southern small arm (present Utah Lake) was shown connected to the larger northern arm (Great Salt Lake) by a strait of water which subsequently turned out to be the 40 mile long Jordan River.

Dominquez and Escalante evidently thought they understood the natives to indicate that a large river drained westward from the northern arm of Lake Timpanogos and Miera drew such a river on his map labeling it the "Tizon". Miera also lifted the Buenaventura (Green River) out of its channel and discharged it into Lake Miera (Sevier Lake). During the next half century imaginative map makers developed a mighty tradition about the Buenaventura and other mythical rivers, variously named and located, draining Great Salt Lake, Sevier and Utah lakes. This imaginative geography was matched by equally imaginative "information" about Great Salt Lake, all of which had considerable influence on those who eventually approached its shores. The notion that the lake must be connected to the Pacific by a subterranean channel at the head of which a huge whirlpool threatened the safety of lake craft was not dispelled until the 1870's, long after people should have known better. As a matter of fact, "eye witnesses" reported the location of the whirlpool about midway between Fremont and Antelope islands, reporting that a "schooner was almost drawn into it." (Salt Lake *Herald*, June 10, 1870). The mythical lake monster lasted even longer. It is indeed difficult to kill myths.

While it is possible that Spanish explorers, Indian slavers or furmen may have penetrated the region as far north as Great Salt Lake during the half-century following the Dominquez-Escalante expedition, and some expeditions are known to have opened trade with the Ute Indians located on the lower Provo River and around Utah Lake, there is no record of such visits.

There is no proof that any white man set eyes on Great Salt Lake prior to the fall or winter of 1824-25. During that season a brigade of William Henry Ashley's trappers under the leadership of John Weber had followed the Bear River from its headwaters in the Uinta Mountains all the way to the north end of Cache Valley. Winter camp was established near the site of present-day Franklin, Idaho. It was doubtless from there that Jim Bridger (riding on horseback--not in a bullboat) was dispatched to determine the ultimate destination of Bear River. Bridger followed the stream to its point of discharge into Great Salt Lake and returned to report that he had reached an arm of the Pacific. This erroneous notion was, of course, soon dispelled.

While James Bridger is the first white man known to have seen the lake, others may have preceeded him.

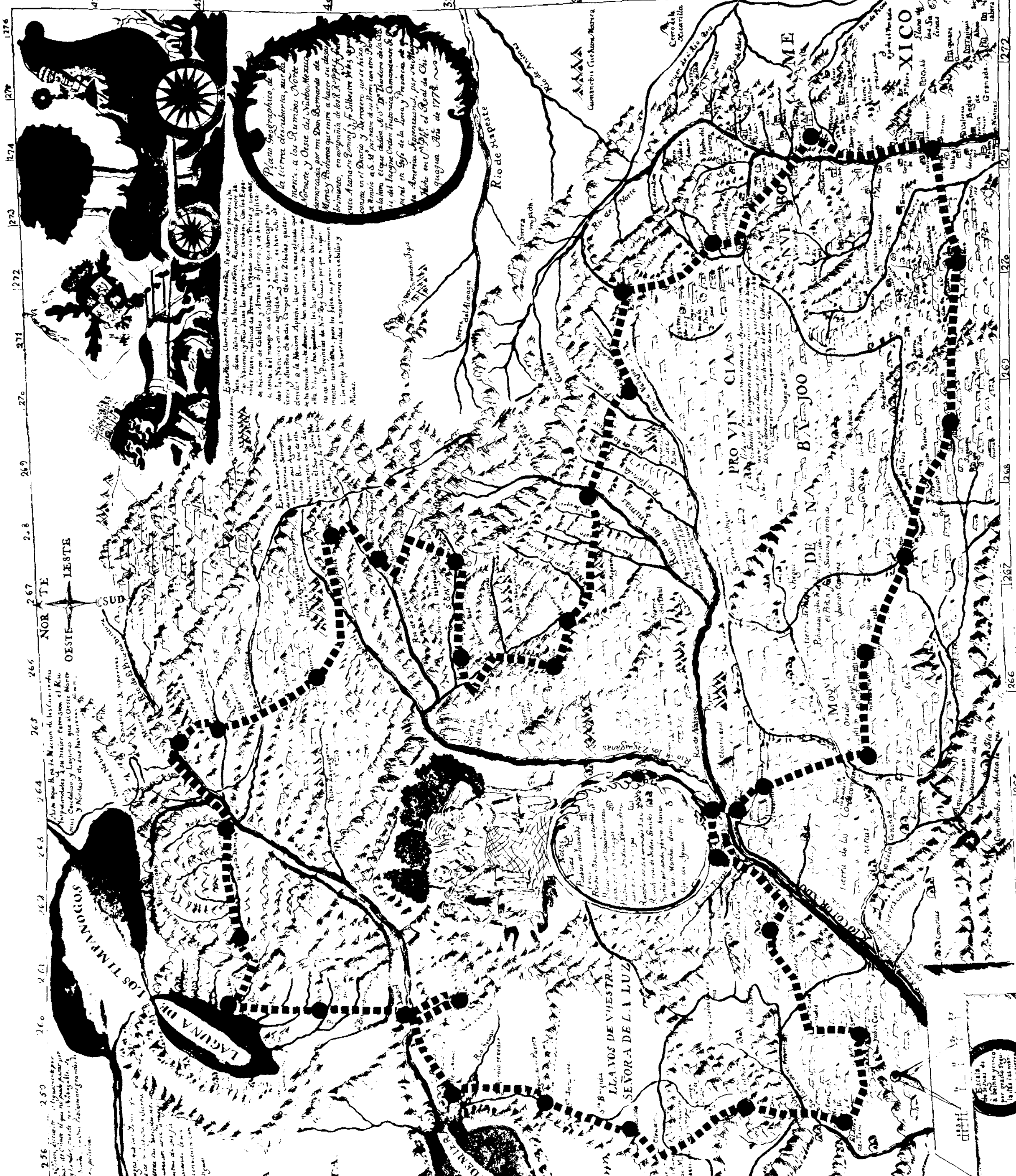

Figure 1. Miera's Map

Courtesy Utah Historical Society

Indeed, Etienne Provost may well have beaten Bridger to its desolate shores - but there is no definite proof of this. It is known that Peter Skene Ogden encountered Provost on Weber River at the present site of Mountain Green on May 22, 1825 and learned that he (Provost) and his twenty-five men had wintered in that vicinity that season - 1824-25. (David E. Miller, "Peter Skene Ogden's Journal of His Expedition to Utah. 1825," Utah Historical Quarterly, April, 1952). Provost and his men might very well have followed the Weber to its point of discharge in the lake, or at least to a point from which the lake could have been seen. It is well known that he and his men were treacherously attacked by Indians somewhere in the vicinity during the fall of 1824. This incident has been "guessed" all over the area - it might well have occurred near the mouth of Weber River. It could also have been on the Jordan River which at one time carried Provost's name (Arrowsmith map, 1835), but since Provost left no record of his activities the question remains a moot one.

Earlier claims for Jedediah Smith and Peter Skene Ogden as possible discoverers of the lake are now known to be without foundation.

In 1826 four men in bullboats circumnavigated the lake in search of possible beaver streams. After three weeks of privation on the lake this party returned to report that no major streams entered it from the west and that they had found no outlet. Theirs is the first report tending to more or less accurately place the lake at the bottom of an interior basin.

After having discovered the Humbolt River in 1828, Peter Skene Ogden approached the northwest arm of Great Salt Lake from present-day Nevada and reported that the lake had no outlet (*Ogden's 1827-29 Journals* published by Hudson's Bay Record Society, 1971, London, England).

In 1833 Captain B. L. E. Bonneville sent Joseph Reddeford Walker on an expedition to California via the northwest end and west side of the lake. From information obtained from that expedition emerged Bonneville's rather famous map of 1837 - the first to actually show basic elements of the Great Basin and Great Salt Lake with interior drainage only (figure 2). On this same map the lake is labeled "Lake Bonneville," the earliest use of that title. It was doubtless from this source that Grove Karl Gilbert conceived the notion of giving Bonneville's name to the huge predecessor of Great Salt Lake. Gilbert, a better geologist than historian, mistakenly understood that Bonneville had been the first white man to see Great Salt Lake. Actually, Bonneville never did see the lake.

The first "scientific" examination of the lake was undertaken by John C. Fremont in 1843. (John C. Fremont, Report of Exploring Expedition, Washington D. C., 1845). On that occasion Fremont, with four companions, launched his "India rubber boat" on the lower Weber River and paddled out to the island which now bears his name. From the island's peak Fremont and Charles Preuss (cartographer of the expedition) scanned the surrounding country with a spy glass and drafted a map based on their observations (figure 3). This rather remarkable map shows various lake islands quite accurately placed as well as the mountains and streams of the region.

Fremont's report, published in 1845, called attention to the fact that he had accidentally left the cover of his spy glass at the island's summit. As a result, almost every visitor to the spot has hunted for the lost object. But they seek in vain, for the brass cap was actually found by Jacob Miller in the mid 1860's when the Miller brothers of Farmington, Utah were using Fremont Island as a stock range. For many years the cap was an object of interest in the Miller home. However, it has subsequently been "lost" again.

While Fremont and Preuss were busily engaged in mapping operations, Kit Carson and companions passed the time carving "a large cross" on the face of a peculiar rock formation near the island's summit. Actually, the cross, a true crucifix, is only about seven inches in length. It is very well preserved and has been an object of curiosity and interest for most people who have climbed the steep slopes to the island's crest (figure 4).

While at the lake, Fremont determined its elevation (4200 feet above sea level) and obtained 14 pints of salt from five gallons of lake brine evaporated over a camp fire.

In 1845 Fremont was again exploring the lake. (John C. Fremont, Memoirs of My Life, Chicago, 1887). On that occasion he and his men rode horseback from the mainland to the south end of Antelope Island which he named in honor of a very successful antelope hunt there. After an exploration of the lake's south shore, Fremont struck a course for Pilot Peak (which he named after having pioneered the first expedition from the site of present-day Grantsville westward across the Great Salt Lake Desert). Unknowingly he had blazed a trail soon to become known as Hastings Cutoff and famous because

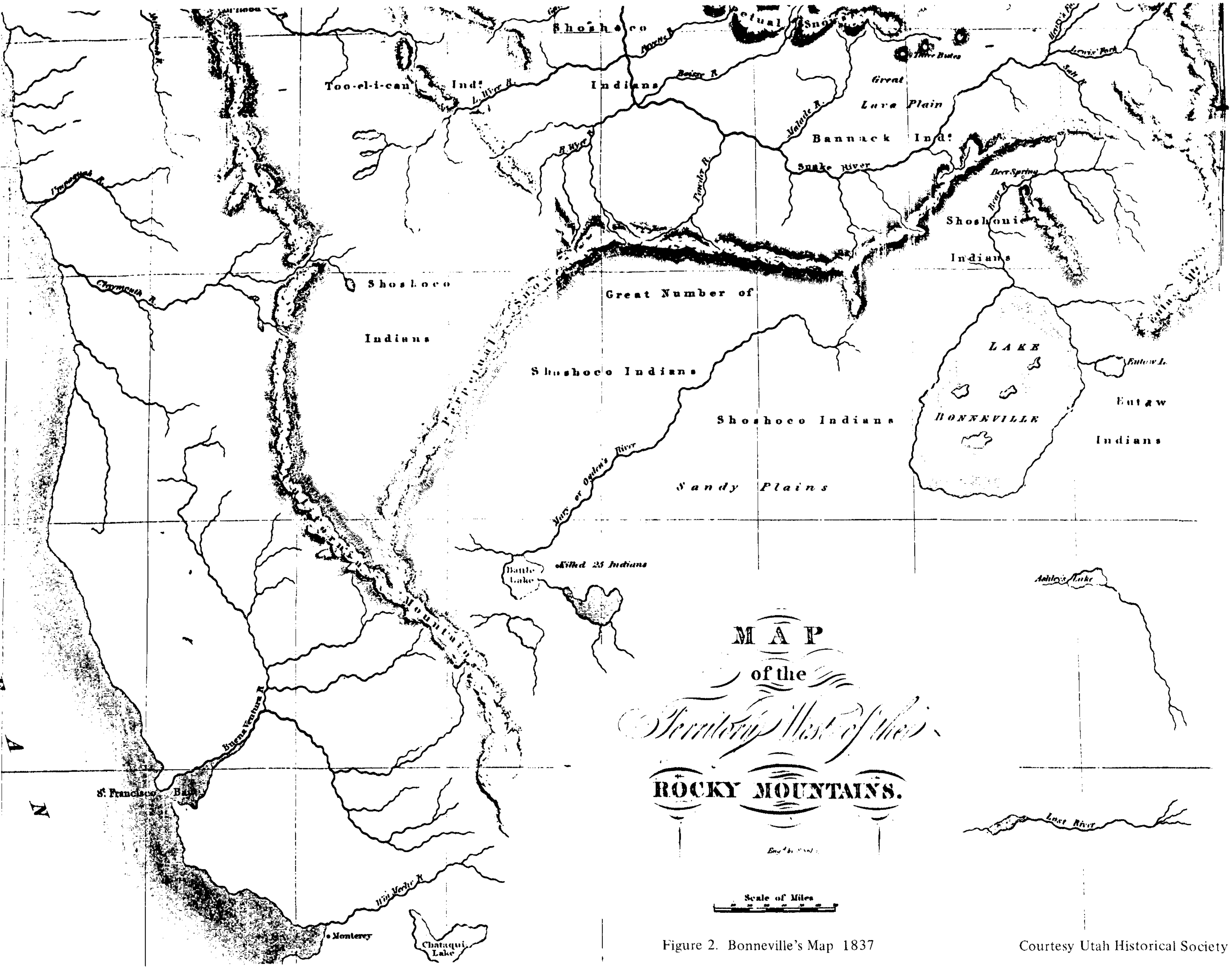

Figure 2. Bonneville's Map 1837

Courtesy Utah Historical Society

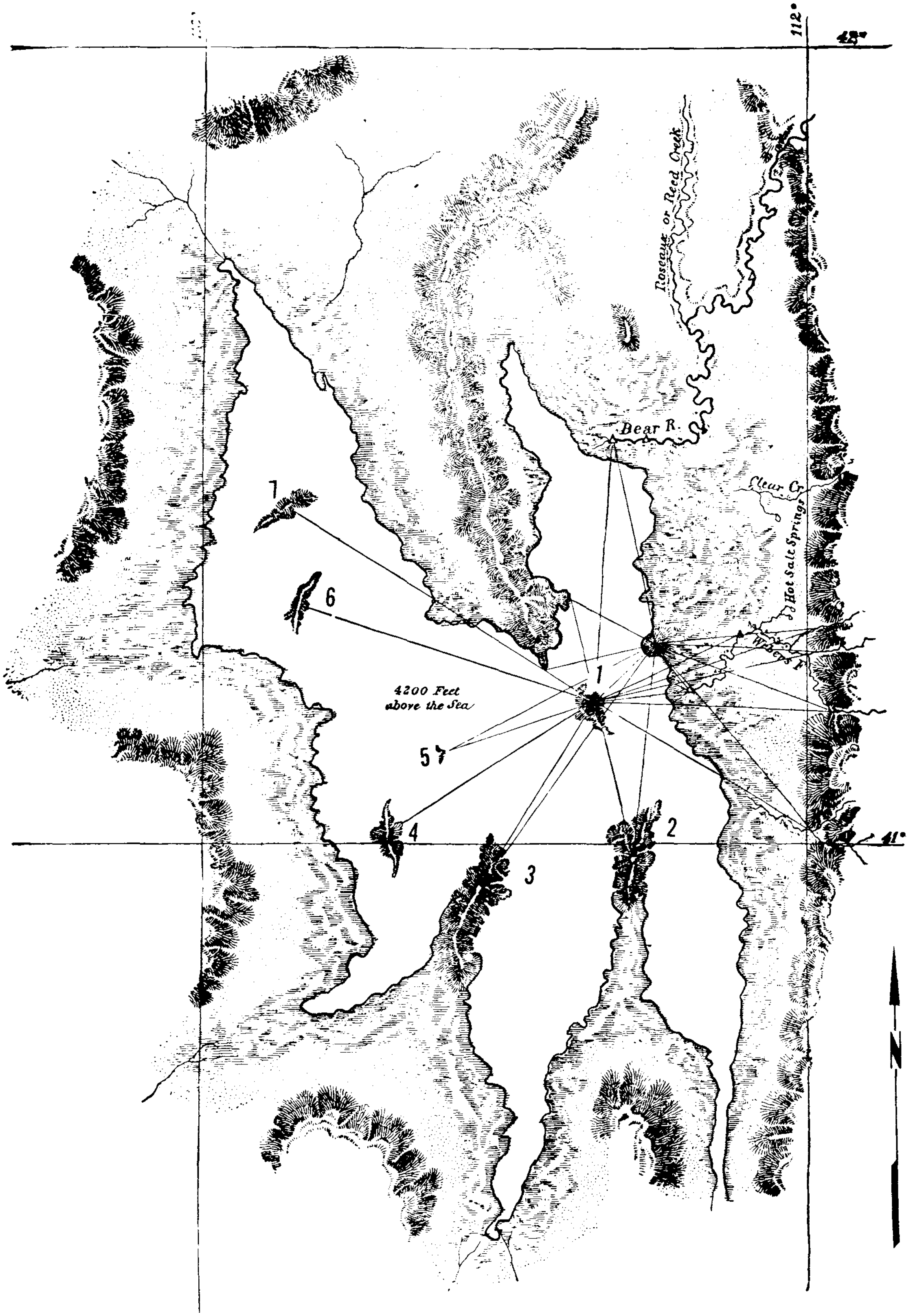

Figure 3. Fremont's Great Salt Lake Map, 1843

Courtesy Utah Historical Society

of the hardships endured by the Donner Party of 1846.

One of the most significant events in the lake's history was the survey conducted by Captain Howard Stansbury (Exploration and Survey...Great Salt Lake, Philadelphia, 1852). In 1849 Stansbury circled the lake on land. His descriptions of the desolation found along the west shore are very graphic. The following year Stansbury and his crew made a complete survey of the lake. Triangulation stations were established on every island and on significant points along the shore for purposes of accurate cartographic work. The whole lake was sounded for the first time. Stansbury also named several of the islands: Fremont; Gunnison (For Captain John Gunnison); Carrington (for Albert Carrington); Stansbury; Egg, and Hat.

Since 1850 several important explorations of the lake have been completed. Special mention should be made of the Fortieth Parallel survey under the direction of Clarence King in 1869-70 which made a complete survey of the lake. At that time the lake was relatively high and the map drawn as a result furnished an interesting contrast with Stansbury's 1850 map.

In 1878-80 Grove Karl Gilbert headed a group that made a thorough study of the shore lines of ancient Lake Bonneville (Lake Bonneville, 1890).

After 1880, numerous explorations and surveys of the lake were made, chiefly for the purpose of water analysis and study of the island bird rookeries.

Dr. T. C. Adams conducted a very significant survey of 1934-35 as part of his study of water resources of the Great Salt Lake region. At that time the lake was at its lowest recorded level to that time. Adams superimposed his map, the King Survey map and Stansbury's map on the same sheet to graphically show the comparative lake area at three periods of its history.

OCCUPATION OF THE ISLANDS

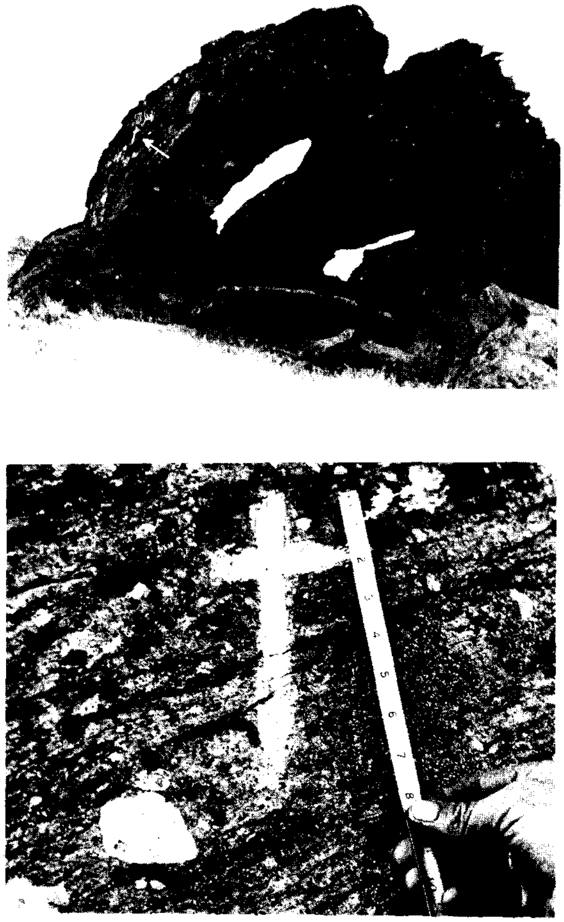

Figure 4. Kit Carson Cross

Several of the lake's islands have been occupied from time to time. During the 1890's Alfred Lambourne homesteaded Gunnison Island, built a cabin of native stone and attempted to establish a vineyard. He planted over 1,000 vines of various kinds, but lack of water for the plants destined the experiment to failure. While Lambourne was making his vineyard attempt, George Frary spearheaded a movement to harvest the extensive guano deposits found on the same island. The Utah Guano Company, operated for three years, shipped rather significant quantities of guano to the mainland, but the venture was not financially successful and had to be abandoned.

Charles Stoddard filed a homestead claim on Carrington Island in 1932, built a cabin (figure 5) but gave up when the well drilled on the island produced nothing but salt water. Attempts to settle Fremont and Antelope islands have been more successful.

Antelope Island

John C. Fremont and his party were apparently the first white men to visit Antelope Island, September 18, 1845. On this occasion he gave the island its name. Although it was later commonly called Church Island, (and still is by many people in the vicinity) the name

Figure 5. Charles Stoddard Homestead on Carrington Island.

Fremont gave it has become very well established. After Fremont, probably the next white men to visit the island were members of the "Mud Hen" crew who made a brief lake survey in 1848.

The first white man to live on Antelope Island was "Daddy" Stump, an old mountaineer, who was there before the Mormon Church took over. Stump built a cabin consisting of cedar post uprights and a dirt floor, near a fine spring. He also planted an orchard and a garden. Peaches produced in this orchard were small, but were Utah's first homegrown peaches.

When the Mormon Church decided to use the island for a stock range in 1849, Fielding Garr was sent there as herdsman and caretaker. He built a five room structure of adobe bricks made on the spot (figure 6). The building still stands and may well be the oldest building in Utah still being used for the purpose for which it was constructed. The Church herd consisted of cattle and horses collected as tithes and privately owned stock placed under church care.

September 14, 1850 the General Assembly of the State of Deseret met in the Bowery at Salt Lake City and incorporated the Perpetual Emigrating Company. Section seventeen of the act of incorporation states: "The islands in Great Salt Lake, known as Stansbury's Island and Antelope Island, are hereby reserved and appropriated for the exclusive use and benefit of said Company for keeping of stock, and etc." (L. D. S. Journal History, September 14, 1850). However, leading church men as well as the "Company" itself pastured their stock on the island. By 1856 this seems to have become a common practice, the island being divided among the various men for this purpose. Brigham Young found it rather entertaining to take friends to the island for weekend visits.

After several transactions and developments through the years, most of the island eventually came under the control of J. E. Dooly, and White and Sons Company. The latter concern leased the Dooly holdings and used the island as a cattle range until 1903. Purebred stock was introduced and a fine herd of cattle roamed the island. In 1903 White and Sons sold to Ernest Bamberger. Shortly thereafter, the Island Improvement Company was organized with J. E. Dooly as president and general manager. For several years the cattle industry operated under the name of "Island Ranching Company". However, the Anschutz Livestock Company subsequently purchased the island's ranching interests.

The Island Buffalo Herd

One of the interesting features of Antelope Island since the turn of the century is its herd of American bison. The island had once been the native habitat of both buffalo and antelope as attested by Osborne Russell (who made annual trips from Fort Hall, at Pocatello, Idaho, to the mouth of Bear River to feast on duck and heron eggs). (Osborne Russell, *Journal of a Trapper*, and John C. Fremont). Buffalo had roamed freely in the Great Salt Lake valley and along streams flowing into the lake. Peter Skene Ogden was glad to find them when in the lake vicinity in 1828, and the Walker Expedition of 1833 killed many of them on Bear River and on the northwest shores of the lake. These animals, however, had long since left the Salt Lake vicinity when the Mormons arrived in 1847.

It was early in the 1890's that the idea was conceived of restocking Antelope Island with buffalo. William Glassman was evidently the first to promote the scheme. In 1891 he purchased twelve head from "Buffalo" Jones of Texas and had them billed to Ogden. However, they were missent to a small siding west of Garfield. Two years later these animals were purchased by John E. Dooly and J. H. White for planting on Antelope Island. The buffalo were shipped to the island in 1893.

J. W. Walker and George Frary were in charge of this special shipment. A flat-bottomed cattle boat was partitioned into special compartments to keep the animals in order during the voyage. "It took several trips to get twelve buffaloes across to the island".

In stocking the island with buffalo, Dooly and White had two purposes in mind, one of which was to preserve the rapidly disappearing "denizen of the plains". The other was for breeding purposes. An attempt was made to cross the buffalo with hornless Galloway cattle. This novel experiment was not successful; only one "Cat-lo" was produced. However, the first objective was achieved. The small herd grew rapidly, and under very limited hunting and slaughtering permits, it soon numbered over 300 head. Being almost completely isolated, the animals were not molested by constant crowds of curious sight-seers and developed much as they might have a hundred years earlier on the open plains. In filming "The Covered Wagon" in 1922, Hollywood producers gained permission from the island owners to shoot the buffalo scenes there, with great success.

In 1926 the interest of the island owners shifted to sheep and cattle at the expense of the buffalo herd. It was decided at that time to conduct a "last great buffalo hunt". Sportsmen from far and near attended, paying $300 each for the privilege of shooting their own game on the island. The hunt was a great success, and the herd was reduced to thirty cows and about twenty-five calves. It has been kept at about this number since 1926.

Fremont Island

After Stansbury's survey of 1850 there were no reported visits to Fremont Island until 1859 when the Miller brothers from Farmington, Utah decided to stock the island with sheep and cattle. Others had possibly visited the island, but it had not been put to any practical use. Henry W. Miller's journal records the beginning of this enterprise:

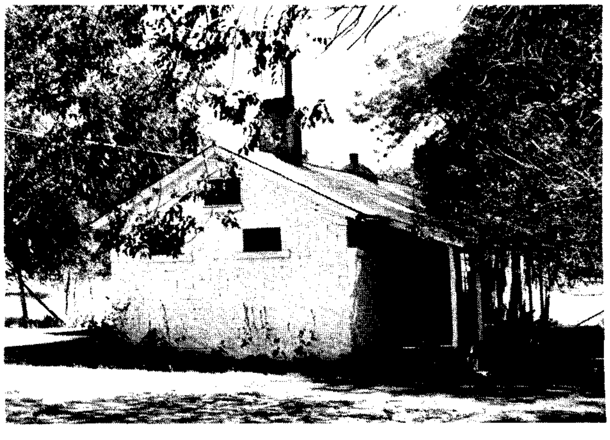

Figure 6. Fielding Garr Home on Antelope Island.

> In the Spring of 1859 I went to the Island known as Fremont Island in the Great Salt Lake and explored it, accompanied by my brother Daniel and Quincey Knowlton. I built a boat and after we had sheared our sheep we took them to the island. There were about 153 head. It was said that there had never been any stock on that Island before we took our sheep there. This island is about 25 miles from Farmington and about six miles north of Antelope Island, where the Church had some stock. This Fremont Island is opposite the mouth of Weber River. After we had taken our sheep on the island, it became known locally as Miller's Island. It proved a good place for sheep, it being about four miles from the mainland and no wild beast on it to destroy the sheep. The herd increased very fast in number and needed no herder to take care of it. We used to visit the Island every few weeks to clean the spring, and at times of lambing, shearing and marketing we spent days on the island at a time. (Journal of Henry W. Miller, unpublished).

In this way, Fremont Island was occupied and for the first time put to practical use. Henry W. Miller and Daniel A. Miller formed a partnership for the enterprise. Their sons and grandsons soon took the most active part in the business, Jacob Miller being one of the most active participants.

Probably the most romantic episode in the history of the lake is the story of Judge U. J. Wenner and his family who made their home on Fremont Island, 1884-91. Mr. Wenner was afflicted with tuberculosis and hoped that the fresh lake air might prove beneficial and perhaps bring about a complete cure.

The Wenner family built a fine home from rock found on the island (figure 7), moved their library and fine furniture to the site and settled down to stock raising. All went well for a few years; the judge's health seemed to be improving. Then quite suddenly he suffered a serious relapse and died before help could be summoned from the mainland. When help finally arrived the body was laid to rest in a grave on the high ground behind the house. Mrs. Wenner with her three children left the island. (David E. Miller, editor, "A Great Adventure on Great Salt Lake", Utah Historical Quarterly, Summer, 1965 and Western Humanities Review, October, 1939). When her mother died later in 1942, Blanche Wenner, who had lived on the island as a child, decided to place her mother's mortal remains beside the judge's grave. Subsequently Charles Stoddard, who was leasing the island as a sheep range, built an appropriate grave marker from stones taken from the old home and built a fence around the grave site. A bronze plaque now

Figure 7. Wenner Family Home on Fremont Island.

carries the vital statistics of the couple who had brought civilization and romance to a desert island in the lake.

Fremont Island was also the scene of one of the strangest episodes of Great Salt Lake history. This was the exile of John Baptiste on that island in 1862. Baptiste had been hired as a grave digger at the Salt Lake City cemetery. However, because of some peculiar mental quirk in his make-up, he could not leave the dead buried and began digging into the graves and robbing the corpses. Some of the stolen articles of jewelry and clothing were then pawned in local shops and eventually put up for sale by the broker. Naturally, people soon began to recognize items they had buried with their loved ones. Thorough investigation and search revealed that Baptiste had robbed over 300 graves and had in his possession several boxes full of clothing taken from the dead.

The grave digger was tried and committed to exile on an island in the Great Salt Lake. Henry W. Miller, who then was using Fremont Island as a sheep range, assisted the sheriff in transporting the prisoner to that desolate place. Several weeks later, however, when the Millers returned to the island to make a routine check, Baptiste was gone. Apparently the exile had torn planks from the cabin for a raft and escaped to the mainland. He was never seen in the vicinity again.

GREAT SALT LAKE RESORTS

Since the arrival of the Mormons in Salt Lake valley in 1847, Great Salt Lake has been relatively popular as a place for swimming. Probably the chief reason for this popularity is the extreme buoyancy of the water. Enterprising people soon began supplying bathing facilities at the most popular locations.

Black Rock was one of the earliest swimming resorts, having been visited by Brigham Young and an exploring party July 27, 1847. Although some bath houses had been established there before 1880, it was not until that time that a systematic attempt was made to develop it into a satisfactory "watering place". Old eyesores such as tumbledown fences, stables and corrals were cleared away and a hundred new bathing houses were built of good lumber. Soon cottages were available for rent by the season. Attractions at Black Rock included: an elegant dance hall, a bicycle track, a pier for boats, and "City Creek" drinking water.

About the same time, Garfield Landing was developed as a swimming resort as well as a steamship pier. A steamboat, the "General Garfield", was securely moored to the 400 foot pier to act as a restaurant and recreation hall. A Salt Lake newspaper announced that $8,000 had been spent on improvements to provide excellent swimming facilities.

In the immediate vicinity of Garfield Landing the Union Pacific Railroad Company erected a resort known as Garfield Beach at a cost of $75,000. It, as well as Garfield Landing, was named in honor of U. S. President Garfield, who had cruised on the lake. Garfield Beach rapidly developed into one of the most popular lake resorts of its time. It boasted a hotel, dancing pavilion, regular concerts during the summer season as well as excellent swimming facilities. This resort was located about 20 miles west of Salt Lake City.

Still farther west, on south shores of the lake, another resort appeared. This was at Lake Point, the location of the first wharf of any importance built on the lake. It was to have been the chief pier for shipping between Corinne and points on the south shore of the lake. When John Muir visited Utah in 1877, Lake Point was a popular resort and was visited by him. Mr. Muir praised the resort, stating that it would become very popular if people but knew half its merits. Fine hotels, dance halls, bath houses, etc. were found there.

In 1866 the Lake Park resort was established west of Farmington. Lake Park became the most popular of all the lake resorts of that time. Founders of the new recreation center were George Goss, Simon Bamberger, Jacob E. Bamberger, W. H. Bancroft, and C. W. Bennett. It was a $100,000 corporation and covered 120 acres. This resort boasted the best in everything: restaurant, bar, orchestra, fine pier, pleasure boats, shooting galleries, bowling alleys - in short, every attraction that could be thought of to make a stay at the resort enjoyable. Later some of the buildings were moved to Lagoon.

Lake Shore resort at Syracuse was constructed and opened to the public on July 4, 1887. It was located near the site of the Syracuse salt works and provided bathing, boating, dancing, and the regular types of recreation associated with the other resorts. It was largely because of its location, well off the Salt Lake - Ogden railway line, that a spur was constructed from Clearfield to the resort, and regular passenger trains reached it from both Ogden and Salt Lake City. Some of the pilings that supported the buildings can still be seen at the entrance of the highway leading from Syracuse to Great Salt Lake Park on Antelope Island. A large sign placed at the site in 1978 gives a brief history of the resort.

Saltair (figure 8), was the last constructed of the old resorts as well as the greatest. The rousing success of this new recreation center drove the others out of business. Better location and first class facilities provided more competition than the other establishments could meet. Furthermore, the receding lake left most of the resorts high and dry in the late 1890's while Saltair, built over the lake in five feet of water, still furnished excellent swimming.

Pile driving for the structure proved extremely difficult because of a very hard, seven foot layer of sodium sulphate just beneath a few inches of sand on the lake bed. Steam had to be applied and holes melted through the "soda". After the piles had been properly placed the material settled around the uprights again making them exceptionally solid. Although fire swept the resort in 1925, these pilings were not destroyed and the resort was rebuilt on them.

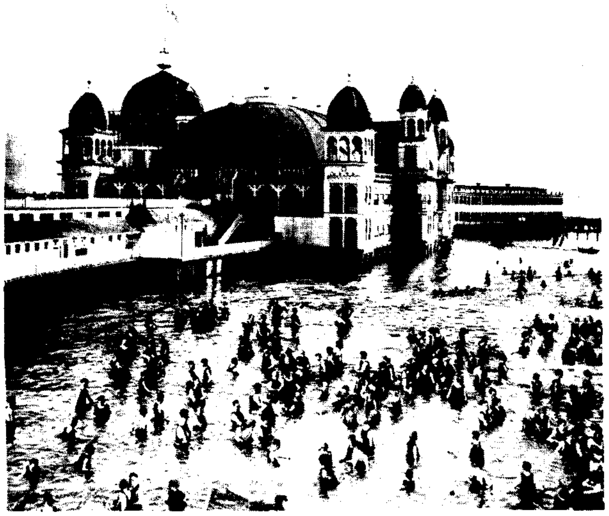

Figure 8. Saltair Resort

Saltair was built by officials of the Salt Lake and Los Angeles Railroad Company at a cost of over $350,000 and was completed in 1893. It had a five-story pavilion with a dance floor large enough to accomodate 1,000 couples. One of its special attractions was its unique electric lighting system.

Saltair rapidly gained in popularity: 160,000 persons were visiting it annually by 1900. For many years, before the 1930-40 low cycle of the lake, "to visit Utah without viewing the grandeur and beauty of Saltair, the largest and most attractive bathing resort in America, would be like visiting Jerusalem and neglecting to see the site of the old Garden of Gethsemane" (George Q. Cannon, City of the Saints). When the lake fell to its low level during the 1960's Saltair was left high and dry; its popularity declined; it was literally abandoned. Several attempts to restore the rapidly deteriorating buildings failed and on November 12, 1971 fire destroyed all that remained. All debris has been cleared from the area; nothing is now left of the once proud "Lady of the Lake".

Other Great Salt Lake resorts were: Sunset Beach, established in the 1930's, and Silver Sands, built in connection with the Salt Lake Boat Harbor. These resorts also suffered as the lake declined during the 1960's and were virtually abandoned before 1975 when the State of Utah acquired more than four miles of south shoreline to create the Great Salt Lake Park–South Shores. This park includes all the shore between Black Rock and Saltair and is rapidly being developed into better bathing and boating facilities. Of special interest is a major development at the Salt Lake Boat Harbor where slips for 200 sailboats of various sizes and colors provide high quality sailing activity. Plans are under way for an additional 300 slips.

ATTEMPTS TO PLANT SEA LIFE IN THE LAKE

Although no fish or large molluscs live in the lake, attempts have been made to propagate oysters, fish, and eels at the mouths of streams. Beadle, writing in 1879, pointed out that:

> Oysters have been planted at the mouths of the rivers but when the wind has been up stream, the dense brine setting in from the lake

> killed them. Jordan was stocked with eels a few years ago, but they floated down into the lake and died. One was picked up long afterward on the eastern shore, completely pickled. The finder cooked and ate it, and found it very palatable. (J. H. Beadle, Western Wilds, 178-179).

That the eel discharged into the lake would be pickled is, no doubt, true. However, that it would be eaten and found palatable is very doubtful. Naturally, fish do occasionally drift into the lake from the various streams that feed it and from Farmington Bay through the Syracuse-Antelope Island causeway. Skeletons of large fish are often found along the shoreline.

Probably the earliest reference to the possibility of planting oysters, salt water fish, crabs and lobsters in the lake appears in the *Deseret News* early in 1853. This article suggested that the salty bays could be tempered to suit the needs of the various forms of life to be introduced. At the mouths of rivers and in certain bays, artificial dams could be constructed and the salt content of the water controlled by strict regulation of the amount of fresh water running into the embayment. The article contains rather definite plans for the construction of such dams, spillways, etc. It further points out that all types of shell fish as well as salt water fish could live in the same ponds, producing enough sea food to supply all the needs of Utah. Fish would find streams satisfactory for spawning. Shad, salmon, and other salt water fish are mentioned as especially adaptable to lake culture.

However, there are few references to actual attempts to plant sea life in the lake. In August 1882 the Deseret News carried this item:

> Fish Commissioner Eugene G. Blackford received an order from Henry House at Corinne, Utah for two barrels of seedling oysters which he intends to plant and cultivate in Great Salt Lake when a suitable place can be found (August 12, 1882).

Much hope was held for the success of the experiment. Two days later the Deseret News carried a second article:

> An effort is to be made once more to raise oysters in the Great Salt Lake...A thorough trial was made several years ago at the mouth of Weber River. The seedling oysters arrived in good condition and were planted and tended carefully. But the conditions were found to be unfavorable. Too much salt impregnated the water at a distance from the river, the mud that washed into the lake from the river's mouth was unsuitable to bivalves, and the oysters soon "petered" out leaving not a sign of their existence.
>
> It is possible that Mr. House may be more successful at the mouth of the Bear River, than the promoters of the scheme were at the influx of the Weber, but his attempt is not the first of the kind. We should be very much pleased to be able to chronicle the successful cultivation of the oysters in the great saline lake of the North American Continent.

Another brief reference to these failures was made in 1891: "Efforts have been made to propagate fish, oysters, etc. in the lake, but without success. They all die". (A. B. Carlton, Wonderlands of the Wild West, 31). Very little publicity was given the attempts.

LAKE SHIPPING: FROM BARRIER TO HIGH ROAD

Boats and Boating

Great Salt Lake has been an asset as well as a barrier to transportation. Shipping on the lake was a relatively important activity during the second half of the 19th century, and some rather grandiose schemes were created to capitalize on the possibilities of using it as a means of transportation for both freight and passengers. However, rapid development of railroads and decline of the lake level became combined forces which limited and almost eliminated lake boating as an economic enterprise.

The earliest boat known to have plied the lake waters was the bullboat of the four explorers who circumnavigated it in 1826. While it is highly probable that the other trappers at times launched boats on the lake, there is no record of such activities. Rafts were used by Indians to reach Antelope Island, as recorded by Osborne Russell in 1841. When Fremont and his party traveled to Fremont Island September 9, 1843 they used an eighteen foot "India rubber" boat. Five years later the first Mormon craft, the "Mud Hen", carried its crew to some of the lake islands. 1850 saw Stansbury's "Salicornia" launched on the lake. This was the largest craft yet to appear on Great Salt Lake and the first to make extensive trips on its water.

With the settlement of Salt Lake Valley and occupation of the lake islands many new boats made their appearance. One of the earliest of these was Brigham Young's boat the "Timely Gull". Built chiefly as a ferry to transport stock to and from Antelope Island, this 46 foot boat was launched on the Jordan

River, June 30, 1854, and christened by Governor Young himself. The new ferry was designed for a stern wheel to be propelled by horses using a treadmill arrangement. Dan Jones was placed in charge of the new craft which soon began hauling salt, cedar posts and cattle from its anchorage at Black Rock to and from various points on the lake. The "Timely Gull" was wrecked in a storm in 1860.

Early boating activities on the lake were limited to the hauling of sheep and cattle to and from the islands, freighting salt, transporting cedar posts from Promontory and other north shore points, and shipping ore from mines opened on the west lake shore opposite Carrington Island. Many sailboats were built and used for these purposes, and piers and landing docks were built to accomodate them. One dock was constructed at Lake Park resort west of Farmington, with a railroad connection. Lake Point and Garfield Landing on the south shores of the lake, and Corinne on Bear River, were other important shipping points.

With the coming of the railroad, more ambitious schemes for lake transportation were formulated. As railroad surveyors rounded the north shores of the lake, General P. A. Connor saw a future profit in transporting railroad ties and telegraph poles from the south end of the lake to north lake points for use on the new road. As a result, he built the first steamboat to ply lake waters. This boat was called the "Kate Connor". The venture must have proved successful, for the next year Connor constructed and launched a second steamer, the "Pluribustah", of 100 tons burden. The "Kate Connor" was bought by Christopher Layton in 1872 for the purpose of transporting sheep to Antelope Island. What eventually became of the two boats is not known.

With the completion of the transcontinental railroad the small town of Corinne began to assume real importance. Located at the railroad crossing of Bear River, the town fathers saw in their village the future metropolis of Utah. They hoped to have it declared the junction point of the Central and Union Pacific railroads and laid plans for its future. Freight wagons were busy bringing ore from Montana mines to Corinne for shipment to smelters; rich ore deposits were being discovered in the Oquirrh mountains south of the lake. In order to capitalize on the ore business, a smelter was built at Corinne to handle the rapidly growing ore trade. Closely associated with the smelter was the plan to make extensive use of the Great Salt Lake as the cheapest and easiest way to bring the ores from the south end of the lake to the smelter. This entailed the construction of a large boat, the "City of Corinne" for the purpose.

The "City of Corinne" was a 300 ton Mississippi River-type stern wheeler with two stacks and three decks. Engines for the new boat were made in Chicago and shipped around Cape Horn to San Francisco, reaching Corinne by rail. From California came the redwood for hull and beams. The 70 foot craft was launched on May 24, 1871, and practically the whole valley population turned out to witness the event. General J. A. Williamson, Mayor of Corinne, officiated at the christening. "The first trip was made to Lake Point in 1872, with machinery for the smelter at Stockton (Utah) and the boat returned with ore from the Tintic district and Nevada". (W. P. A. Writers' Project, Utah, *A Guide to the State*, p 363).

The "City of Corinne" made several trips between Corinne and Lake Point, hauling cattle, ore, and passengers. The route, shown on maps of the time, was from Corinne down Bear River, through Bear River Bay, east of Fremont Island, then between Fremont and Antelope islands to Lake Point or Black Rock on the south shore. However, obstacles soon hindered the progress of this new freighting venture: Bear River waters decreased in volume and sand bars blocked its entrance. The "City of Corinne" was unable to make port with her heavy load of ore, and the project had to be abandoned. Captain C. A. Dahl converted the "City of Corinne" into an excursion boat. As such it cruised the waters of Great Salt Lake for many years, stopping at the resorts where landing facilities were available: Black Rock, Lake Point, Lake Park, and Garfield Beach.

Early settlers along the east shore of the lake between Salt Lake City and Ogden often saw the boat, ablaze with lights, and heard music from the orchestra aboard. And in the daytime the American flag proudly preceded the boat's two smokestacks. Lower decks were used for transporting herds of cattle and sheep to the islands in the lake where they were pastured during part of the year. (Kate Carter, ed., *Heart Throbs of the West*, IV, 166).

Many prominent people cruised the lake aboard the "City of Corinne", among them James A. Garfield, "who was, it is said, first nominated to the Presidential office by a party of gentlemen and ladies with whom he was making a cruise on the lake...", (August 12, 1872, C. R. Savage, Views of Utah, 12). In honor of Garfield's visit the name of the boat was changed to "General Garfield". A few years later the craft was moored to the pier at Garfield Landing Resort to become a restaurant and recreational center. In 1904 fire swept the resort and the "General Garfield" was burned to the water line.

Another steamboat, "The Lady of the Lake", was launched on the lake on August 8, 1871. The craft was built in New York and given a test run from a Brooklyn pier June 23 before being dismantled for shipment for Salt Lake City. According to the New York *Herald* the new craft was the "smallest steamer afloat", drawing only 18 inches of water. She was only 50 feet long and 10 feet wide.

Numerous other boats, built and operated on the lake, are mentioned in various accounts of Utah pioneers, but their history and activity remain virtually unknown.

THE LUCIN CUTOFF

By the 1890s the railroad track between Corinne and Lucin around the lake to the north had become a major "bottleneck" on the whole transcontinental line. The climb of over 600 feet to Promontory Summit required three engines and restricted the load that could be pulled. When the old line reached its capacity of 600,000 tons a year, railway officials began casting about for a means of overcoming this obstacle.

Distance was not as important an obstacle as grade, so the railway officials first considered building a line southeast from Lucin to Salt Lake City by way of the west shore of the lake. This would afford a level road and only the southwest arm of the lake would need to be crossed. The scheme was given serious consideration before the Lucin-Ogden route across the lake was selected. Plans for a cutoff had been made by Oliver P. Huntington but the actual construction of the new road was under the direction of Edward H. Harriman, president of the Southern Pacific Company at that time. After having made complete lake soundings and surveys of the proposed new route, work was begun in March 1902. Approach to either side of the lake was relatively simple; the real task began when the first piles were driven on August 2, 1902.

The Lucin-Cutoff shortened the route between Ogden and Lucin by 43.77 miles and the time by seven hours; 3,919 degrees of curvature were eliminated and 1,515 feet of grade avoided. The sharpest curve on the new line is at Promontory Point and is a curve of only 1.5 degrees, compared with curves of 10 degrees on the old line. The steepest grade on the cutoff (21 feet to the mile) lies west of the lake. A climb of as much as 90 feet to the mile was encountered on the old route.

The final rails were laid in about the middle of the west arm of the lake on November 13, 1903. Celebration of the occasion was held November 26, with hundreds of celebrities attending. No special spike driving ceremony was held. The road was turned over to the operations department December 31, 1903, but regular runs were not scheduled over the new line until March 8, 1904, because of trouble on the fills. The first regularly scheduled train to cross the new cutoff was 25 cars bearing Asiatic freight. Passenger service was not inaugurated until September 18, 1904.

Note: The original paper by Dr. Miller included sections on lake levels and the Great Salt Lake Authority. These have been omitted because the same subjects are discussed elsewhere in this volume in greater detail.

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* * *

David E. Miller

IN MEMORIUM

Professor David C. Miller's impact in bringing to life the early history of the intermountain area is immeasureable. He was Chairman of the Department of History at the University of Utah, and Director of the Western History Center. He also served as Secretary of the Organization of American Historians and as President of the Utah Academy. His untimely death at the age of 69 found him still actively engaged in research on the history of Utah and of the west.

LEGAL BATTLE OVER OWNERSHIP OF THE GREAT SALT LAKE

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In the early 1960's the Bureau of Land Management of the United States Department of the Interior served notice on the Utah State Land Board (now Division of State Lands) that it intended to survey a boundary line along the Great Salt Lake to separate state and federal ownership, and that it would locate such boundary line at an elevation of 4201.8 feet above mean sea level, which was the same elevation as the water level on January 4, 1896, when Utah obtained statehood. Utah believed that the State owned the Lake, the water-covered bed, and the shorelands located within the surveyed meander line as officially surveyed and approved by the United State Government. This claim was based on the "Equal Footing" Doctrine, which holds, among other things, that all States receive at the date of statehood title to all navigable waters and their beds. Since statehood, Utah assumed control of the lake and shorelands, and had managed them for various uses, including recreation, wildlife, mineral development, grazing and a variety of other purposes.

At this early point in the conflict, the area in dispute was a narrow belt of land around the lake located between the statehood elevation of 4201.8 and the higher elevation of the surveyed meander line. The surveyed meander line did not represent a uniform or consistent elevation, but ranged between about 4202 and 4212 feet above mean sea level, with an "average" elevation of about 4205. The different elevations resulted from the fact that the meander line was surveyed in segments by different surveyors over a period of several decades. The water level of the lake fluctuated and was at different elevations when the different segments were surveyed--hence, a composite surveyed meander line located at various elevations.

The acreage in dispute at this time, being the area of "dry" or exposed shorelands located between the statehood elevation and the surveyed meander line, was approximately 150,000 acres. The United States believed that this land was not a part of the lake at statehood, and had not been a part at any time since statehood.

Utah believed otherwise, and therefore "protested" the proposed new survey by the Bureau of Land Management, and this protest was adjudicated through administrative procedures within the Department of the Interior with an ultimate administrative ruling which held that the United States owned all of the shorelands located above the actual water's edge at any given time. This ruling was based on the administrative conclusion that the doctrine of reliction applied to the Great Salt Lake, and that the only feasible boundary was the water level, however it might fluctuate.

As a result of this decision the United States actually enlarged its claim. Since the "actual" water level of the lake in the 1960's was far below the statehood level (sometimes more than 8 feet lower), the federal claim could, depending on the water level at any particular time, extend to more than 600,000 acres, as contrasted with the 150,000 acres earlier claimed. This administrative decision caused much concern in the State of Utah.

Over a period of several years, various efforts were made in Congress by the Utah congressional delegation to enact legislation that would disclaim any federal interest in the disputed lands and thus "confirm" in Utah title to all lakebed lands located within the official surveyed meander line (which, as indicated above, was located substantially above the water's edge during the 1960's and also above the water level of the lake as it existed at the date of statehood). Largely through the efforts of Senator Frank E. Moss, but with the support and cooperation of the entire congressional delegation, the Great Salt Lake Lands Act was finally passed and signed into law by President Lyndon B. Johnson in 1966. That statute did not confirm in the State of Utah title to any of the disputed lands but it did provide, among other things, that the State of Utah could elect either to purchase the land from the United States at a price to be determined by the Secretary of the Interior or, as an alternative, to bring an original action in the United States Supreme Court to adjudicate the respective claims of ownership of Utah and the United States.

Utah elected to litigate, and filed an original action on March 1, 1967. The litigation was extremely complicated and lasted for a decade before the final round was concluded. The following brief sketch of the litigation will illustrate the five principal phases of the original action.

The first phase related to the procedures to be followed and the parties to be admitted, and involved difficult questions of the "original" jurisdiction of the United States Supreme Court. Several private corporations and other parties attempted to intervene, and the United States supported such intervention, but the State of Utah opposed it. After extensive briefing and several hearings, Special Master J. Cullen Ganey, Senior Circuit Judge of the United States Court of Appeals located in Philadelphia, ruled in favor of Utah by holding that the only admissible parties were Utah and the United States. This determination by the Special Master was upheld by the United States Supreme Court, and the litigation then turned to the merits of the ownership questions.

The second phase of the case addressed the question as to whether the Great Salt Lake was a navigable body of water at the time the State of Utah was admitted into the Union. Everyone had seemingly conceded the navigability of the lake while the various Great Salt Lake bills were being debated in Congress. However, the Justice Department decided to contest the navigability of the lake on the theory that the shorelands were remote and barren, and that in most places along the shore the water was so shallow for several miles lakeward that it would be impracticable to construct docks, wharves, piers or other facilities for meaningful navigation on the lake. It should be noted that this claim by the United States once again expanded the federal claim. If the lake was not navigable, Utah would own no part of the lake--and the United States would own everything.

Thus, Utah contended in response that the lake had demonstrated a physical capacity to support meaningful waterborne commerce whenever and to the extent that the need had arisen, or might arise in the future. The evidence at the hearings on navigation showed that both before and after the date of statehood the lake had been used for a variety of navigational purposes, including recreation as well as transportation of ore, railroad ties, guano and other supplies. One of the most striking illustrations of the navigability of the lake was the construction of the earth-fill causeway by the Southern Pacific Transportation Company in the 1950's, involving a fleet of water craft ranging from huge barges to tug boats, patrol boats and other vessels. Special Master Ganey ruled that the lake was navigable at the date of statehood and that as a result thereof Utah obtained title to the bed, and the United States Supreme Court affirmed this determination by the Special Master.

The third phase of the litigation involved a dispute as to the ownership of the brines and minerals in solution in the waters of the lake and also the minerals contained in the bed of the lake. This phase did not require separate hearings by the Special Master, but was a contest of legal theories directly before the United States Supreme Court as to the necessary implications and consequences that flowed from the Court's earlier decision on navigability. After briefs and motions were filed with the Court, the United States withdrew its claim to the brines and other minerals before the Supreme Court issued its decision on the mineral controversy. The Court thus entered a decree in favor of the State of Utah with respect to mineral ownership.

Perhaps there should be some further clarification at this time of the legal effect of the Court's rulings on navigability and mineral ownership. These rulings made clear that Utah obtained title at the date of statehood to the lake and its bed, including all minerals in the waters and beneath the bed--but there had been no determination as to the actual "boundary" of the lake either at the date of statehood or at any other time. The Great Salt Lake Lands Act contained a provision which required the United States to issue a deed to Utah, quit-claiming the federal interest, and further providing that Utah either had to pay the United States for lands purportedly conveyed by the deed or to litigate the ownership claims and then pay for any lands which the Court determined had passed by virtue of the deed.

Since the question of a "boundary" for the lake had not yet been addressed in the previous hearings, the Court simply concluded that under no theory could the United States any longer claim the lake or any lands covered by the waters of the lake at the date of the deed. In other words, the United States could not claim more than the shorelands located above the water level at the date of the deed. Since the deed was dated June 15, 1967, when the water level was at an elevation of approximately 4194, this meant that Utah owned everything within a boundary line located at an elevation of 4194, and that the belt of land located between 4194 and the surveyed meander line was still in dispute. The disputed area consisted of approximately 600,000 acres.

In the fourth phase of the litigation, the United States claimed the area remaining in dispute under the theory of reliction. Reliction is a common law doctrine which holds that the boundary of a navigable body of water can change if through a gradual, imperceptible and natural process the water level lowers so as to expose shorelands that previously were water-covered, and thus to permanently create new uplands. While natural lakes ordinarily fluctuate to some extent between high-water and low-water seasons during each year, they ordinarily are self-regulating in the sense that they have outlets as well as inlets, and when unusually high volumes of water flow in, then comparably high volumes of water likewise flow out of the lake, thus leaving the lake within a normal range of seasonal fluctuations.

But the Great Salt Lake is unique in that it has no outlet and water can escape from the lake only by the process of evaporation. Thus, during a period of several wet years, the lake tends to rise rather dramatically, and during a period of several dry years the lake tends to shrink dramatically. If the doctrine of reliction had been applicable to the Great Salt Lake as the United States contended, the title of the United States and other upland owners would follow the water's edge as it moved from day to day or month to month. But if reliction did not apply, as Utah contended, the fluctuating water level would have no effect on title to the shorelands and the actual boundary, wherever located, would be stable and permanent.

Special Master J. Cullen Ganey died after the navigability hearings, and the Supreme Court appointed Charles Fahy, Senior Circuit Judge for the United States Court of Appeals for the District of Columbia, as the new Special Master. Judge Fahy held hearings on the reliction issue and ruled in favor of the State of Utah, holding that the fluctuating water levels of the Great Salt Lake did not constitute reliction because these processes were not gradual, were not imperceptible, and were not permanent. This ruling was upheld by the United States Supreme Court. The result of the Court's decision on this issue was to confirm in Utah ownership of all shorelands located below the actual water level of the Great Salt Lake at the date of statehood, which, it will be remembered, was an elevation of approximately 4201.8 feet above mean sea level. This is to say that title was not quieted in Utah to an additional 450,000 acres, which comprised the belt of shorelands located between the elevations of 4194 and 4201.8. There still remained for adjudication questions as to the ownership of the shorelands located between 4201.8 (the water level of the lake at the date of statehood) and the official surveyed meander line, consisting of approximately 150,000 acres.

This area was the subject of the fifth and final phase of the case, and it is interesting to pause for a moment and note the chronological transition of the litigation. In the early stages, the United States expanded its claims step by step, until it claimed everything within the surveyed meander line. Then, in successive decisions, the Supreme Court methodically cut back the federal claims to the point that, when the fifth phase of the litigation was reached, the federal claims had been pared down to exactly what the initial Bureau of Land Management claim was when first asserted in the early 1960's.

There was no legal precedent whatsoever in Anglo-American jurisprudence to guide resolution of the final phase of the conflict. The State of Utah based its claim to the remaining lands on a host of practical and equitable factors, emphasizing the various improvements and developments that had occurred on these lands by various agencies and lessees of the State of Utah. The United States argued in favor of a boundary line located at or slightly above the water level at the date of statehood, contending that such a boundary would accommodate an average annual fluctuation.

Special Master Fahy again ruled against the United States and in favor of the State of Utah. The United States, after reviewing the report of the Special Master, decided not to file exceptions in the United States Supreme Court, and the Court thus accepted the report of the Special Master without further briefing or argument, and entered a final decree in favor of the State of Utah. This decree concluded approximately ten years of litigation and was the capstone which finalized in Utah ownership of all lands, brines and other minerals within the waters of the lake and within the bed and all shorelands located within the official surveyed meander line.

As an aside, it might be observed that the Utah Supreme Court reached the same result as the United States Supreme Court, in a decision rendered in 1971 resolving a dispute between the State of Utah and the Hardy Salt Company.

Since the surveyed meander line is not physically apparent on the shorelands, there are a number of small areas where future disputes might still arise in order to locate the meander line on the ground and thus establish an identifiable boundary between state ownership and claims by upland owners. The primary area of prospective controversy probably will concern two or three private duck clubs that might be utilizing lands for private purposes that are located below the surveyed meander line.

While it might be necessary to resolve a few minor conflicts such as these, the major battles have been fought, and the State of Utah is the unquestioned owner of the lake and its minerals, the value of which was estimated several years ago to be in excess of $90 billion.

THE HUMAN PREHISTORY OF THE GREAT SALT LAKE REGION

by
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ABSTRACT

Until about 600 years ago, the marsh and lake edge resources were of primary importance in the subsistence economies of local prehistoric peoples. Fluctuations in the level of the Great Salt Lake greatly affected the availability of these resources; changes in population density and settlement patterns can be attributed in part to changes in the lake. The area was probably initially occupied about 10,000 years ago by Paleo-Indians who relied on a mix of big-game hunting and collecting of lake margin resources. By about 8,500 years ago, relatively sedentary Archaic peoples occupied cave/rockshelters on the lake edge. Mid-Holocene desiccation of the lake 5,500 to 3,500 years ago resulted in a shift to a more nomadic lifestyle and to a reliance on upland as well as lake margin resources. Flooding of lake periphery resources resulted in the abandonment of lake margin sites and a subsistence economy based on upland flora and fauna. By about 2,500 years ago the area had been virtually abandoned. A Formative Stage Culture, characterized by small villages, domesticated plants, and pottery, occupied the lake margin and marsh areas between about 1,500 and 600 years ago. Their subsistence economy was very similar to that of previous area occupants; corn was not a dominant resource and was apparently of minor importance. By 500 years ago these people had been replaced by Shoshonians moving in from the southwestern Great Basin. The Shoshonian groups differed from earlier inhabitants in that they relied more on upland resources, such as pinyon nuts, rather than lake shore resources.

INTRODUCTION

The "prehistory" of the area immediately adjacent to the Great Salt Lake is ordinarily limited to placing pre-Columbian aboriginal groups in spatial and chronological perspective. However, this approach is primarily descriptive and does not reveal the changing patterns of human adaptation which occur in response to fluctuating environmental conditions. Generally speaking, the size and complexity of a culture is a product of environmental conditions (that is, the type and amount of resources available to the culture) and its technological capabilities (that is, the tools and labor organizations used to transform those resources into usable forms). As a result, the examination of cultural change in an area of marked environmental instability, such as the area around the Great Salt Lake, can provide a clearer insight into the processes of cultural evolution. The alternate flooding and desiccation of the lake and of spring and river-fed marshes on its periphery can be shown to have greatly affected the history of pre-historic human adaptation in the region throughout the ten thousand-plus years of occupation. The examination of the relationships between these environmental changes and the corollary cultural changes is fascinating and rewarding in terms of understanding the nature of the culture. In addition to discussing the area's prehistory, focus will be on changes in the environmental conditions in and around the lake; the effects these changes had on adaptation and settlement patterns, and the processes through which these changes occurred.

A word of caution must be offered about the interpretations which follow. The archeology of the eastern Great Basin and western Colorado Plateau is currently in a state of flux. Between 1975 and the present, a number of new hypotheses have been offered that radically conflict with previous widely accepted interpretations. That these hypotheses are partially contradictory is due primarily to the lack of an adequate data base. As a result, the discussion which follows is only my current interpretation of the prehistory of the Great Salt Lake area; subsequent modifications are bound to occur.

ENVIRONMENTS AND RESOURCES OF THE GREAT SALT LAKE

The initial impression of the lake and the Great Salt Lake desert today is usually one of stark desolation. The barren salt flats and low-elevation fault-block mountains appear to have insufficient flora and fauna to support more than an extremely sparse population. This is simply not the case, however; and this impression can probably be attributed to the cultural biases of modern civilization. We tend to see only those resources we are accustomed to using. Therefore, clarification of the nature of the resources available to the prehistoric inhabitants of the area is a necessity. Specific environmental data from the Great Salt Lake area cannot be given here.

The first and probably most important resource areas are the extensive marshes which surround the lake and the Great Salt Lake desert (figure 1). The most

Figure 1. Aerial view of lake periphery marsh environments near Bear River Bay. (Photo courtesy of Department of Anthropology, University of Utah).

obvious of these are the large Farmington Bay and Bear River Bay marshes. In addition, a number of springs found on the periphery of the Great Salt Lake desert, such as Fish Springs in western Juab County, still support relatively large marsh areas. Other spring-supported marshes, such as those at Wendover, Utah, have been modified to the extent that it is presently difficult to conceive of the size of the marshes they once supported. Extensive marsh areas are also found along the Bear River which drains into the Salt Lake basin. The area's riverine marshes have been greatly reduced by present day water control, which has altered the environment to one more appropriate for European types of resource utilization (Nielson, 1978).

Marshes are the single richest ecosystem yet defined in terms of available energy, even when compared with most types of intensive farming (Odum, 1963). The number of types of edible flora and fauna, as well as the amount of each type, far exceeds that found in other terrestrial ecosystems. As a single example, an acre of cattails (*Typha sp.*) produces up to 4,896 kg (10,792 lbs) of harvestable roots and tubers which can be reduced to 2,494 kg (5,500 lbs) of edible flour (Claassen, 1919). This flour is equal to or exceeds rice, wheat, and corn in nutritive value. Even more important is that cattails grow rapidly throughout most of the year and can rapidly replace those harvested (Niering, 1966; Reimold and Queen, 1974).

Prior to the nineteenth century these extensive and extremely productive marsh areas were the focus of human subsistence and habitation. In one relatively small (50 mile) stretch of the central Sevier Valley, for instance, there were more than an estimated 10,000 acres of cattail/bulrush marshlands (Nielson, 1978), and estimates of the even more extensive marshlands which surrounded Utah and Great Salt lakes prior to water control have never been made.

The second area of resources is the margin of the salt flats. These margin areas ring the entire Great Salt Lake basin between the foothills of the fault-block ranges and the true salt flats. They are flat to slightly sloping areas of highly saline soils that support large populations of salt-loving halophytic plants. Although the variety of plants is limited, the distribution of the few edible species is extensive. For example, pickleweed (*Allenrolfia sp.*) is a low ground cover herb which is a prolific producer of small edible seeds. These seeds, readily collected and stored, are known to have served as one of the basic dietary staples of prehistoric human inhabitants (Aikens, 1970). Many of the spring marshes are immediately adjacent to extensive halophytic-dominated flats, and the utilization of both resource zones was a relatively simple matter.

The third and relatively minor area of resource utilization is in the mountains which surround the lake basin. A variety of ecological zones are found on the Wasatch Range to the east of the lake; on the Raft River Mountains to the north, and the Pilot and Deep Creek ranges to the west. These zones range from pinyon-juniper forests through montane scrub oak, mountain mahogany to Alpine zones on some of the higher peaks. With a single exception, these mountains produce little in the way of edible plant resources and were used primarily as a source of game. The exception is the pinyon forests which produce large quantities of edible nuts. However, until the advent of protohistoric Shoshonian groups, there is little evidence that pinyon nuts were used as a basic staple, if at all.

The pattern of utilization of the various resource zones is readily apparent from the distribution of the more than 500 archeological sites that have been identified in the area (Madsen and Berry, 1974, 1975). Less that 5% are at elevations above 1,850 m (6,070 feet). By far the large majority of the remaining sites are either in or adjacent to marsh areas at elevations of 1,275 to 1,375 m (4,200 to 4,500 feet). This limited distribution is critical to understanding the impact of the lake on prehistoric groups, and should be kept in mind in the discussion which follows (figure 2).

PRE-PROJECTILE POINT (EARLY MAN) CULTURES (40,000 to 12,000 B. P.)

The presence of man in the New World prior to the close of the last glacial stade has been one of the more controversial topics in American archeology. Unfortunately, no sites clearly substantiate the presence of human groups in North America prior to ca. 20,000 years ago. In every case there are questions as to whether or not the artifacts are really of human origin or whether or not the geological units are accurately dated.

In the area of the Great Salt Lake, the single purportedly Early Man site is questionable, but it is a good example of the type of evidence usually marshalled in support of these claims. The site, possibly 40,000 years old, is located on the highest (1,610 m) (5,280 feet) Lake Bonneville terrace near Lehi, Utah (figure 2) and has been described by Clark (1975). It consists of two small, apparently wave-cut caves on the beach terrace. Flakes and bifacially retouched stone tools were found associated with fire hearths in the caves and on the slope above the beach terrace. The human origin of the artifacts and their association with the cave deposits appears to be relatively well-established. However, the estimated age of the site is based on some unfounded assumptions. The first of these, that the beach is about 40,000 years old, is based on the assumption that dates on carbonates, taken from cores in the Great Salt Lake, date the lake when it was at the 1,610 m level. This has yet to be adequately demonstrated, and work by others (e.g., Morrison, 1966, Currey in this volume) suggests the lake was at or about this level about 18,000 years ago and again about 14,000 years ago. The second assumption is that since the artifacts are on top of the beach, they are the same age as the beach. Obviously, the artifacts could have been deposited anytime after the caves were cut and the water receded. In other words, they could be any age from 0 to 14,000 years old, but probably not 40,000 years old.

PALEO-INDIAN/BIG GAME HUNTERS (ca. 12,000 to 9,000 B. P.)

The earliest widespread, well-recognized cultural stage in North America has been variously termed "Big Game Hunting" or "Paleo-Indian". Information concerning the technology and subsistence adaptation of these peoples is extremely sparse. Little is known about these groups except that they were adapted to the hunting of large Pleistocene mammals such as the mammoth and camel, and that they used well-made "fluted" projectile points to procure them. Most information concerning these cultures comes from excavated "kill sites" in the Southwest and High Plains areas. Dating of those sites suggests that reliance on the killing of large herbivores persisted from around 13,000 to 8,500 years ago. The sites can only be classed together because of demonstrated reliance on Pleistocene megafauna, but the large majority of the sites give little or no indication of the overall subsistence adaptation or settlement pattern. The fluted projectile points associated with the kill sites are quite distinctive. The best known and most widely distributed of these points are the Clovis (figure 3) and Folsom fluted points. Surface finds of these points in the vicinity of the Great Salt Lake suggest that Paleo-Indian groups may well have inhabited the region.

In the immediate vicinity of the lake, the surface finds are from the Curlew Valley north of the lake (Butler, 1973), the Sevier Desert area near Delta, Utah, (Madsen, Currey, and Madsen, 1976), and the Deep Creek Mountain area southwest of the lake (Lindsay and Sargent, 1977). Locations are shown in figure 2. Both the Clovis and Folsom varieties of points have been found, as well as a possible later Paleo-Indian biface known as a Cody Knife. The presence of all three types suggest occupation of the area throughout the entire Paleo-Indian period.

Several sites on the western periphery of the lake contain basal cultural deposits which date prior to 10,000 years ago. Danger Cave (Jennings, 1957), Deer Creek Cave (Shutler and Shutler, 1963), and Smith Creek Cave (Bryan, 1972) (figure 2) all contain dated cultural materials of a nondiagnostic nature. These early occupations have been attributed to later Archaic groups because of the presence of overlying, readily identified Archaic diagnostics (e.g., Fry, 1976), and because of the assumed absence of large Pleistocene mammals (e.g., Jennings, 1966, 1978). However, neither of these assumptions is valid, and in light of numerous finds of megafauna which postdate the earliest cultural sites, the sites may well represent Paleo-Indian occupations.

One of these fossil sites is of particular importance since it occurs near a recessional beach of Lake Bonneville. This site, in the Draper Formation near Sandy, Utah, (figure 2) contained a mammoth dated from 6,000 to 8,800 years ago (Madsen, Curry and Madsen, 1976).

The probability of such contemporaneity is strengthened by the association of Pleistocene mammals and cultural materials at several sites in relative proximity to the Great Salt Lake. At the Pine Springs site

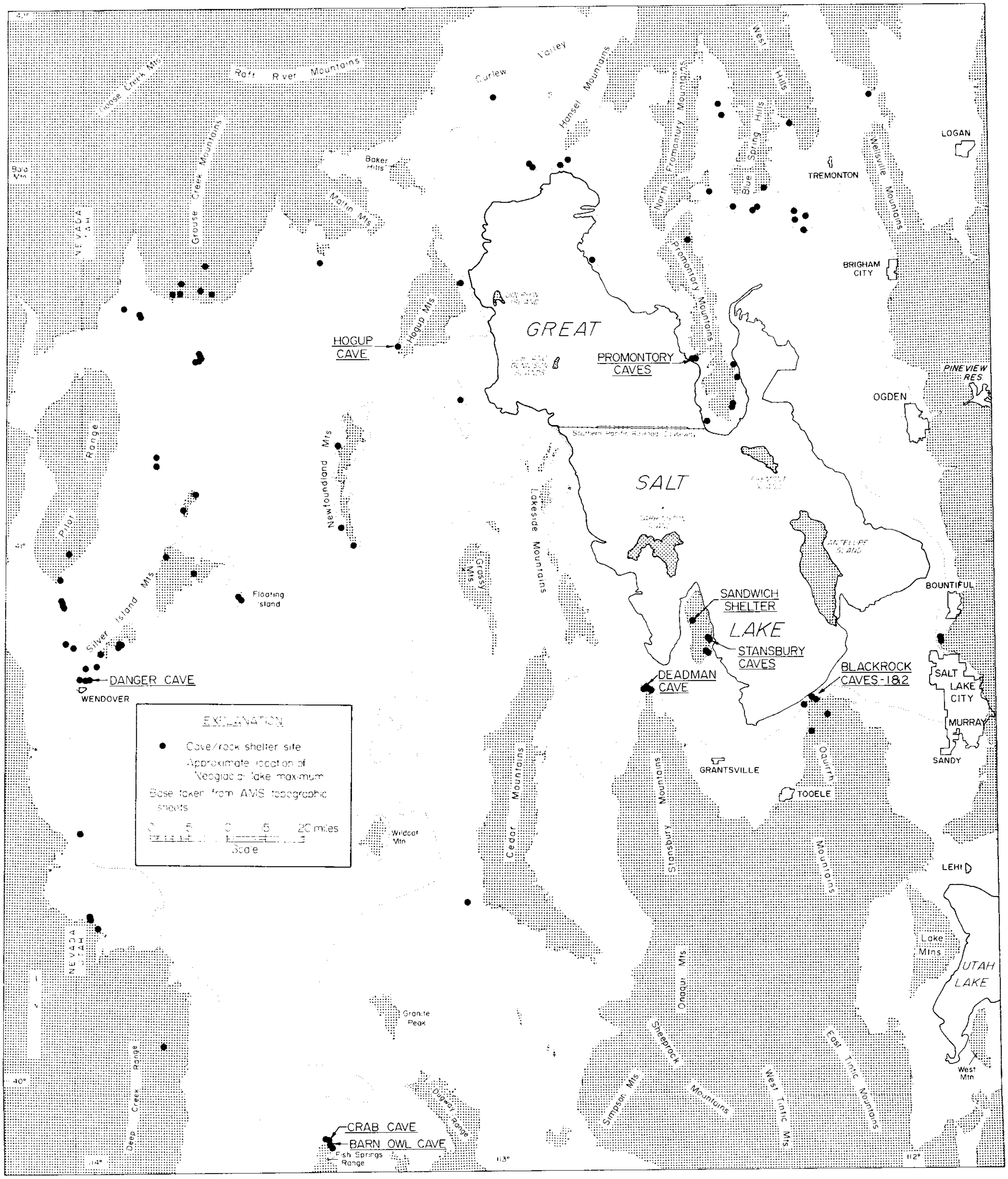

Figure 2. Plot of known archeological cave/rock shelter sites on the periphery of the Great Salt Lake. Outer line is the approximate location of Neoglacial lake maximum.

Figure 3. Clovis projectile point from the eastern Great Basin portion of Utah.

(Sharrock, 1966) in southwestern Wyoming, bison and camel bones, found in association with Paleo-Indian materials, were dated to ca. 9,750 years ago. At the Wasden site in south central Idaho, fluted points were found associated with mammoth remains (Miller and Dort, 1978). This important kill site has been radiocarbon dated to 11,000 to 12,000 years ago.

Another rarely used source of data is rock art. Several rock art sites in Utah (figure 4) contain elements which seem clearly to be representations of proboscideans (Stokes, 1972; Madsen, Currey and Madsen, 1976), and the existence of these sites gives ancillary support to the probable co-occurrence of these animals and man in the region. However, since rock art cannot be dated and because it is rarely associated with cultural materials, the art should only be used to support more concrete sources of information.

Figure 4. Proboscidean pictograph found near Moab, Utah.

In summary, several lines of evidence support the presence of Paleo-Indians of the shores of Great Salt Lake between 9,000 and 12,000 years ago. Although most of the evidence for the Paleo-Indian culture is derived from kill sites which give little indication of the overall subsistence strategy, recently completed surveys and excavations in the Great Basin area indicate that Paleo-Indian groups were primarily adapted to lake, spring, and river peripheries and were probably adapted as well to the collection of marsh resources (e.g., Davis, 1976; Thomas, 1978). This means that Paleo-Indian groups probably did not differ greatly from the later Archaic cultures, and their adaptation to marsh environments, such as that found around the Great Salt Lake, is a pattern which has remained basically stable for the last 10,000 to 12,000 years. Therefore, it may well be that what changes did occur during Paleo-Indian times and during the transition to the Archaic were the result of lake level changes and the concomitant effect on the availability of periphery marsh resources.

ARCHAIC STAGE (8,500 to 2,500 B. P.)

The Archaic Stage in North America is defined as a broadly based subsistence adaptation, with subsistence varying "from season to season as it focused first on one species or community of species and then on another . . . a fundamental lifeway, not geared to any one ecosystem " (Jennings, 1974; 110-111).

Unfortunately, the term "Archaic", based as it is on a subsistence adaptation definition, is something of a misnomer. In actual use, Archaic cultures have come to be defined on the basis of technological and chronological criteria. That is, cultures are assigned to the Archaic Stage because they follow big game hunters and precede agriculturalists; because they use tools such as the atlatl (spear-thrower); grinding stones, stone vessels, basketry, and skin robes; and because they lack other tools such as fluted points, pottery, and the bow-and-arrow. This confusion is due to the ambiguous definition of the stage originally provided by Willey and Phillips (1955, 1958). They defined the stage as a "migratory hunting and gathering" type of subsistence adaptation, but the criteria they used to distinguish this stage from others are primarily technological, not economic/environmental. This confusion has led to the classification of both sedentary collectors and big game hunters as Archaic Stage cultures. The problem is much the same when dealing with the "Archaic" cultures of the Great Salt Lake area. In terms of subsistence adaptation these groups cannot readily be distinguished from preceding and following groups, and technological and chronological criteria must be used.

These criteria indicate that Archaic peoples appeared in the Great Salt Lake area about 8,500 to 9,000 years ago, and occupied the area continuously until about 2,500 years ago. Whether or not they occupied the area continuously until the introduction of agriculture about A. D. 400 is presently a subject of contention.

Between 9,000 and about 5,500 years ago, the focus of Archaic subsistence adaptation was the marsh/salt flat ecosystem that surrounds the lake. During this period Archaic peoples lived in cave/rockshelters adjacent to the fresh-water springs on the lake periphery (figure 5).

Simms (1977) suggests that during this period the population around the lake was gradually increasing. This hypothesis is based on the gradual increase with time in the number of sites occupied on the lake periphery. Only two sites, Danger Cave (Jennings, 1957) and Hogup Cave (Aikens, 1970), date to the earliest period of Archaic occupation. Basal dates suggested by Simms (1977) for other sites are Sandwich Shelter (ca. 7,000 B. P.), Stansbury Caves I and II (ca. 7,000 to 5,000 B. P.), Promontory Cave No. 2 (ca. 7,000 to 5,000 B. P.), Deadman Cave (ca. 7,000 to 5,000 B. P.), and Fremont Island (ca. 5,500 B. P.) (see figure 2 for locations). All these sites were continuously occupied, so the apparent increase in the number of sites cannot be attributed simply to a shift of a group from one site to another. Some evidence that entirely different groups of people occupied the different sites (Fry and Adovasio, 1970), implies that the number of groups as well as group size was increasing.

This increase in population appears to be tied directly to changes in the level of the lake. Throughout the early Archaic period the people lived almost entirely on lake edge resources such as pickleweed, sedge, rodents, and marsh birds. There is evidence that they used some upland game, such as sheep and deer, and that some of their tools were made of upland plant species. However, there are no known upland sites occupied during this early era; at best, these areas were supplemental. It presently appears that these Archaic peoples were relatively sedentary, and that the resources on the periphery of the lake were sufficient to support a growing population.

The size of this lake edge ecosystem and the amount of available resources are inversely tied to lake

Figure 5. View of spring bog and surrounding salt flats from the mouth of Barn Owl Cave, Fish Springs, Utah. The environmental setting is typical of Archaic sites on the periphery of the lake.

level fluctuations. As the lake level fell from its Pleistocene high, due to reduced precipitation or higher temperatures, it gradually exposed fresh-water springs, more extensive marsh habitats, and larger areas of halophytic plant dominance. The amount of available resources was actually increased. This increase in resources resulted in a larger human population that was largely dependent on the productivity of the lake periphery ecosystem.

This relationship between decreasing lake levels and increasing resources is not continuous, however. As the lake is reduced in size, a point of diminishing returns is reached when the water table can no longer support fresh-water flow in several of the springs, and flow is much reduced or becomes brackish in many of the others. Simms (1977) suggests that this point occurs at around 1,280 m (4,200 feet), and that the decrease in lake size had reached this point by 5,500 years ago. This is in accord with general estimates for a mid post-Pleistocene warm period (e.g., Antevs, 1955), and time estimates of mid-Holocene desiccation of the lake (Eardley et. al., 1957).

It is not surprising then, that around 5,500 years ago sites in upland areas began to be occupied, probably the result of the combined pressure of increased population and decreased lake margin resources. Lake edge sites continued to be occupied, but apparently in a less sedentary fashion. Subsistence adaption was more of a classic "Archaic" type, in that it consisted of a migratory shift from site to site, from one ecosystem to another, as resources became available in differing areas.

Excavated upland sites are found in the fault-block mountains west and south of the lake (Gruhn, 1972; Sargent, 1978; Fowler, 1968; Heizer, Baumhoff, and Clewlow, 1968; Shutler and Shutler, 1963); in the Grouse Creek and Raft River Mountain area northwest of the lake (Dalley, 1976); and in the Wasatch Range southeast of the lake (Mock, 1971). They are situated in pinyon/juniper zones in locations that would allow access to sage/grass communities and higher montane resources. These upland sites apparently were used primarily as hunting camps, although grasses such as Indian ricegrass (*Oryzopsis hymenoides*), were also collected. The preferred (or perhaps the most abundant or the most readily procured) faunal resource was mountain sheep. Deer and rabbit remains are also abundant, and bison remains are occasionally recovered. Evidence from these sites (e.g., Dalley, 1976) indicates occupation by "family groups" rather than small male hunting parties. This strengthens the probability that these sites are related to the lake edge sites through an occupational pattern often referred to as a "seasonal" or "annual" round. This Archaic pattern of group movement from lake edge to foothills to lake edge apparently continued from ca. 5,500 to 3,500 years ago until another change, again probably caused by a lake level fluctuation, occurred.

Between 3,500 and 2,200 years ago a period of increased effective moisture known as the Neoglacial period resulted in rising lake levels that reached 1,298 m (4,260 feet) in elevation (Mehringer, 1977). At this level, the high water essentially eliminated the majority of marsh areas and halophytic-dominated salt flat margins and flooded a majority of the peripheral fresh-water springs. Resources around such lake edge sites as Hogup Cave (Aikens, 1970) were eliminated, and there is evidence that these sites were abandoned at this time (Madsen and Berry, 1975). However, Archaic occupation of the upland sites continued, and in all probability the carrying capacity of these upland areas was somewhat enhanced by the increased effective moisture. However, there is presently no evidence of an increase in the number of upland sites during this period, and a population decline of unknown magnitude probably occurred in the Great Salt Lake area. This scenario is strongly supported by a recent study of projectile point densities in lake periphery sites (Holmer, 1978).

At the end of the Neoglacial period, Archaic occupation of the Great Salt Lake area apparently ended. Why the region was abandoned is not clear at present, but of the 25 to 30 excavated Archaic sites in the general area, none give an unequivical indication of occupation between ca. 2,500 and 1,500 years ago. The cause is most probably a combination of cultural and environmental factors. The carrying capacity of the upland areas was again reduced; and while lake edge resources were again available, after a thousand or more years of upland occupance, these groups were probably not familiar with or adapted to lakeside ecosystems and, hence, could not and did not use them. The probability of an occupational hiatus or of cultural continuity is presently a matter of contention (e.g., Madsen and Berry, 1975; Aikens 1976), but whichever case is ultimately supported, it seems clear that the population density of the area was markedly reduced after 2,500 years ago.

In summary, Archaic occupation of the Great Salt Lake area began about 8,500 years ago and continued to about 2,500 years ago (possibly later). Change in the number and location of sites in and around the lake suggests an increasing population until about 5,500 years ago, then a reduction in population, a moderate regrowth, finally followed by a marked reduction in population. The subsistence adaptation, settlement pattern, and indeed, the very life-style of these Archaic groups, were intimately tied to the lake and the effect its level had on lake edge resources. Initially these groups were basically sedentary and shifted to a pattern of seasonal mobility only when the lake was reduced beyond a point where it would not support a stable existence. With the subsequent flooding of the lake edge resources, a radical change to primary dependence on upland ecosystems occurred. When these resources were in turn reduced, Archaic groups essentially abandoned the region.

FORMATIVE STAGE, SEVIER CULTURE (1,500 to 500 B. P)

In North America (north of Mexico) post-Archaic cultures are grouped together into what has been defined as the "Formative Stage" (Willey and Phillips, 1958). This stage is characterized by the advent of agriculture (principally corn, beans, and squash), pottery, bow-and-arrow, and settled villages. Due to the definitional confusion which surrounds the Archaic, the transition between the two stages is rather ambiguous. Fortunately, this problem does not exist in the eastern Great Basin. The apparent Archaic abandonment (or, at the very least, markedly reduced occupation) of the area makes it easy to separate the Formative Stage culture found around the Great Salt Lake from the preceding Archaic Stage.

The Formative Stage culture in the eastern Great Basin has been defined as the Sevier Culture (Madsen and Lindsay, 1977), and represents a redefinition of cultural variants once classed with the Fremont Culture (Marwitt, 1970). The following is modified from Madsen and Lindsay's (1977) definition: Settlement pattern is characterized by villages located on alluvial fans in intermontane valleys adjacent to marsh or riverine ecosystems and by temporary encampments spread throughout other environmental zones surrounding these centrally located villages. The ratio of temporary camps to villages is roughly ten to one. Subsistence economy is based on collecting wild flora and fauna, primarily from marsh environments, and is supplemented by corn agriculture. Given the type of settlement pattern and the lack of restrictions imposed by the seasonality of agriculture, the social organization probably consisted of loosely confederated family aggregates. Architecture is characterized by semisubterranean dwellings and rectangular adobe surface storage units. Masonry is extremely rare. With the exception of some variation in pottery types, the artifact inventory is fairly consistent in all areas where the culture is found, and is characterized by plain and decorated varieties of coil-made gray ware, corner- and side-notched arrow points, trough metates, one-rod-and-bundle basketry, and a variety of bone implements and ornaments. The Sevier Culture can be identified as a distinct entity from about 1,300 to 650 B. P.

In the specific area of the Great Salt Lake, significant variations in artifacts, architecture, and adaptation have suggested a larger degree of interaction with the Plains area and possibly even an origin in that region (Aikens, 1966; Madsen and Lindsay, 1977). Distinctive features include paddle-and-anvil pottery, shallow basin-shaped dwelling structures, and an adaptation to bison hunting. Prior to the definition of the Sevier Culture, post-Archaic groups in the Great Salt Lake area were described as the Great Salt Lake Variant of the Fremont Culture (Marwitt, 1970; Fry, 1970). This variant was divided into two temporal phases which are characterized primarily by slight differences in architecture, projectile points, and pottery (figure 6). Two phases, the Bear River Phase (A. D. 400 to 1,000) and the Levee Phase (A. D. 1,000 to 1,350+), have been identified (Fry and Dalley, 1973). The earlier Bear River Phase is more characteristic of the Plains, and the later phase is characterized by features more closely resembling southern areas of the Sevier Culture. The differences between the two phases may be due to shift in interaction with the Plains area to interaction with the southeastern Great Basin.

The subsistence adaptation of these Sevier groups greatly resembles that of the preceding Archaic peoples. With the exception of a single site, all of the village sites are located in marsh areas on saline soils which preclude agriculture (e. g., Aikens, 1966, 1967; Fry and Dalley, 1973). The majority of these are on the 1,283 m (4,209 feet) contour (indicating the lake was probably slightly below this level) in the Bear River Bay and Farmington Bay areas of the east side of the lake. Protein resources were primarily bison and large waterfowl such as the Canada goose. Plants known to be collected were bulrush (*Scirpus* sp.) and goosefoot (*Chenopodiaceae* sp.). Other, more perishable and/or less readily identified plant types, such as cattails (*Typha* sp.) were also probably collected. The exceptional site at Willard, Utah, (Judd, 1926), contains adobe storage structures and charred corncobs. This site suggests some reliance on agriculture, but corn appears to represent a minor portion of the overall subsistence economy. Other

Figure 6. Paddle-and-anvil made vessel from the Levee Site, Bear River Bay. Vessels such as these suggest an origin from or extensive interaction with Plains cultures. (Photo courtesy of Department of Anthropology, University of Utah).

possible agricultural sites, in the Grantsville/Tooele area, may be related to those on the eastern side of the lake, and further research in these areas may demonstrate a heavier reliance on agriculture than is presently indicated.

The cave/rockshelter sites around the lake and in the upland areas, such as Swallow Shelter (Dalley, 1976) and Hogup Cave (Aikens, 1970) (figure 2), were occupied by Sevier peoples and appeared to have been used as temporary base camps with hunting as the primary focus. Depending on the location of the site, the primary game sought was either mountain sheep, deer, antelope, or bison. Grasses and other plants were also collected at these sites, but they appear to have been of minor importance. These temporary hunting camps appear to be related to the marsh village sites in the overall subsistence economy. At Crab Cave, in the Fish Springs marsh area, there is evidence suggesting that hunting and pinyon nut collecting occurred in the fall and that the marsh areas were subsequently occupied during the late fall and winter (Madsen, 1979). At present, the pattern appears to have been one of a relatively sedentary existence in and around the marsh areas, with occasional movement into other environmental areas to procure meat and wild plants. This relatively settled condition, supported by marsh collecting and hunting, has occurred throughout the entire time-span of human occupation in the area. The high degree of similarity between the Archaic and Sevier subsistence economies argues for some sort of cultural continuity between the two groups.

After about 600 years ago, the Sevier Culture can no longer be recognized in the eastern Great Basin. At present there is no clear evidence why these people disappeared, or indeed, what happened to them. There is some speculation that they reverted to a nomadic way of life due to environmental pressures, and may be recognized as the protohistoric Shoshonian groups (Gunnerson, 1969). However, current evidence suggests instead a wholesale replacement of the Sevier peoples by Shoshonian groups (e.g., Aikens, 1970). The Sevier peoples may have emigrated to other areas, or simply died out. An examination of the unique basketry styles (Adovasio, 1978, personal communication) supports the latter theory.

In summary, the Formative Stage in the eastern Great Basin is represented by the Sevier Culture. Settled village life was supported by the collection of marsh resources and hunting, supplemented by agriculture. The culture can first be recognized about 1,500 years ago, and may have either developed *in situ* from an older Archaic culture or may have resulted from an influx of people from the Plains area and/or the Southwest. By 500-600 years ago the culture had disappeared and had been replaced by the protohistoric Shoshonians.

PROTOHISTORIC SHOSHONIANS
(550 B. P. to present)

The best current evidence suggests that the predecessors of the historic aboriginal groups in the Great Salt Lake region arrived in the area about 500-600 years ago. The Shoshonian peoples speak dialects of the Numic branch of the Uto-Aztecan language family. Linguistic analysis of the Numic languages suggests that they diverged from a common language about 1,000 years ago, and that at that time, Numic-speaking peoples lived in the southwestern Great Basin (Lamb, 1958; Miller et. al., 1971; Fowler, 1972). This linguistic hypothesis is supported by dates on distinctive Shoshonian pottery which indicate the Numic-speaking peoples began to move north and east from their homeland 900 to 1,000 years ago (Madsen, 1975). In the Great Salt Lake area, Shoshonian pottery first occurs about 600 to 700 years ago (e.g., Aikens, 1970).

Distinctive Paiute/Shoshoni artifacts, such as pottery, have been found in association with Sevier Culture materials at a number of sites, suggesting that the two groups co-existed in the region for a period of several hundred years (Madsen, 1975). Although the two cultures seem to have had somewhat different types of subsistence systems, the large number of sites with both Sevier and Paiute/Shoshoni artifacts suggests a relatively large degree of interaction. In the absence of any indications of warfare or other violence, we assume that this interaction was amicable.

The subsistence adaptation of historic Shoshonian groups has been described in detail by Steward (1938), and was probably very similar during the prehistoric period. Briefly, subsistence was based on a mixture of collecting wild flora and hunting. It was based on the movement of small groups from one area to another as differing resources became available. Occasionally, when local resources were particularly abundant, these small groups came together to participate in a variety of social activities. However, Shoshonian subsistence and settlement patterns were highly variable and substantial modifications of this general pattern occurred. The Shoshoni seem to have relied less on lake, river, and spring edge resources than did previous groups, but there were exceptions, such as the virtually sedentary Shoshonian groups on the shores of Utah Lake.

The small, mobile groups of Shoshoni differed from previous occupants of the region in their heavy reliance on pinyon nuts. These nuts were extensively collected in the fall and served as the winter staple. The entire seasonal round revolved around the quantity of nuts collected, and years of feast or famine depended on variations in the yearly productivity of the pinyon.

Following years of poor pinyon nut production, the Shoshonian groups relied on ephemeral grasses, such as Indian ricegrass, during the late spring. Since the productivity of these grasses is based largely on highly variable precipitation, reliance on these resources rather than the more permanent and more reliable marsh resources necessitated a smaller group size and a more migratory type of existence.

In summary, Shoshoni groups appeared in the Great Salt Lake area about 500-600 years ago and replaced or displaced Sevier peoples. Their subsistence adaptation generally differed from previous cultures, and was not particularly well adapted to the lake and its spring and river tributaries.

SUMMARY AND DISCUSSION

The human prehistory of the Great Salt Lake area can be summarized as follows:

1. Brief Paleo-Indian occupation (ca. 12,000 to 9,000 B. P.); evidence of type of subsistence limited, but probably combination of hunting Pleistocene megafauna and collecting lake periphery resources.

2. Early Archaic (ca. 8,500 to 5,500 B. P.); basically sedentary on lake periphery with subsistence focused on marsh and lake-edge resources; growth of population.

3. Mid-Archaic (ca. 5,500 to 3,500 B. P.); migratory hunting and gathering based on both upland and lake-edge resources; population reduction.

4. Late Archaic (3,500 to 2,500 B. P.); upland hunting and gathering subsistence and occupation; little evidence of lake margin habitation or use; population markedly reduced or regional abandonment.

5. Sevier (1,500 to 500 B. P.); sedentary village life based on collecting of marsh resources and agriculture; supplemented by seasonal procurement of animals.

6. Proto-Shoshoni (550 B. P. to Present); migratory hunting and gathering; the degree of sedentarism was variable and dependent on local resources.

Throughout this prehistoric period, the Great Salt Lake and the resources which surround it have been a primary factor in the development of local cultures. The only real exception to the lake/river margin adaptation pattern was the Shoshoni subsistence system, which may have been modified by displacement of the Indians by European settlers. In a way it is unfortunate that the Shoshoni groups were the only occupants of the area when historic contact was made. They had arrived not long before the arrival of groups of European origin and maintained a subsistence economy that was in many ways as dissimilar from previous cultures as the European subsistence economy was dissimilar. Archeologists with a European cultural background, knowing only the historic record of Shoshonian subsistence economies, presented a somewhat biased view of prehistoric cultures in the area. Past cultures are most often viewed as "Desert Dwellers with Few Resources" (Jennings, 1978) and statements such as the following are common:

> "The Basin had long been an inhospitable land. To those who lived here on the edge of subsistence, the slightest change, an unusually dry period, for example, could mean disaster. More than once, groups must have moved out of this area, not knowing what lay before them, but well aware that death lay behind them (Wormington 1955).

Such images are poetic but are quite misleading. Throughout most of the prehistory of the Great Salt Lake area, people appear to have led life-styles that were not nearly so marginal. While they were surrounded by desert environments, they were not wholly adapted to them. They lived by collecting lake/river/spring flora and fauna and by hunting upland game animals. They were not adapted to desert ecosystems, and it is something of a misnomer to refer to them as desert dwellers. It is also misleading to conceive of these groups as having few resources, and, by implication, of living a hand-to-mouth existence. The carrying capacity of the area was much larger than the surrounding deserts, and it is evident that at times in the past the region supported a large and relatively stable population.

More importantly, the conception of "desert" oriented groups precludes an understanding of the importance the Great Salt Lake had in the subsistence economy of past cultures, and the impact lake level fluctuations had on the development of culture in the area. It has been argued here that many of the changes which occurred in the region were a direct result of increasing and decreasing resource availability, and that the quantity of these resources was a direct result of the size of the lake. Only by focusing on prehistoric subsistence adaptations (and on the environments to which these adaptations were made) will we fully understand the lifeways of prehistoric man in the region.

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RECREATION ON THE GREAT SALT LAKE

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INTRODUCTION

To "float like a cork" has become a world-wide trade mark of the Great Salt Lake, as anyone can float in its heavy, natural brines. For over 125 years, the lake has been a major Utah attraction to visitors from around the globe who enjoy its beauty and bathe in its waters. Today, the Great Salt Lake State Park, consisting of the Saltair Beach and the northern portion of Antelope Island, provide excellent recreational facilities on the lake not only for swimming, but for boating, hiking, camping, recreational vehicles, and other activities.

HISTORY OF GREAT SALT LAKE RECREATION

History records a number of legendary frontiersmen reportedly seeing or hearing of the salty body of water that is now known as the Great Salt Lake, and of Indians bathing in the lake as an ablutionary experience. It was not until the exploration of the lake by the Stansbury Expedition in 1849, however, that mention was made of a white man bathing in the salty water:

> "We frequently enjoyed the luxury of bathing in the lake. No one without witnessing it can form any idea of the bouyant properties of this singular water. A man may float, stretched at full length, upon his back, having his head and neck, both his legs to the knee, and both arms to the elbow entirely out of the water. The water is nevertheless extremely difficult to swim in, on account of the constant tendency of the lower extremeties to rise above it. . . . After bathing it is necessary to wash the skin with fresh water, to prevent the deposit of salt arising from evaporation of the brine. Yet a bath in this water is delightfully refreshing and invigorating (Talmage, 1900, p. 35)."

The Resort Era

Eighteen forty-seven witnessed the settlement of the Salt Lake valley by Brigham Young and his entourage of Mormon pioneers. Just four years later, on July 4, 1851, Brigham Young led the first organized bathing excursion to the lake. Morgan (1947, p. 348) relates that the excursion attracted nearly the entire population of Salt Lake City and lasted until afternoon of the next day. The success of the excursion prompted plans by some to build a bath house, hotel and boating facilities on the lake; these plans were not immediately realized.

During the next twenty years or so, before the first resorts were finally built, numerous accounts of bathing or enjoying the beauty and unique properties of the lake were recorded (Morgan, 1947, p. 348-352).

The Resorts

Lake Park

"Lake Park (see figure 1) was developed by John W. Young in 1870 on the east shore. The resort featured a saloon, cafe, train depot, roller skating rink, merry-go-round, pavilion, pier, and dance hall with a 15-piece orchestra. Lake Park was the home of the Salt Lake Racing Club and sponsored several successful regattas. As many as 10,000 spectators would turn out to witness the sailing events. In addition, Lake Park featured the *City of Corinne*, a three-decked stern wheeler over 130 feet long. From Lake Park, the *City of Corinne* ferried excursioners to attractions on the lake, including a rival resort of the south shore, Lake Point. Because Lake Park was conveniently located on the railroad line from Salt Lake City to Ogden, it was easily accessible to a large segment of the population.

"Lake Park's pavilion was built over the water with a pier connecting it to the shore. Because the beaches were shallow and constantly covered with mud, in 1888 it was suggested that wooden boards be laid on top of the mud to make conditions more conducive for entering the water.

"While these beaches were less attractive than the sandy beaches of the south shore, Lake Park's convenient access nevertheless enabled it to enjoy a majority of the tourist business during its existence. By 1894, Lake Park had been left high and dry by the receding lake level, forcing abandonment. Some of the abandoned structures were moved from Lake Park to the outskirts of Farmington and renamed Lagoon (figures 2 and 3).

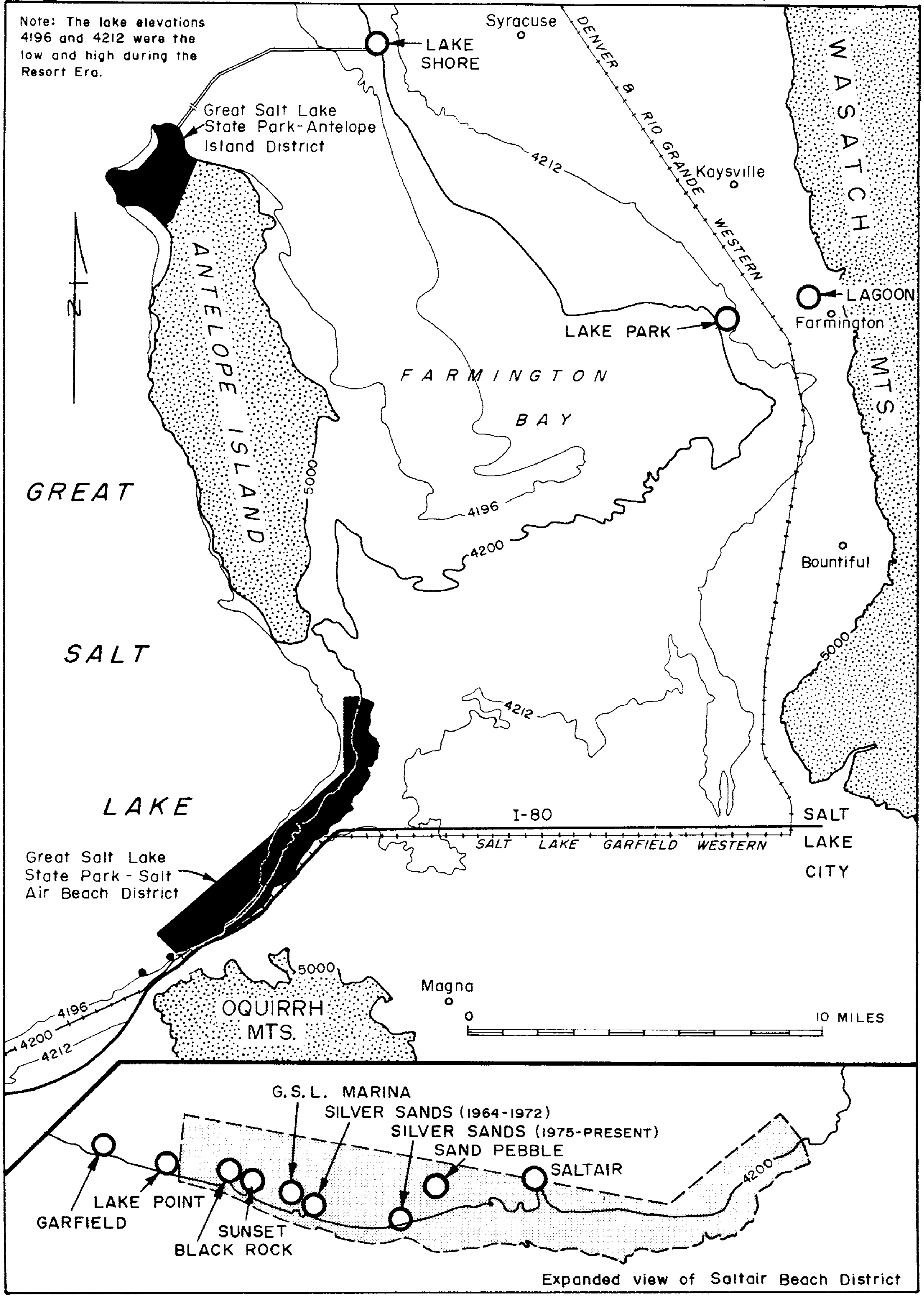

Figure 1. Map of the southeastern portion of the Great Salt Lake showing the locations of past and present resorts and of the Great Salt Lake State Park system.

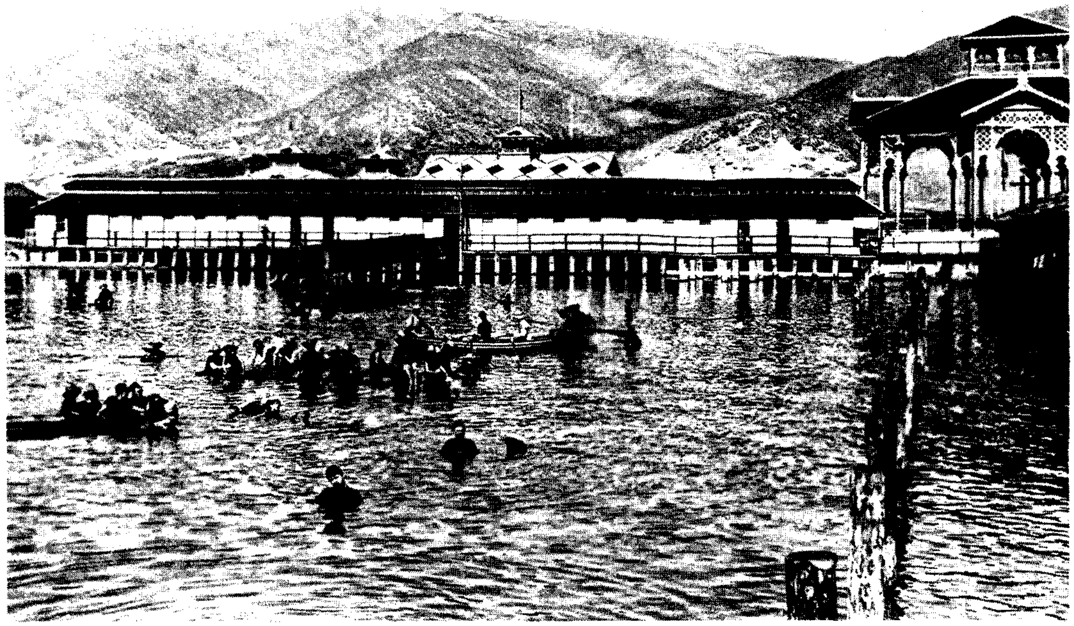

Figure 2. Lake Park Resort on eastern shore of Great Salt Lake.

Figure 3. Lagoon, near Farmington, Utah – 1898 gathering. Note pavillion that was moved from Lake Park Resort. Similar structures can still be seen today at Lagoon.

Lake Point

"Another development started in 1870 was Lake Point, a resort built on the south shore by Dr. Jeter Clinton. Lake Point originated as a commercial port for transporting ore as well as railroad and telegraph supplies across the Great Salt Lake. Because the south shore represented a good location from the standpoint of water and land (Utah Western Railway) access, it was a natural spot for a resort as tourist and resident interest in recreation increased.

"Clinton's resort included a stone hotel, small pavilion, pier, 100 bathhouses, and a train depot. The abundance of fine sand in the Lake Point area contributed to the resorts considerable success. A visiting port for the *City of Corinne*, Lake Point later became home port for the steamboat *Kate Connor*, which competed with the *City of Corinne* and ferried as many as 300 passengers to Stansbury Island and other islands on the lake.

"Lake Point's success began to wane in 1881 due to the transfer of the *City of Corinne* to a new home at Garfield beach. By 1890 the lake had receeded far from Lake Point's pier and although the resort itself was abandoned, other attempts were made in that year to restore some of the activity in the Lake Point area. Land speculator William Glassman announced the planning of Garfield City, Salt Lake Beach, and Stansbury Beach in the area adjacent to Lake Point. Building lots were offered to the public for sale. Of the three proposed developments, Garfield City was the only one to see any progress. The success of this project was limited since recreational emphasis along the south shore was shifting toward the east with the development of Black Rock and Garfield beaches.

Black Rock

"A development that enjoyed a long and relatively successful life was Black Rock. Built on the south shore by Alonzo Hyde and David Taylor, this modest resort was in operation from 1880 to 1959 and included a picnic bowery, refreshment stand, and bathhouses. Rising more than fifty feet above the lake's surface the great rock was a prominent and charismatic natural landmark. The panorama visible from the top of Black Rock was magnificent. Its crevices were utilized for shelter from the sun and wind and also served to provide privacy for changing into swimming suits.

"Black Rock resort survived longer than any other in the lake's history partly because it offered families a simple beach and bathing facility without a great deal of commercial development and expense. A combination of poor maintenance of facilities and a receding shoreline caused the resort to close in 1959.

Garfield

"Until the construction of Saltair in 1893, Garfield was the most popular resort on the Great Salt Lake. Built in 1881 on the south shore, Garfield featured a large pavilion built on pilings out over the water, a pier, boardwalks, restaurant, lunch stand, picnic bowery, casino, hotel, opera house and bathhouses. The *City of Corrine* moved to Garfield in 1881 and was renamed the *General Garfield*. The resort hosted sailing regattas, sometimes in conjunction with other resorts on the lake, had orchestras for dancing and dining, and provided facilities for national conventions (figures 4 & 5).

"After 1893 Garfield did not lose out completely to Saltair in popularity. This may be attributed to the fact that Garfield had one amenity unavailable elsewhere--a beach! At Garfield, a bather could enter the water either from the pier or from the beach, while even at Saltair only pier access was available.

"Transportation to Garfield was adequate, but rail connections to the eastern south shore resorts were always better. By 1904, business had declined and when Garfield was destroyed by fire in that year, it was not rebuilt (Terracor, 1979)." The *General Garfield*, moored to the pier at that time, was burned to the waterline.

Lake Shore (Syracuse Resort)

"Often regarded as a competitor to Garfield was Lake Shore, a resort built on the east shore of the Great Salt Lake in 1887. Lake Shore included a substantial pier, bathhouses, dance pavilion, and bowery. The resort was easily accessible by train (the train continued on to the pier to a Y-shaped turn-around), and it had a grove of trees 300 yards from the shore that provided comfort and shade for picnickers. Lake Shore, however was never quite as popular as Garfield and was closed when the lake receded (figure 6).

Saltair

"From its beginning in 1893, Saltair was one of the most successful resorts on the lake. Its large victorian pavilion was built entirely over the water . . . . The first

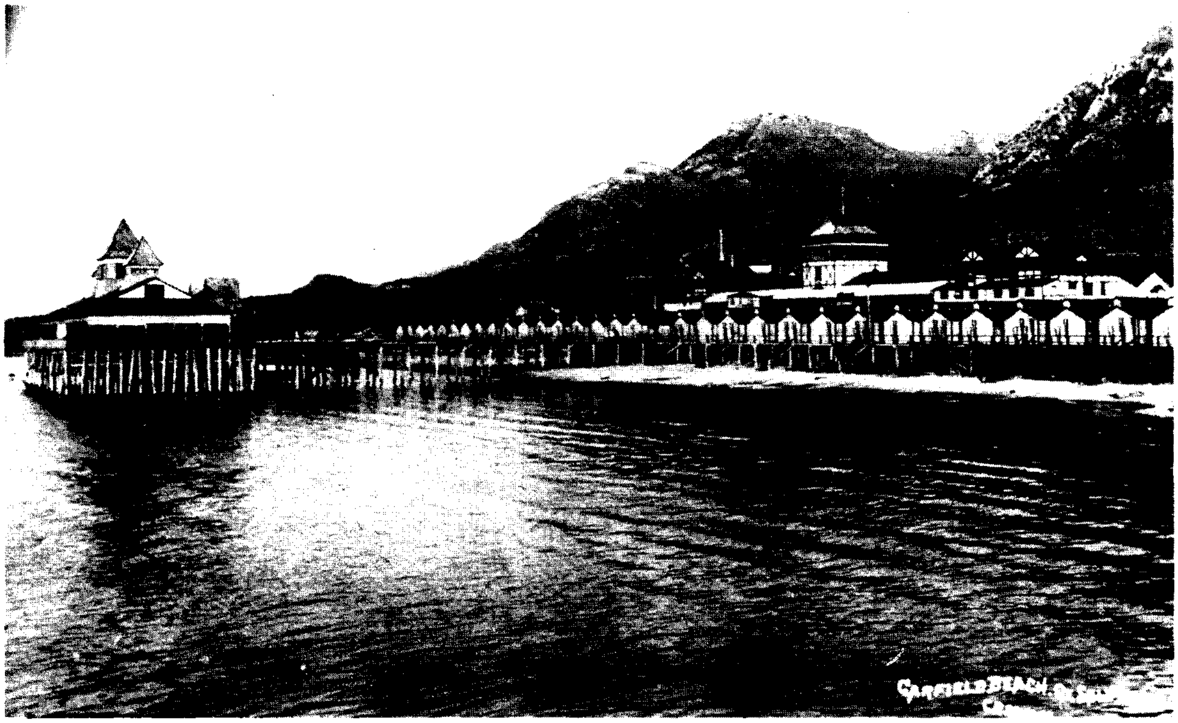

Figure 4. Garfield Beach Resort with dressing rooms on the shore and the pavillion over the water. The northern tip of the Oquirrh Mountains are in the background.

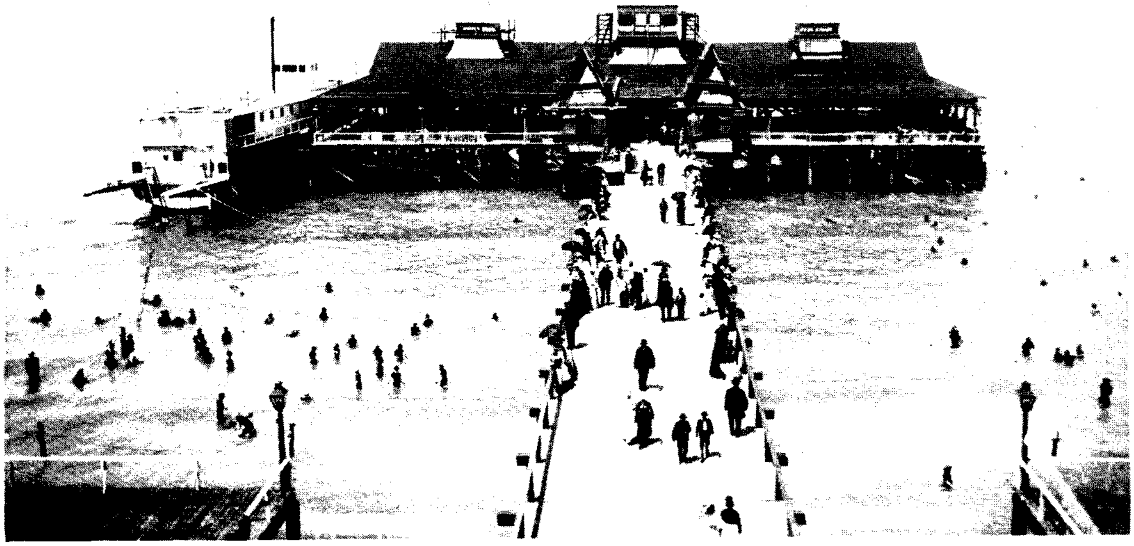

Figure 5. Garfield Beach Resort pavillion with the General Garfield moored alongside.

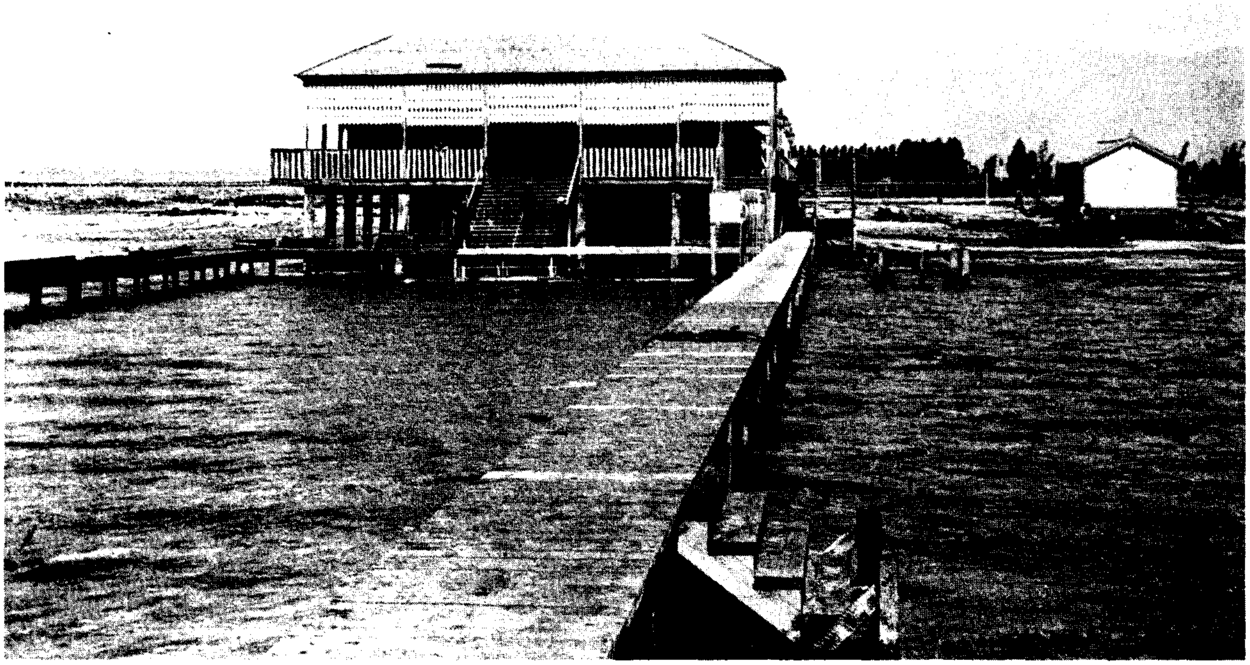

Figure 6. View of Lake Shore (Syracuse) Resort.

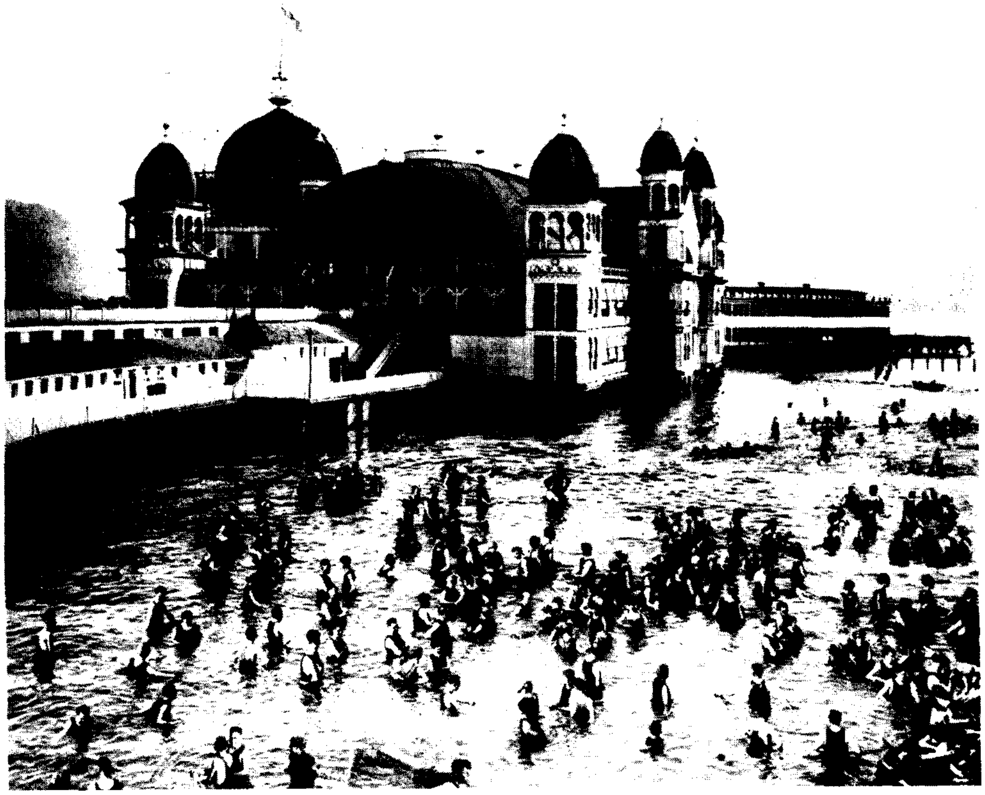

Figure 7. Lakeside view of Saltair pavillion.

floor of the pavilion contained restaurant stands, picnic areas, and restroom facilities. The second floor included dressing rooms, club rooms, parlors, and a large dance hall. The third and fourth floors had spacious promenades: the fifth, a massive cupola and observation deck. (Terracor, 1979)."

In 1900, shortly after its construction, Dr. J. E. Talmage recorded the following physical description of the Saltair resort:

"The Saltair Beach resort is a monumental testimonial to the enterprising energy of Utah capitalists. The pavilion is situated thirteen miles due west from Salt Lake City, and may be reached by a twenty-minute ride on the Salt Lake and Los Angeles railroad. The railway here runs over a recently desiccated portion of the old lake bottom, which preserves many features of actual desolation, and affords an illustration of what the entire valley was in the geological yesterday. . . .

"The train runs on a pile-supported track 4,000 feet into the lake before the pavilion is reached. The buildings form a symmetrical group, with a large central structure connected with a semicircular extension at each end curving toward the lake. The architecture is after the Moorish sytle, and the general effect is as beautiful as the structure is substantial and serviceable. The pavilion was erected in 1893 at a cost of a quarter of a million dollars (figure 7).

"In length the buildings extend over 1,115 feet, with a maximum width of 335 feet. The top of the main tower is 130 feet above the water surface. Part of the lower floor serves as a lunch and refreshment pavilion: the area thus utilized is 151 by 252 feet. The upper floor in the main building is used as a ballroom: its dimensions are 140 by 250 feet. The dance floor is domed by a roof constructed after the plan of that covering the famed Salt Lake City Tabernacle, and the proportions of the two vast assembly rooms are nearly the same.

"On the semicircular sweeps which flank the central pavilion 620 bathrooms are provided. The bathing appointments are of the best, and the many flights of stairs leading to the water reach the bottom at points having a range of depth from fifteen inches to four feet. Deeper water may be reached at some distance outward. During the bathing season the observed temperature of the water ranges from 50 degrees to 86 degrees F.

"At night the pavilion is brilliantly illuminated by means of electric lamps. There are 1,250 incandescent lights and 40 ordinary arc lights, with one arc light of 2,000 candle power surmounting the main tower.

"As would be naturally expected, a resort of such attractiveness is secure in the matter of patronage. The records show an annual total of over 160,000 visitors."

Recreation at Saltair: Aside from its physical beauty and uniqueness, the Saltair story also has a human interest side which was lived and relived by the hundreds of thousands of people who frequented the famed resort until 1925. One such individual was Mrs. Alice Joplin (personal communication, November, 1979), who moved to Salt Lake City in 1911 and who, as a young woman, remembers Saltair in its "hey day".

"The only way you could get to Saltair in 1911 was by train. You couldn't get out there by automobile or anything else. The train ticket was 25 cents for a roundtrip. It had several cars, six or eight, but it had one that was a closed-in-car. The others were open and the seats went along the car not across like they do now. And the train went right on to the pavilion.

"The train went right on to the trestle and when you got your bathing suit you would follow that trestle and there would be steps to go down to the water. The first one was six feet deep, and it got more shallow as you went back toward the beach. Along the water there was a rope for you to hang on to, because when you got into the water you would bob so (figure 8).

"You could take your own suit if you wanted to, but if you didn't, you could get one at the bathing window. That was 35 cents and included a room to dress that was very primitive and a shower. You had to take a shower, because you would be full of salt. All the fresh water for the showers was tanked in. You were given a tag, and when you were done bathing, an attendant would let you into your room so you could shower.

"And I always wore a bathing cap and put a clean handkerchief underneath it. And that was so if you got a dose of salt you would have a clean handkerchief to wipe your eyes. One time there was a man there from the east and he got a terrible dose of salt. I took my handkerchief out and gave it to him and said, 'put your finger in your mouth and wet it and then rub your eyes with it', and he handed me back the handkerchief and he got out of that water too fast for words, and I never saw

Figure 8. Saltair pavillion and train. Passengers are unloading onto the 4,000 foot pier.

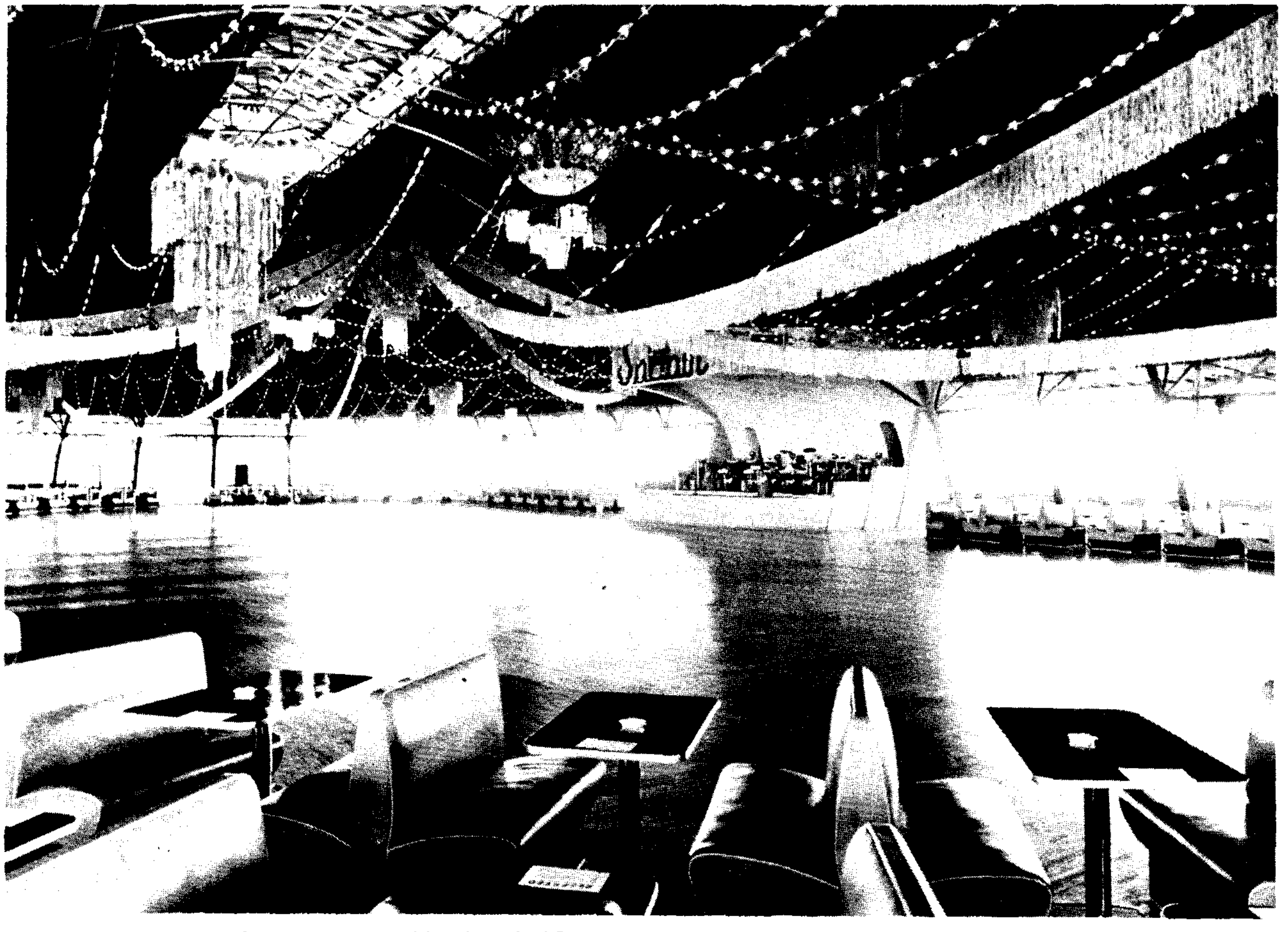

Figure 9. Dance floor and bandstand of Saltair pavillion. The dance floor was mounted on springs.

him again. Of course, I guess that didn't seem very sanitary, but you had to do something quick to get the salt out of your eyes. The eye, ears, and nose doctors got plenty of business. So that was that!

"There was very little what you would call swimming and no diving whatever because the water was like hitting a board. Now there was lots of floating on the back and one of our favorite pastimes was to make a chain. There would be a leader and the next one would hook his arms over the leader's feet and then the next one and the next one and then the leader would guide everyone around.

"When you would get out and shower then you would go back to the tables for lunch. There was a restaurant there of sorts on the first floor that you could buy your food, if you didn't bring your lunch. We always took a lunch and put it on a table on the lower floor. The lower floor had tables for lunches, the top floor was the dance floor, and if we had a coat or a wrap we would put that on the table too, and when you would come back it was always there. We didn't have much thievery then (figure 9).

"Then there was always a band there to dance and that was free. You really got a lot for your money. Sometimes I think if you charge a big amount that you don't get the number of people. And you know that a lot of families went out there and had their picnics.

"The dance floor was on springs. They had just one orchestra on a regular day, but on the 4th of July and the 24th and on Labor Day they had two, and when one would stop for a rest the other would start. It was really nice. The bands would play until 12 midnight.

"That's when the last train would go back to Salt Lake City. One time there was such a crowd that they couldn't get everyone onto the train, so a group had to wait for the train to go and come back to get us and we didn't get home till 3 o'clock in the morning. So that was that!

"And they had all kinds of concessions out there. They had a roller coaster that was just terrible. We had taken a girl out there with her boyfriend, and she wanted to go on that roller coaster and he didn't, but she insisted so he went. And on that first dip she fainted and he couldn't stop the coaster so he put her on the floor and held her down with his knees. He couldn't do a thing, he just had to wait till they got down to the bottom so they could get her out, and that was that!"

"Saltair was renowned for the famous bands playing in its dance hall, but the hall was also used for political rallies and conventions, acrobatic and gymnastic shows, and various other events. Boat excursions and amusement rides were also popular attractions. A fine restaurant was featured aboard the ship "Leviathon", which tied to the pier at Saltair.

"Saltair faced and overcame very difficult site constraints. Problems began with the driving of the pilings for the resort and 4,000 foot walkway. Steam had to be forced down through the lake bed to melt the hard sodium underlaying the site before the pile foundations could be driven. A few hours after the piles were placed, the sodium hardened, creating a virtually immovable foundation. Dense waves and high winds constantly threatened and damaged the building. The pavilion had to be repainted annually due to the severe nature of the microclimatic conditions (Terracor, 1979)."

On April 12, 1925, the Saltair pavilion was totally destroyed by fire, an incident that was to mark the diminishing use of the Great Salt Lake, and particularly the use of recreational pavilions for the next fifty years. Saltair was reopened in 1929, but never regained its previous popularity due partly to the fact that between 1929 and 1935, the lake dropped another seven feet and removed the visitor further from the water, by as much as three quarters of a mile.

With the stock market crash in 1929 and the resultant Great Depression of the 1930's, very few industries were able to make ends meet. Most affected were those industries (i. e. recreational) that were dependent upon expendable incomes in a time when few people could afford anything other than the basics needed for day to day living.

With World War II, priorities for the war effort rerouted the trains and further reduced the number of visits to the lake, and by the late 1940's, the auto was no longer a novelty. People were becoming more mobile; Big and Little Cottonwood canyons were now accessible to the Salt Lake valley residents and were to become the primary recreational areas.

Efforts to keep Saltair financially afloat continued until 1968 when the resort was finally closed to the public. On November 12, 1970, the structure once again burned and there remains now only a short section of old railroad bed as a reminder of an era.

Sunset Beach

"Sunset beach was located on the south shore in 1934. It provided modest facilities for families who wanted to enjoy the lake at minimum expense. Access to Sunset was entirely by automobile, and the lure of simple beach facilities made Sunset both popular and profitable. Although it survived a rising lake level in 1953 and the extreme low of 1963, Sunset Beach finally closed in 1967.

Sand Pebble

"In 1969 a south shore resort named Sand Pebble was built on a tailings test jetty constructed by Kennecott Copper Company in 1965. Facilities included several small buildings that provided basic services. The beach closed in 1972 after only four years of operation when the rising lake destroyed its facilities.

Silver Sands

"Of all the resorts developed on the shores of the Great Salt Lake, Silver Sands is the only one still operating. John Silver began work on Silver Sands in 1959 and was open to the public in 1964. At first, small tents served as dressing rooms and fresh water was supplied by a tanker truck which also pumped water to the showers. The tents were later replaced by wooden cabanas which were built on skids and joined together. In case of rising water, a truck could tow them to higher ground. This exemplifies Silver Sands development methods, unique in the history of south shore resorts, which was based on the concept of portable facilities.

"The development offered a number of activities. Brightly colored amphibious vehicles provided tours around the south shore. In 1966, a refreshment stand, canoes, water bikes, miniature golf and go-carts were added (the latter two proving unprofitable). Beginning in 1970, *The Islander*, a 57-foot catamaran touring dinner cruise yacht, was featured. The yacht, which is no longer operating, offered gourmet dinners and live Hawaiian entertainment. In 1972, the marina was started using the remains of the old Salt Lake County Boat Harbor breakwater. In 1975, a concession-gift shop was constructed one- and-one half miles east of the original Silver Sands resort.

"Silver Sands continues to be financially successful. In 1965, over 200,000 people paid admittance to the beach, and in 1972, Silver Sands had 480,000 visitors with an average revenue of 60 cents per person. Today, the concession-gift shop is very successful, with south shore visitor totals of over one million people per year. Together with facilities provided by the State, Silver Sands provides services that make a large area of sandy beach on the south shore available to the public. These existing services and facilities, however, seem extremely inadequate considering the potential visitor demands at Saltair Beach (Terracor, 1979)."

Boating on the Great Salt Lake

The early history of boating on the Great Salt Lake was concerned mainly with transporting freight and passengers to and from the islands or from point to point around the lake. The first vessel to be used for recreational purposes was the *City of Corinne*, a 300 ton Mississippi River type stern wheeler, that was used for carrying freight until the waters in the lake and in the Bear River became too shallow. It was then used as an excursion boat in the deeper portions of the lake.

By 1877, the Salt Lake Yacht Club was a functioning organization which had goals not only to develop an increasing interest in boating, but to enhance and promote the facilities necessary for this to flourish. At the same time that the yacht clubs were organizing, rowing clubs were being developed. In 1888, the Mississippi Valley Rowing Association held a regetta in the lake (Morgan, 1947, p. 362).

But the same problems encountered by the resort facilities also plagued the boating activities. The receding shorelines either kept the boatsman from his vessel or prevented the boat from reaching waters deep enough to navigate. It was also found that corrosion of metal parts subjected to the brine made the maintenance of motor powered boats an expensive activity. In the early 1900's interest in boating on the Great Salt Lake diminished, but recent years have seen a resurgence of the sport. There are now more than 200 sail boats anchored on the lake year around at Silver Sands harbor, which is hard pressed to find space for all those wanting to sail. The advent of fiber glass and totally contained cooling systems has made maintenance of power boats easier and has encouraged their use (figure 10).

THE GREAT SALT LAKE TODAY

The 1970's have witnessed the revival of the Great Salt Lake as a recreational resource in Utah. Annually, more than 1,000,000 people visit its shores to enjoy the available recreational facilities. While interest in some types of recreation, such as swimming, has remained relatively constant over the years, several new activities have emerged. Camping, trail-biking and jogging have increased significantly over the past few years. One of the most popular of the newer sports has been the annual National Sand Drags held near Sand Pebble Beach, on the south shore of the lake. The National Sand Drags draw large crowds every year (figure 11).

Antelope Island

The purchase of 2,000 acres at the north end of Antelope Island by the State Park system in the 1960's provided another recreational area on the Great Salt Lake. Antelope Island is reached by a seven mile road that crosses the eastern portion of the lake from the mainland west of Syracuse. This portion of the park offers the visitor the opportunity to swim, sunbathe, picnic and perhaps see and photograph local wildlife, which includes a herd of buffalo, deer, bobcats, kit fox, mountain lion and various species of birds and water fowl.

The state today is faced with the problem of providing adequate facilities and services for these areas, such as parking lots, boat slips, picnic and camping sites with shade, water and sewage. This problem is complicated by the everchanging levels of the water in the lake.

THE FUTURE OF RECREATION ON THE LAKE

Plans are being made that will ensure recreation facilities on the lake in the future. But, what kind of recreation will be popular, and what type of amenities would the public like to see remain undeveloped? To answer these questions, studies were made which led to the following recommendations:

1. The lake appears to have a high potential for the following types of recreational opportunities: sail, power and air boating, swimming, and natural hot water mineral baths. Recreation on the land includes hiking and horseback trails, scenic overlooks, camping and picnic areas with natural shade, bird watching, and the establishment of primitive areas. Areas for trail bikes and off-road vehicle activities should also be established.

2. Restrooms, showers and drinking water facilities as well as roads should be built or improved and maintained, and shade facilities should also be established.

3. Brine flies, mosquitoes and other insects should be controlled.

4. The development of the recreational, educational, historical and view sites around the lake to be oriented towards the needs of tourists as well as Utah residents; and that private capital will be attracted to develop motels, restaurants and amusement parks.

Ross B. Elliott, the Director of the Utah Division of Parks and Recreation discusses the future of the Great Salt Lake in providing recreational facilities for the citizens of Utah and for its visitors:

"To say that the Great Salt Lake has recreational potential is truly an understatement. The earliest written reports that we have available to us indicate that the lake has long been a unique attraction.

"In the ensuing 100 years the depth of the lake has fluctuated, but as a unique attraction, visitation has not diminished. This is apparent from the lake's visitation records. In 1978 the Great Salt Lake South Shore and Antelope Island were visited by 1½ million people; and visitation has increased annually.

"The combination of the lake's unique geological environment, its proximity to 80 percent of Utah's population, and its convenient access from interstate highways all assure a growing popularity. The State Legislature has responded to this increasing demand for close-to-home recreation at the Great Salt Lake with appropriations for development of the South Shore and authorization for the purchase of the remainder of Antelope Island.

"Quite frankly, the Divison of Parks and Recreation is excited about the possibility of recreational facilities becoming a reality. The task before us, however, is not a simple one. With careful planning and continued support from the legislature, we believe that our development will not only provide the quality experiences the lake's visitors desire, but will also encourage complementary private development in the adjacent areas (figure 12).

"We whole heartedly feel that the Great Salt Lake can maintain the nation-wide stature it has long enjoyed.

"The appearance of the Saltair Beach District and the Antelope Island District of the Great Salt Lake State Park 30 years from now is left to your imagination. How people may be "recreating" in these areas in the future is pure speculation. Perhaps hang-gliding from the mountains on Antelope Island or hot air ballooning over the Great Salt Lake may be in demand. Will the hovercraft

Figure 10. Great Salt Lake South Shore Marina – 1979. Note breakwater built by Parks and Recreation. Antelope Island is in the background.

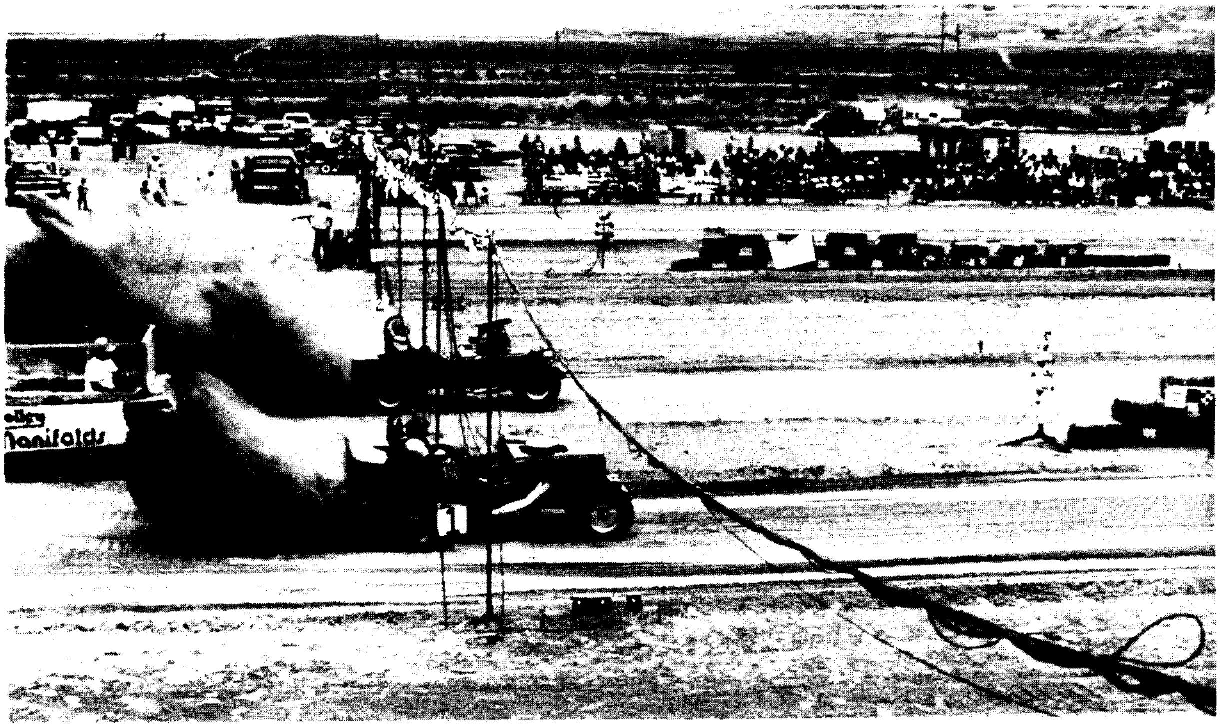

Figure 11. 1979 Sand drags held at Sand Pebble Beach on the southern shore of the Great Salt Lake.

be as popular as skateboard riding down the road from Buffalo Point? In any event the Division of Parks and Recreation plans to meet the increasing demand for safe recreation at Utah's great natural resource, the Great Salt Lake." (figures 12 and 13)

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Note - Photos in figures 2 through 9 are provided by courtesy of the Utah Historical Society.

Figure 12. State Parks and Recreation Rescue Boat EX 1 was purchased for the safety of boaters on the Great Salt Lake.

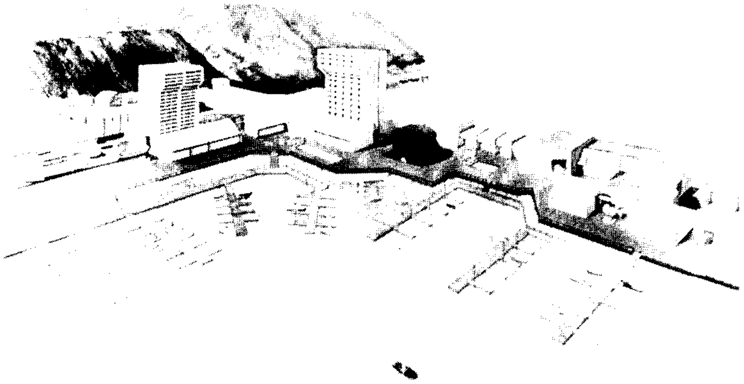

Figure 13. Artists conception of Great Salt Lake Beach near Blackrock in the year 2000.

THE GREAT SALT LAKE COMPREHENSIVE PLAN

by Owen W. Burnham

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ABSTRACT

After many years of litigation, the State of Utah obtained sole ownership of lands and lake surface of Great Salt Lake in 1975. The Utah Legislature provided for preparation and adoption of a comprehensive plan for development and management of the lake in 1975 through the Great Salt Lake Division of the Utah Department of Natural Resources. This comprehensive plan was adopted by the Great Salt Lake Board in 1976. The plan sets forth goals and policies to govern development and use of the lake and adopts a general use plan for development of minerals, wildlife resources, recreation and tourism, transportation and the hydrologic system.

INTRODUCTION

The Great Salt Lake has been considered one of the unique geographic features of the Great Basin since first viewed by white man. Resource development commenced on the lake soon after the arrival of the first settlers in the Basin. The lake has been the subject of many hundreds of investigations and studies since it first became known, ranging from specific scientific investigations to general investigations of conditions and potential for resource development of the lake. A study conducted by the lake subcommittee (1973) identified in excess of 600 different reports and investigations which had been made pertaining to various subjects of the lake.

The lake has been recognized as a unique resource in the State of Utah. It has great potential for multiple-use development including minerals extraction industries, recreational development, wild life management areas and other related uses.

After many years of litigation between the State of Utah and the United States government the Supreme Court of the United States in 1975 confirmed the sole ownership of the lake as resting with the State of Utah. In response, the 1975 general session of the Utah Legislature enacted House Bill Number 23 which established a division of the Great Salt Lake within the Utah State Department of Natural Resources. The purpose of the bill was stated as follows: (1) to establish policies designed to accomplish the proper planning and management of the lake; (2) to direct the preparation of a comprehensive plan for the lake in a manner which will assure the maximum interchange of information and would accomplish the goals set forth stated in the bill as follows:

> "The legislature determines that the Great Salt Lake is a unique natural resource of the State, locally and world renowned as a wonder of nature, economically and esthetically productive through mineral extraction, recreational activities and wildlife resources, and intrinsically valuable as a natural body of saline water. The Legislature recognizes that the coordination must be done in a manner which will ensure a balanced use of the resources of the lake, within the constraints established by nature and the needs of the people residing in the lake's area of influence, and retain the lake's basic identity as a unique natural body of saline water. To this end, the Legislature determines that the public interest dictates that the State should adopt an appropriate institutional arrangement, utilizing existing agencies, divisions or authorities of State, federal and local governments wherever possible, to provide an affective, coordinated management of the lake and its resources."

In establishing the Division of the Great Salt Lake, the Legislature provided for jurisdiction of the lake below the official meander line. This meander line has been established through a series of official land office surveys beginning in the 1800's with the last survey made in 1966. The meander line does not precisely follow any given elevation but has varied with the level of the lake at the time each survey was made. The meander line varies between the elevations of 4,212 and about 4,202 above mean sea level.

With the establishment and directive of House Bill Number 23 the Great Salt Lake Division began preparation of a comprehensive plan in July of 1975. The plan was developed through the efforts of an inter-agency technical team which was established under the terms of the basic 1975 legislation. The inter-agency technical team is made up of representatives from various interests, both public and private, and includes representatives from several divisions of the Department of Natural Resources, Department of Transportation, County Commissioners of the five counties surrounding the lake and other representatives who serve on the basic committees.

The following Goals and Policies for the Great Salt Lake were adopted by the Great Salt Lake Board on January 9, 1976, in harmony with the provisions of House Bill Number 23 establishing the Great Salt Lake Division and Board.

Goal One

To prepare, adopt, and maintain a general, comprehensive plan of the lake and its environs consistent with Goals 2 through 4: to insure a continuing planning process: and to keep lake plans and programs responsive to current and future needs.

POLICY 1. Seek the cooperation and assistance of concerned federal, state, county, and other public agencies, private groups, and interested individuals in developing and maintaining the comprehensive plan, guidelines, rules and regulations, and additional policies.

POLICY 2. Prepare, adopt, and maintain a general, comprehensive plan of Great Salt Lake through the use of commonly accepted planning practices and procedures using existing and future studies and information, and developing new information as required, and in cooperation with federal, other state, and county general plans.

POLICY 3. Encourage the five counties surrounding the lake and the Great Salt Lake Division to work harmoniously in the preparation of compatible comprehensive plans for the use of land surrounding the lake and adopt ordinances and rules and regulations to effectuate those plans.

POLICY 4. Develop guidelines aimed at pointing out the desirable direction of activities and operation for the lake in cooperation with other agencies having jurisdiction on the lake.

POLICY 5. Adopt, in cooperation with other appropriate federal, state, and local agencies, rules and regulations relating to operations at the lake.

POLICY 6. Define and identify the Great Salt Lake flood plain and recognize it as a hazard zone for management and development.

POLICY 7. Act as a central clearinghouse for all studies, investigations, and activities related to the lake and publish or encourage the publication of information obtained.

Goal Two

To preserve, insofar as reasonable, the Great Salt Lake's basic identity as a useable and unique natural body of saline water.

POLICY 1. Investigate the desirability and the physical, economic, and political feasibility of procedures which would be used to control the level of the Great Salt Lake, recognizing the impact of extreme high and low water levels on management, planning, and development of the lake.

POLICY 2. Until approved and adopted procedures for controlling the level of Great Salt Lake are found, the formulation of the comprehensive plan and the ongoing planning process will recognize varying lake levels resulting from nature's wet-year and dry-year cycles.

POLICY 3. Maintain contact with various agencies having control of upstream water to insure a foreknowledge of any radical change of inflow into the Great Salt Lake.

Policy 4. Encourage the management of present and future up-stream storage facilities including appropriate lakes, reservoirs, and underground water basins to retain maximum water storage in wet-year cycles and to encourage the release of water on a planned basis.

POLICY 5. Evaluate alternative actions and make a determination concerning modification of the Southern Pacific Railroad causeway between Promontory Point and Lakeside or maintenance of the causeway as presently constructed.

POLICY 6. Give special consideration to the effect on salinity and lake levels of existing and future dikes or other man-made structures.

Goal Three

To encourage, promote, and protect the harmonious and compatible development of recreation, industry, wildlife, aesthetic, and other multiple uses of the lake and its environs.

POLICY 1. Advise existing industrial, recreational, and other interests on the lake of flood plain hazards and projected lake levels.

POLICY 2. Brief future tenants of the lake on the problems identified in Policy 1 to enable them to consider the same in their planning.

POLICY 3. Identify areas of the lake and the land surrounding it which should be allocated to the most appropriate uses; give emphasis in grouping harmonious uses together, but where necessary identify areas which should be protected from encroachment of incompatible uses.

POLICY 4. Identify and foster new uses which are compatible with existing uses of the lake and its shore lands to broaden the industrial and recreational-tourism economy.

POLICY 5. Support the recreational development of Antelope Island, Farmington Bay, and the south shore as an integrated recreational complex.

POLICY 6. Evaluate the lake its adjacent lands, and its related resources to identify the locations that would be most desirable for future industrial development.

POLICY 7. Encourage oil exploration within the boundaries of the Division's jurisdiction provided the necessary safeguards are taken to protect the environment of the lake.

POLICY 8. Support the maintenance and expansion of existing state, federal, and privately managed marshlands and rookeries now located on the lake.

POLICY 9. Identify additional areas, such as Gunnison, Cub, Carrington, Hat, and Dolphin Islands, that might be suitable for wildlife protection and propagation and that should be developed or protected from undue encroachment by incompatible uses.

POLICY 10. Support the development of better public access to the facilities for the lake's general recreation, hunting, and fishing areas.

POLICY 11. Support the establishment of an off-limit zone around Gunnison and Cub Islands and other areas as appropriate during the nesting season and maintain an appropriate off-limit zone during the remainder of the year.

POLICY 12. Encourage and assist the establishment of high standards of design, building construction, and landscaping for all developments, specifically considering, among others, the views from highways, recreation areas, and boats.

Goal Four

To encourage acceptable standards of health and safety of persons and property in the waters of the Great Salt Lake and on adjacent shore lands.

POLICY 1. Encourage greater and safer water recreational use of the lake through the provision of adequate marinas, a navigational aid system, education, and appropriate search and rescue operations.

POLICY 2. Encourage appropriate research to define the status of pollution on the lake, to understand the fate of pollutants in the lake, and to assess the capacity of the lake to receive waste.

POLICY 3. Consider the need for a water quality management program for the lake itself.

* * *

The actual development of the comprehensive plan was begun by dividing it into elements including minerals, wildlife, recreation, tourism, transportation and hydrology.

Subcommittees made up of representatives from the Great Salt Lake Board, from the Interagency Technical Team, and from other organizations and individuals having a particular interest in these elements, with the help of the Great Salt Lake Division staff, developed a preliminary plan for each element. It became obvious, early in the studies, that all of the six elements would be affected by and would affect the other elements of the plan. This was particularly true of the hydrology elements dealing with actions recommended to manage the lake during periods of unusually high level. (For further information on the detailed contents of each of the comprehensive plan elements, the reader is referred to the reference section of this report and to the studies dealing directly with the comprehensive plan).

The general objective of the comprehensive plan was to identify the areas of the lake which would be suitable for the various uses such as mineral extraction, recreation development, wildlife management areas, industrial development, and other uses which may become important in future years. The transportation element and utilities were intended to serve all of the uses of the lake. It was found that the existing uses were compatible and there were few areas identified where there were serious conflicts of land use.

The Interagency Technical Team and the Board of the Great Salt Lake considered input from other interested individuals and agencies at more than 50 meetings during 1975-1976. A final comprehensive plan document was prepared and was adopted by the Board as a guide to present and future development and management of the Great Salt Lake.

The comprehensive plan is considered as the basic document to be used as a coordinating mechanism among the many public and private agencies having interest in and around the Great Salt Lake. Development proposals which come before the Great Salt Lake Board and the Interagency Technical Team are considered in light of the general plan and then are reviewed in detail as to their affect on surrounding land uses and on the future long-term development of the lake. The Great Salt Lake Division has prepared and adopted a management plan and procedure by which the proposals for development by all public or private agencies are reviewed and opportunity is given for comment before approval is given for development. The nature of the comprehensive plan is such that it will require review and updating on a continuing basis.

Research on certain elements of the plan will be carried into greater detail. For example, parts of the hydrology element, dealing with actions necessary to reduce chances of the lake level exceeding elevation of 3,202 feet, have been studied in greater detail during 1977 and 1978 after the comprehensive plan was adopted. Several research projects dealing with salinity distribution and the biology of the lake have also been conducted and will form a basis for future decisions relating to development of the lake.

Prevention of flood damage to facilities at or adjacent to the lake in the case of increasing lake levels was studied in greater detail. A preliminary plan for management of lake levels contemplates the expansion of evaporative ponding areas to be used in case of rising lake level. The Great Salt Lake Division in cooperation with other agencies is now preparing a contingency plan for developing additional evaporative ponding areas. The contingency plan will be considered by the Great Salt Lake Board and then recommended to the Governor and the Legislature for the necessary funding.

In summary, the comprehensive plan coordinates the many different interests and agencies involved in development and management of lake resources. It enables the long and short term effects of proposals to be reviewed and evaluated and it is the means by which all of the agencies, both public and private, that have an interest in the lake may be aware of what others are doing as the resources of the Great Salt Lake are developed.

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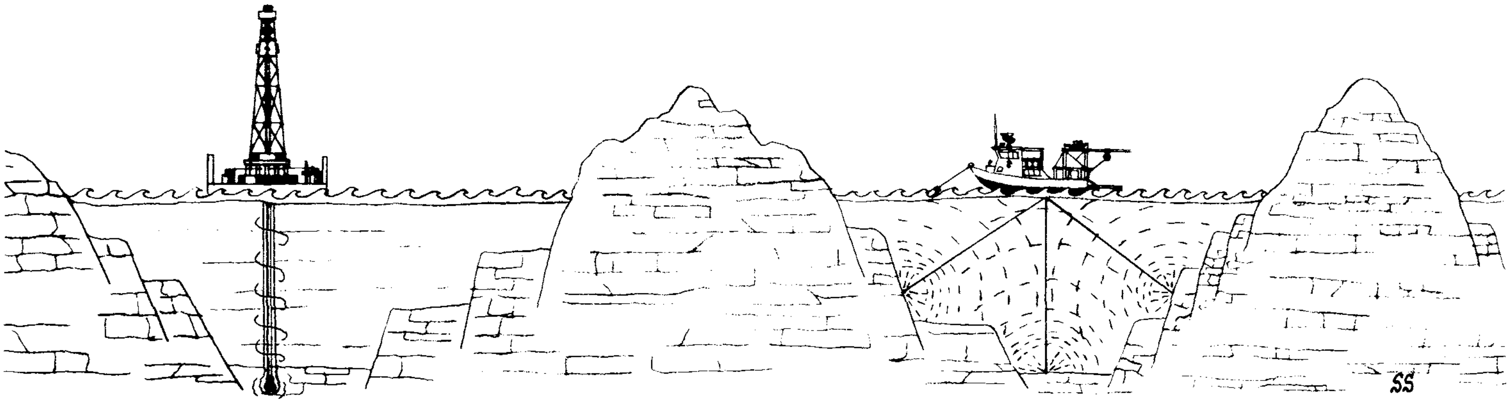
GEOLOGY AND GEOPHYSICS



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GEOLOGIC SETTING OF GREAT SALT LAKE

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INTRODUCTION

Great Salt Lake occupies the lowest spot in a drainage basin of 22,060 square miles. Although the lake is situated in the Great Basin province it receives very little water from local sources; the rivers that keep it alive come from adjacent portions of the Rocky Mountains and Colorado Plateau. How the contributing rivers come to occupy their anomalous courses across and around the Wasatch Range is an unsolved geomorphic problem. That the amount of water delivered to the central low spot has been subject to great variation is obvious from geomorphic and stratigraphic evidence, but the causes of these volumetric changes is not fully explained.

Geologically speaking Great Salt Lake is variable, transitory, and ephemeral. Even within historic time water depth has ranged through almost 20 feet and consequent migrations of the shoreline have been extensive. A map of the contours of the lake drawn during the known historic high stage of 1873 is very different from one depicting the low stage of 1963, as shown in figure 1. A succession of water bodies has occupied this particular space for at least several million years (Morrison, 1966).

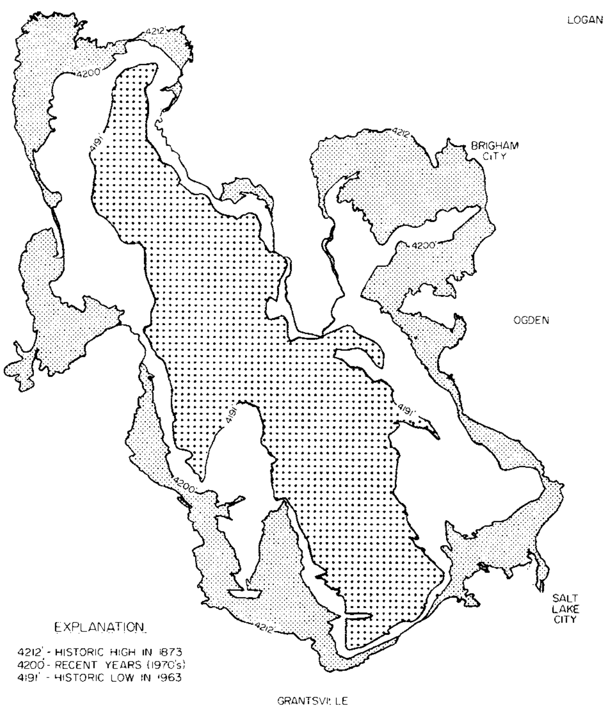

Figure 1. Map of Great Salt Lake showing area between 4200 foot elevation and historic high of 1873 (small dots) and at historic low of 1963 (large dots).

STRUCTURE

The present lake, as did the deeper parts of its predecessors, occupies three interconnecting fault-bounded depressions or grabens flanked by two parallel horsts and crossed by two other discontinuous and partly submerged horsts that give rise to the various islands (figure 2). The Wasatch Range may be said to confine the lake on the east side. The section of range adjacent to the lake is Farmington Mountain, a relatively narrow and straight horst of resistant Precambrian crystalline rocks (Bell, 1952). Parallel with and immediately west of the Farmington Mountain Horst is the Wasatch structural trough (Cook and Berg, 1961) mostly filled by Tertiary and Quaternary sediments. This depression is complex; according to geophysical interpretations of the south and east part of Great Salt Lake (Cook and others, 1966), it consists of a number of subsidiary blocks designated from east to west as the Farmington Graben, the Farmington Bay Horst, and the East Antelope Island Graben.

The proximity of the Farmington Mountain Horst has had expectable effects on the shape of Great Salt Lake. An apron of alluvial material derived from the mountains descends directly into the lake and has in effect displaced the water westward. It is surprising that the graben area has remained low enough to be even partly flooded. Sediment supply has evidently not been sufficient to entirely fill the space created by downsinking of the trough. The situation calls to mind the relation of high and low spots along the eastern base of the Sierra Nevada, the mirror-image equivalent of the Wasatch Range, 500 miles to the west.

The next structure to the west is the Antelope-Promontory Horst, which shows on the map as an island chain. The southernmost member, Antelope Island, has a long axis trending N18° W and is disconnected from the land when lake level reaches 4,211 feet. A middle member, Fremont Island, has a triangular outline and longest dimension trending N71° W. To the north is Promontory Point, a relatively wide peninsula extending almost due north to separate Bear River Bay on the east from the North Arm to the west.

West of the Antelope-Promontory chain the main body of the lake occupies a complex graben for which the designation Great Salt Lake Graben would seem to be appropriate. The trend of this major depression is N 30° W along an axis between Blackrock and Kelton, which divides it into two fairly equal parts. It is signi-

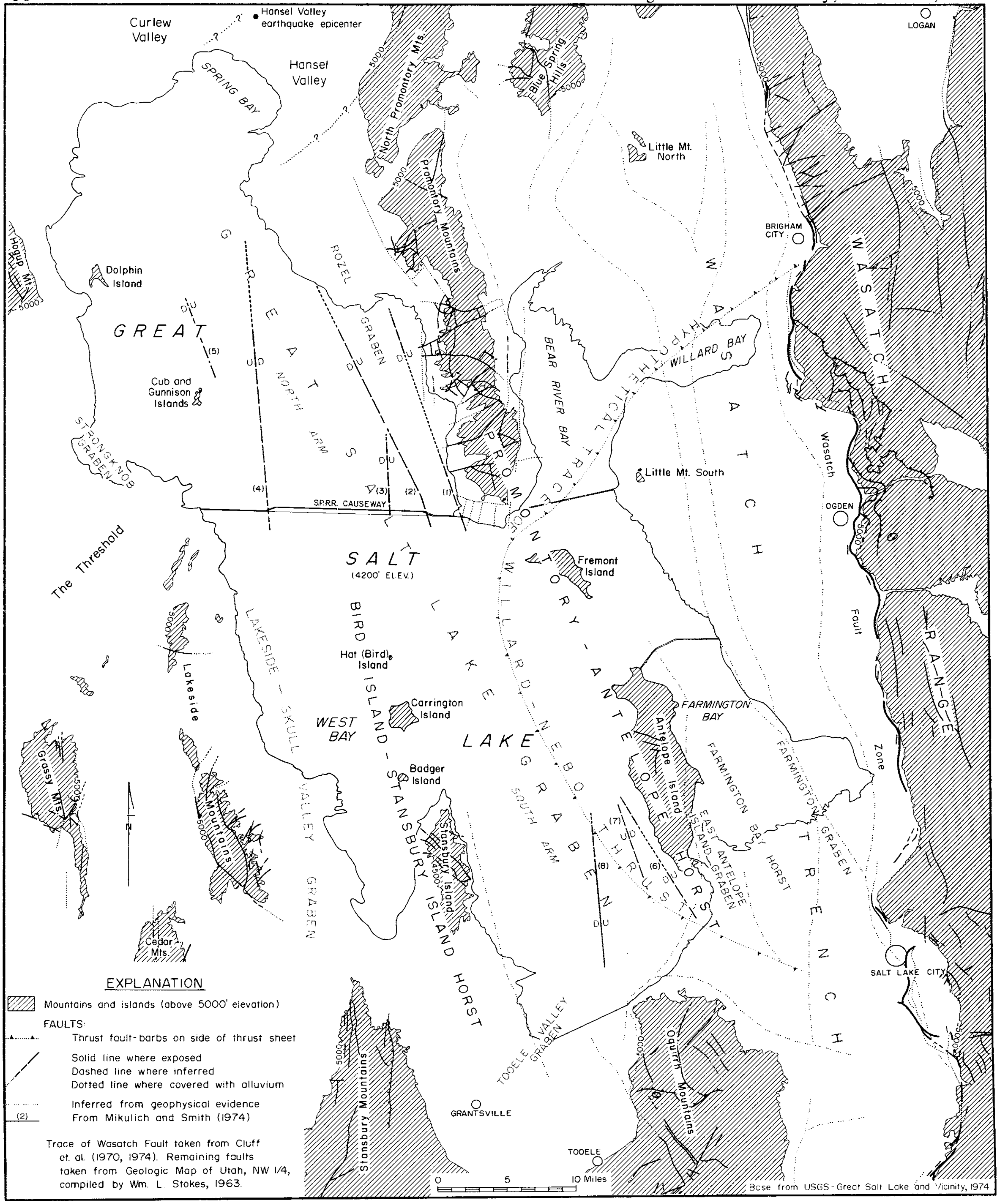

Figure 2. Map of Great Salt Lake and surrounding region, showing major structural features.

ficant that if the water level fell to 4,175 feet, Great Salt Lake would have a narrow ribbon-like shape about 6 miles wide and 66 miles long with the same trend as the present main water body.

West of the Great Salt Lake Graben another horst is made evident by the alignment of Stansbury, Carrington and Bird islands, trending roughly N15° W. This horst seems to narrow and terminate near the center of the lake. The Stansbury-Bird Island Horst separates the Great Salt Lake Graben from the westernmost graben of the system, occupied in part by Skull Valley and in part by West Bay of the lake. The name Skull Valley-West Bay Graben is proposed. The two grabens merge north of the horst to form the North Arm of the lake.

On the west, Great Salt Lake is bordered by a complex series of low mountains consisting of the Lakeside Range on the southwest (Doelling, 1964; Young, 1955) and the Terrace-Hogup Ranges on the northwest (Stifel, 1964). Although the general trend of these ranges is slightly west of north, in conformance with the outline of the lake, the group is clearly not a simple horst like the Farmington Mountains to the east. A topographic discontinuity between the Lakeside and Terrace Mountains is known as the Threshold. Through this gap the Great Salt Lake overflows into the Great Salt Lake Desert when the water level reaches approximately 4,215 feet.

The extreme northern edge of the lake is marked by an anomalous, rather sharp, almost right angle bend into Hansel Valley. This configuration creates Spring Bay and is almost certainly controlled by late Cenozoic faults. As shown by the State Geologic Map (Stokes, 1963), the faults bounding Hansel Valley curve westward so as to confine the adjacent water body. The strongest Utah earthquake of historic record (6.6 on the Richter scale) had an epicenter in the southeast quarter of T.12 N., R. 8 W., in Hansel Valley. The ground was broken and there was a general subsidence of 20 inches. Deformation of this sort could have easily created Hansel Valley and Spring Bay in a geologically short time period.

The known and inferred faults in and adjacent to the Great Salt Lake do not fall into a simple pattern. Although there is a distinct northerly trend to practically all faults and fault controlled structures, there is a peculiar twist along a zone including the southern Lakeside Mountains, Carrington Island, Fremont Island, and the Wasatch Range between Ogden Canyon and Brigham City. The axis of major uplifts such as the Stansbury Mountains, Stansbury Island, Farmington Mountains, Promontory Point, and Antelope Island trend within 20°W of north and presumably their bounding faults do the same. But this is not the trend of the axis of the main water body of the Great Salt Lake, or of the Farmington-Bear River Bay trough or of the Wasatch Range north of Ogden River. All of these trend more than 20° west of north. Spring Bay at the extreme north end of the lake has an axis trending about N45° E. While the meaning of these structural trends is obscure, they are no more varied than those of most areas of equal size within the Basin and Range province.

Structural Elements Discovered by Gravity Surveys

Many structural features in and marginal to the Great Salt Lake were named by Cook and others (1966). These include the previously mentioned Farmington Graben, Farmington Bay Horst, and East Antelope Island Graben, all with trends parallel to Farmington Bay. Other features with negative gravity anomalies named by Cook and coworkers are Bear River Bay Graben and Rosell Graben, so designated for their corresponding surface features.

The Lakeside-Stansbury Graben (or the Skull Valley-West Bay Graben), with the same trend as the central water body, lies between the Lakeside Mountain and the Stansbury-Carrington-Bird Island group. The depression of Skull Valley extends southward well beyond the Lakeside Range. The Tooele Valley Graben, traced into the extreme southern part of the lake from near Grantsville, trends about N45° E, somewhat out of harmony with surrounding structure and is apparently responsible for the blunt foot-like shape of the south end of the lake. This creates a curious symmetry of the north and south extremities of the lake that must be coincidental.

With a few significant exceptions the inferred configuration of the deeply buried bedrock surfaces corresponds with the outline and water depths of the lake. Thus the Farmington-Bear River Bay graben appears to determine the shape of the lake east of the Antelope-Promontory alignment; the Tooele Graben follows the trend of Tooele Bay and the southeast edge of the lake, while the Lakeside-Stansbury (Skull Valley-West Bay) graben occupies roughly the same territory as West Bay. Two gravity configurations that correlate less well with visible features are the Farmington Bay horst, which has no surface evidence, and the Rozell Graben, which is topographically higher than adjacent territory.

Structural Elements Determined by Seismic Reflection and Aeromagnetic Surveys:

In contrast to the gravity surveys which were made by land-based instruments, the latest geophysical surveys were taken from water and airborn craft. Mikulich and Smith (1974) used air-gun and sparker devices to take continuous seismic reflection profiles along more than 750 km (450 mi) of traverse and have evaluated an aeromagnetic survey retracing the same lines. Results of these surveys coupled with the gravity surveys emphasize the correlation of the lake basin with regional structure.

In addition to locating troughs and basins by discontinuities along boundary faults, the seismic data provide information as to probable contacts of (1) unconsolidated Quaternary mud, clay, salt and sand; (2) semi-consolidated Quaternary sediments; (3) consolidated Tertiary sediments, and (4) Paleozoic and Precambrian bedrock. The seismic reflection survey located 8 significant faults, five mainly north of the causeway and three south of it (Mikulich and Smith, 1974, figure 12); (figure 2, this paper). The longest fault (4 on figure 1), trends an estimated 27 miles diagonally across the North Arm. Fault 3, with the same trend, crosses the causeway about 13 miles east of 4. Two faults, 2 and 1, cross the area between Rozell Point and the Little Valley Boat harbor. All these faults are downdropped toward the central axis of the lake. Structurally, 4 of the northern faults create a basin of Tertiary sediments near the axis of the North Arm and 3 shallower Quaternary basins offshore from Promontory Point (See Mikulich and Smith, 1974, figures 7, 13).

Three normal faults (6, 7, & 8) were traced in a 5-mile wide band immediately west of Antelope Island. Except for the outermost fault, (8), these are parallel with the southwestern shoreline of the island. Fault 8 trends N5° W essentially the same as (4) of the North Arm. The arrangement of the southern faults creates a graben next to Antelope Island and beyond this an offshore horst with no surface expression (see Mikulich and Smith, 1974, figure 11).

NOTE: The following sections on shoreline mountains and islands of Great Salt Lake are abstracted from Guidebook 20, Utah Geological Society. I thank R. E. Cohenour and K. C. Thompson, (1966) authors of the paper, *Geologic Setting of Great Salt Lake*, for use of this material.

THE SHORELINE MOUNTAINS

Great Salt Lake contains and is defined by strikingly linear mountain ranges and intervening depressions, all of which have a northerly trend. The eastern shore is limited by the alluvial slopes of the northern Wasatch Range. West of the Wasatch Range and across Jordan Valley, to the south of Great Salt Lake, are the imposing Oquirrh Mountains. Next to the west are the broad and gentle alluvial slopes of Tooele Valley which rise to the Stansbury Mountains, whose northernmost extension marks the southwest corner of the lake. Still farther northwestward across the barrens of Skull Valley are the Lakeside Mountains which define over one-third of the west shore. Northwestward from the Lakeside Mountains across a threshold area leading to the Salt Lake Desert are the subdued Terrace and Hogup Mountains which bound most of the western shore of the northern part of the lake. The southeast slopes of the Raft River Mountains, Curlew Valley, the Hansel Mountains and Hansel Valley fringe the northwestern arm of the lake. The Rozel Hills and Promontory Mountains disrupt the rather orderly outline of the lake on the northeast, thereby creating Bear River Bay which terminates against the slopes of the Wasatch Range.

Wasatch Range

The Wasatch Mountains, an impressive barrier range, are bounded by the continuous north-south Wasatch Fault zone. More than 7,000 feet of relief is presented between mean lake level of 4,200 feet and nearby peaks which tower in excess of 11,200 feet. More than 70,000 ft. of strata, ranging from Precambrian through Tertiary, comprise the core of the Wasatch Range. The structure of the range, though varied and in places complex, can be explained by an early period of essentially west to east compression followed by relaxation which allowed tensional forces and isotatic adjustments to prevail. The early period of compression produced thrust faults, while the subsequent period of tension favored the development of north-south normal faults.

Oquirrh Mountains

The northern portion of the Oquirrh Mountains, together with the northerly slopes of Jordan and Tooele Valleys, limits the lake to the south and southeast. Coon Peak, the highest point in the northern Oquirrhs, rises to over 9,000 feet, or about 4,800 feet above the lake. The mountains are steep and rugged, with many exposures of limestone, the principal bedrock. The northern Oquirrh Mountains are composed principally of thick units of the Oquirrh Formation, of Pennsylvanian and Permian age. Seven units of the Oquirrh Formation with an aggregate thickness of 11,600 feet have been mapped. Limestone, shale, sandy limestone, quartzite, cherty limestone, and dolomite represent the dominant rock types of the formation.

Structurally, the Oquirrh Range resulted from an interplay of two earlier compressive forces which were followed by the later Basin and Range faulting. The earlier orogeny was directed eastward and produced the broad north-south folds, which are the typical structures of the central and southern portions of the range. Following the eastward compression, forces acting from slightly west of north, more or less along the present long axis of Great Salt Lake, created east and northeast folds in the northern half of the range. The forces from the north evidently were dissipated as the northern block overthrust the central portion along the North Oquirrh Thrust (Roberts and Tooker 1961). The Oquirrh Range is the site of the world famous open-pit Bingham Canyon Mine and the "ghost towns" of Ophir and Mercur.

Stansbury Mountains

The Stansbury Mountains rising on the southwest edge of Great Salt Lake are narrower and less impressive than the Oquirrh Range to the east. Rocks of Cambrian, Ordovician, Silurian, Devonian and Mississippian periods are present. These have been folded by west to east compressive forces. Broad folds, localized reverse faults, and major normal faults typify the internal structure. The geology of the range has been described by Rigby (1958).

Lakeside Mountains

The Southern and Northern Lakeside Mountains fringe most of the south-western shore of Great Salt Lake for a distance of about 30 miles. The highest peak is Black Mountain, elevation 6,620 feet, a maximum relief of 2,420 feet above the 4,200 foot level of Great Salt Lake.

Twenty-nine formations have been recognized in the Lakeside Mountains (Young, 1955; Doelling, 1964). Doelling measured 7,003 feet of Cambrian, 3,094 feet of Ordovician, 653 feet of Silurian, 2,562 feet of Devonian, 6,646 feet of Mississippian, 3,541 feet of Pennsylvanian and 14,517 feet of Permian strata, for a total of 37,916 feet. An additional 5,377 feet of strata is inferred or estimated, which totals 43,292 feet, one of the thickest Paleozoic sections in Utah.

The structure of the Lakeside Mountains is dominated by westerly dips and open north-south folds, especially in the western blocks. Normal faults, trending in broad arcs concave to the west, partially separate the eastern and western portions of the range. The eastern segments contain many transverse normal faults, several north-easterly trending folds and one northerly trending fold.

Terrace and Hogup Mountains

The Terrace and Hogup Mountains border a portion of the northwest shore of Great Salt Lake. They form a mountainous area about 16 miles long, with a maximum width of 10 miles. Elevations in excess of 6,500 feet provide relief of 2,300 feet above mean lake level. The Terrace Mountains were named for their abundant and excellent display of Bonneville beaches not only at the major lake levels but also many intermediate stages. Hogup derived its name from the unpopular reputation of either a sheepman or early railroaders who supposedly tried to dominate or "hog up" the area.

Most of the bedrock exposures are late Paleozoic strata. According to Stifel (1964) over 22,200 feet of strata are exposed. The Pennsylvanian Oquirrh Formation, incompletely exposed, is the oldest. The lowermost strata of the Oquirrh Formation seen in the area are orange-hued calcareous sandstone, tan to gray siltstone, and pink to purple orthoquartzite. Younger Oquirrh deposits are essentially clastic; the lower units are calcareous siltstone, arenaceous bioclastic limestone, and fine-grained crystalline limestone, all interbedded with calcareous sandstone and orthoquartzite; the upper units are more siliceous. The Diamond Creek Sandstone is comprised of orthoquartzite and calcareous sanstone. Clear, well-rounded, and essentially well-sorted, fine- to coarse-grained quartz granules in a siliceous cement comprise the rock. In some intervals cross-bedding is prominent. The Loray (?) Formation is a transitional unit which has affinities with both the underlying Diamond Creek Sandstone and the overlying Grandeur Member of the Park City Formation. It is fine-grained calcareous sandstone intermixed with silty and cherty limestone and dolomite. The Park City Formation consists of the Grandeur Member which is mainly dolomite, silty dolomites and limestones, sandstone and cherty carbonates. The Phosphoria Formation is represented by two members, the Rex Chert and the Mead Peak Member. The Mead Peak Member contains two phosphatic intervals, one in the basal 10 feet and the other near the middle; the phosphate zones are separated by 160 feet of siliceous carbonates. The upper portion of the Mead Peak consists of laminated mudstone, siltstone and shale. The Rex Chert Member is a sequence of bedded chert, cherty siltstone, and cherty mudstone, with a few strata of limestone and dolomite. The Gerster Formation is the uppermost unit of the Permian system. It is mainly crystalline and bioclastic limestone, silty limestone, with intervals of cherty limestone and a few beds of pure chert.

The oldest Triassic strata in the range, the Dinwoody Formation, though parallel in outcrop with the Gerster Formation, overlies it unconformably. The Dinwoody is 1,670 feet thick; it is exposed over an area of three square miles, the best exposures being along the axis of the West Terrace syncline in Section 5 of T. 8 N, R. 12 W. The Dinwoody is divisible into two zones; the lower is mainly interbedded maroon and greenish gray shale, with maroon and gray bioclastic and crystalline limestone; shale constitutes about 75% of the total. The lower third of the remaining 1,320 feet of the Dinwoody is comprised of strata much like the lower zone, with a greater percentage of limestone; the upper part of this zone contains thin lamellar beds of greenish yellow to buff, arenaceous (calcarenite) limestone. Ripple marks are common in the calcarenites. An incomplete section of the conformably overlying Thaynes Formation is 330 feet thick. Approximately 80% of the formation is thin-bedded, silty limestone with hues of yellow, green and gray; the rest of the formation is gray bioclastic limestone.

Strata of the Pliocene (Salt Lake Group) are poorly exposed but bentonitic clay, vitric tuff and fresh water limestone or marl have been reconginzed at scattered localities. Isolated remnants of basalt flows of probable Pliocene Age are present in and near the Terrace Mountains; some of the smaller flows appear to be related to the major normal faults.

Structurally, the Terrace Mountains consist of two blocks which are separated by the Big Pass graben, which trends nearly northwest just northeast of Tangent Peak, the highest point of the western block. Long, high angle, north-south boundary faults and minor east-west normal faults are characteristic of both blocks. A typical system of rotational faults, with pronounced arcuate trends, is present in the western block. Broad north-south folding is in evidence at the western and northern limits of the western block; however, east-west and northeast trends of fold axis are characteristic of the narrower folds of all other segments and blocks comprising the mountains.

Rozel Hills

The Rozel Hills comprise a 16 square-mile area forming a westward bulge from the northern side of the Promontory Range. The bedrock of the Hills rises about 300 feet above the lake and consists of interbedded basalt and limestone of the Salt Lake Group, of probable Miocene-Pliocene age. The structure is simple and the exposed strata dip 15 degrees to the northeast. This area is interesting in that asphalt seeps occur in the lake off the southern margin of the Hills. About twenty shallow wells have been drilled around Rozel Point but to date no sustained commercial production has been attained (Slentz and Eardley, 1956).

Promontory Mountains

The Promontory Mountains form a range between four and eight miles wide, which, together with the Rozel Hills, protrude about 30 miles southward into Great Salt Lake. The mountains rise only 1,800 feet above mean lake level. The area is sufficiently watered to support grazing.

More than 33,000 feet of sedimentary rocks have been measured in the Promontory Range (Olson, 1956). Nearly 7,500 feet of younger Precambrian strata, probably correlative with that of Fremont Island, are exposed in the southern tip of the range. Eleven Cambrian formations or units comprising over 11,315 feet of strata are recognized. Almost half of the total is the basal Prospect Mountain Quartzite, with the remainder principally limestone, shale, dolomite and quartzite. The Ordovician is represented by 2,200 feet of sediments divisible into three formations consisting respectively of limestone, quartzite and dolomite. One Silurian formation, the Laketown, is represented by 1,618 feet of dolomite, with thick beds of black chert. The Devonian System is represented by two formations, the Water Canyon Dolomite, 639 feet thick and the Jefferson Dolomite at least 940 feet thick, consisting of dark gray dolomite, with interbeds of thin limestone and quartzite. The Mississippian rocks consist of 5,100 feet of limestone, calcareous siltstone and sandstone, subdivided into the Madison Limestone (475 feet), the Deseret-Humbug Formation (1,416 feet), the Great Blue Limestone (2150 feet) and the Manning Canyon Formation (1100 feet). The Oquirrh Formation (3,400 feet) principally fine-grained sandstone, quartzite and the predominant crystalline limestone, represents the Pennsylvanian System. No Permian, Mesozoic or Tertiary rocks are found in the range.

Structurally, the Promontory Mountains are relatively simple. Many north-trending and transverse faults of large displacement outline large tilted and faulted blocks. Although no mines are currently in operation the Promontory District is credited with almost a million dollars worth of zinc and lead ore.

THE ISLANDS OF GREAT SALT LAKE

The islands of Great Salt Lake increase or decrease in size and number as the lake rises and falls. Provisionally all of the land areas which were islands when the lake was at its historic high level of 4,212 feet in 1875 are designated islands. The number of true islands ranges from 8 at high water to none during low water, a change encompassed in a water level difference of 20 feet. The islands appear to float mirage-like on mud or shallow water. The largest islands as defined above are Antelope, Stansbury and Fremont; the smaller ones are Carrington, Gunnison, Cub, Dolphin and Bird; other tiny rocks or shoals are Egg Island, White Rock, and Black Rock.

The islands are mainly uninhabited, but Antelope Island is sufficiently large to support a permanent ranch. Grazing is the principal use for the larger islands. Gunnison, Cub, Bird and Egg Islands are rookeries for the California gulls (seagull) and pelicans. During low water, Bird and Gunnison Islands are the only ones which remain sufficiently isolated to offer security to the sensitive birds.

Antelope Island

Antelope Island, the largest island of Great Salt Lake, lies in the south-eastern part of the lake. It trends almost north for 15.5 miles; is 4.5 miles wide with the southern tip a scant 3 miles from the south shore. The island is tied to the shore until the lake attains an elevation of 4,200 feet at which time its 43 miles of shoreline encompasses approximately 23,175 acres of rocky hillsides, cliffs and alluvial slopes scantily clad with desert shrubs and grasses. Two small rocky islands, Egg Island and White Rock, lie respectively in North and White Rock Bays of the northern and northwestern tip of Antelope Island. Their isolation makes them desirable as bird rookeries.

The highest peak on Antelope Island is in the northern portion, where Peak "6596", of the same elevation, has a relief of 2,396 feet above a nominal lake level of 4,200 feet. The average elevation of the island is about 5,500 feet and the surface may be classified as precipitous. Both the Bonneville and Provo levels are marked by terraces and shoreline debris, respectively, at 5,200 and 4,820 feet; the shoreline features of the Provo stage of Lake Bonneville are the most prominent and can be traced without interruption around the island.

Antelope Island is largely composed of some of the oldest rocks in the local geologic column. Two sequences of Precambrian metamorphic rocks of differing age have been recognized. The older sequence, the Farmington Canyon Complex, is tentatively dated as Middle Precambrian (Eardley and Hatch, 1940a) with an age of 1,580 million years. According to Larsen (1957), units of this older terraine, by reason of their mineralogy and moderate regional metamorphism, correspond to the amphibolite facies. Larsen identified and described three subdivisions, none of which he formally named. The younger Precambrian sequence, less metamorphosed than the older, contains a mineral assemblage corresponding to the green schist facies. The tillite, dolomite, slate and quartzite are tentatively correlated with the Mineral Fork Tillite and Mutual (?) Formation of the Wasatch Range.

Except for Quaternary alluvial and lacustrine deposits, the only other rocks present are Tertiary conglomerate and fresh water limestone.

Stansbury Island or Penninsula

Stansbury Island, the second largest in Great Salt Lake, is attached to the southwest shores of the present lake. It becomes an island when the lake rises to 4,200 feet. The island is named after Capt. Howard Stansbury, Corps of Topographic Engineers of the U.S. Army, who in 1849 and 1850 headed an expedition charged with surveying the lake. Stansbury Island (or Penninsula) is oriented north-south and is slightly more than 11.5 miles long and about 4.5 miles wide; the shoreline is about 24 miles long. The island comprises 22,314 acres of mainly rugged cliffs, rocky slopes and desert beaches.

The highest point on the island is Stansbury Peak at 6,645 feet above sea level, or 2,445 feet above the present lake level. Abandoned shorelines are well marked and the Bonneville and Provo beaches with sea cliffs are prominently displayed along the north, northwest and eastern sides of the island.

The island is a typical desert mountain; there are a few fresh and brackish water seeps near the present lake level along the eastern side but the western side of the Island is essentially waterless. The island is uninhabited and is used principally as a winter grazing area for sheep. The average precipitation, accumulated principally in the fall and winter, is about 6 inches.

Rocks of the island are mainly early Paleozoic age. Precambrian strata, mainly quartzite and shale of the Big Cottonwood Formation, are present at the north tip and along a portion of the northeast shore of the island. The remaining northern third of the island is of Cambrian rocks, consisting of a small outcrop of Tintic quartzite but mainly of middle Cambrian limestone, shale and dolomite. The central and southern third of the island is comprised of Upper Cambrian to Upper Mississippian strata, mainly limestone, dolomite, quartzite and shale. The prominent quartzite ledge displayed in the southern part of the island is Devonian in age. Fish plates are present in thin dolomite at the base of the unit. This quartzite has been mistaken in the past for the medial Ordovician quartzite, the Swan Peak, and is of significance because it is evidence for a penninsula-like landmass which extended westward from the ancestral Uinta Mountains in Devonian time. It further demonstrates that the lower Paleozoic miogeosynclines were locally interrupted by transverse adjustments or forces prior to late Paleozoic orogenies.

The structure of the island is fairly simple. The southern half has been folded into a broad southward plunging anticline. The northern half of the island is comprised of a series of northwesterly trending fault blocks in which the strata dip westerly. The faults in the northern section are transverse in trend and may have some strikeslip component.

Fremont Island

Fremont Island, the third largest island in Great Salt Lake, lies near the eastern shore about 5 miles north-northwest of Antelope Island and nearly 2 miles southeast of the mainland at Promontory Point. The island is named after Colonel John C. Fremont who in 1845 made the first scientific observations of the lake; he determined that its surface was about 4,201 feet above sea level and that a gallon of its water yielded three pints of salt. Fremont Island, shaped like a flattened isosceles triangle, trends northwesterly with its apex to the north-east. It is 5.5 miles long, 1.5 miles at its widest point and its 12 miles of shoreline encompass about 2,945 acres of rocky plateau-like desert. Fremont Island is one of the most persistent true islands of the lake; the water level must drop to 4,193 feet before it merges with the mainland.

The highest point on the island is Castle Peak at 4,995 feet, giving a relief of 795 feet with respect to the present lake level. When Lake Bonneville was at its highest level, Fremont Island was covered by 140 feet of water, and at the Provo stage the island became two small remnants comprising several hundred acres.

Fremont Island is comprised of late Precambrian strata, some of which may be correlative with rocks on Antelope Island and with the Precambrian on Promontory Point. Eardley and Hatch (1940) described a sequence of over 5,000 feet of dark phyllite, 700 feet of tillite, about 1,700 feet of quartzite, chlorite schist, and greenstone, and 100 feet of dolomite for an aggregate thickness of 7,500 feet of Precambrian metasediments.

Smaller West Shore Islands

Five small islands: Carrrington, Bird (Hat), Gunnison, Cub and Dolphin are distributed along the west portion of Great Salt Lake. The largest is Carrington Island, which is about six miles north from Stansbury Island. It is a rocky barren wasteland comprising 1,767 acres. Most of the time it is bound to Stansbury Island by bars of oolitic sand. A lake stage of 4,199 feet is sufficient to make it a true island. The highest point, Lambourne's Rock, is 4,720 feet in elevation, giving it a relief of only 520 feet. From any direction the low profile resembles that of a broad-brimmed hat. The Island is composed principally of gneisses and schists of Precambrian age. The younger rock lying along its extreme eastern limit is Tertiary basalt, approximately 105 feet thick. No Paleozoic or Mesozoic rocks are present.

Bird Island is a small circular island of 22 acres situated 4.5 miles north of Carrington Island. A shallow threshold of relicted algal bioherms (reefs) partially concealed by oolitic sands separates it from Carrington Island. It becomes isolated when the lake stands at 4,198 feet. The island is practically devoid of vegetation and its relief is but 90 feet. The island is composed entirely of Precambrian tillite, which here is a black slaty rock with fragments of quartzite and other metamorphic rocks ranging to boulders in size.

Gunnison Island is a small island in the northern arm of the lake. It is 7.5 miles due north of the railroad siding at Lakeside at the north extremity of the Lakeside Mountains. It is 155 acres in area; the highest point is 85 feet above Lake level. Bedrock consists of northerly dipping sediments provisionally identified as Silurian, Devonian and Mississippian in age.

Cub Island, a tiny exposure subsidiary to Gunnison Island, consists of Mississippian rocks.

Dolphin Island is a small island in the northern section of the lake. It is 11 miles northwest of Gunnison Island or approximately 3 miles from shore and due east from the highest point of the Terrace Mountains. The main portion of the island is three-quarters of a mile long, one-third of a mile wide, and the maximum elevation is 4,235 or some 35 feet above mean lake level. Stansbury (1853, p. 191) reports: "the island consists mainly of conglomerate in horizontal strata and varying much in the size of the cemented stone." Stifel (1964, p. 145) adds the following: "The island is formed essentially of calcareous tufa-cemented conglomerate, the constituents of which are sub to well-rounded, large-cobble to sand-sized clastics apparently derived from the sandstones and black limestones in the eastern Terrace or the Hogup Mountains. Wave action and south-flowing currents formed small cliffs on the north end of the island and produced two wing-like spits of gravel and sand which extend to the south on either side of the island. Oolitic sand is abundant immediately around the island and on the surrounding flats."

PRESENT SHORELINES

Bedrock

Outcrops of consolidated Precambrian and Paleozoic formations are actually washed by lake water at very few places, but a rise of 10 feet above the 4,200 foot level would create a number of rocky headlands. Examples are the west-central side of Antelope Island; a small stretch near Indian Caves on the west-central side of Promontory Penninsula; the vicinity of Black Rock, northern termination of the Oquirrh Range; Strongknob, north of Lakeside, and stretches of the eastern side of Stansbury Island which is the most rocky shoreline of the entire lake.

Shoreline Deposits of Older Lakes

The Great Salt Lake is nested in the deposits of a long succession of older and more extensive lakes. These created numerous terraces, bars, spits, and deltas. Such features built of material too heavy to be moved by currents and waves of the present lake are still in evidence on the shoreline. Examples are the north end of

Antelope Island; much of the east, south and west sides of Promontory Point, and marginal to Fremont Island.

Pre-lake Surfaces and Deposits

Alluvial fans and locally perhaps pediments surrounded most ranges in the Great Basin before the arrival of the interior lakes. These deposits may date back to early Pleistocene or even Pliocene. Locally they consist of material too coarse to be moved by lake currents and may thus maintain their original forms to the present time. Examples are the east central margin of Antelope Island and stretches of eastern Promontory Penninsula.

Younger (Post-lake) Alluvial Surfaces

Under existing arid conditions little or no sediment is brought into Great Salt Lake except by the major permanent streams. Shorelines fringing alluvial fans, deltas, and other sloping surfaces formed within the Holocene are therefore rare. Examples of weak delta fronts greatly modified by marshes and dikes are seen in the distributory areas of the Bear River and Jordan Rivers.

Aeolian Deposits

Winds blowing over the area come mainly from the southwest or northwest; where conditions are right for picking up sand and silt, this material may be heaped near the shoreline. The west side of Stansbury Island has some fairly large continuous dunes of oolitic sand and there are discrete barcane dunes between Strong-knob and the south end of the Terrace Mountains. These can be washed by water only with a rise of lake levels by 10 feet or more.

Relicted Lake Bottom

Great Salt Lake is notorious for the barren shelving mud flats that constitute much of the shoreline. These receive very little sediment and the water is too shallow to exercise notable erosive effects. The shoreline migrates great distances across such areas with even minor fluctuations in lake level. Most of the north and west shores of the Northern Arm, West Bay, and Carrington Island are fringed by this type of shoreline. So also are the shores of Bear River Bay not reached by distributaries of the Bear River and most of the unmodified southeast margin of the lake between the mouth of the Jordan River and Stansbury Penninsula. Another large tract is that connecting Stansbury Penninsula with the mainland. A relicted lake bottom shoreline is to be expected from the history and setting of the lake, and it is by far the most common type of shoreline.

Artificial Constructions

Two of the most notable engineering constructions on earth cross Great Salt Lake. One is the Lucin Cutoff of the Southern Pacific Railway built on 28,000 wooden pilings in 1902-03. The second is its successor, the modern causeway constructed of 50,000,000 cubic yards of earth and rock in 1956-59. These have little effect on the configuration of the Great Salt Lake, but other less well known embankments do affect the shoreline. One is the causeway built for the Western Pacific Railway southwesterly from Black Rock to the southwest corner of the lake. Along this for about six miles the shoreline is perfectly straight when the lake is slightly above the 4,200 foot level. Other embankments with straight or angular configuration determine the shoreline when the lake is a few feet above the 4,200 foot level. These are the dikes of the Farmington Bay Waterfowl management area, the Harold Crane Waterfowl Management Area, the Bear River Migratory Bird Refuge, and Willard Reservoir.

Marshes

Marshes are characterized by abundant vegetation and cannot exist when saturated with highly saline water. Insofar as Great Salt Lake is concerned, vegetation tends to accumulate and trap sediment only where there is dilution by fresh water sources. The most extensive marshlands are associated with Bear River, the waters of which disperse widely across the bay area. The fresh water area has now been surrounded by dikes. Most of the eastern shoreline from the vicinity of Brigham City to the Salt Lake City Sewage Canal is marshland fed by surface streams from the Wasatch Range or by seepage from adjacent irrigated land. There are important spring-fed marshes associated with Locomotive Springs east of Kelton and adjacent to Spring Bay.

Constructional Deposits of the Present Lake

The Great Salt Lake is stirred by waves and currents especially during storms when 8 foot waves may be generated. The lake water, because of its heaviness, up to 76 pounds per cubic foot, is particularly effective in moving the lighter grades of sediment. Minor spits, bars, and barrier beaches have been built along or near the existing shoreline. Examples are Bridger Bay on Antelope Island and much of the west side of Stansbury Peninsula.

Several peculiar finger-like spits interrupt the shoreline in various places. The most prominent is attached to the shore between Stansbury Peninsula and the southwest end of the lake. It trends due east and has an underwater extension well beyond the visible portion. Another even larger spit attached to the east shore of Spring Bay extends due west and is accompanied by a smaller secondary spit about 3/4 mile to the north. What may be incipient spits of similar nature give cuspate contours to the shoreline east of the northern Hogup Range.

These artificial-looking configurations must be the result of opposing currents that are forced to turn away from the shore as they converge and lose energy.

PROBLEMS AND SPECULATIONS

Location of the Great Salt Lake

A factual description of the tectonic setting of Great Salt Lake as revealed by surface outcrops and inferred subsurface configurations does not in itself answer a number of important questions. Chief of these is why the lake is where it is. An obvious answer is that it is the lowest tract in an area of 22,000 square miles. This begs the question: a better one is, why is this particular area the lowest spot? Two possible answers come to mind. It is low because the troughs it occupies are structurally deeper and more actively downsinking than any other in the vicinity. The second is that the filling of these particular structural troughs has lagged behind the filling of adjacent ones.

Now that geophysical surveys have revealed the depths of most of the faulted depressions (grabens) of northern Utah and the Wasatch Front, it is possible to make meaningful comparisons among them. Without designating the major grabens individually it is possible to generalize that the Great Salt Lake Graben is no deeper and probably even less deep than several others in the near vicinity. Depth to bedrock under the main water body is estimated at almost 7,000 feet (Mikulich and Smith, 1974, p. 1001). Depth to bedrock in Curlew Valley immediately north of and continuous with Great Salt Lake Graben is approximately 6,000 feet (Cook and others, 1964, p. 727). An estimated 12,000 feet of fill occupies the Tooele Valley Graben (Cook and others, 1966, p. 66). The fill of Utah Valley is estimated at about 5,000 feet and that of Ogden Valley at about 6,000 feet.

Evidently localization of the lake is not due to relatively greater downsinking beneath it. Considering only bedrock configuration, the water body could just as well be in Curlew Valley to the north or Tooele Valley to the southwest, or even in the Great Salt Lake Desert.

Many facts support the second possible explanation, that the basin occupied by Great Salt Lake has received relatively less sediment. Sediments now being deposited in the lake basin, as well as those penetrated by drilling, are of the finest possible grades: mud, silt, and evaporitic products such as halite and mirabilite. The major rivers, the Bear, Weber, and Jordan, arrive at low gradients almost free of coarse material. Any coarse sediment these streams pick up in their higher reaches settles out before it reaches the lake. Utah Lake is the most effective settling pond of the system. Bear River drops its sediment along numerous alluvial stretches even before it gets to Cache Valley which was clearly an effective dumping ground or sediment sink during Bonneville time. The conclusion is that the sediment ultimately delivered to Great Salt Lake Graben has been insufficient to fill it and expell the water. Perhaps it is not inaccurate to say that the lake is there because it has nowhere else to go.

A more significant control of deposition in the lake basin than that exercised by the large contributing rivers is the nature of the nearby bedrock supplying material to alluvial fans and other fringing deposits. The interior islands and nearby Farmington Range, which would be expected to contribute most of the locally derived sediment to the lake, are of predominantly Precambrian crystalline rocks, while those making up nearby ranges are chiefly late Paleozoic formations dominated by the excessively thick Oquirrh Formation.

High areas composed of the Oquirrh Formation are surrounded by massive alluvial fans and sediments (west side of Salt Lake Valley) or by great embankments of gravel (Grassy Hills, Blue Springs Hills, Point of the Mountain). Although there has been little drilling in valleys flanked by mountains of the Oquirrh Formation, it is safe to assume that the sediments of such valleys are of much coarser grades than those under the Great Salt Lake. The Oquirrh is mostly hard and brittle limestone, dolomite, sandstone and quartzite, which fracture easily to produce small blocks and chips that can be moved by ordinary run off and shifted by ordinary lake currents in the form of gravel and sand.

By contrast, Farmington Range, Little Mountain, Fremont Island, Antelope Island and Bird Island are resistant Precambrian metamorphic rocks, chiefly gneiss and schist (Eardley and Hatch, 1940; Bell, 1952; Cohenour and Thompson, 1966). Mostly these rocks weather in place to produce granular material or individual boulders, as is seen in the margins of these uplifts. Promontory Point is an intermediate case; the bedrock here is Precambrian quartzite that does provide blocky weathering products but on a smaller scale and with less chippy fraction than does the Oquirrh Formation.

The puzzling fact that Great Salt Lake, one of the most recent features of the Great Basin, is located upon the Northern Utah Highland (Eardley and Hatch, 1940), one of the oldest features, is thus explainable as a result of scanty sediment supply rather than of tectonics. The fact that this area of faulted crystalline rocks appears to have been the center of a long succession of Cenozoic water bodies including Bonneville and Great Salt Lake suggests that bedrock types, erosion products, and sedimentation have been fairly constant for several million years, perhaps ever since the Miocene. Although all depressed areas were being filled by deposition, the Great Salt Lake Graben, because of the nature of the bedrock in surrounding uplifts, has always lagged behind so as to be the low spot of the drainage system.

Possible Outlet

The sedimentary record of predecessors of Great Salt Lake suggests that shallow bodies of fresh water occupied the site for long periods of time before saline lakes appeared (Eardley and others, 1973). Assuming these fresh water lakes did not reach the depth of Lake Bonneville and hence could not flow over Red Rock Pass, it may be that there were other exit routes now dammed and abandoned. Considering the general geography, the obstructions in various directions and the distance to major rivers, a northward course into the Snake River seems the most plausable one.

Today this possible exit is clearly choked with lava at its northern end and there are scattered exposures of igneous rock southward to the Great Salt Lake. The geophysical evidence that the Rozel Point flows are at depths of 2,000 feet near the axis of the lake and have a lobe-like configuration in conformance with the Great Salt Lake Graben suggest that they could have constituted a dam in late middle Tertiary time. Mikulich and Smith speculate that flows or debris from the flows may have reached as far south as the causeway (1976, p. 999). The flows have been dated on stratigraphic evidence as Miocene-Pliocene (Slentz and Eardley, 1956). No radiometric dates appear to have been taken. The Snake River Plain, to the north, is underlain by lava and sediments of late Cenozoic age, chiefly Miocene flows (Mabey, 1976). The formation of this depression and associated deposits could have effectively blocked drainage from the south and ponded it to form water bodies in northern Utah.

Overthrust Faults

Whether or not the trace of a major Laramide overthrust fault traverses the bedrock below the lake is an important unsolved problem. This fault is considered almost as geological necessity to explain regional geologic relations (Crittenden, 1972). The thousand-mile long zone of thrust plates extending from southern Nevada into Montana is interrupted in a significant way in the vicinity of the Northern Utah Highland and Great Salt Lake. Segments are visable and mappable both north and south but are absent or covered between the Traverse Range and Ogden (Crittenden, 1972, p. 2878). Visible displacements are seen in the Wasatch Range, but the area west of the range has been depressed to the west of the Wasatch fault zone and covered by alluvial fill and lake sediments. It is thought that the fault trace passes between Antelope Island and the Oquirrh Range - the mountains are part of the allochthon, the islands are part of the autochton (figure 2).

Since it is not possible to find evidence of this great discontinuity in the almost continuous line of uplifts on the west side of the lake or in the Promontory Mountains, it is assumed that all of these are also allochthonous and that the fault trace must turn eastward toward the visible traces high in the Wasatch Range above North Ogden. Crittenden's conclusion, shown by his regional reconstructions and cross-sections (Crittenden, 1972, p. 2878), is that the fault circles Antelope Island to pass south of Fremont Island and Little Mountain. This course is entirely defensible but so far has not been provable. It is understandable that it should escape detection by geophysical means, as rocks in the overlying and underlying plates are not significantly different in density and have shared the same history and movements over the past 60 million years.

Possible geophysical evidence of the Nebo-Woodruff thrust is seen in the peculiar zone of confused and compressed structures identified along the west margin of Antelope Island by Mikulich and Smith (1974). They describe this in some detail and attribute it to rebound along the nearby fault (on figure 2), to differential compaction, and to a pre-faulting structure (Mikulich and Smith, 1974, p. 998).

General Eastward Dip

Mikulich and Smith (1974, p. 997) state that "The most consistent feature identified from the seismic data of the southern part (of the lake) is the gentle 5° eastward dip of the Tertiary and Quaternary sediments". The seismic profiles leave no doubt as to the reality of this inclination but other evidences for its existance, particularly anything of a surficial nature, are difficult to detect or decipher. The rebound of the Bonneville basin after the withdrawal of the lake has been shown by Crittenden (1963) to have caused a significant warping of the Bonneville shoreline. According to Crittenden's map, the post-lake rebound gave rise to a difference in elevation of 130 feet across the southern part of Great Salt Lake between the Bonneville level on the Lakeside and Wasatch Range. A uniform dip of 5° across the same distance brings a decline of 340 feet. Subtracting the tilt due to rebound from the total tilt leaves a relative subsidence of over 209 feet to be accounted for by something that seems to have happened before the rebound began. Mikulich and Smith are certainly right in concluding that crustal rebound alone is an insufficient cause of the observed deformation. However, no explanation for this tilting is apparent to the writer.

Igneous Rocks

Geophysical evidence indicates more igneous material in and adjacent to Great Salt Lake Graben than might be expected from surface exposure. The basalt flows cropping out at Rozell Point are indicated to extend westerly and southwesterly in the subsurface for 20 miles to or beyond the causeway. They may even be related to the remnant on Carrington Island. What is apparently the same group of flows also extends northward and northwestward out of the area of the lake. The general configuration of the aggregate igneous mass suggests that the Great Salt Lake Graben had a topographic expression in Pliocene time and that the gradient southward along it was at least as steep as that existing today. However, the relations of the Rozell flows to other incompletely exposed flows to the north in Curlew Valley and across the lake basin in the vicinity of the Raft River Mountains, as well as the correlation of basalt flows in Utah with the much more extensive ones of the Snake River Plain, must remain entirely speculative. It is possible that lava flows blocked and ponded a series of lakes in the Great Salt Lake Graben during late middle Tertiary time as mentioned in the section on "Possible Outlets".

A sharp magnetic anomaly immediately north of Dolphin Island is interpreted by Milulich and Smith as indicating a volcanic plug or volcanic ridge. This is entirely compatible with other exposures of extrusive rock to the north and northwest. The cause of anomalies under Stansbury Island and Fremont Island is not so easily related to igneous bodies. The Stansbury Island anomaly may be caused by a buried igneous extrusion but there is no evidence for this other than the anomaly itself.

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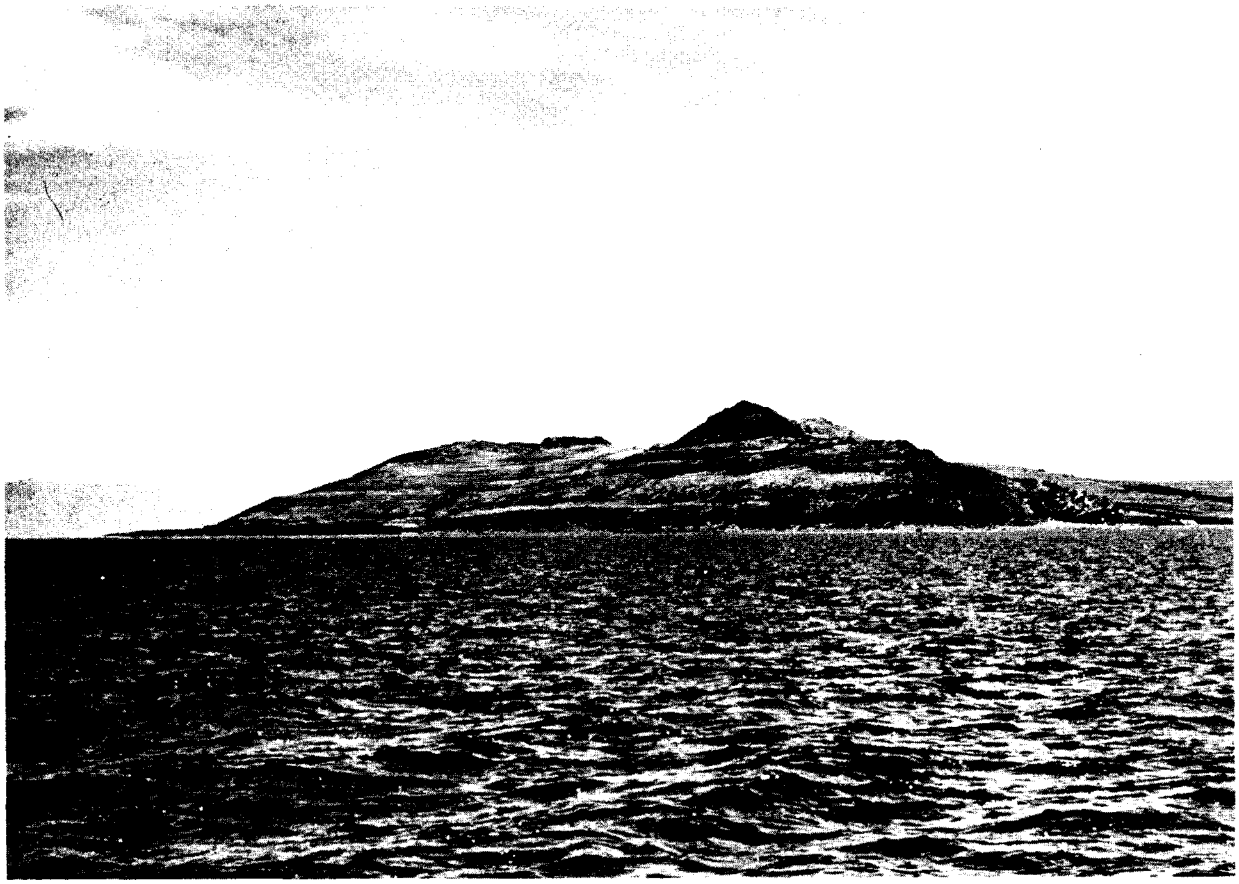


Fremont Island, Great Salt Lake, Weber County. Island consists entirely of Precambrian rocks. Photo by Ward Roylance.

West shores of Antelope Island, Great Salt Lake, looking south. The white curving beach circles Bridger Bay on the left; the barren slopes and peaks are Precambrian Farmington Complex, Oquirrh Range in the distance. Photo - Utah Tourist and Publicity Council.

Desert ranges and Great Salt Lake Desert, Tooele County. North end Cedar Mountains in center; Newfoundland Mountains surrounded by salt flats, distant right; Pilot Range with Pilot Peak on distant skyline. Photo - Utah Tourist and Publicity Council (Dugway Proving Ground).

COASTAL GEOMORPHOLOGY OF GREAT SALT LAKE AND VICINITY

by Donald R. Currey, University of Utah

ABSTRACT

The Great Salt Lake coast is subdivided into three shoreline zones: high, submerged, and historic, and the geomorphic history of prominent features dating from late Pleistocene Lake Bonneville and Holocene Great Salt Lake is summarized. The initial transgression of the Bonneville lacustral cycle, to a threshold-controlled set of earlier Bonneville shorelines, caused extensive geomorphic modification of the coast. A subsequent mid-Bonneville regression was followed by a final transgression to a later Bonneville shoreline, at which time the original, Bonneville-level threshold in southern Idaho was breached and the lake regressed rapidly as downcutting established a much lower, Provo-level threshold. During the ensuing stillstand an earlier and a later Provo shoreline were separated by slight additional downcutting of the threshold. Increasing aridity finally caused abandonment of the Provo threshold and regression to the Stansbury shoreline, and shortly thereafter to the threshold of Lake Puddle, which was briefly fed by inflow from Lake Bonneville. Further regression to basin-floor levels and then a minor transgression to the Gilbert shoreline concluded the Lake Bonneville saga.

Great Salt Lake apparently diminished to a large playa surrounded by giant desiccation polygons during one or more intervals of maximum mid-Holocene aridity. Fracture zones near Dolphin Island and west of Antelope Island also occur in the submerged shoreline zone. Late Holocene and historic geomorphic features include several shorelines, transverse and parabolic dunes of oolitic sand, and bird-foot deltas at the mouths of the larger influents, particularly the Bear River.

INTRODUCTION

The Great Salt Lake landscape is coastal in character, perhaps to a greater degree than any other non-marine landscape in the western hemisphere. Conspicuous landforms and immense volumes of near-surface materials owe their coastal character to processes that have operated not only along the shores of the present lake, but also along the shores of its much larger and much smaller predecessors. Although the Great Basin hydrologic region (figure 1) includes more than 150 other desert basins (Morrison, 1965, p. 265), none of the other basins contains a lake that rivals Great Salt Lake in area or in extent of active shoreline. During the last major glacial-lacustral cycle, in late Pleistocene time, none of the others contained a lake that closely rivaled Lake Bonneville in area, depth, volume, and intensity of coastal processes. The geomorphic history of some of the more prominent features in the Great Salt Lake coastal landscape, as reconstructed by ongoing studies, is summarized in this chapter.

COASTAL ZONES

The coast of Great Salt Lake can be regarded as extending from the highest level attained by Lake Bonneville to the lowest level exposed in post-Bonneville time. Furthermore, the Great Salt Lake coast can be readily subdivided into three major zones (figure 2), viz., a high shoreline zone above the highest level reached by the lake in historic time (about 1284 m, or 4212 feet), a submerged shoreline zone below the lowest historic level (about 1277 m, or 4191 feet), and a historic shoreline zone in the altitude range between 1277 and 1284 m (4191 and 4212 feet).

High Shoreline Zone

Several shorelines in the high shoreline zone are so well developed that they are apparent to even a casual observer. The conspicuous shorelines are all products of the last major lacustral cycle, or Bonneville cycle, and in large part acquired their distinctive form during the maximum and regressive stages of that cycle. Shorelines related to transgressive stages of the Bonneville cycle are locally conspicuous, but are very discontinuous in visible expression and are considered here only briefly. Shorelines related to pre-Bonneville lacustral cycles are preserved only in the subsurface at scattered localities and are not considered here.

Bonneville Shoreline

Water bodies in the Bonneville basin during the Bonneville cycle were limited in size by topography at Red Rock Pass, in southern Idaho, where the lowest point on the perimeter of the basin had an altitude of about 1550 m (5085 feet) (Crittenden, 1963, p. E14). The geomorphic features that developed along the shores of the largest water bodies comprise the Bonneville shoreline (plate 1 in pocket), which in the vicinity of Great Salt Lake is really a zone containing several individual shorelines. The type locality of the Bonneville shoreline can very appropriately be regarded as "the great bar at Stockton, Utah" (Gilbert, 1890, p. 97 and plate IX), 10 km (6 miles) southwest of Tooele. In the vicinity of Great Salt Lake the upper limit of the Bonneville shoreline zone now ranges in altitude from about 1573 to 1623 m (5160 to 5325), or up to 73 m (240 feet) above the original threshold-controlled altitude, because of isostatic rebound due to subsequent decreases in water load. Many interpretations regarding the number and age of lake stands in the Bonneville shoreline zone have been proposed by previous workers and have been summarized by Morrison (1965, p. 274, and 1966, p. 86). Ongoing studies utilizing available radiocarbon dates place the ages of an earlier set of Bonneville shorelines and of a separate later Bonneville shoreline between 19,000 and 13,000 years ago.

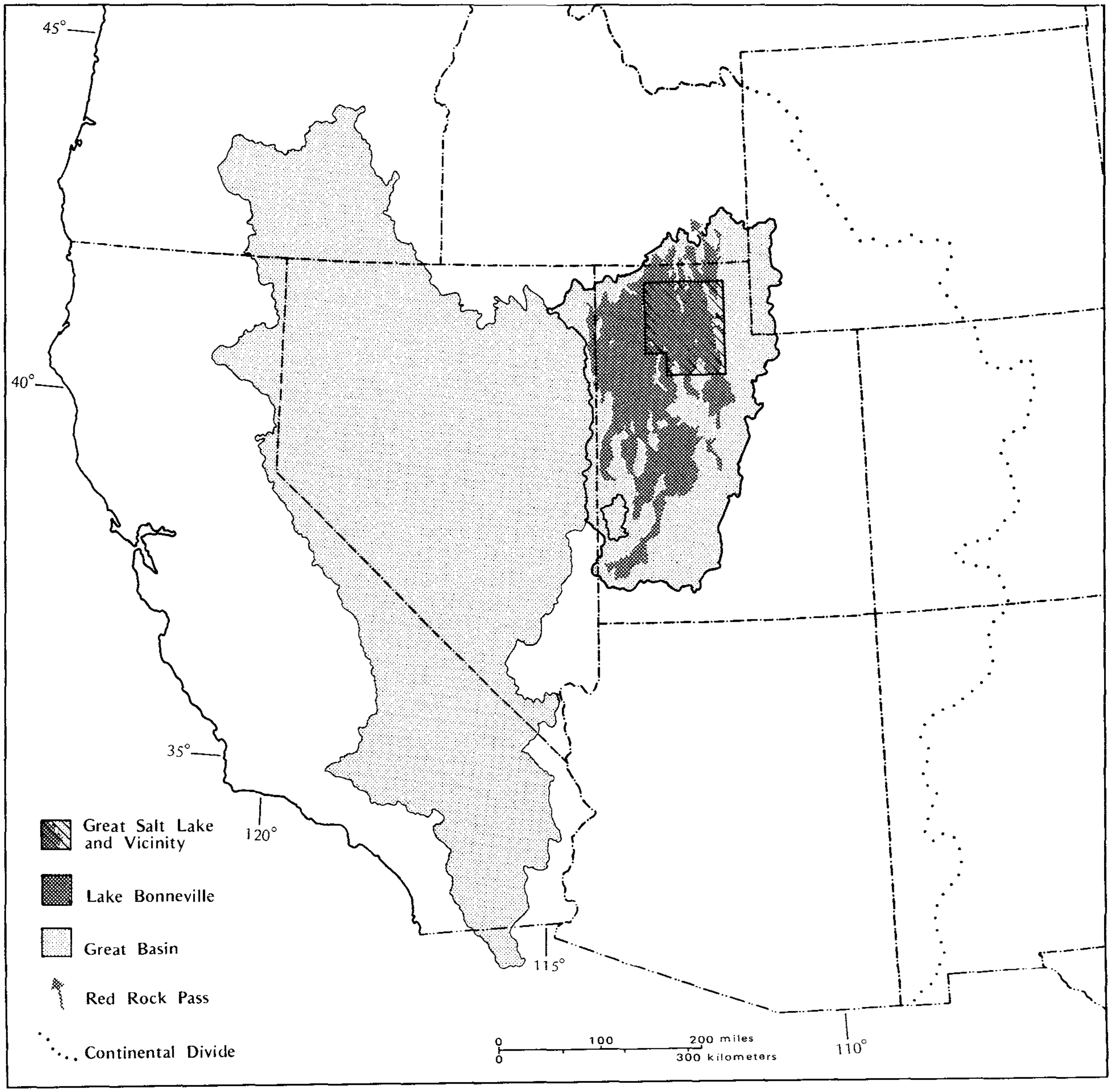


Figure 1. Location of Great Salt Lake and vicinity within the Great Basin hydrologic region.

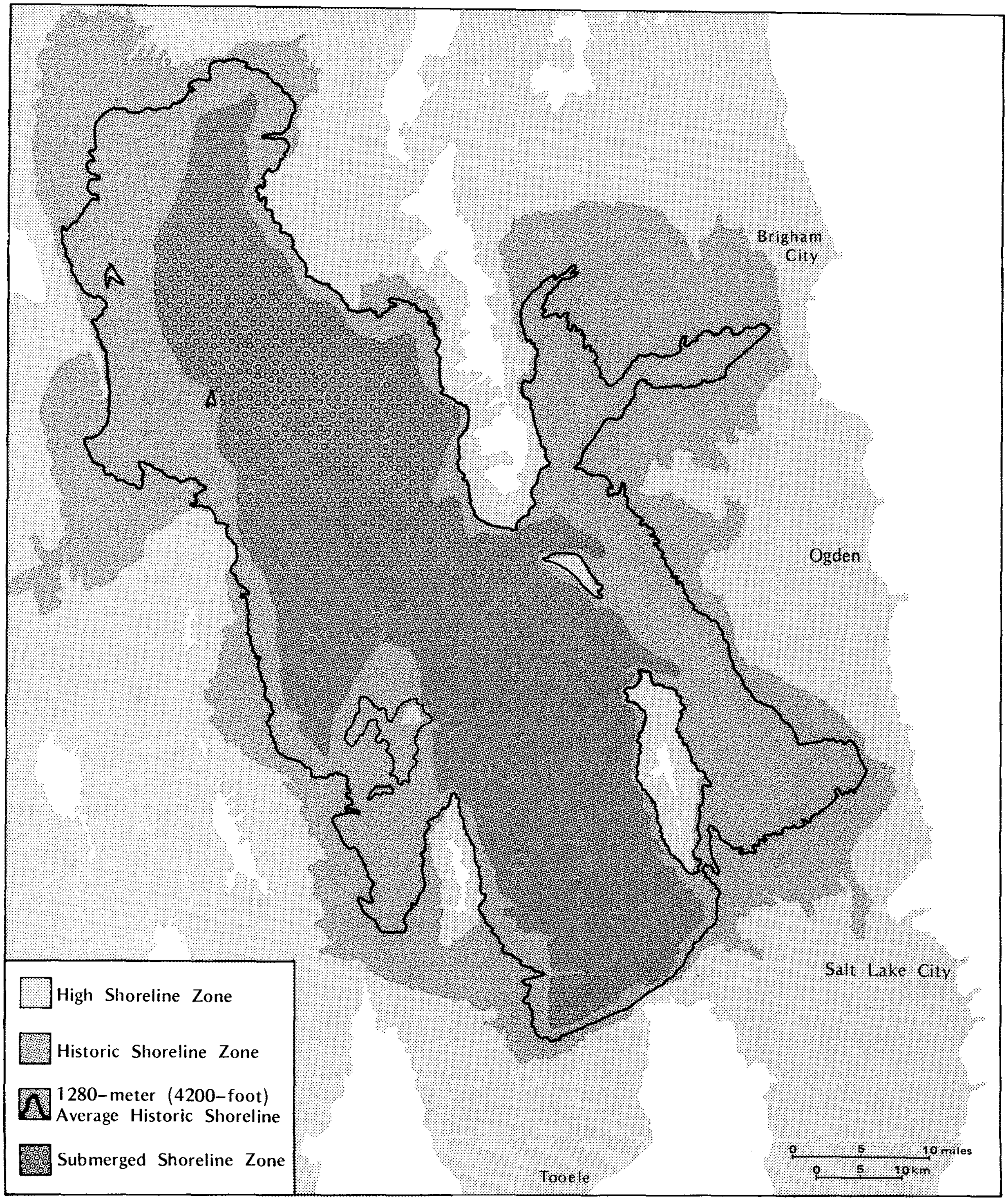


Figure 2. The three major coastal zones of Great Salt Lake and vicinity.

At localities with abundant beach deposits, such as baymouth barriers and cuspate forelands, gravels were laid down at three closely-spaced levels as the initial Bonneville transgression haltingly culminated under threshold control in the Bonneville shoreline zone. Away from the stable threshold at Red Rock Pass, which was subject to only negligible loading, the basin responded to the enormous water load imposed by Lake Bonneville–then approaching a maximum depth of about 350 m (1150 feet)–by sustaining substantial rates of isostatic depression. Therefore, in what is now Great Salt Lake and vicinity, between 64 and 225 km (40 and 140 miles) south of Red Rock Pass, lake stages that successively reached and were stabilized by overflow at the Pass produced beaches at successively higher positions. Of the three beaches that comprise the earlier set of Bonneville shorelines, the lowest contains nearly half of the total sediment; the second also contains about half of the sediment and partially to completely overlies the first at altitudes that average about 6 m (20 feet) higher; the third, with less than 5 percent of the sediment, typically occurs as a single beach ridge or small spit at the top of the morphostratigraphic sequence, again about 6 m (20 feet) above the previous level.

At localities with less abundant deposits, geomorphic expression of the Bonneville shoreline is typically incomplete because the uppermost beach ridge is so weakly developed. Wherever present, however, the uppermost ridge seems to represent the same, relatively brief event. Despite diligent search, ongoing studies thus far have failed to detect a higher shoreline, however faint, at any locality in the northern half of the Bonneville basin. Following the brief stand at the uppermost earlier Bonneville shoreline, a major regression to levels considerably below the Bonneville shoreline zone appears to have occurred in the midst of the Bonneville cycle.

After significantly lower stages had intervened for several thousand years, the Bonneville cycle waxed again in a final transgression to the Bonneville shoreline zone. Relatively limited geomorphic work appears to have been accomplished by the final transgression, possibly because equilibrium coastal landforms and materials were already largely in place on the terrain that was being transgressed. The final transgression culminated at the later Bonneville shoreline. At sites favorable for deposition, such as the north edge of the Stockton Bar, where a good cross-sectional view is available, the later Bonneville shoreline is expressed as a single beach ridge inset into or superimposed on the much more massive deposits of the earlier Bonneville shorelines. At many erosional sites, such as Long Bench (figure 3), near North Ogden, the later Bonneville shoreline is a distinctive boulder-beach trimline on foreshore slopes that date from the initial transgression. In the vicinity of Great Salt Lake the altitudes of the later Bonneville shoreline now range from approximately 1567 to 1606 m (5140 to 5270 feet), or up to 56 m (185 feet) above the original threshold-controlled altitude and about 6 to 17 m (20 to 55 feet) below the uppermost of the earlier Bonneville shorelines. The later shoreline was clearly controlled by the Bonneville threshold, but was positioned slightly below the earlier high shorelines because net isostatic rebound during the preceding low-stage interval had caused central-basin topography to emerge relative to Red Rock Pass. The stand at the later Bonneville shoreline was short-lived, being terminated prematurely by a precipitous regression of Lake Bonneville to the Provo level, about 105 m (345 feet) below.

Along erosional segments of the Bonneville shoreline, cliffs and shore platforms are developed far more prominently in piedmont alluvium (figure 3) than on bedrock. In alluvium, the cliff/platform junction appears to approximate closely the highest water level. On bedrock, the only evidence of the uppermost Bonneville shoreline is commonly a faint erosional trimline. Moreover, at many bedrock localities the uppermost shoreline is obscured by post-shoreline talus, and whatever visible expression of the Bonneville shoreline does exist is due to the two more protracted stands that occurred somewhat before and slightly below the highest stand.

Alluvial fan sediments, colluvium, and other unconsolidated materials of non-lacustrine origin are readily reworked during the transgressive portion of a lacustral cycle. The most massive depositional features, including Gilbert's (1890, p. 135-153) "embankments of the intermediate shore-lines," appear to date from the initial transgression, when the preexisting landscape was in maximum disequilibrium with shore-zone hydrodynamics and, hence, was most vulnerable to wholesale reworking by lacustrine processes. As the initial transgression approached the Bonneville shoreline zone, pre-lacustral materials were eroded, clay and silt sizes were winnowed away in suspension, and, at many localities, prodigious quantities of sand and gravel were delivered to depositional sites by longshore transport. Where clearly evident, directions of longshore transport are shown by arrows in plate 1. Partial cementation of gravels by interstitial tufa occurs widely in the Bonneville shoreline zone, but tufa that is lithoid and nodular in form seems to be localized mainly at the later Bonneville shoreline. Beaches at and near the Bonneville shoreline appear to have been the sources of at least some of the silica sand that comprises isolated parabolic dunes high on the west slope of the Lakeside Mountains.

Streams, discharging runoff and sediment from upland drainages adjacent to the coast of Great Salt Lake, have shaped the Bonneville shoreline in two main ways–by supplying sediments to beaches and deltas as the shoreline was being formed, and by dissecting segments of the shoreline during regressive stages and in post-Bonneville time. Beaches were nourished with sediments from incoming streams at many localities, but deltas were able to prograde the Bonneville shoreline only at the two localities where glacial outwash was most abundant. A small fan-shaped delta was deposited at the mouth of Big Cottonwood Canyon, about 5 km (3 miles) downvalley from the termini of contemporaneous glaciers. A compound fan-shaped delta was deposited at the mouths of Little Cottonwood and Bells canyons in direct contact with contemporaneous glaciers (plate 1). A recent study has shown that the contiguous moraines and shoreline at Bells Canyon date from the maximum of the last major glacial-lacustral cycle (Madsen and Currey, 1979). Elsewhere in the Great Basin, comparably juxtaposed moraines and

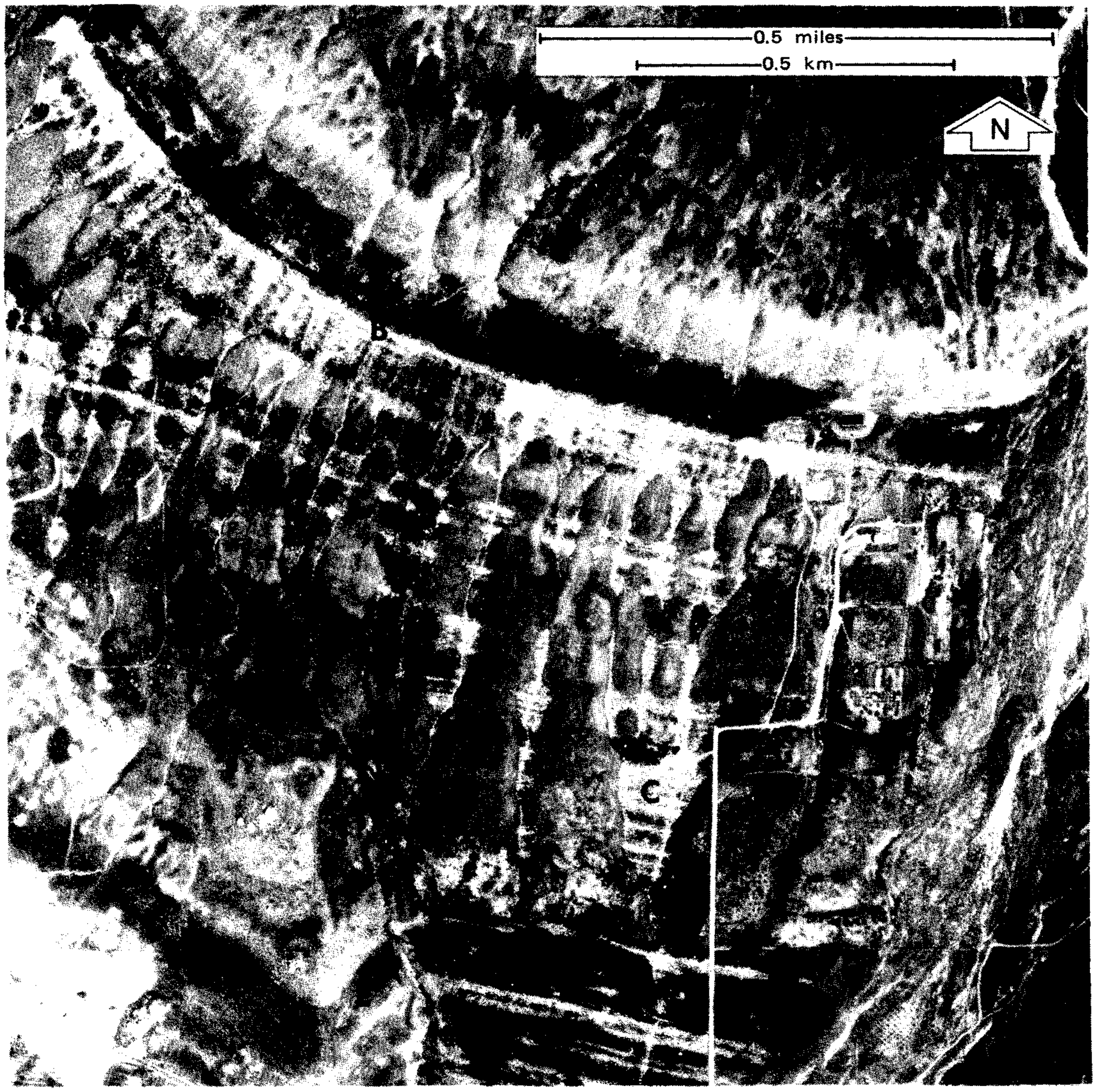


Figure 3. Long Bench, 2.2 km (1.4 miles) north of North Ogden, showing a pre-Bonneville alluvial fan (upper right) deeply notched by earlier Bonneville shorelines (A) and further modified by the later Bonneville shoreline (B). Transgressive boulder beaches (C) are overlain by lacustrine silts (D) that were not removed during the rapid regression to the Provo shoreline (E). Aero Service Corp. photo 5-000077, 13 Apr 1962

shorelines occur only near Mono Lake, in eastern California. At literally hundreds of localities, including the two glacial outwash deltas, shoreline features have been conspicuously dissected by cross-cutting drainage in post-shoreline time.

Provo Shoreline

The shoreline having the greatest geomorphic development, representing the lake level of greatest duration, is the Provo shoreline (plate 1). The type locality of the Provo shoreline is the Provo River delta, in the vicinity of Provo (Gilbert, 1890, p. 126). Probably during the later stages of the Bonneville-cycle transgressions and certainly at the earlier Bonneville shorelines and again at the later Bonneville shoreline, lake levels had several times reached and been controlled by the Bonneville threshold at Red Rock Pass. What had begun as intermittent, non-catastrophic overflow eventually led to hydraulic breaching of weakly indurated geologic materials and rapid lowering of the threshold about 105 m (345 feet). The resulting catastrophic flood, which severely devastated downstream reaches of the Snake River drainage in Idaho, has been termed the Bonneville Flood (Malde, 1968, p. 2). Much of the regression from the later Bonneville shoreline to the Provo shoreline was so rapid that at many localities recently-deposited, fine-grained lacustrine sediments suffered very little erosion at the edge of the receding lake (figure 3). The lowering of Red Rock Pass ceased in resistant bedrock at an altitude of about 1445 m (4740 feet), as indicated by ongoing studies, thereby establishing the Provo threshold and stabilizing the level of Lake Bonneville at the Provo shoreline. In the vicinity of Great Salt Lake the altitudes of the Provo shoreline now range from about 1460 to 1501 m (4790 to 4925 feet), or up to 56 m (185 feet) above the original threshold-controlled altitude, because of post-Provo isostatic rebound. As with the Bonneville shoreline, previous workers have offered a host of interpretations regarding the number, age, and duration of lake stands at the Provo shoreline (Morrison, 1965, p. 274, and 1966, p. 86). Increasing numbers of radiocarbon dates gradually appear to be placing the Provo shoreline in the interval from about 14,000 to 12,500 years ago.

Figure 4. Evaporating Ponds Spit (Eardley and others, 1957, p. 1159), 5 km (3 miles) southwest of South Jordan, showing a cuspate foreland with the earlier Provo shoreline (A) and the later Provo shoreline (B) accentuated by dikes. USDA-ASCS photo AAL-2MM-27, 9 Oct 71.

Exceptionally well developed depositional landforms, including spits, tombolos, cuspate forelands, bayhead beaches, and baymouth barriers, occur at many localities along the Provo shoreline. At localities with extensive progradational sequences, beach ridges were deposited at two quite distinct levels (figure 4). The two sets of beach ridges contain roughly equal volumes of sediment, with the upper set having prograded first, apparently under conditions of waning isostatic rebound to waxing isostatic depression, and the lower set having prograded subsequently, but with no evidence of interruption, apparently under conditions of continuing to waning isostatic depression. Wherever observed in the Bonneville basin, the later set of Provo beach ridges is consistently about 3.7 m (12 feet) below the earlier set. The beach ridges at the Provo shoreline, therefore, appear to record a slight downcutting at Red Rock Pass following the isostatic "turnaround" that resulted from unloading and reloading during the mid-Bonneville subcycle. Abandonment of the Provo shoreline, from patently hydroclimatic causes, seems to have been relatively abrupt. The regression of Lake Bonneville apparently continued with only minor pauses to the Stansbury shoreline, over 110 m (360 feet) below.

Where erosion predominated over deposition at the Provo shoreline—typically on steep bedrock headlands fully exposed to wave energy from the northwest, west, and southwest - an erosion platform that attained widths of as much as 100 m (330 feet) is at many localities the most conspicuous landform in the Great Salt Lake landscape. The platform, which slopes gently basinward from the cliff/platform junction, is a shelf of truncated bedrock that is overlain by a shallow cover of beach gravels. Almost invariably, the outer edge of the platform is fringed with seemingly enormous quantities of conglomeratic and lithoid tufa, generally as a double-layered tufa drapery extending 10 m (33 feet) or more downslope from the platform level. Development of the erosion platform was very dependent on local variations in exposure to wave energy, but development of the tufa drapery tended to be quite consistent from place to place. Individually and in combination, the erosion platform and tufa drapery are almost unmistakable geomorphic signatures of the Provo shoreline. Traced laterally to progradational segments of the Provo shoreline, the erosion platform merges with the lower beach ridge level. Isostatic "turnaround" coupled with a very slight lowering of the controlling threshold apparently provided optimum conditions for sustained local erosion within a narrow altitudinal range at the Provo shoreline. The erosion platform is, in general, overlain by remarkably little post-Provo coverhead.

Almost every Wasatch Front stream that entered Lake Bonneville at the Provo shoreline deposited at least a small delta, although much of the deltaic form was subsequently destroyed by dissection as the streams regraded downward in post-Provo time. The two largest deltas, one at the mouth of the Weber River and one fed by drainage from Big Cottonwood, Little Cottonwood, and Bells canyons, are several tens of square kilometers in area. All of the deltas are of the high-gradient, fan-shaped type, and consist mainly of bed-load sands and gravels. In many respects, the Lake Bonneville deltas are more akin to alluvial fans than to the low-gradient, suspended-load deltas that are typical of large modern rivers. The relatively coarse sediments received by Wasatch Front deltas included alluvium from high-energy mountain streams, outwash from glacial and periglacial sources, and materials from fluvial trenching of higher beaches. In every case, deltas at the Provo shoreline are larger than those at the Bonneville shoreline, mainly because of the longer continuous stand at the lower shoreline and because large volumes of upstream sediments were scoured and then redeposited as streams regraded to the lower shoreline. The large size of the Provo-level delta at the mouth of the Weber River is probably due in part to material scoured from Morgan Valley and other upstream reaches of the Weber River drainage, which had been heavily alluviated during the peaks of the Bonneville cycle. The Big Cottonwood-Little Cottonwood-Bells delta at the Provo level was in part constructed of materials recycled from Bonneville-level deltas at the same localities. Although glaciers and Lake Bonneville probably were never contiguous after the time of the earlier Bonneville shorelines, glacial outwash must have continued to be locally abundant at least until the abandonment of the Provo shoreline, by about which time the main glacier in Little Cottonwood Canyon had receded to what is now the location of Snowbird (Madsen and Currey, 1979).

Stansbury Shoreline

The most conspicuous shoreline between the Provo level and the surface of Great Salt Lake is in many places the Stansbury shoreline, about midway between (plate 1). The type locality of the Stansbury shoreline is Stansbury Island (Gilbert, 1890, p. 134), where it stands out on very steep slopes as a solitary tufa band with a vertical width of about 10 m (33 feet). The Stansbury shoreline is unrelated to any exterior threshold, posing what was once termed the "Stansbury problem" (Gilbert, 1890, p. 187) and leading to a search within the Bonneville basin for topography that might have provided interior threshold control at that level. No such interior threshold has been found and the Stansbury shoreline is now believed to have resulted from hydrologic equilibrium within its closed basin (Eardley and others, 1957, p. 1164). Incomplete studies suggest that in the vicinity of Great Salt Lake the altitudes of the Stansbury shoreline now range from about 1347 to 1378 m (4420 to 4520 feet), implying about 31 m (100 feet) of differential isostatic rebound since the shoreline features were formed. The most recent stand at the Stansbury shoreline clearly postdates the Provo shoreline and probably occurred between about 12,000 and 11,000 years ago, according to the chronology that is emerging from ongoing studies.

The Stansbury shoreline is notable for the variability of its geomorphic expression, which is usually as beach ridges, erosion platforms, or tufa deposits, and which ranges from very conspicuous to scarcely perceptible. The beach ridges, which are usually best developed in bays, seem to mark the upper limit of the Stansbury shore zone. The tufa-band deposits, which are most conspicuous on the steepest slopes, clearly mark the lower limit, although interstitial tufa is common in gravels throughout the Stansbury shore zone. The erosion platforms, seemingly intermediate within the zone, are not nearly as flat as those at the Provo shoreline, and probably reflect a greater range of water levels due to the absence of threshold control. Additional study will help to clarify the extent to which earlier stands at or near the Stansbury level may have been involved in creating the assemblage of geomorphic and stratigraphic features that have customarily been ascribed to the Stansbury shoreline.

Lake Puddle Shoreline

Shortly after Lake Bonneville regressed below the Stansbury shoreline, probably between 12,000 and 11,000 years ago, a lake formed in Puddle Valley, about 100 km (62 miles) west of Salt Lake City. Lake Puddle, which had a maximum area of 114 km^2 (44 square miles) within a basin of 404 km^2 (156 square miles) and a maximum depth of about 20 m (65 feet), was fed at its north end by inflow from Lake Bonneville (plate 1). The site of the inflow, now traversed by a paved highway 21 km (13 miles) north of the I-80 interchange at Low, is marked by a lobate, steep-fronted delta. Giant ripples on the top of the delta are indicative of high-velocity inflow. The altitude of the Lake Puddle shoreline, or diffuse shore zone, is now about 1340 m (4400 feet). Strong development of shore features was precluded by the lake's small size and brief duration. Precipitation within Puddle Valley basin, the maximum altitude of which is now only 2015 m (6612 feet), could not have been sufficient to prevent rapid dwindling of Lake Puddle after Lake Bonneville fell below the inflow threshold. The life span of this curious lake-on-a-peninsula-in-a-lake may have been no more than a few hundred years.

Gilbert Shoreline

Of the more frequently-mentioned shorelines in the high shoreline zone, the Gilbert shoreline (plate 1) occurs at the lowest altitudes and is generally the least conspicuous. What can be regarded as a series of type localities of the Gilbert shoreline has been described by Eardley and others (1957, p. 1156-1157 and plates 1-3). In the vicinity of Great Salt Lake the altitudes of the Gilbert shoreline now range from about 1292 m (4240 feet) to about 1310 m (4300 feet), which implies that up to 18 m (60 feet) of differential isostatic rebound has occurred in post-Gilbert time. That magnitude of differential rebound, together with ongoing studies utilizing radiocarbon dating, suggests that the Gilbert shoreline dates from latest Pleistocene time, probably from between 11,000 and 10,000 years ago. The Gilbert shoreline is clearly fresher than any of those above it and, particularly on alluvial piedmonts, is clearly less preserved than any of the visible shorelines below it.

The Gilbert shoreline appears to represent a transgression and fluctuating stand following an interval of lower lake stages. Indications of this are seen in the Great Salt Lake Desert, for example, where it appears that prior eolian dunes were flooded and reshaped in the Gilbert shore zone. Cliffs and erosional platforms are best developed where pre-Gilbert coastal materials were poorly indurated, as along Bluff Road, near Syracuse (figure 5). Nevertheless, cliffs and boulder-strewn abrasion ramps are locally quite evident on well-exposed bedrock headlands. At many localities, sand and gravel from erosional sites was moved by longshore transport to accreting beach ridges at adjacent depositional sites, commonly at the heads of small bays. The largest constructional features at the Gilbert shoreline are spits, among the more notable of which are the distal portion of The Fingerpoint, on the northwest shore of Great Salt Lake, and those near Magna and Mills Junction, near the south shore. Most of the large constructional features at the Gilbert shoreline consist of two contiguous or partially superimposed beach ridges, the crests of which may be as much as 2 m (7 feet) above laterally-adjacent, coeval abrasion platforms. Some of the beaches are capped by dune sand, most of which is well stabilized by vegetation. Deltas graded to the Gilbert shoreline, most notably portions of the Bear River delta north of Corinne, tend to be of the low-gradient, flood-plain type, and consist mainly of suspended-load sediments. The configuration of the Gilbert shoreline appears to be almost completely unrelated to possible control by outflow over an interior threshold within the Bonneville basin, but ongoing studies do suggest the possibility that surface water from the now-separate Sevier River system may have last flowed into the northern half of the Bonneville basin, via the Old River Bed that terminated in what is now Dugway Proving Ground, during the stand at the Gilbert shoreline.

Late Holocene Shorelines

Several shorelines, not mapped in plate 1, are locally conspicuous in the altitude range between the Gilbert shoreline and the historic shoreline zone. Although the stratigraphy of these fresh-appearing shorelines has only recently come under intensive study, it seems certain that most of them date from late Holocene time. As such, they postdate not only the Gilbert shoreline, but the principal geomorphic features in the submerged shoreline zone (discussed below) as well. Informal names and possible ages suggested by Currey (1977, p. 87) for the two most conspicuous late Holocene shorelines in Great Salt Lake State Park, on the north end of Antelope Island, are adapted for use here.

The higher of the two, approximately halfway between the modern surface of Great Salt Lake and the Gilbert shoreline, is the Fremont shoreline, which may date from between 5000 and 4000 years ago. The lower one, approximately midway between the modern lake and the Fremont shoreline, is the Eardley shoreline, which may date from between 3000 and 2000 years ago. However, it is quite apparent that when ultimately resolved, the late Holocene geomorphic history of Great Salt Lake will prove to be far more complex than is suggested by this simple two-fold model.

On gently-shelving portions of the Great Salt Lake coast the late Holocene shorelines generally occur as low-relief erosional scarplets (figure 5) and as discontinuous depositional ridges. In more steeply-shelving areas the shorelines tend to be more strongly developed, usually as boulder beaches at sites that were predominantly erosional and as beach ridges at depositional sites. As many as a dozen late Holocene beach ridges occur locally in cross-bay and cuspate sets, such as at the south end of Stansbury Island. At some localities the beach ridges are capped by relatively inactive foredunes that

Figure 5. Davis County coast, 3 km (2 miles) west of Syracuse, showing the Gilbert shoreline (paralleled by Bluff Road, upper right diagonal) and two prominent late Holocene shorelines (at left). The east-west highway (center) crosses Farmington Bay (left edge) to Antelope Island. USDA-ASCS photo AAK-2FF-37, 29 May 65.

were essentially contemporaneous with the beaches, and at others the late Holocene beach ridges have been overridden by transverse and parabolic dunes that were initiated later, within the historic shoreline zone. Abandoned channels on the surfaces of low-gradient deltas, and alluvial terraces farther upstream, mark the former courses of streams, such as the Jordan River, that were once graded to late Holocene lake levels.

Submerged Shoreline Zone

There is much paleoclimatic evidence (e. g., Street and Grove, 1979, figure 12a) to indicate that exceptionally low lake levels occurred in the Southwest during mid-Holocene time. A convergence of absolute dates and age estimates places this interval—often referred to by terms such as Altithermal, Hypsithermal, and Climatic Optimum—between 7500 and 5000 years ago. Indeed, there is a large body of evidence from many areas in the western U. S. to suggest that two intervals of maximum aridity about 7000 to 6500 and 6000 to 5500 years ago were separated by an interval of increased effective moisture about 6500 to 6000 years ago (Benedict and Olson, 1978, p. 184). Given the documented paleoclimatic history of the intermountain region, it is reasonable to hypothesize that Great Salt Lake declined to levels significantly lower than the historic shoreline zone at least once during mid-Holocene time. Detailed stratigraphic analysis of Holocene bottom sediments in Great Salt Lake, which eventually can be expected to provide a definitive test of this hypothesis, is still in its infancy. However, two geomorphic features that occur widely in the submerged shoreline zone—at altitudes below 1277 m (4191 feet)—do seem relevant to broad aspects of the mid-Holocene history of Great Salt Lake and are discussed in the next two sections.

Mid-Holocene Playa

The floor of Great Salt Lake rivals the Bonneville Salt Flats in flatness. The lowest and fattest part, now at altitudes almost entirely between 1271 and 1274 m (4170 and 4180 feet) is about 100 km (62 miles) long in a north-northwest direction, up to 26 km (16 miles) wide, and about 1450 km^2 (560 square miles) in area (plate 1). On the floor of the south arm (Katzenberger, 1975) this submerged plain has a uniform slope of about 0.2 m per km (1 foot per mile) to the east-northeast, with the result that the edge of the plain near Fremont and Antelope islands is about 3 m (10 feet) lower than the edge near Carrington and Stansbury islands. After adjusting for the east-northeast slope, the residual local microrelief on the plain is almost everywhere less than 0.4 m per km (2 feet per mile) and in many places is essentially nil.

From a geomorphic standpoint, the planar floor of Great Salt Lake is best explained by a very shallow or transient water body, wherein wave base and particularly the water surface itself frequently coincided with and smoothly graded the bottom. Apart from now being under 6 to 9 m (20 to 30 feet) of water, the floor of Great Salt Lake is topographically indistinguishable from many of the large subaerial playas that are flooded only intermittently in drier regions of the Basin and Range Province. The east-northeast slope of the lake floor is of a magnitude and direction that can be readily accounted for by differential isostatic rebound since mid-Holocene time, although tectonism involving subbottom fault blocks could also have been a factor. Even at the lowest lake stages, salt marshes and saline ponds would have been maintained along the eastern margin of the basin floor by diminished, but still significant, runoff from the Wasatch and Uinta mountains. Elsewhere on the basin floor, ground-water-discharging salt flats grading into moist, saline mud flats would have been the most extensive surface types. As the available evidence is reconstructed here, the floor of Great Salt Lake was a playa landscape at least briefly during mid-Holocene time.

Mid-Holocene Polygons

Polygonal fissure patterns, in every respect identical to giant desiccation polygons described from 39 playas elsewhere in the Great Basin (Neal and others, 1968), occur in the submerged shoreline zone of Great Salt Lake. Polygons ranging from clearly visible to partially veiled by younger sediments occur over about 400 km^2 (155 square miles) of the lake bed (plate 1), and have been observed at altitudes as low as 1275 m (4183 feet) on aerial photographs taken in November, 1965, when the surface altitude of Great Salt Lake was 1277.8 m (4192.3 feet) (figure 6). The polygonal patterns tend to be irregular random orthogonal; most of the individual polygons are between 15 and 100 m (50 and 330 feet) across, and the largely-infilled fissures usually appear to be about 1 m (3 feet) wide at the top. The reported tendency of fissure spacing to be about 10 times fissure depth (Neal and others, 1968, p. 83) and the habit of desiccation fissures to develop above the water table provide a basis for estimating former water levels. On this basis, it can be inferred from observable polygons that at the time of polygon formation water levels were probably no higher than the adjacent playa surface. The desiccation polygons and the playa surface would seem to have formed simultaneously during one or more mid-Holocene intervals of maximum aridity.

Fracture Zones

What appear to be fracture zones can be observed on the bed of Great Salt Lake in two areas (plate 1). From near Monument Point, at the south end of Hansel Valley, the Dolphin Island fracture zone has an arcuate trend that averages approximately S 25 W over a distance of at least 21 km (13 miles). The zone includes two prominent parallel linears and a roughly parallel pattern of what may be sink holes produced by solution of evaporites or by ground-water discharge. The Dolphin Island fracture zone was modified by, and therefore predates, shore-zone processes during Holocene low-lake stages. Topographic expression suggests that the bed of Great Salt Lake may be downthrown or may have subsided to the east.

From 4 km (2.5 miles) west of White Rock, near the northwest end of Antelope Island, the White Rock fracture zone trends N 30 W for about 1.6 km (1 mile). The zone consists of at least 10 subparallel, *en echelon* elements (figure 6), each of which appears to be slightly downthrown to the southwest. The visible fractures in the zone appear not to have been modified by coastal processes and may be of very late Holocene age.

Historic Shoreline Zone

As described elsewhere in this Bulletin, the shoreline of Great Salt Lake has ranged from a historic high altitude of 1284 m (4212 feet) in 1873 to a historic low of 1277 m (4191 feet) in 1963. Although a very dynamic zone from the viewpoint of its human contemporaries, the lacustrine features of the historic shoreline zone are inherently less pronounced than those of the high shoreline zone, where greater fetches were conducive to higher shoreline energies. Some of the geomorphic features in the historic zone, it should be added, represent prehistoric shorelines within the zone. In many gently-shelving areas partial planation of the historic shoreline zone has tended to produce knob-and-swale topography, with remnants of older lake beds projecting above intervening washouts. On steeply-shelving headlands erosional shorelines are marked by lag deposits that range from distinctive boulder beaches to

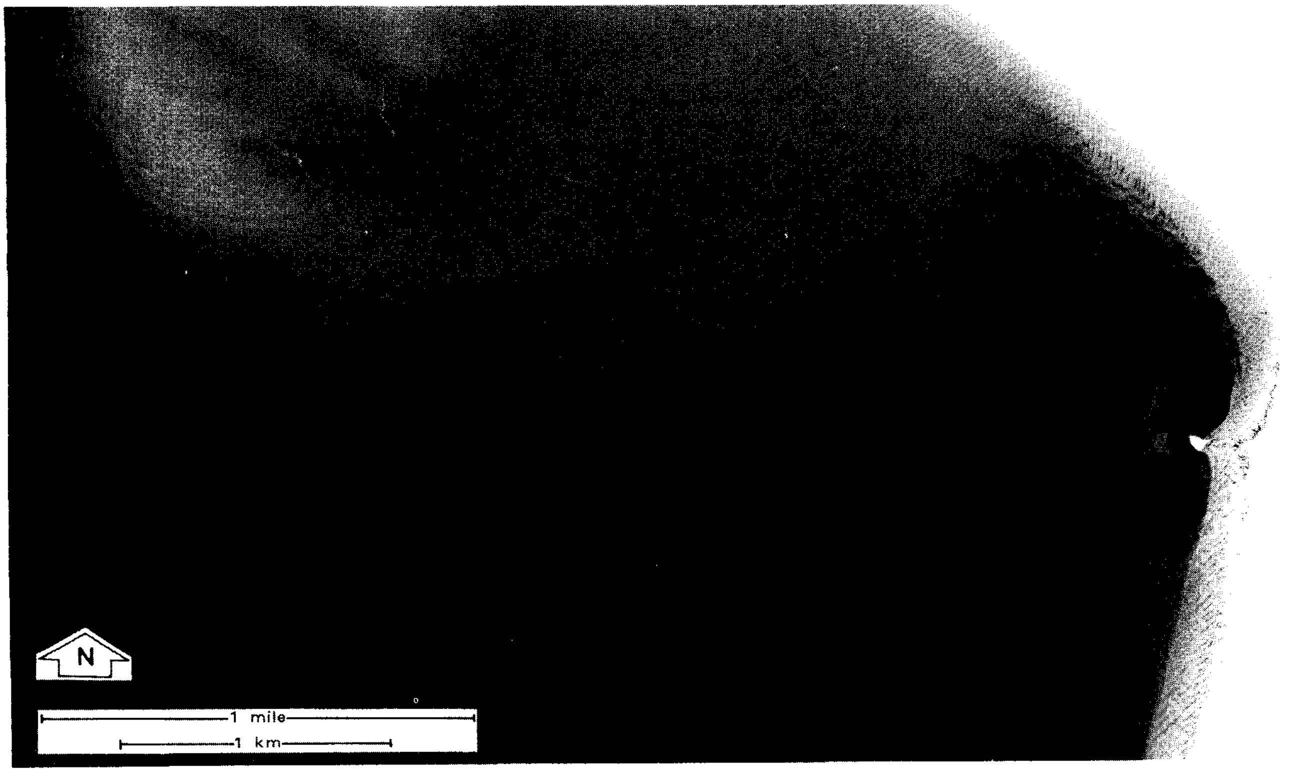


Figure 6. White Rock Bay, near the northwest end of Antelope Island, showing submerged features, including mid-Holocene desiccation polygons (center) and the White Rock fracture zone (left center). White Rock is at right center. Intermountain Aerial Surveys photo GS-VBIV 2-192, 9 Nov 65.

indistinct stone lines. Small berms, usually either of oolitic sand or of gravel derived from oolitic beachrock, are common constructional landforms. Shallow lagoons are locally enclosed by barrier berms, particularly where the coast is embayed. In terms of area, saline mud flats are by far the predominant landform in the historic shoreline zone.

At many localities in and adjacent to the historic shoreline zone, lacustrine landforms are subordinate to landforms produced by eolian processes. Water-laid berms are buried by foredune ridges at localities where the wind has been able to transport ample quantities of oolitic sand from the exposed foreshore to the vegetation line. Where copious quantities of sand have been moved in that fashion the coastal landscape is dominated by small dune fields (plate 1). Almost without exception, sand dunes in the vicinity of Great Salt Lake are predominantly oolitic and are oriented to receive onshore winds from the northwest (Dean, 1978, p. 104). The dunes range from highly active to quite stable and are primarily of the transverse type, with secondary parabolic dunes projecting downwind from local blowouts.

Of final geomorphic note within the historic shoreline zone are the mouths of the three largest entering rivers, where predominantly fine-grained fluvial loads and minimal lacustrine energies have combined to produce deltas that locally approach the classic bird-foot form. The most striking example is the Bear River delta (figure 7), in North and South bays of the Bear River Migratory Bird Refuge. Incipient bird-foot deltas occur at the mouths of Weber River distributaries in the

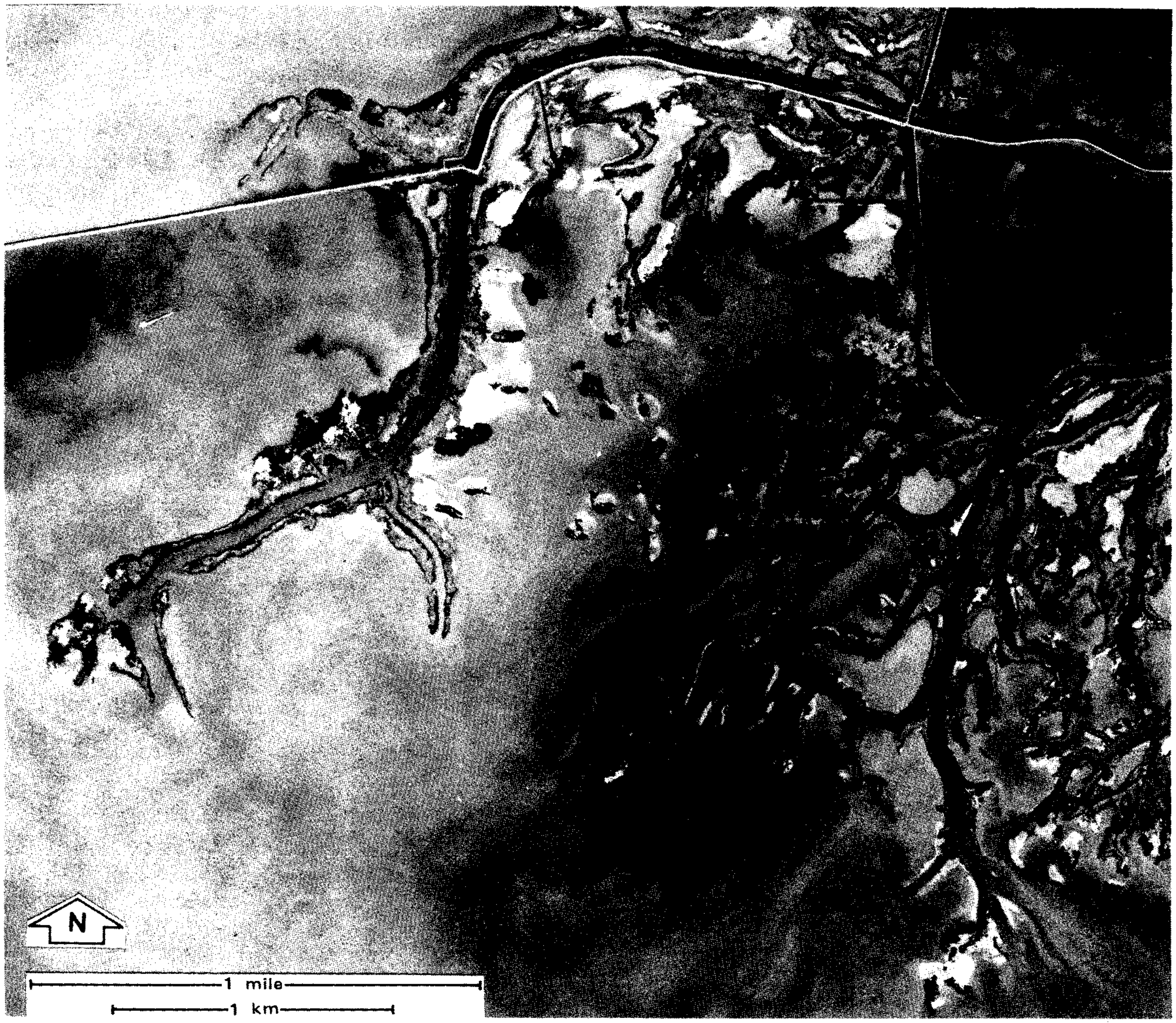
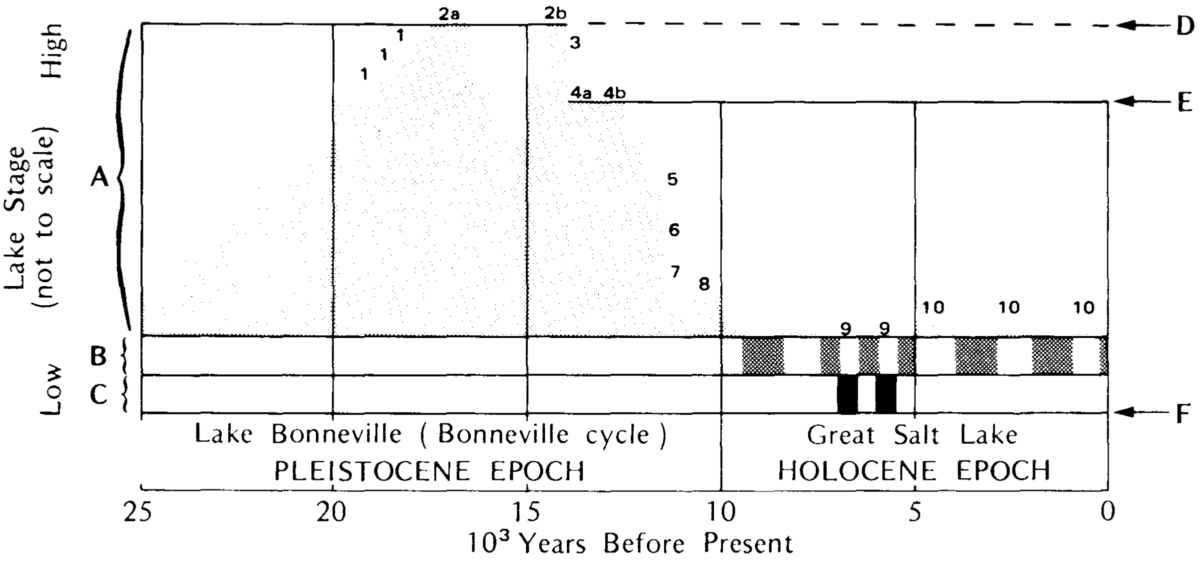


Figure 7. Bear River delta, showing the inactive Old River Channel (upper left) and the active Mouth of Bear River (lower right), with bird-foot distributary patterns of natural levees. Intermountain Aerial Surveys photo GS-VBIV 2-149, 9 Nov 65.

Harold S. Crane, Ogden Bay, and Howard Slough waterfowl management areas, and at the mouth of the Jordan River, in Farmington Bay Waterfowl Management Area. At the mouth of the Bear River, greater quantities of suspended sediment have resulted in higher rates of deltaic progradation. In each area, lacustrine energies have been artificially minimized by dikes or causeways.

SUMMARY OF LATE QUATERNARY GEOMORPHIC HISTORY

The geomorphic events reviewed above, which substantiate major aspects of interpretations proposed in the early 1950s (Morrison, 1965 and 1966, figures 2C, 2D, and 2E), but depart somewhat from previous interpretations on the basis of information being developed by ongoing studies that are utilizing regional-scale morphostratigraphic, tectonostratigraphic, and chronostratigraphic methods, are summarized schematically in figure 8. Several transgressive shorelines (figure 8-1), some possibly under threshold control, prograded locally during the later stages of the initial Bonneville transgression. The initial transgression culminated under threshold control at three earlier Bonneville shorelines (figure 8-2a), the uppermost of which is only moderately developed. A subsequent regression to relatively low stages during mid-Bonneville time was followed by a final Bonneville transgression that culminated at the later Bonneville shoreline (figure 8-2b), which was below the earlier Bonneville shorelines because of intervening net isostatic rebound. The later shoreline is weakly expressed, its development having been arrested by hydraulic failure of the Bonneville threshold (figure 8-D) at Red Rock Pass, which produced a catastrophic flood (figure 8-3) and a rapid regression to the Provo threshold (figure 8-E). A long stillstand at the earlier Provo shoreline (figure 8-4a) was continued at the later Provo shoreline (figure 8-4b) after a small additional increment of threshold downcutting. Growing aridity eventually caused abandonment of the Provo threshold and regression to a fluctuating stand at the Stansbury shoreline



A. High shoreline zone
B. Historic shoreline zone
C. Submerged shoreline zone

D. Bonneville threshold
E. Provo threshold
F. Great Salt Lake playa

1. Transgressive shorelines
2a. Earlier Bonneville shorelines
2b. Later Bonneville shoreline
3. Bonneville Flood
4a. Earlier Provo shoreline
4b. Later Provo shoreline

5. Stansbury shoreline
6. Lake Puddle level
7. Danger Cave level
8. Gilbert shoreline
9. Mid-Holocene playa stage(s)
10. Late Holocene shorelines

Figure 8. Schematic representation of late Quaternary fluctuations of Lake Bonneville and Great Salt Lake.

(figure 8-5). Quickening regression lowered lake stages briefly to the inflow threshold of Lake Puddle (figure 8-6) and then, stepwise through a series of minor shorelines, to levels approaching the floor of the basin, well below the level of Danger Cave (figure 8-7), near Wendover. A minor transgression that culminated in a dual stand at the Gilbert shoreline (figure 8-8), was the final episode in the history of late Pleistocene Lake Bonneville. Little is known about the early Holocene history of Great Salt Lake. It is probable that the floor of the Lake was exposed as a large playa (figure 8-F), with extensive surrounding tracts of giant desiccation polygons, during one and possibly two mid-Holocene intervals of maximum post-Bonneville aridity (figure 8-9). A complex sequence of shorelines, including two or three that are locally quite prominent (figure 8-10), developed at relatively low altitudes in late Holocene time.

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RECENT SEDIMENTS OF THE GREAT SALT LAKE BASIN

by J. Wallace Gwynn and Peter J. Murphy

ABSTRACT

Since man began to populate the Great Salt Lake Basin and to alter the natural hydrologic conditions that existed within it, the environment of deposition within Great Salt Lake has changed significantly both physically and chemically. The basin contains as much as 12,450 feet (3,658 m) of sediments and has been accumulating these sediments through most of Tertiary and Recent time. The major sediment types found associated with the present lake are clays, silts and sand, oolites, algal bioherms, fecal pellets, and minor amounts of gypsum. In addition, halite and mirabilite (Glaubers salt) are intermittent sediment types whose presence in the lake is dependent upon the salt concentration and the temperature of the water.

INTRODUCTION

Climate change since the end of the Pleistocene has greatly altered the nature and extent of lakes in the Great Basin. The moist pluvial conditions that prevailed during the time of the large, deep and freshwater Lake Bonneville have given way to the present arid conditions. The result of these changes is the relatively small, shallow and highly saline remnant that is the Great Salt Lake today. The natural changes in climate, areal extent, depth and water chemistry have resulted in significant changes in the environment of deposition in the Great Salt Lake Basin.

According to J. A. Campbell (personal communication, 1978), "The Great Salt Lake Basin is one of the largest and possibly the deepest intermontane basins in Utah. Geophysical studies (Cook and others, 1966) and drilling indicates that the basin is at least 12,000 feet (3,700 m) deep in its deepest part. The deepest part of the basin is mainly west of the Promontory Range and Antelope Island and east of the Terrace and Lakeside Mountains and Stansbury Island. The basin is probably part of a complex of fault-bounded basins which may extend southward into central Utah and northward as far as the Idaho border . . .

"In general, the basin fill consists of alluvial deposits near the margins, commonly observed in outcrops at the edges of the existing lake and on the flanks of the uplifts. These interfinger with a great variety of lacustrine, marginal lacustrine, and playa deposits towards the central part of the basin which are almost entirely obscured from view and are known only from a few relatively shallow drill and core holes, and from rare surface exposures along the margins of the basin.

"Structural evidence summarized by Loring (1976, p. 100) suggests that intermontane basins were formed as early as Paleocene time in the Salt Lake Valley. McDonald (1976, p. 283) believes that lacustrine sedimentation occurred near Salt Lake City in the Eocene. Studies of the Salt Lake Group by Adamson and others (1955) and Slentz (1955) have defined as much as 9,000 feet (2,800 m) of clastic, volcanic, and local lacustrine valley-fill of Neogene age near the margins of the uplifts. Even greater quantities of lacustrine sediments may occur in the central part of the basin.

"The extensive literature on the Pleistocene and Holocene sedimentary history of the basin begins with Gilbert (1890). The great variety of sedimentary rocks have been further described by Hunt and others (1954), Eardley and others (1957), Eardley and Gvosdetsky (1960), and Eardley and others (1973), to name only a few."

The purposes of this paper are first, to discuss the environments of deposition that have existed and presently exist within the Great Salt Lake, and second, to discuss the sediment types found in that area of the lake bounded by the 4,212 foot (1,283.8 m) contour (see figure 1).

ENVIRONMENTS OF DEPOSITION BEFORE MAN'S INFLUENCE

From approximately 10,000 years before the present time until man began to alter the lake and its immediate environs, conditions in the lake varied only with fluctuating lake levels resulting from seasonal and long term climatic changes. Historically, the lake level is known to have fluctuated over twenty feet (6.1 m), and seasonally the lake level fluctuates through a distance of several feet (less than 1 meter). With these variations in lake level, large areas of mud flats are alternately submerged and exposed; brine is diluted and concentrated, and the area of the lake varies considerably.

Structure of lake

Until about 1900, the lake could be divided into four distinct bodies of water. The main body of the lake, at an assumed surface elevation of 4,200 feet

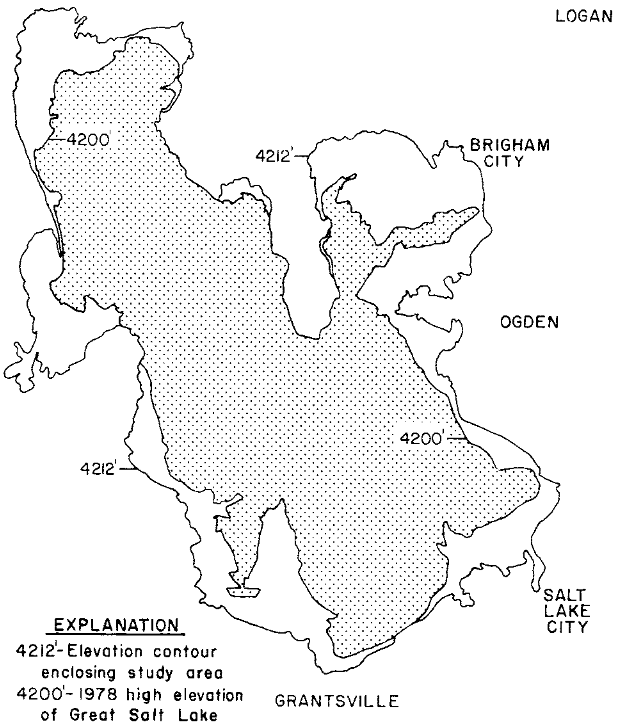

Figure 1. Map of Great Salt Lake showing 4212 foot elevation contour enclosing study area.

(1,280 m) above sea level, was an uninterrupted stretch of water some 75 miles (120 km) long, striking north northwest, and 32 miles (51.5 km) wide. Its maximum depth of about 30 feet was attained within a long trench paralleling the axis of the lake. Farmington Bay, on the southeast, was separated from the main water body by Antelope Island, and Bear River Bay, to the north of Farmington Bay, was separated by the Promontory Mountains. West Bay (Stokes, 1979), in the southwestern portion of the basin, was separated by Stansbury and Carrington Islands. All three of these bays were shallow and to varying degrees isolated by natural barriers from the overall physical and chemical environment of the lake (see figure 2).

Sources of sediments

Five major sources of clastic sediment contributed materials to the lake. These sources were: 1) the Bear River, which entered through Bear River Bay; 2) the Jordan River, which entered through Farmington Bay; 3) the combined Weber and Ogden rivers, plus other minor streams, that entered along the east shore; 4) the confining mountain ranges adjacent to the lake; and 5) the Great Salt Lake Desert. Of these sources, all of the streams originated within the Wasatch Mountains or the north flank of the Uinta Mountains.

Very little coarse clastic material entered the lake by way of the major rivers, and much of the fine-grained material was deposited in the bay areas. The remainder of the sediment load, mostly clays, fine silts and organic matter, was carried out into the lake and dispersed by the lake currents. The mountain ranges adjacent to the lake provided most of the small amounts of coarse clastic materials found in the lake and along some of its beaches (Eardley, 1938, p. 1359). Beach materials were subject to redistribution in the littoral zone under the influence of prevailing north-northwesterly winds. A number of active and dormant spits and baymouth bars are evidence for the longshore transport of beach materials, and it appears that the prevailing transport direction was, before the construction of the causeway, from north to south.

Chemical environment

The chemical environment that existed in the main body of the lake prior to the building of the causeways is not well documented, but the lake was undoubtedly more homogeneous than at present. The exchange and mixing of waters was dependent upon currents which circulated the water throughout the entire lake, and were restricted only by natural barriers.

Vertically, the lake was probably oxidizing in nature near the surface and reducing near the bottom. The specific gravity of the brine varied with the elevation of the lake. As the elevation dropped below 4,195 feet (1278.6 m) the water became saturated with respect to NaCl, and this salt was precipitated from solution and deposited on the bottom of the lake. Because of fresh water inflow, the water in the Farmington and Bear River Bay areas was less saline than that in the main lake. As the main lake level decreased to the point of saturation, the bay areas greatly decreased in size but remained undersaturated.

ENVIRONMENTS OF DEPOSITION AFTER MAN'S INFLUENCE

Although no major climatic and meterological changes have occurred in recent times, large scale construction projects on the Great Salt Lake and urbanization of the Wasatch Front have combined to alter the physical and chemical environments of the lake. These projects include the construction of the Southern Pacific Railroad causeway through the center of the lake in 1959; the Antelope Island-Syracuse causeway that now isolates Farmington Bay from the lake proper; the diking of large areas within Bear River Bay, and the

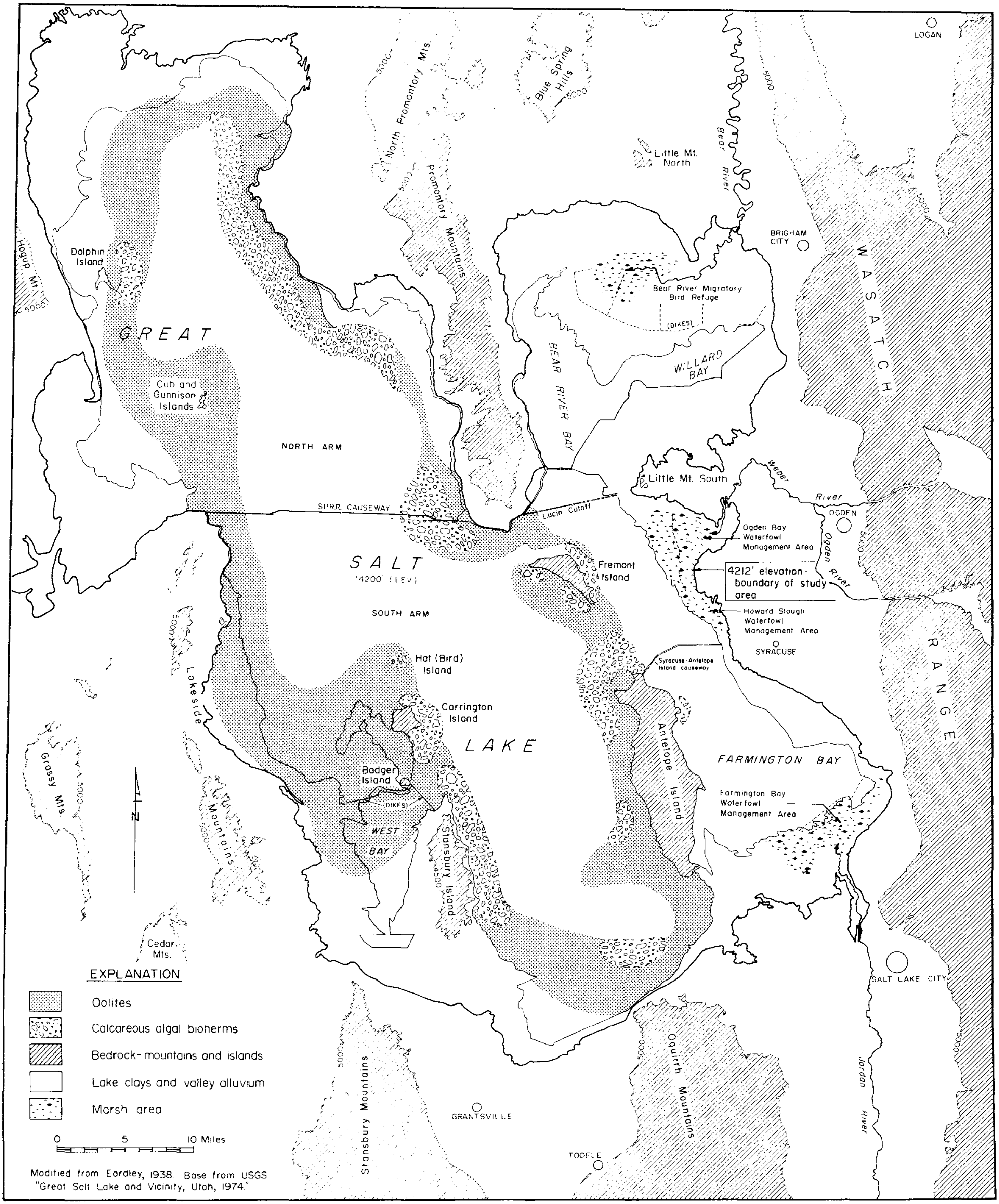

Figure 2. Map of Great Salt Lake showing distribution of most common types of sediments.

dikes that now isolate the West Bay area. Each has created unique environments of deposition. These environments are the north arm, the south arm, and the three bay areas: Farmington, Bear River and West Bay.

Effects of artifical barriers

Construction of the causeway in Bear River Bay has (1) temporarily increased the quantities of clastic sediments being deposited in the upper reaches of the bay and decreased the quantity of clastics being carried and deposited out into the lake and (2) chemically and physically isolated the bay from the lake. As a result the bay is being filled more rapidly with sediments, and its extent and depth are being decreased; the chemical interface between the bay and lake waters has become more abrupt, and the dikes now shelter the bay from lake-generated storm and waves. Large quantities of well-aerated fresh water from the Bear River continue to flow through the bay, creating an oxidizing environment.

The construction of the Antelope Island-Syracuse causeway has caused similar changes in Farmington Bay. Since the movement of lake brines into Farmington Bay has been restricted, fresh waters from the Jordan River and small intermittent streams entering the bay make it less and less saline. In addition, untreated urban wastes, once disposed of in the bay, have severely altered both the physical and chemical characteristics of the bay's water and bottom muds. Bacterial action on the organic wastes in the freshened water has resulted in a reducing chemical environment that is producing great quantities of noxious hydrogen sulfide gas in the water and bottom muds.

Diking projects along the eastern shore have caused sediment from the Ogden and Weber Rivers to be dropped behind the dikes at the Ogden Bay Waterfowl Refuge. This area, once salt flat, is now a brackish swamp.

North and South arms

The main body of the lake has been divided by the Southern Pacific Railroad causeway into a north and a south arm. The fill material of the causeway acts as a semipermeable barrier that has shortened the fetch of the winds that blow over the lake and altered the character of the waves that they produce. Prior to the installation of the causeway, winds from the northwest built waves that traveled the full length of the lake. In addition the presence of the causeway has disrupted the pre-causeway currents and a new set of currents now operates independently in each arm of the lake (Katzenberger and Whelan, 1975). The longshore transport of beach sands from north to south has been interrupted, and any south to north movement of clays, fine silts and organic debris must move through the two culverts that cut the causeway.

The most dense brine in the lake is found in the north arm, where it is relatively homogeneous from surface to the bottom. At and beyond its saturation density sodium chloride precipitates from the brine. The upper portion of the water in the north arm is aerated and is oxidizing in nature, but a reducing environment can be found at depth within the north arm.

In contrast, brines in the south arm of the lake are less saline than in the north, but are stratified into two distinct types. The upper brine is relatively clear and odor free, and under present undersaturated conditions does not precipitate sodium chloride nor will it precipitate appreciable amounts of mirabilite during the cold winter months. The lower heavier brine is brown in color, due to the organic matter suspended in it, and is laden with hydrogen sulfide gas. There is a sharp transition zone or interface between the two brine layers. The upper brine is well aerated and oxidizing in nature, while the lower brine is reducing. Why there are two layers is not fully understood, but may be related to the absence of the semi-annual or annual temperature-related turn over experienced in fresh water lakes.

The chemical differences between the north and south arm brines are the result of a combination of factors: 1) all major sources of surface and ground water inflow discharge into the south arm of the lake; 2) evaporation is the only method by which large quantities of water can leave the lake; 3) the causeway acts as a semipermeable barrier to the movement of lake brine; and 4) evaporation off the north arm has been greater than inflow through the causeway structure and culverts, causing a lowering of the north arm water surface relative to the south arm water surface by as much as three feet (1 m) during the past twelve years. As a result, the salinity of the north arm brine has increased relative to the salinity of the south arm brine.

The difference in head between the north and south arms, together with the concentrated force of south to north flow through the culverts, may also influence the currents of the north arm. Investigations are presently being planned to determine if this influence is significant.

SEDIMENT TYPES

The sediment types within the environs of the lake include the clay-silt-sand size materials (hereinafter referred to as clastics), oolites, algal bioherms, fecal pellets and gypsum crystals, as well as the soluble salts, mirabilite and halite.

Clastics

Clastics constitute the major sediment type, by volume, within the environment of the Great Salt Lake; these are found not only near the shore lines, but constitute a large percentage of the lake bottom materials and a majority of the deep basin fill. The areal distribution of the clastics throughout the lake, and that of oolites and calcareous algal bioherms, has been discussed by Eardley (1938, p. 2011), and shown by Stokes (1963, Geologic Map of Utah - N. W. quarter) and by Hedberg and Perry (1971, p. 2). Figure 2, showing the areal distribution of clays as well as oolites and bioherms around the lake has been adapted from Eardley (1938, p. 1311). Studies of shallow (to 30 feet - 10 m) and deep (to 600 feet - 180 m) subsurface sediments in and around the lake were completed by Eardley and Grosdetsky (1960) and by Schreiber (1958). Both of these investigations show clastic type sediments to predominate. More recent investigations by Dames and Moore for the Amoco Production Company in 1974 and 1975, and deep drilling by Amoco in 1978, support the findings of prior investigations.

Color

The physical properties of the clastic sediments vary throughout the areal extent of the lake and with depth. The color of the lake clastics including both bottom muds and those from drill cores include shades of brown, gray, red, blue, olive gray, yellow, green and completely black (Eardley, 1938, p. 1334; Grim, 1960, p. 517-183; Schreiber 1958, p. 11-12; and unpublished reports by Dames and Moore for the Amoco Production Company, 1974, 75). Whitish and light colored clastics were also reported. The color of the materials was observed to change laterally as well as vertically. The color changes may be gradational, for example from gray to black or from yellow to red or brown, or abrupt, with knife edge transitions from one color to another.

The color of the clastics depends upon the color of original source rocks, the environment of the time of deposition, and the presence or absence of organic material.

Particle Size

Particle size distribution in the clastic sediments was studied by Eardley (1938, p. 1336) and Schreiber (1958, p. 13-18). Like the color, the size distribution of the clastics varied and was dependent upon the collecting locality.

In nine representative clastic samples collected and analyzed by Eardley the coarse to very fine sand fraction accounted for 6.4 to 53 percent of the bulk sample, with an average of 20 percent; the silt size ranged from 7.7 to 33.7 percent with an average of 21.8 percent; and the clay size material ranged from 7.7 to 35.4 percent with an average of 15.7 percent. The remaining portion of the samples was composed of acid soluble carbonate minerals, and ranged from 26.1 to 70.0 percent and averaged 41.4 percent. (NOTE: Eardley had removed the carbonate fraction of the samples by dissolving it with hydrochloric acid prior to making the size analyses).

The same size fractions described by Schreiber from shallow cores were reported as follows: the coarse to fine sand fractions represented 5 to 53 percent of the samples; the silts, 34 to 70 percent, and the clays, 12 to 25 percent.

The size distribution of the sediments has been observed to vary much the same way as the color of the sediments.

Plasticity and Structure

Plasticity, a mechanical property of the sediments, was observed by Dames and Moore investigators (1974, 75) to be gradational, ranging from "slight" to "high". Clays with slight plasticity were stiff and those with high plasticity were soft.

The structure of the sediments was observed to vary between "no apparent structure" and "blocky". Voids, cemented layers, embedded salt and gypsum crystals, and laminations were also seen in the cores (Dames and Moore, 1974, 75).

Organic Material

Some lake sediments, especially those containing black organic material, may eminate a foul odor due to the presence of hydrogen sulfide gas. The gas is attributed to the action of anaerobic bacterial action on the organic material in the sediments. Such odors have been observed throughout the Great Salt Lake, but they are especially noticeable in the sediments of Farmington Bay and those in the main south arm of the lake. The source of the organic material is believed to be, at least in part, the raw sewage that was emptied into the lake for many years prior to the construction of treatment plants. Other sources of organic material in the lake are the remains of brine shrimp and algae.

Mineralogy

The mineralogy of the clastic sediments can best be considered by dividing them into two size fractions: one containing the sands and silt, and the second containing the clays.

Sand and Silt. The sand and silt fraction contains detrital mineral grains that Eardley (1938, p. 1359) believes ". . . reflect the nature of the rocks of the nearest shore, but probably contain some admixture from more distant regions by wind transport". During his study of the lake sediments, Eardley reported the identification of at least thirty different mineral species in the silt-sand fractions, of which biotite and muscovite, micas, chlorite, epidote, hornblend, orthoclase, plagioclase, quartz, tourmaline, zircon and calcite were the most abundant. It is evident from the mineral assemblage that the predominant source of the coarse grained sediments was from the Pre-Cambrian metamorphic rock outcrops around the lake. In addition to single mineral grains, specific rock types were identified which included felsites, schists, slates and shales. Oolites, brine shrimp fecal pellets and eggs, diatoms, glass shards and abundant organic matter were also identified. Schreiber (1958) and Eardley and Gvosdetsky (1960) reported similar coarse grained mineral assemblages.

Clay. The clay fraction of the lake sediments contains both clay minerals and clay size chemical precipitaties which exist together.

The clay mineralogy of the lake has been studied by Grim and others (1960), Hedberg and Perry (1971), and by Eardley (1938). The clay minerals identified by Grim include the following species: montmorillonite, illite, kaolinite and possibly chlorite. Attapulgite-sepiolite clay minerals were not found in the lake. Of the clay minerals, Grim made the following conclusions:

1. The clay mineral assemblage of the lake bottom sediments is very similar to that of the post-Provo age sediments.

2. The montmorillonite shows relatively poor organization, probably due to the high sodium content in the lake, especially in samples containing considerable organic material or those found immediately below the surface (of the lake). Better organization of the montmorillonite was found in samples from the bottom or below the bottom of the lake.

3. Montmorillonite is more abundant in the vicinity of basalt outcrops, suggesting it may be, in part, detrital; and some may have formed from the alteration of volcanic ash.

4. Illite is detrital and is generally well organized.

5. Kaolinite is almost certainly detrital as the brines are not compatible with its formation. It is possible to confuse the identification of kaolinite with that of chlorite.

6. Attapulgite and sepiolite minerals were not found in the lake sediments.

Hedberg and Perry (1971) studied both the clays of the brine-sediment interface and the clays being transported into the lake by its three major tributaries. They determined that the lake clays contained 51 percent K-mica, 39 percent montmorillonite and interstratified illite-montmorillonite, and 10 percent kaolinite. They also concluded that no attapulgite-sepiolite minerals were present.

The clay minerals from the lake were compared to those found in the three major rivers that flow into the lake and it was observed that K-mica was slightly more abundant in the lake sediments while kaolinite and montmolillonite were less abundant.

The clay-size chemical precipitates which constitute the remainder of the clay size sediments are mainly the calcium- and magnesium-carbonate minerals aragonite and dolomite. These minerals are formed from ions in the lake brine, which precipitate under the proper conditions of temperature, pressure and ionic concentrations. Calcite, the other dimorphic form of calcium carbonate, was not found as part of the chemical clay size precipitate assemblage (Eardley, 1938, p. 1338). Even though the majority of the calcium and magnesium carbonate precipitation in the lake can be accounted for through physico-chemical processes, Eardley (1938, p. 1343) suggests that lake bacteria may also play an important part in the formation of carbonate compounds.

Oolites

Oolitic sands are a distinct and somewhat unique sediment type found in and around the Great Salt Lake. The areal distribution of oolite deposits, as depicted by Eardley (1938), is shown in figure 2.

At the time of Eardley's observations in 1933, the oolites extended from the shoreline elevation 4,197 feet to a maximum depth of twelve feet below the surface of the lake. In general, oolitic sands are confined to the shore areas of the western portion of the two main arms of the lake. Because these sands are sorted and relatively clean, they make excellent recreational beaches. The eastern portions of the lake (the areas generally east of Fremont Island, Bear River Bay and Farmington) are devoid of oolites.

Oolite beds up to 18 feet in thickness have been measured in the vicinity of Badger Island, and near the south shore recreation areas oolites have been measured to depths in excess of six feet. Eardley and Gvosdetsky (1960) reported the presence of layers of oolites, in a nearly continuous core taken near the south end of the lake, to a depth of 600 feet. It was tentatively concluded by the authors that these sediments were deposited as early as the Aftonian stage of the Pleistocene.

Oolites appear as rounded, light colored grains and range in shape from nearly spherical to cylinderical; their surfaces are usually smooth, like a miniature pearl, but sometimes they are mottled and speckled. The external shape of an oolite can usually be attributed to the shape of the nucleus around which concentric layers of calcium carbonate have formed. Figure 3 shows the shape of typical oolites from several unspecified locations around the Great Salt Lake.

The size of oolites, sometimes measured as their long diameter, ranges from .015 to 1.5 mm (Eardley, 1938, p. 1364), but the variation is not this great within a given sample. The average size is approximately 0.31 mm. Oolites collected from various locations around the lake may have different sizes. Eardley noted that the largest oolites were from the sandbar on the west shore of Antelope Island.

The basic structure of an oolite is similar to that of a pearl, although oolites are not formed within the body of a living organism. The nucleus or central core is usually a mineral fragment or possibly a tiny brine-shrimp fecal pellet. The minerals most commonly found as the nuclei material are quartz, feldspars and calcite. The outer shell is built around the nucleus material in the form of concentric layers of aragonite. Through the microscope the concentric layers of some oolites are seen to have been replaced by, or to have superimposed upon them, a radiate structure. This structure is thought to develop as aragonite changes to its dimorphic counterpart, calcite. Figure 4 shows examples of the various types of nuclei materials found in oolites, and examples of various types of internal structure.

The chemical composition of the outer shell consists mainly of calcium carbonate, though some calcium-magnesium carbonate (dolomite) is also present. Other mineral species that have been found in minor quantities include clays, gypsum and amorphous silica. The latter is found as a residual product after oolites have been dissolved in hydrochloric acid, and may or may not represent a decomposed clay material. Detailed discussions concerning the internal structure, classification and chemical makeup of oolites are presented by Eardley (1938) and by Carozzi (1962).

Theories to explain the formation of oolites within the environs of the Great Salt Lake have been preposed by a number of investigators, and are reviewed by Eardley (1938, p. 1386-7), who considers the oolites to be a product of the unique physical and chemical regime of the lake.

Algal Bioherms (Biostromes)

Algal bioherms are calcareous structures, mainly of algal origin. Their distribution is shown on figure 2 as paralleling that of the oolites (Eardley, 1938) and they are restricted to the same main western portion of the lake. Their depth of occurrence within the lake is also similar to that of the oolites, extending from near the surface to depths of 10 to 12 feet.

The bioherm structures are built principally by the blue-green colonial alga *Aphanothece Packardii* (Carozzi 1962, p. 246). Looking down at the structures, Carozzi describes them as follows: " . . . an upper surface matted over with a brown to pink gelatinous film of algal cell secretion. From this film extend filament-like gelatinous masses, of the same color, 0.5 to 1.5 inches long, attached at one end and rhythmically waving in the slightly agitated water." Below the living surface, the nonliving portion of the structure is solidly seated on the bottom

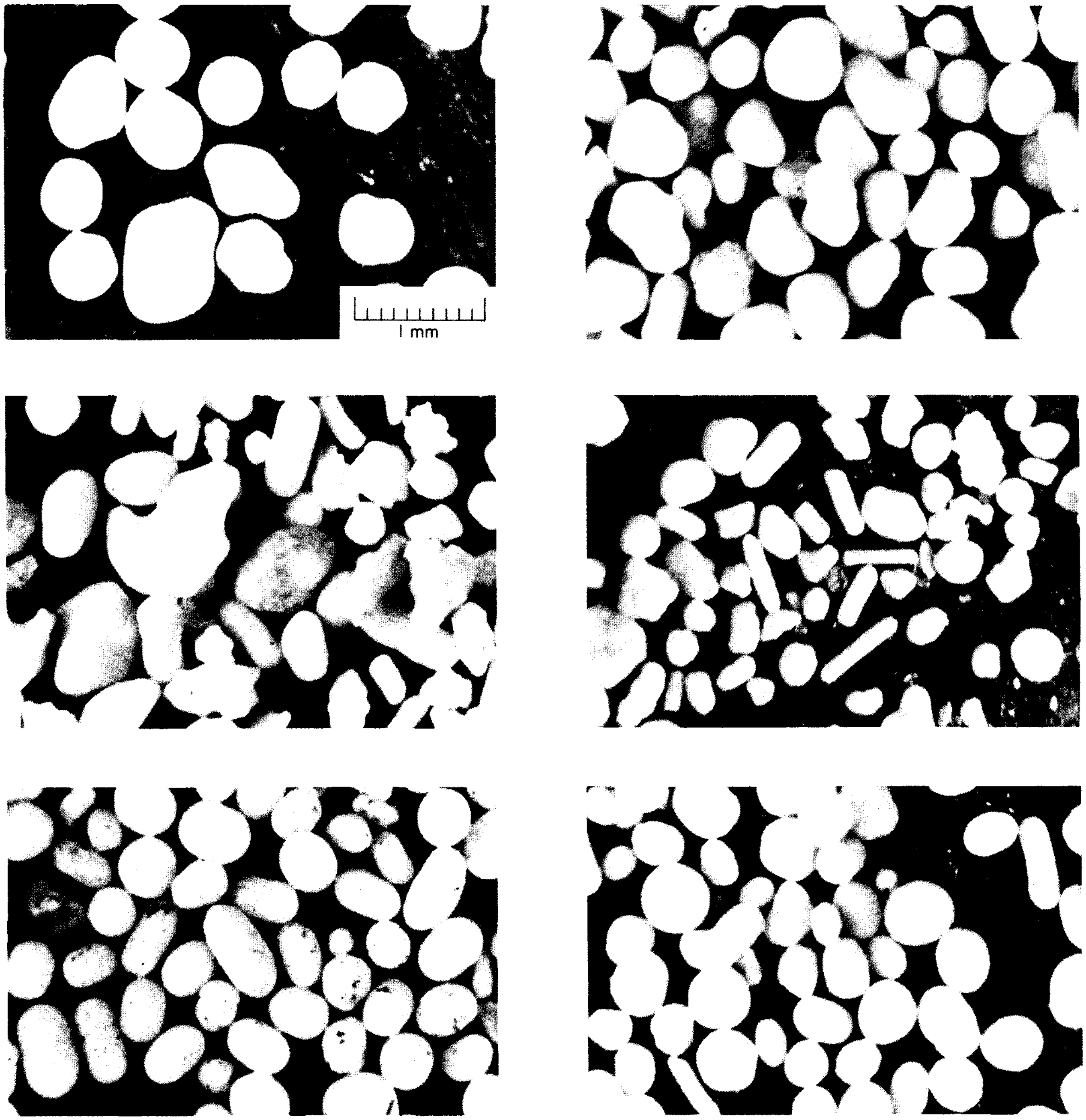

Figure 3. Oolites collected from six different localities around the Great Salt Lake, locations unspecified - all photos same scale.

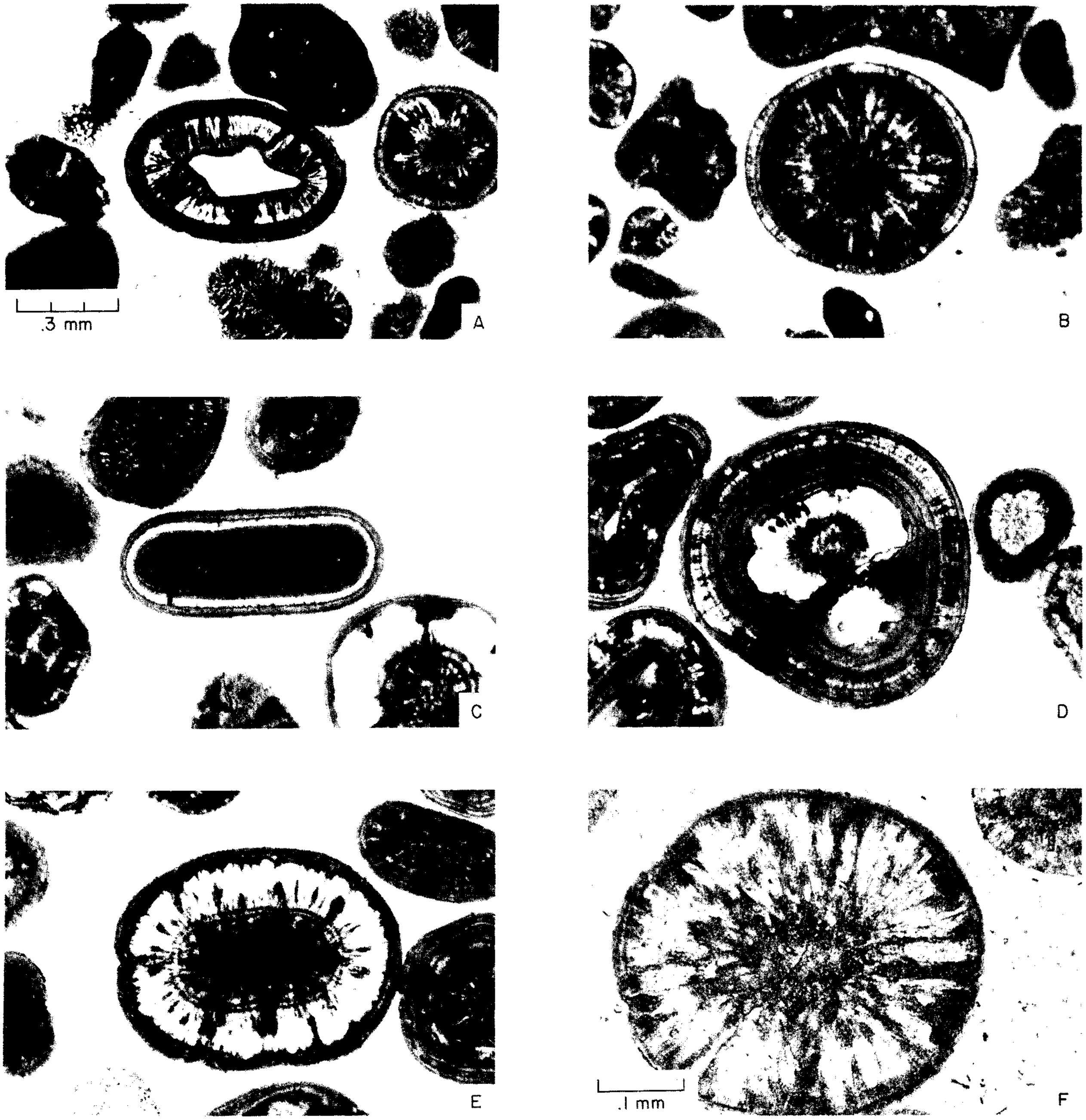

Figure 4. Core composition and internal structure of oolites.
a. Oolite with a quartz fragment nucleus.
b. Oolite with a calcite nucleus.
c. Oolite with a fecal pellet nucleus.
d. Oolite with dominant concentric ring structure.
e. Oolite with both concentric and radiate structure.
f. Oolite with dominant radiate structure.
Photos a - e all have same scale.

of the lake. Figure 5 shows an extensive area near the south end of the Great Salt Lake covered by algal bioherms.

Figure 5. Algal bioherms near the south shore of the Great Salt Lake.

Rather rigorous descriptions of the algal bioherms are given by both Eardley (1938, p 1392-1401) and by Carozzi (1962, p. 246-252). Carozzi states: "The morphological zonation of a characteristic *Aphanothece* biostrom along the shores of the Great Salt Lake indicates that these algal colonies have no typical growth pattern of their own but merely reproduce and frequently exaggerate an underlying topography carved in firm argillaceous and oolitic sands".

Algal bioherms are composed mainly of calcium and magnesium carbonates, precipitated by the living alga. Eardley (1938, p. 1400) suggests that "the algae extract carbon dioxide from the water during photosynthesis and that this is the cause of calcium and magnesium carbonate precipitation".

Fecal Pellets

The fecal pellets of the tiny brine shrimp are a very common component of the lake sediments. Fecal pellets cover the entire floor of the Great Salt Lake, including the areas generally east of Fremont Island and in Farmington Bay.

Chemically, fecal pellets consist mainly of calcium and magnesium carbonate, similar to oolites, plus occluded, fine, white clay and small mineral fragments (Eardley, 1938, p. 1404). These inorganic materials represent a substantial portion of the material ingested by the brine shrimp along with algae,bacteria and other nutrients. For a more complete discussion of fecal pellets, refer to Eardley (1938, p. 1401-1408).

Gypsum

Gypsum (selenite) is a minor constituent within the lake sediments. It is found around the shores of the Great Salt Lake, where it occurs in the soft sodium-rich muds or clays. Rozel Point on the north shore of the lake, west of the Promontory Range peninsula, is especially known for gypsum crystals (Eardley and Stringham, 1952). The crystals are also found on the southeastern end of Stansbury Island (Eardley, 1969). Gypsum or selenite crystals have been reported from numerous other locations around and within the lake in canals or cores taken from the lake bottom muds.

Many of the crystals are clear and well formed; others contain gray-green mud inclusions and may show poor crystal definition because of weathering. Selenite crystals break very easily revealing a flat shiney, internal cleavage surface. Their size varies from one eighth of an inch up to six inches in length (figure 6). Schreiber (1958, p. 18) describes the size and crystal form and depth of burial of selenite crystals observed in the coarse sand fraction of lake sediment cores.

Gypsum sand dunes, found in the Great Salt Lake desert near Knolls, Tooele County, have been described by Jones (1953, p. 2530), as follows: ". . . The dunes are composed primarily of gypsum crystals and cleavage fragments, oolites, with minor amounts of shell fragments and fine quartz, derived from lake waters during the waning stages of Lake Bonneville in the area of the present Great Salt Lake Desert . . ." Figure 7 shows a sample of the gypsum dune material.

Halite

Depositon of halite (sodium chloride), an intermittent sediment type within the lake, is dependent upon the chemical concentration of the brines. When the lake brine becomes saturated with respect to sodium chloride, at about 340 grams per liter of total dissolved solids, halite precipitates (figure 8) and settles on the floor of the lake.

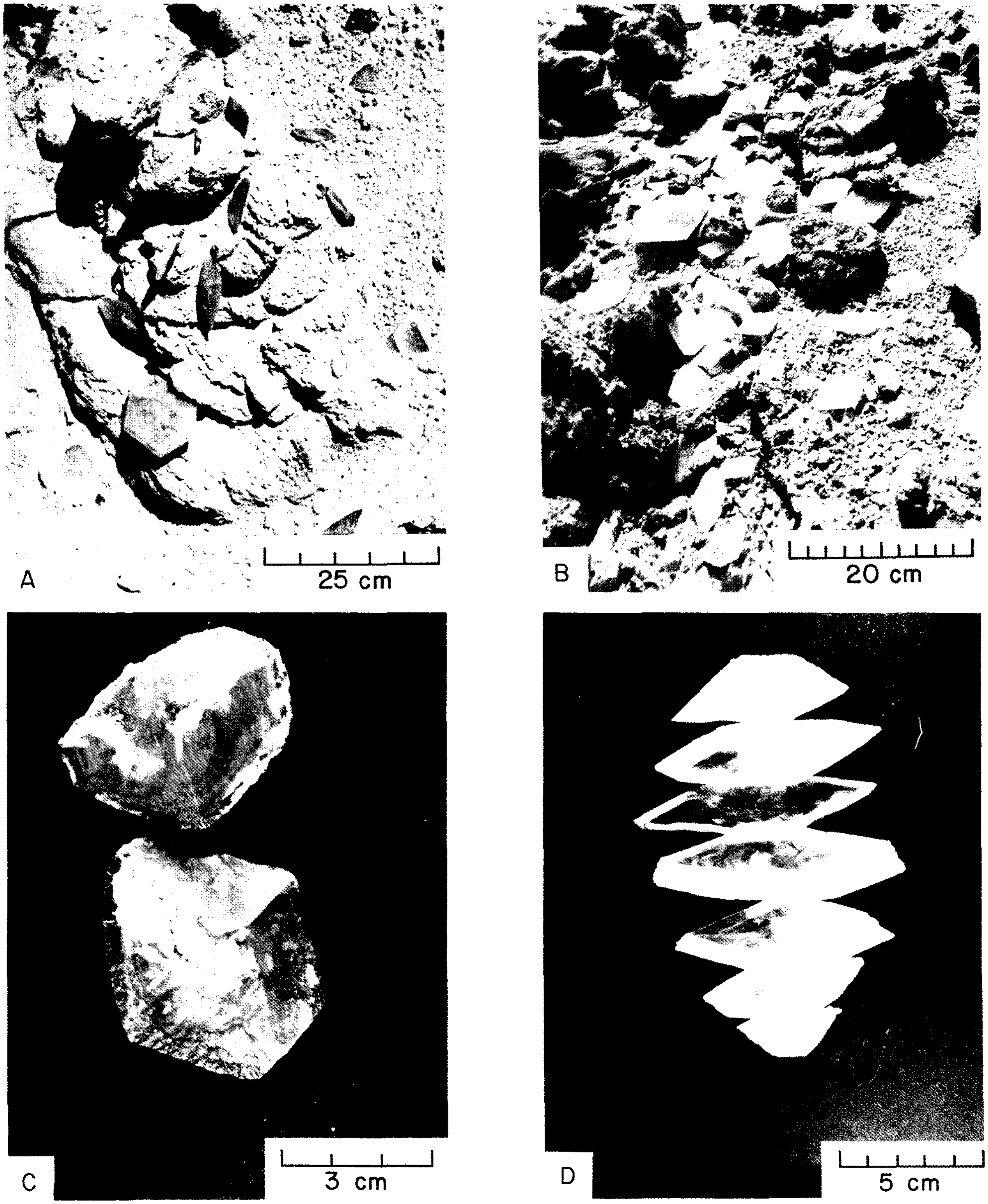

Figure 6. The size, crystal form, and cleavage of Great Salt Lake gypsum crystals.
a. Large gypsum crystals, b. Small gypsum crystals, c. Close-up view of gypsum crystals, d. Close-up view of broken crystal -- showing perfect basal cleavage.

Figure 7. Photomicrograph of gypsum sand grains collected near Knolls, Tooele County, Utah.

Figure 8. Sodium Chloride crystals precipitated from Great Salt Lake brine.

During the early 1960's, about the time that the Southern Pacific Railroad causeway was being completed and following a relatively dry period, the entire Great Salt Lake became sufficiently concentrated to deposit a thick blanket of salt over much of the bottom of the lake. The quantity of salt deposited during this period of time was estimated by Goodwin (unpublished UGMS report) to be approximately one billion metric tons. This figure is in agreement with the calculated quantity given by Whelan (1973, p. 7). As the lake level began a rising trend in 1963, the concentration of the brine decreased and, when it was no longer at saturation, salt was taken back into solution from the deposits at the bottom of the lake.

The damming effect of the causeway caused the south arm of the lake, which receives the majority of the fresh water inflow, to become dilute faster than the north arm. As a result the salt on the bottom of the south arm was dissolved first. In early 1976 the salt crust on the floor of the north arm was completely dissolved (W. M. Katzenberger, personal communication). However, as the elevation of the lake began its seasonal decline, the water in the north arm was again saturated and began to reprecipitate salt.

1976 also marked the start of a cyclical decline in lake level that has continued through 1978. The salt concentration of the north arm has remained at or near saturation since mid 1976 and salt has continued to precipitate. At the end of 1978, the thickness of the salt on the floor of the north arm has been estimated to exceed five feet.

It is not known if the downward trend of the lake will continue until the south arm is concentrated sufficiently to reach saturation. Due to the effect of the present causeway, however, the north arm is expected to remain at or near saturation, and sodium chloride will remain as an integral part of the bottom sediments in the Great Salt Lake for the time being.

Mirabilite (Glauber's salt)

Mirabilite (sodium sulfate with 10 waters of hydration) is a seasonal sediment type found in the lake (figure 9). Like sodium chloride, it precipitates from a concentrated or saturated brine, but does so only during the very cold winter months and as the water warms up each spring, the salt goes back into solution. Mirabilite deposits are normally formed on the bottom of the lake, but during storms, long windrows of "soda" have been reported to form along the southern shores of the lake. Only the north arm of the lake is at present sufficiently concentrated to allow any appreciable precipitation of mirabilite.

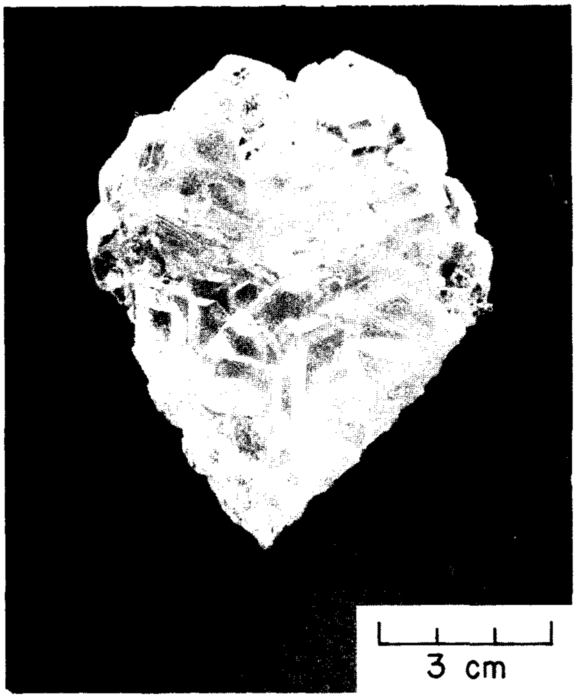

Figure 9. Mirabilite (Glaubers Salt) precipitated from Great Salt Lake brine during the winter months.

Mirabilite precipitated from the lake waters may be preserved as a deposit when the salt is separated from the mother liquor, or when the temperatures remain low. Mirabilite deposits are known to exist on the south shore and west of Promontory Point in the north arm of the lake.

Wilson (1957, p. 5) describes two deposits of mirabilite on the south shore of the lake, one in Salt Lake County and the other in Tooele County, as follows: "The sodium sulfate deposits occur as hard, brittle beds of Glauber's salt mixed with sand and clay. The beds are covered by pervious sand composed of well-rounded grains and, in places, are underlain by clay. The beds seem to have been formed by variations in seasonal climatic conditions. Sodium sulfate crystals precipitate from the brines of the Great Salt Lake during the wintertime when temperatures are low. The crystals float on the water and are deposited on the beaches by prevailing winds from the north west. As the temperatures rise in the spring, the salt dissolves in its own water of crystallization. With the aid of rainwater it is carried down through the loose sands and reprecipitates where temperatures are lower. The distance below the surface where precipitation occurs appears to be about 20 inches". In the same vicinity, Glauber's salt was encountered while the pilings were being driven to support the Saltair pavilion. The method employed to penetrate the "soda" is discussed by Miller (1969, p. 16; also Miller, this volume).

The second mirabilite deposit is located west of Promontory Point in Box Elder County. The deposit was discovered in about 1900 when the causeway trestle was being built across the lake. It was again encountered while the solid rock-fill causeway was being built across the lake in 1955-59. Eardley (1962) described the deposit as lying 15 to 25 feet below the bottom of the lake, interbedded with the soft lake-bottom clays, and having a maximum thickness of about 32 feet. The salt bed extends about 9.5 miles from a point one mile west of Promontory Point, and is bounded on the east by a fault.

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A SUMMARY OF PLEISTOCENE, FOSSIL VERTEBRATE LOCALITIES IN THE NORTHERN BONNEVILLE BASIN OF UTAH

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ABSTRACT

Late Pleistocene, fossil vertebrate localities in the northern Bonneville Basin of Utah are documented to facilitate and stimulate further, detailed studies. Information for each locality includes specific fossil material recovered, published references, and general comments by the authors of this paper.

INTRODUCTION

This compilation of fossil vertebrate localities in the northern Bonneville Basin of Utah is an outgrowth of the ongoing, cooperative research by the Division of State History (Utah) and Fort Hays State University (Kansas). Nearly all of the exposures listed (figure 1) are depositional features of late Pleistocene, Lake

Frontispiece: Artist L. A. Ramsey's interpretation of some Pleistocene Mammals on the shore of Lake Bonneville. Note Mammoth in foreground and in the background from left to right are a horse, deer, camel, bighorn sheep (male & female), and a Musk Ox.

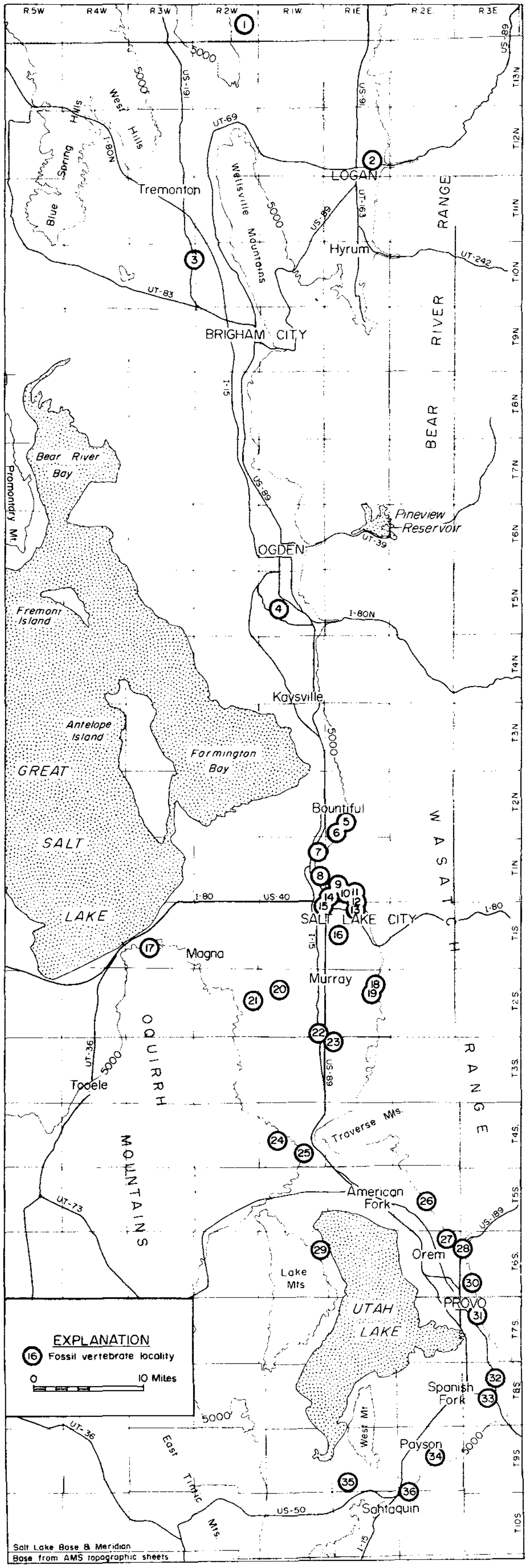


Figure 1. Outline map showing some fossil localities in the northern part of the Bonneville Basin.

Bonneville sedimentation in northern Utah. No attempt has been made to document other localities, either in the southern Bonneville Basin or outside of Utah. Additional information on late Pleistocene faunas relevant to a paleontological study of the Bonneville Basin can be found in Miller (1976).

In addition to the value of documenting known information on this segment of the Pleistocene Lake Bonneville fauna, it is our intent to stimulate further thoughts, deliberation, and publications on the Pleistocene fossil vertebrates of Utah.

ANNOTATED LOCALITY AND SPECIMEN LIST

1. Clarkston, Utah; exact locality unknown: Elevation: unknown.
    Blackwelder, Eliot, 1939.
        Mammoth, Proboscidean (no number): tusk fragment.
            Comments: Specimen cannot be located.

2. Logan City Cemetery; SW¼, Section 26, T. 12 N., R. 1 E., Cache County, Elevation: 4780'±.
    Nelson, M. E. and J. H. Madsen Jr., 1978.
        Musk Ox, *Symbos cavifrons* (USU 1347): horn core and cranial fragment.
        Musk Ox (?) *Bootherium* sp. indet. (USU 3529): one of the best preserved specimens of *Bootherium* known from Utah.
            Comments: Collected from deltaic gravels of the Provo Formation. A fragment of the Symbos *horn corn yielded a radiocarbon date of 7080 ± 160 years B.P.*

3. Bear River City, Utah; exact locality unknown, but near "edge of town". Elevation: unknown.
    Blackwelder, E., 1939.
        Mammoth, *Mammuthus* sp.: tooth
            Comments: Specimen cannot be located.

4. Weber River; Section 20, T. 5 N., R. 1 W., Weber County. Elevation: unknown.
    Feth, J. H., 1955.
        Horse, *Equus niobrarensis* (?): suggested age of Alpine Formation might be pre-Wisconsin.
            Comments: Specimen misidentified and reassigned to E. caballus *of recent origin (written communication, G. Edward Lewis).*

5. Warner Gravel Pit; exact locality data missing, but apparently from southeast of Bountiful, Utah. Elevation: unknown.
    Pack, F. J., 1939.
        "Horse", *Equus* sp.: recovered from deltaic beds of Provo Formation.
            Comments: We are unable to authenticate this account, as the specimen has been lost

6. Foss-Lewis Sand and Gravel, Woods Pit; east of Bountiful, in SE¼, SW¼, SE¼, E½ Section 31, T. 2 N. R. 1 E. Davis County, Utah. Elevation: 5150'±.
    Nelson, M. E. and J. H. Madsen Jr., 1978.
        Bighorn Sheep, *Ovis* sp. (UVP 003, 008, & 019): partial skulls with horn cores. A radiocarbon date of 14,410 ± 110 years B.P. has been established for part of UVP 003.

        Musk Oxen, *Symbos cavifrons* (UUVP 8501): partial cranium.
            Comments: The sand and gravel operation is quarrying aggregate from at least two different Bonneville formations. The Ovis *specimen was collected from the Provo? Formation, while the Musk Oxen probably came from the Alpine Formation.*

7. Concrete Products Company, White Hill Pit; south of Bountiful in SW¼, NW¼, Section 12, T. 1 N., R. 1 W., Davis County. Elevation: 4420'±.
    Nelson, M. E. and J. H. Madsen Jr., 1978.

Musk Oxen, *Symbos cavifrons* (UUVP 8531): horn core and fragments.

Comments: Collected from Alpine? or Provo Formation.

Bighorn Sheep, *Ovis* sp. (UVP 007 Pr.): skull with horn cores complete, but lacking facial region. A part of one horn core has yielded a radiocarbon date of 19,760 ± 200 years B.P.

8. Monroc Gravel Pit, North Salt Lake; Salt Lake County, NE¼, SE¼, NW¼, Section 24, T1N, R1W, Elevation: 4880' (e).

   Bighorn Sheep, *Ovis* sp. (UVP 040): scapula, (UVP 041): premaxillae, dentary, and nasals, and (UVP 023 Pr.): horn core.

9. North bench area of Salt Lake City; SW¼, SW¼, Section 29, T. 1 N., R. 1 E., Salt Lake County. Elevation: 4950'±.

   Bighorn Sheep, *Ovis* sp. (UUVP 8502): skull and horn cores.

10. Hardman Gravel Pit, now the site of the Ensign Elementary School overlooking the Salt Lake City Cemetery; NE¼, NE¼, NE¼, Section 32, T. 1 N., R. 1 E., Salt Lake County. Elevation: 4900'±.

    Pack, F. J., Jr., 1939.

    Buffalo, *Bison* sp.: discovery of two skulls was reported. One specimen has since been lost; however, the other is on display in the Utah Museum of Natural History (figure 2).

Figure 2. Artists conception of *Bison antiquus.*

Camel, *Camelops* cf. *hesternus*: two discoveries of jaws and teeth were reported, but this find is unsubstantiated. The original material cannot be found.

Mule deer, *Odocoileus hemionus:* the skull of a "deer", as described by Pack, was re-examined by us in the spring of 1978 and determined to be of recent origin.

Bighorn Sheep, *Ovis* sp.: there were reported discoveries of numerous skulls.

Stokes, W. L. and K. C. Condie, 1961.
Bighorn Sheep, *Ovis catclawensis:* at least ten specimens of mountain sheep collected in the gravel pits were tentatively assigned to the species, *O. catclawensis.*

Stokes, A. D. and W. L. Stokes, 1969.
Bighorn Sheep, *Ovis canadensis:* additional material and information available necessitated assigning the sheep to *O. canadensis* rather than *O. catclawensis* as previously reported by Stokes and Stock (1961) (figure 3a, 3b).

Musk Oxen, *Symbos cavifrons* (UUVP 8536): assigned a musk oxen skull reported by Pack (1939) to this species.

Nelson, M. E. and J. H. Madsen Jr., 1978.
Musk Oxen, *Symbos cavifrons:* assigned 5 musk oxen specimens in the University of Utah Collections to *S. cavifrons.*
Musk Oxen, *Bootherium* sp. indet. (UUVP 8532): a single horn core of this enigmatic bovid was reported.

Comments: Evidence suggests that quarrying operations in the now abandoned Hardman Gravel Pit were in the Alpine Formation. Morrison (1965) believes the deposition of the Alpine Formation began about 68,000 years B.P. and ended about 33,000 years B.P. Although this quarry has produced specimens of approximately 15 Bighorn sheep and 6 musk oxen, it will probably not, at least in the near future, again yield vertebrate fossils of consequence. The continued northward expansion of Salt Lake City has resulted in this classic area being subdivided and landscaped for residential and school construction.

11. University of Utah Medical Center Addition; SW¼, Section 33, T 1 N., R. 1 E., Salt Lake County. Elevation 4960′ (e).
Rodent, ? *Citellus* sp. (UVP 047): ulna of a small rodent collected from a transgressive gravel of the Alpine Formation.

12. Fort Douglas Military Reservation, east of Salt Lake City; NE¼, Section 4, T. 1 S., R. 1 E., Salt Lake County. Elevation: 4820'±.

Musk Oxen, *Symbos cauifrons* (UVP 045): large tibia

13. Fort Douglas Military Reservation east of Salt Lake City; SW¼, SW¼, Section 3, T. 1 S., R. 1 E., Salt Lake County. Elevation: 4820'±.
Big horn Sheep, *Ovis* sp. (UVP 009): fragment of horn core.

14. Mouth of City Creek Canyon; SW¼, SW¼, SW¼, Section 31, T. 1 N., R. 1 E., Salt Lake County. Elevation: 4294'±.
Madsen, D. B., D. R. Currey, and J. H. Madsen Jr., 1976.
Mammoth, *Mammuthus* sp.: tusk fragments submitted for radiocarbon analysis yielded an age of 14,150±800 B.P.
Bighorn Sheep, *Ovis canadensis:* at least two of the specimens described by Stokes and Condie (1961) were from the Bonneville (?) Formation near the mouth of City Creek Canyon.

Figure 3a. Artists conception of Bighorn Sheep, *Ovis canadensis.*

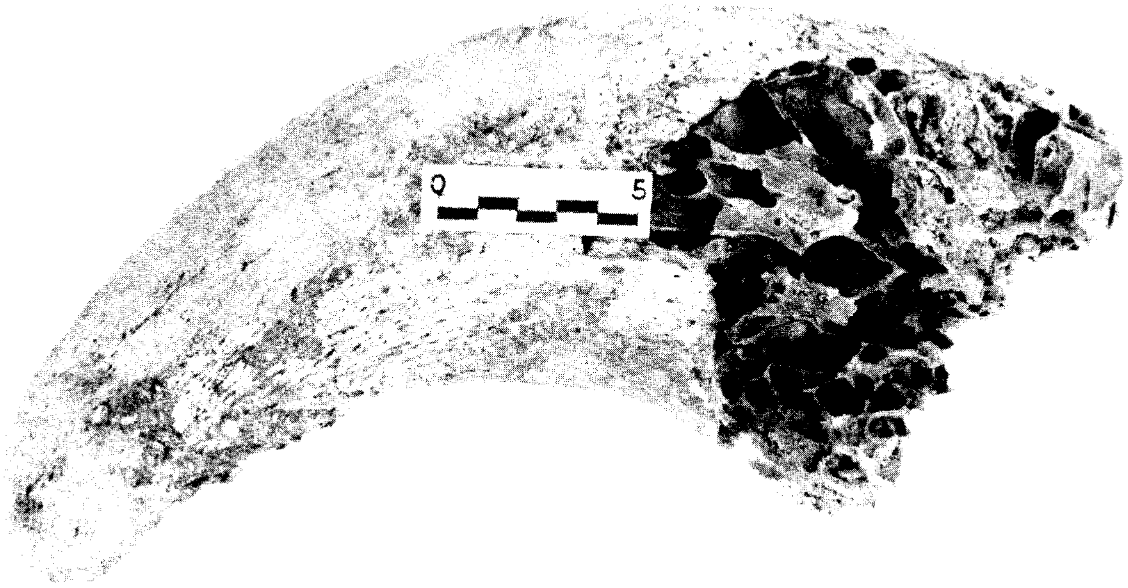


Figure 3b. A typical fragment of an *Ovis* (Bighorn Sheep) Horn core. scale is 5 centimeters.

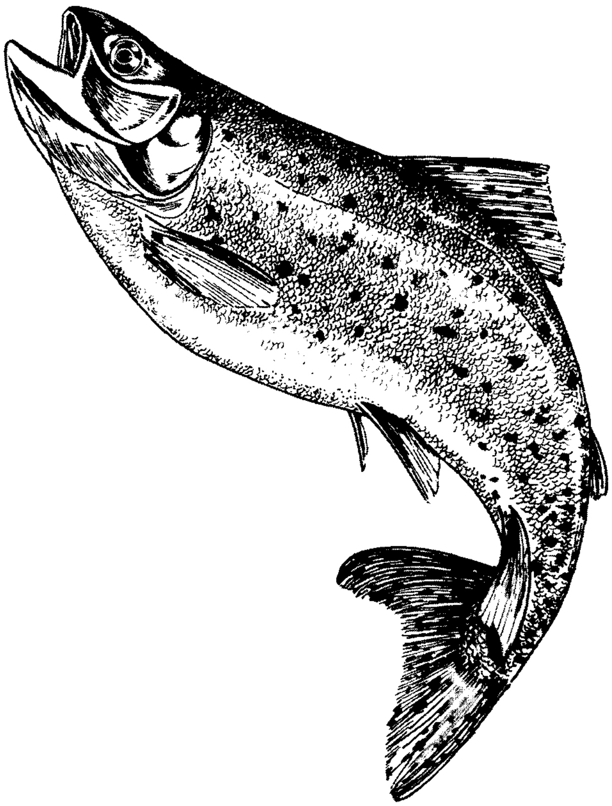


Figure 4a. An extinct species of trout, the Bonneville cutthroat, (*Salmo calrkii)*, which lived in Lake Bonneville.

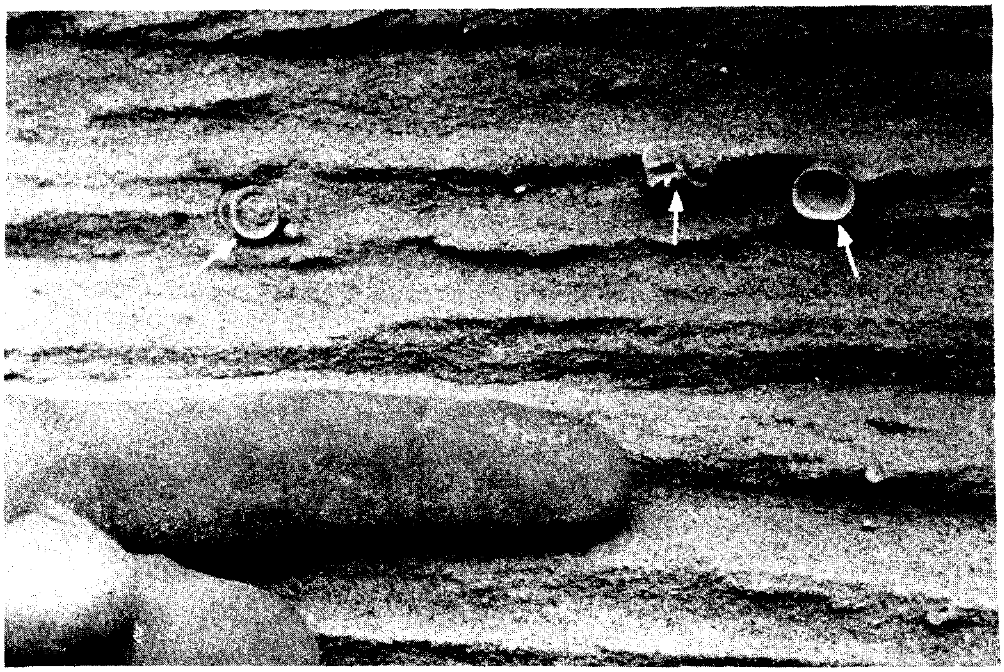


Figure 4b. Vertebrae of the Bonneville cutthroat *(salmo clarkii)* in place as found in Black Rock Canyon on the south end of the Great Salt Lake.

15. Downtown Salt Lake City; NE¼, Section 1, T. 1 S., R. 1 W., Salt Lake County. Elevation: 4335'±.

Chadbourne, P. A., 1871.

Musk Oxen, *Symbos cavifrons* (UUVP 8536): this "buffalo skull" found by workmen constructing a house was in reality the skull of a musk oxen.

Hay, O. P., 1927.

Musk Oxen, *Symbos cavifrons* (UUVP 8536): a photo of the skull described by Chadbourne (1871) appeared in Hay's treatise.

Nelson, M. E. and J. H. Madsen Jr., 1978.

Musk Ox, *Symbos cavifrons* (UUVP 8536): the Chadbourne specimen was assigned to *S. cavifrons*. *Comments: More than likely the specimen came from the sand and gravels of the Provo Formation. No absolute dates have been assigned to bracket the duration of deposition of the Provo; however, Morrison (1965a, 1965b) believes it to be younger than 25,000 years B. P.*

16. Ure mammoth locality, Salt Lake County, SW¼, SW¼, SW¼, Section 17, T, 1 S, R. 1 E, Elevation: 4310' (e).

Mammoth, *Mammuthus* sp. (UVP 037 Pr.): partial lower molar dredged from an irrigation canal.

17. Black Rock Canyon; NW¼, NW¼, SW½, Section 20, T. 1 S., R. 3 W., Elevation: 4760'±

Bighorn Sheep, *Ovis* (UUVP 8526): partial skull and broken fragment of a metapodial. *Comments: Associated with other fossils representing a bird, fish. (Smith, et. al. 1968) (figure 4a, 4b), gastropods, and ostracodes. The skull has been stolen from the University of Utah Collections; however, photographic evidence remains (figure 5). The metapodial is missing and presumed lost.*

18. Southeast Salt Lake City; Salt Lake County. SW¼, SW¼, NE¼, Section 11, T. 2 S., R. 1 E. Elevation: 5020'±.

Musk Oxen, *Symbos cavifrons* (UVP 038): dentary.

Figure 5. Heavy equipment operators examing a skull of the Bighorn Sheep *(ovis)*. They uncovered in Black Rock Canyon west of Salt Lake City, near the south end of the Great Salt Lake.

19. Harper Sand and Gravel Pit, Southeast Salt Lake City; Salt Lake County. NE¼, NE¼, SW¼, Section 11, T. 2 S. R. 1 E., Elevation: 4600'±

    Mammoth, *Mammuthus* sp. (UVP 039): tusk fragments, a sample of which has been submitted for radiometric analysis.

20. Sorensen Construction Gravel Pit; SE¼, SE¼, SW¼, Section 8, T. 2 S., R. 1 W., Salt Lake County. Elevation: 4535'±.

    Stokes, W. L. Megan Anderson and J. H. Madsen Jr., 1966.

    Buffalo, *Bison (Simobison) antiquus* (UVP 032): cranial fragment with horn cores, a sample of which has yielded a radiocarbon date of 11,930 ± 210 years B.P.

    Comments: Probably collected from Provo Formation.

21. MONROC Gravel Pit, Kearns; E½ SW¼ Section 13, T. 2 S., R. 2 W., Salt Lake County. Elevation: 4750'±.

    Nelson, M. E. and J. H. Madsen Jr., 1978.

    Musk Ox, *Symbos cavifrons* (UUVP 8535): this is a partial skull of a large, mature male.

    Comments: Several additional, partial skulls (UVP 011, UVP 012, UVP 013, UVP 016, Pr., and UVP 017) of S. cavifrons, *have recently been collected from the Provo Formation at this gravel pit. A Carbon 14 date run on collagen extracted from a left horn core has given a date of 11,690 ± 190 years B. P. Also, partial remains (femur, tibia, pelvis, several vertebrae) of a very large bear (UVP 015), which is similar to the genus Arctodus, and a horn core of* Ovis *(UVP 025) have been recovered (figure 6a, 6b).*

22. Sandy Mammoth Site; NE¼, SW¼, SE¼, Section 36 T. 2 S., R. 1 W., Salt Lake County. Elevation: 4360'±

    Madsen, D. B., D. R. Currey, and J. H. Madsen Jr., 1976.

    Mammoth, *Mammuthus* cf. *M. columbi* (UMNH VP0018): a large, partial skeleton recovered (figure 7a, 7b).

    Comments: Bone fragments were dated at 14,150 ± 800 B. P.

23. Sandy, Utah; NW¼, Section 6, T. 3 S., R. 1 E. Elevation: 4400'±

    Camel, *Camelops* cf. *hesternus* (UVP001): axis (figures 8a, 8b).

    Comments: Discovered by a boy digging a pit in his backyard.

24. Merrico Gravel Pit, Bluffdale, Utah: Section 20, T. 4 s., R. 1 W., Elevation: 4520'±.

    Horse, *Equus* sp. (UUVP 8521): miscellaneous vertebrae (figure 9).

    Buffalo, *Bison* sp. (UUVP 8520).

    Comments: specimens missing from University of Utah Collections.

25. Point-of-the-Mountain, south end of Salt Lake Valley; Section 23, T. 4 S., R. 1 W., 1 N., Utah County Elevation: unknown.

    Nelson, M. E. and J. H. Madsen Jr., 1978.

    Musk Oxen, *Symbos cavifrons* (DI 004): partial cranium.

    Comments: Probably collected from gravels of a spit in the Bonneville Formation.

26. Pleasant Grove vicinity in Utah County; however, the exact locality data is missing. Elevation: unknown.

    Stokes, W. L. and G. H. Hansen, 1937.

    Musk Oxen (?) *Bootherium bombifrons* (?): cranial fragment.

    Nelson, M. E. and J. H. Madsen Jr., 1978.

    Bootherium sp. indet.: evidence inconclusive for assignment to *B. bombifrons.*

    Comments: Original specimen missing from Brigham Young University collections; however, photographic evidence remains.

27. Orem in Utah County; exact locality data missing. Elevation: unknown.

Figure 6a. An artists sketch of the MONROC bear, *Arctodus*. (?)

Figure 6b. Photo comparing femur and thigh bone of the MONROC bear (top) *Arctodus* (?) with that of a young male American black bear. Scale is 15 centimeters.

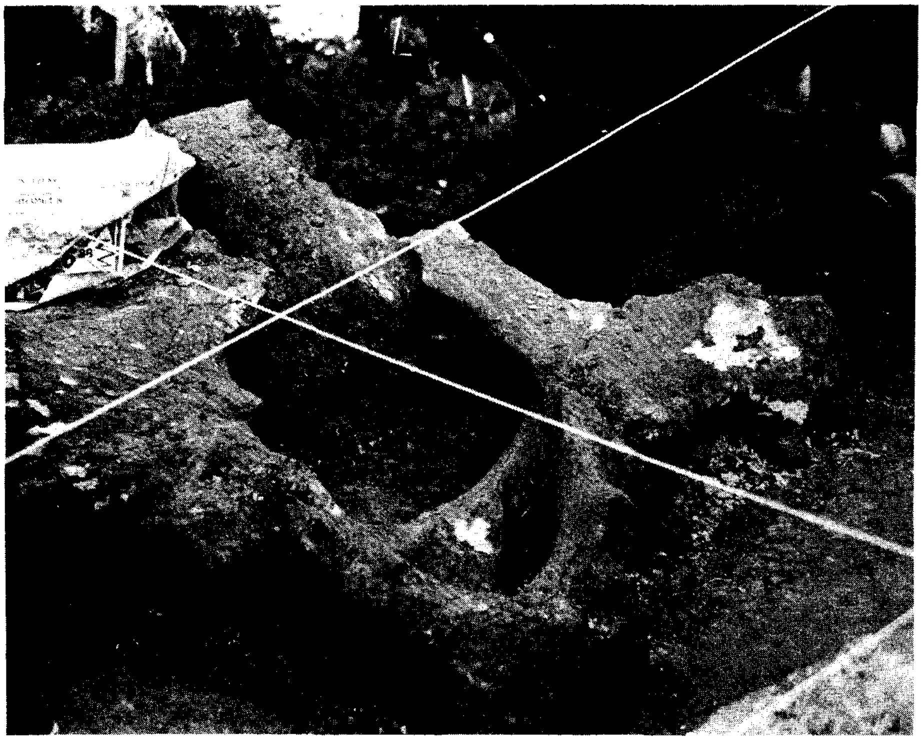


Figure 7a. Pelvic bones of mammoth found in Sandy, Utah (courtesy of Utah Museum of Natural History).

Figure 7b. Plaster cast being prepared prior to removal of Sandy mammoth pelvis (courtesy of Utah Museum of Natural History).

Figure 8a. The camel *Camelops hesternus,* a less common element of the Pleistocene Bonneville fauna after a sketch in the Los Angeles County Museum of Natural History.

Figure 8b. Camel axis, part of the first neck vertebrae, which support the skull. Found by Steve Dean of Sandy, Utah.

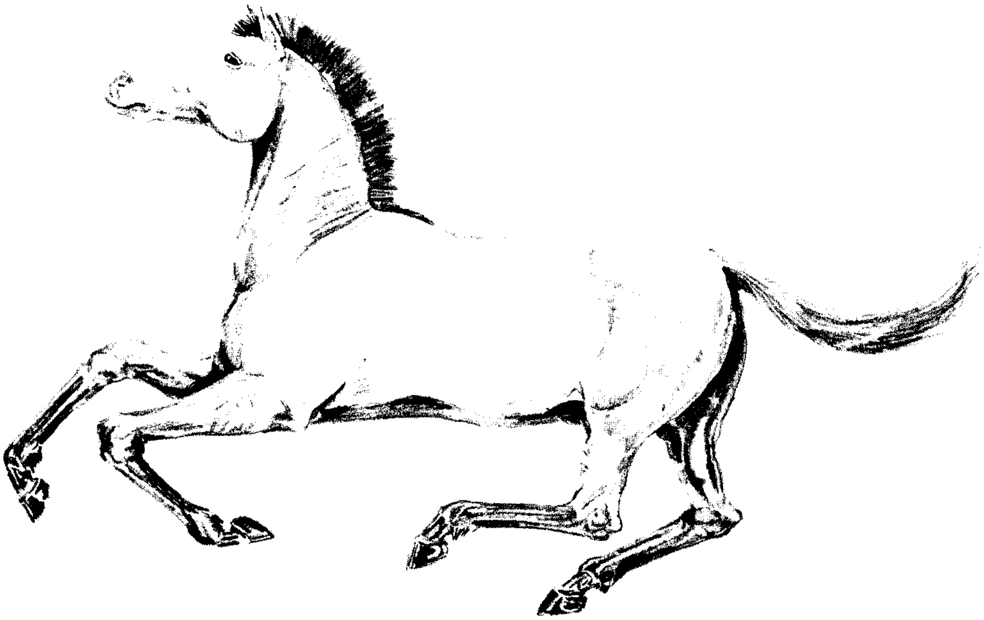


Figure 9. Horses are known from Bonneville sediments and their fossils are possibly one of the most recent records prior to this animal's extinction in North America.

Stokes, W. L. and G. H. Hansen, 1937.
Musk Oxen, *Symbos cavifrons:* reported an atlas, axis, and vertebrae collected.

Nelson, M. E. and J. H. Madsen Jr., 1978.
The material collected by Stokes and Hansen could not be located in the Brigham Young University Collections.

28. Miscellaneous localities
King, Clarence, 1878.
Buffalo, *Bison latifrons:* reported from "subaerial gravels" in Utah. Elevation: unknown.
Comments: Probably not B. latifrons *as the species is now known, but* B. antiquus. *The specimen has not been located.*

Pack, F. J., 1939.
Mammoth: north of Provo River bridge.
Comments: May be the Provo River bridge north of Provo, but exact locality and present location of specimen unknown. Specimen is probably Mammuthus columbi.

29. Utah Lake; SE¼, Section 12, T. 6 S., R. 1 W., Utah County. Elevation: unknown
Hunt, C. B., H. D. Varnes and H. E. Thomas, 1962.
Pocket Gopher, *Thomomys talpoides:* jaw found in silts of the Provo Formation west of Utah Lake.

30. Provo Utah; exact locality data missing. Elevation: unknown.
Nelson, M. E. and J. H. Madsen Jr., 1978.
Musk Oxen, *Symbos cavifrons* (BYUG-103): well preserved set of horn cores.

31. Slate Canyon; SW¼, Section 8, T. 7 S., R. 3 E., Utah County. Elevation: 4750'±
Stokes, W. L., and G. H. Hansen, 1937.
Musk Oxen, *Symbox cavifrons* (BYUG 834): partial cranium of "Bonneville age".
Musk Oxen, *Bootherium bombifrons:* partial cranium.

Nelson, M. E. and J. H. Jadsen Jr., 1978.
Musk Oxen, *Symbos cavifrons* (BYUG 834)
Musk Oxen (?) *Bootherium* sp. indet. (BYUG 102): the available evidence was not conclusive enough to assign this specimen to *B. bombifrons.*
Comments: Specimens probably collected from Provo Formation as mapped by Bissell (1963).

32. Springville, Utah; exact locality data missing. Elevation: unknown.
Nelson, M. E. and J. H. Madsen Jr., 1978.
Musk Oxen, *Symbos* cf, *cavifrons* (BYU 0884, BYUVP 0885): atlas and axis.
Comments: Probably collected from the NW¼, T. 8 S., R. 3 D., Utah County in the Provo Formation.

33. Spanish Fork; exact locality data missing but approximately two miles east of Spanish Fork in Utah County. Elevation: unknown.

Pack, F. J., 1939.
Mammoth, *Mammuthus* sp.: entire skeleton present in deltaic sediment of the Provo (?) Formation; however, only the teeth were recovered.
Comments: Probably Mammuthus columbi.

34. Payson Area; numerous reports, but no exact locality data. Elevations: unknown.
Pack, F. J., 1939.
Mammoth, *Mammuthus* sp.: leg bones from the southwestern part of the city of Payson.

Hansen, G. H., 1928.
Mammoth, *Mammuthus* sp.: several skeletal elements and two well-preserved tusks from the Provo Formation. Assigned to *Elephas primigenius* by Hansen (ibid.).

Bissell, H. J., 1963.
Mammoth, *Mammuthus* sp.: several bones reported as collected near Payson
Comments: Probably all specimens belong to Mammuthus columbi *(Figure 5a).*

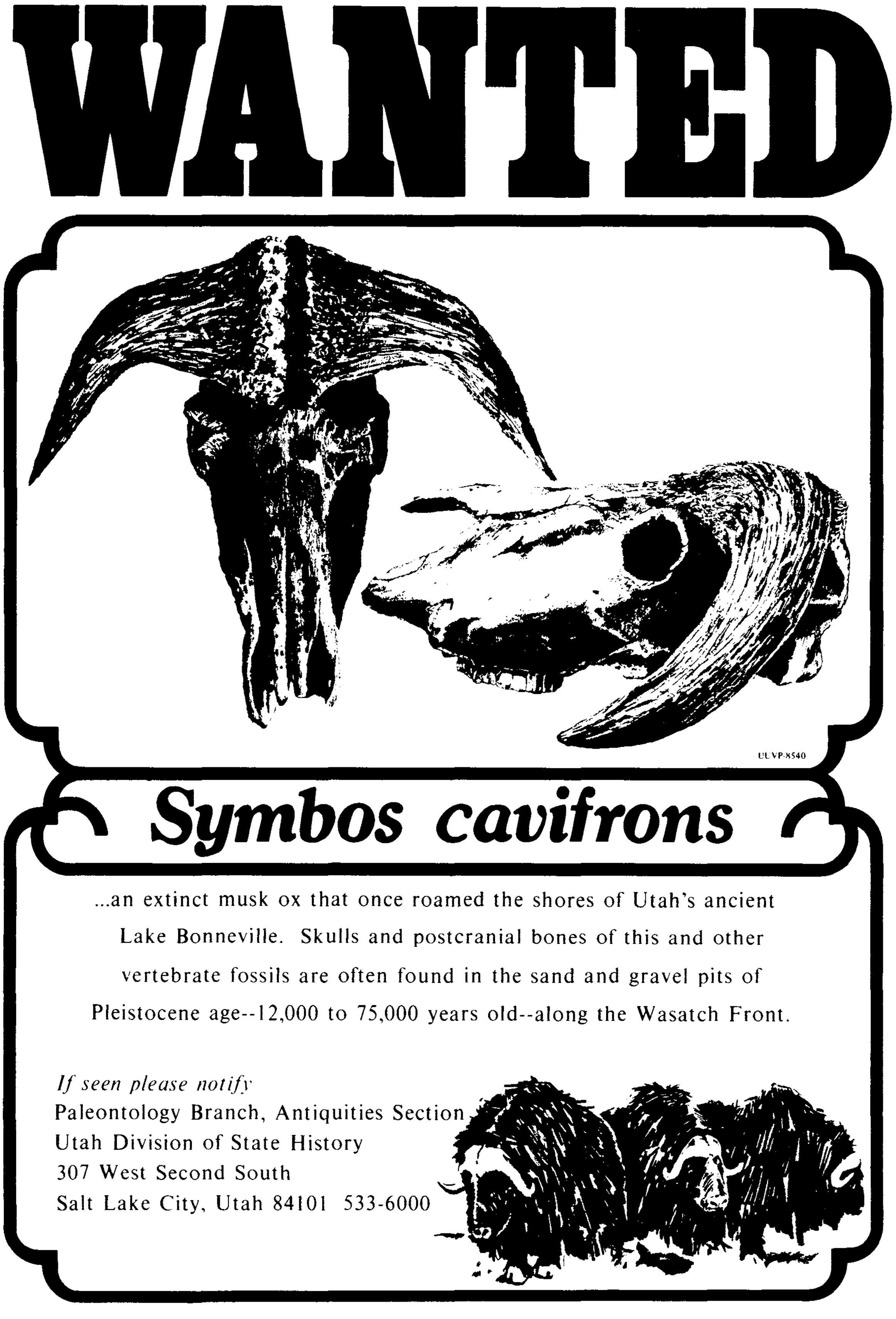
35. Johnson Gravel Pit; NW¼, Section 32, R. 1 E., T. 9 S., Utah County. Elevation: unknown.
Musk Ox, *Symbos cavifrons* (UVP010 Pr.): major part of cranium with left horn core.

36. Santaquin gravel pit, northeast of Santaquin in Utah County; however, the exact locality data is missing. Elevation: unknown.
Bissell, H. J., 1963.
Musk Oxen, *Symbos* sp. (USNM 17914). partial cranium.

Nelson, M. E. and J. H. Madsen Jr., 1978.
This specimen is now in the collections of the U. S. National Museum.

Abreviations

UMNH	Utah Museum of Natural History
UUVP	University of Utah. Vertebrate Paleontology
UVP	Division of State History, Vertebrate Paleontology
Pr	Privately owned specimen on record at the Paleontology Branch of the Antiquities Section, Division of State (Utah) History
e	Estimated



WANTED

UUVP-8540

Symbos cavifrons

...an extinct musk ox that once roamed the shores of Utah's ancient Lake Bonneville. Skulls and postcranial bones of this and other vertebrate fossils are often found in the sand and gravel pits of Pleistocene age--12,000 to 75,000 years old--along the Wasatch Front.

If seen please notify
Paleontology Branch, Antiquities Section
Utah Division of State History
307 West Second South
Salt Lake City, Utah 84101 533-6000

Figure 10. "WANTED" poster circulated to educate the pubic and encourage support of preservation of Paleontological resources.

Abreviations

USU . . . . .Utah State University, Geology Department
BYUG,
BYUVP, DI . . . .Brigham Young University, Vertebrate Paleontology Collection
USNM. . . . . . . .United States National Museum

SUMMARY: Although fossil remains of mammals from Lake Bonneville sediments are somewhat common, the fauna is not very diverse. At this writing, only musk oxen (*Symbos* and *Bootherium),* bighorn sheep (*Ovis),* a horse (*Equus),* the mammoth *(Mammuthus),* buffalo *(Bison),* a camel *(Camelops),* a bears *Arctodus),* a pocket gopher *(Thomomys),* and a small rodent have been collected. In the future, excavation monitoring at gravel pits in the Bonneville Basin, careful collecting, and education of the public at large (figure 9) will undoubtedly produce many more specimens of importance to the interpretation of an endemic fauna now largely extinct in North America.

What was the climate like? Had man the big game hunter arrived in Utah? These are questions often asked, and hopefully the information in this discussion will help in the search for the ultimate answers.

The too frequent reference to lost or stolen specimens is as frustrating to us as it must be to the reader, but we feel it is necessary to accurately document the present, known availability of all materials useful for future study at the time of this writing.

ACKNOWLEDGEMENTS

We would like to express our appreciation to Dr. Wade E. Miller, Department of Zoology, Brigham Young University; and Mr. Donald Hague, Director, of the Utah Museum of Natural History at the University of Utah, for permission to examine specimens in their care. We also profited greatly from many conversations with Dr. David Madsen, State Archaeologist, Utah State Historical Society. Dr. Robert Stuckenrath, Radiation Biology Laboratory of the Smithsonian Institution provided the radiocarbon dates. Sketches were prepared by staff artists, Greg McLaughlin and Sandy Stewart, of the Utah Geological and Mineral Survey.

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CURRENT HYDROCARBON EXPLORATION ACTIVITY IN THE GREAT SALT LAKE

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INTRODUCTION

The Great Salt Lake Basin is one of the largest and possibly one of the oldest Tertiary basins in the Basin and Range Province. Oil and gas shows in the area of the Great Salt Lake indicate that the basin is prospective for hydrocarbons. However, until recently the basin has gone untested due to the logistical problems related to drilling and seismic data acquisition.

Amoco Production Company has long been interested in the lake but it was not until 1973 that Amoco was able to acquire approximately 610,000 acres of Utah State oil and gas leases under the Great Salt Lake. Presently Amoco is carrying out an active exploration program consisting of offshore drilling and the acquisition of seismic data. This paper will review Amoco's current exploration activity in the lake and will attempt to summarize the geologic thinking that has led to this activity.

PREVIOUS EXPLORATION INTEREST IN THE GREAT SALT LAKE AREA

Occurrences of hydrocarbons have been known in the Great Salt Lake area (figure 1) for some time. In the latter half of the nineteenth century, vague and undocumented reports were made of hydrocarbons in the area between the Great Salt Lake and the Wasatch Front. The only known reliable documentation of such hydrocarbons during this period is found in the work of Stansbury (1852) who described small quantities of bitumen along the northeastern shore of the lake.

Just after the turn of the century, minor gas production in the Ogden-Salt Lake City Trough and reports of asphaltum seeps on the northeast shore of the lake stimulated interest in the hydrocarbon potential of the area. This interest resulted in the publication of several short articles between 1904 and 1905 discussing the asphaltic occurrences in the Great Salt Lake (Maguire, 1904, 1905; Gibbs 1905).

More comprehensive studies by Richardson (1905) and Boutwell (1905) were also published by the U. S. Geological Survey. Subsequent publications by Schneider (1921), Eardley and Haas (1936), Hansen and others (1949) and Heylmun (1963) have continued to maintain interest in the hydrocarbon potential of the area.

Throughout the 1900's, exploratory interest in the Great Salt Lake was indirectly maintained through the drilling of numerous wildcats in surrounding basins. The Great Salt Lake Basin proper, however, has received only limited shallow drilling at the basin edge, and the deeper, more prospective reaches of the basin have yet to be tested.

AMOCO PRODUCTION COMPANY'S EXPLORATION ACTIVITIES IN THE GREAT SALT LAKE

Amoco Production Company finds the Great Salt Lake Basin attractive in that it is a large, untested, Tertiary basin with an asphalt seep located at the basin margin. Although encouragement for exploration in the Pre-Tertiary rocks can be found in the Great Salt Lake Area, Amoco's exploration emphasis to date has been directed towards the Tertiary sedimentary section. An excellent discussion of the geology of the basin is presented in this volume by William Lee Stokes. However, a brief discussion of the Tertiary geologic history of the region surrounding the Great Salt Lake is germane to the understanding of Amoco's activity in the lake.

Tertiary Geologic History and Production Potential

In latest Cretaceous time the Sevier Orogeny was ending and the Laramide Orogeny beginning (Armstrong, 1968), resulting in the destructional phase of the Rocky Mountain Geosyncline. This initiated a period of intermittent fluvial and lacustrine deposition that has existed to the present. Evidence of lacustrine deposition during the Tertiary provides the most encouragement for exploration in the lake, and the following discussion will deal exclusively with the possibility that significant sequences of Tertiary lacustrine deposits exist within the basin. For the purpose of this paper the lacustrine deposits of the Tertiary will be subdivided into two groups; the first group extends in

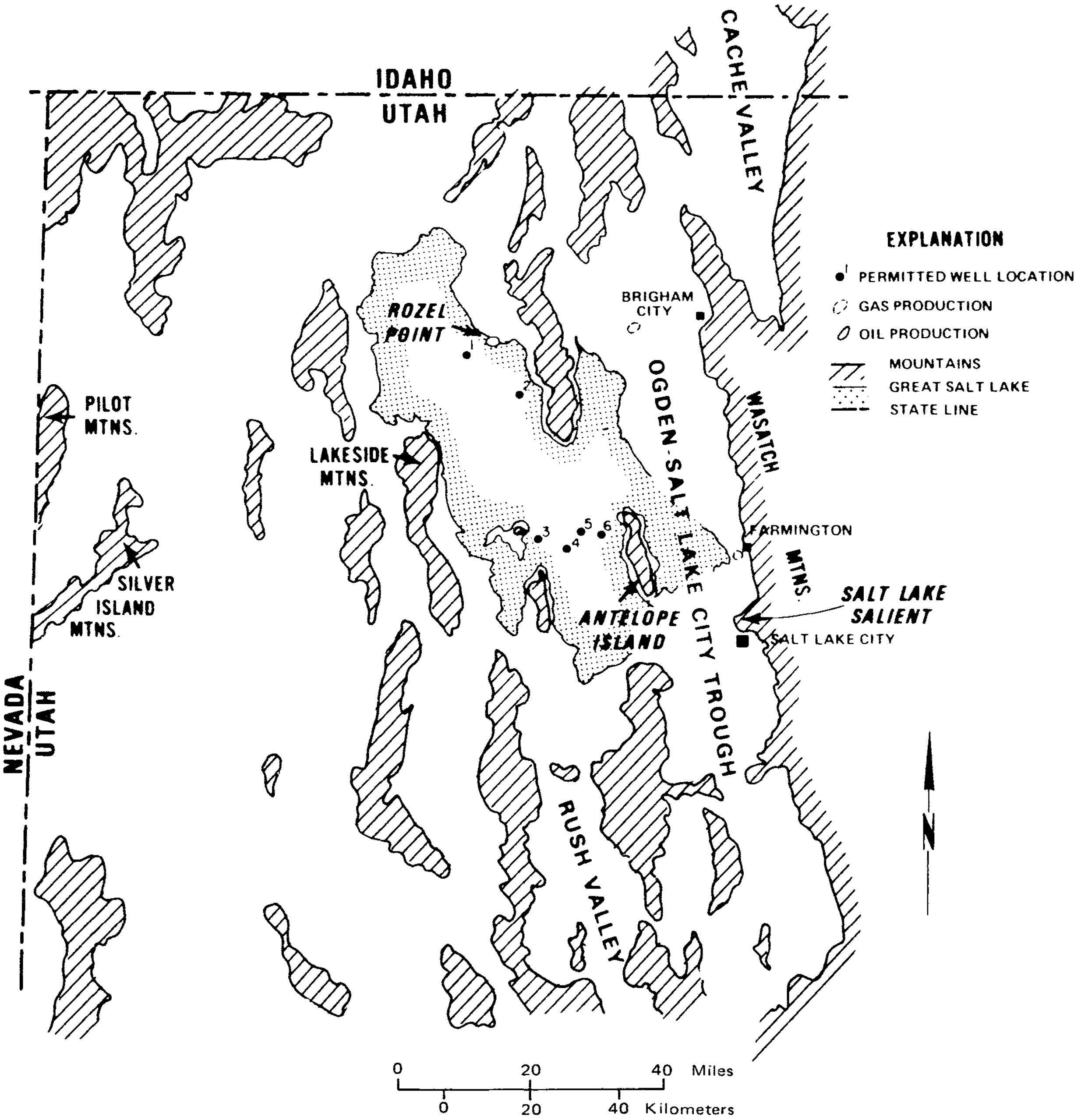

Figure 1. Index map of the Great Salt Lake area.

age from latest Cretaceous to Late Eocene and possibly into earliest Oligocene, while the second group of lacustrine deposits was initiated in the Miocene and continues to the present. The division is centered around the Oligocene, a time of radical climate change and volcanism. Lacustrine deposition during this epoch likely occurred only in the deepest and most well developed of basins.

The areal distribution of early Tertiary lacustrine units is shown in figure 2. Extensive lakes were developed in eastern Utah, southern Wyoming and northwestern Colorado, while less well developed lakes existed intermittently in eastern and central Nevada. Some of these lakes had dimensions of several hundred kilometers and depths of up to 30 meters (Ryder and others 1976).

The distribution of the late Tertiary lacustrine units is shown in figure 3. These units are more intimately associated with the area of Basin and Range

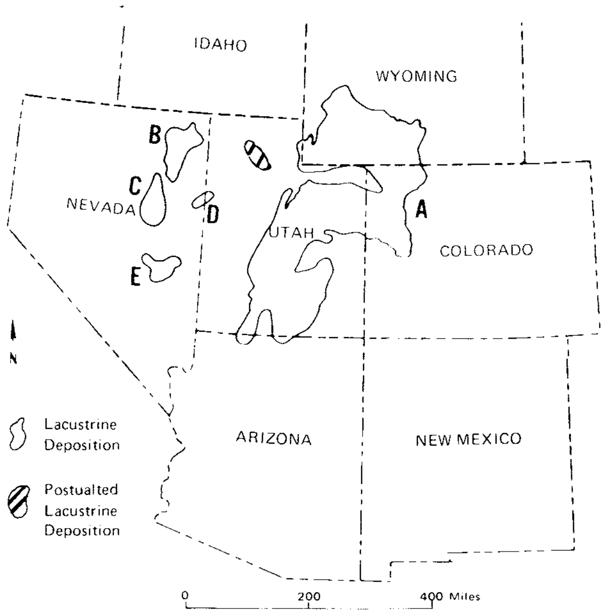

Figure 2. Early Tertiary lacustrine deposition in the area surrounding the Great Salt Lake. A. - Uinta, Piceance, Washakie and Green River basins lake complex. B. - Humbolt Lake. C. - Newark Canyon Lake. D. - White Sage Lake. E. - Sheep Pass Lake (after McDonald, 1976, Robinson, 1972, and Winfrey, 1960).

development and the geometry of these lacustrine deposits commonly coincides with areas of graben development. The lakes are generally long and narrow and are bounded by steep-sided horst blocks.

Fouch (1975), and Ryder and others (1976) discuss a model for facies development in the Uinta Basin and its relationship to hydrocarbon production. In this model, the development of those facies that are prospective for hydrocarbon exploration in lacustrine deposits appears to be intimately associated with changes in climate and the degree of tectonic activity. Periods of intense tectonic activity and an arid, cool climate resulted in the extensive development of the nonprospective alluvial facies, whereas periods of no or mild tectonic deformation and hot humid climates likely resulted in the maximum development of open-lacustrine and marginal-lacustrine facies which are more prospective for hydrocarbon exploration.

Lacustrine rocks that were deposited during both the early and later Tertiary were associated with orogenies of significant magnitude: the Laramide and the Basin and Range orogenies. Although differences in the styles of the two orogenies effect facies development (e. g. the long and narrow basins bounded by steep-sided horsts developed during the Basin and Range Orogeny would hinder the development of extensive open-lacustrine facies), we feel that the most significant difference that existed between these periods of lacustrine deposition was one of climate. Figure 4 shows that the Paleocene through earliest Oligocene was characterized by warm-temperate to sub-tropical climates whereas the Miocene and Pliocene Epochs were dominated by warm-temperate and cool-temperate climates. It is suggested from this that the source and reservoir facies produced in a lucustrine environment are likely to have been extensively developed in the early, rather than late, Tertiary lacustrine sequences.

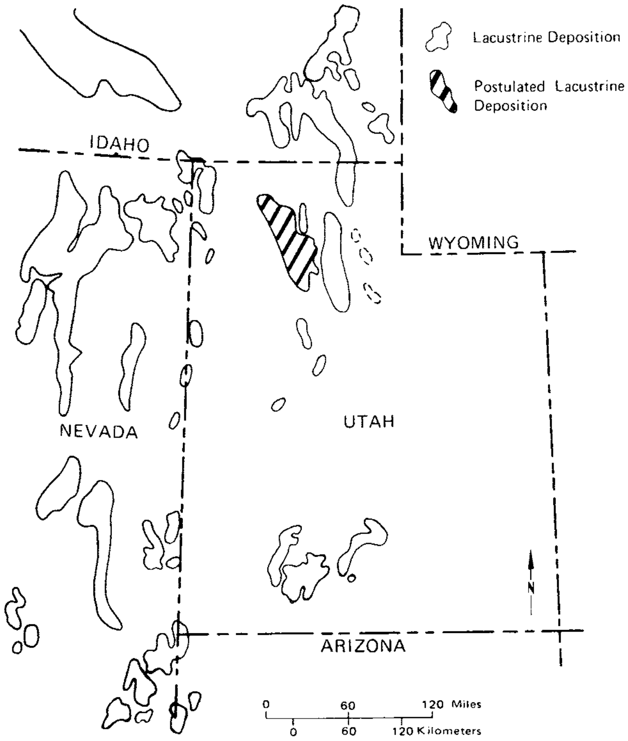

Figure 3. Late Tertiary lacustrine deposition in the area surrounding the Great Salt Lake (after Feth, 1964, and McDonald, 1976).

Field and production data (though meager in the Basin and Range Province) tend to support this assertion. Production in the Uinta, Piceance, Washakie and Green River Basins (figure 2) is well documented, and adequate exposures of both reservoir and source facies are abundant on the surface in these areas. Production occurs from the Late Cretaceous - early Tertiary, Sheep Pass Formation in Railroad Valley, Nevada (figure 2), Fouch, 1977; Winfrey, 1960) and although reservoir rocks are documented on the surface, the presence of source facies is more difficult to establish. However, Fouch (1977) has located source rocks in the subsurface capable of generating four gallons of oil/ton. The Humboldt Formation oil shales of northeastern Nevada

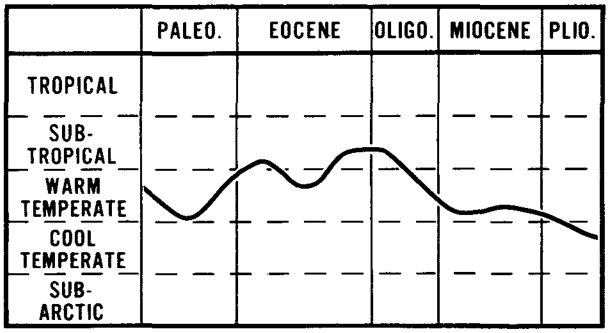

Figure 4. Cenozoic climate variations for the Western United States (Flint, 1971).

(figure 2) also have a history of limited production. Winchester (1923) reports efforts by the railroad to use the oil shales for fuel in the late 1800's, and the efforts R. M. Catlin in 1909-16 to retort oil from the shales. Retorts of up to 86.8 gallons of oil/ton are reported by Winchester (1923). The operation was eventually shut down due to excessive overburden. Some of the other early Tertiary lacustrine deposits of central and eastern Nevada show encouraging geology for hydrocarbon exploration; however, they have not yet produced.

Significant production is yet to be found in the late Tertiary sediments in the region surrounding the Great Salt Lake. While late Tertiary reservoir rocks of marginal-lacustrine facies are abundant, areal mapping of these reservoirs is hampered by the poor quality of outcrops. Source facies comparable to those of the early Tertiary appear to be essentially absent, although this absence may also be related to inadequate exposures.

Postulation of Early and Late Tertiary Lacustrine Sequences Within The Great Salt Lake Basin

It is apparent that it would be desirable, though not necessarily essential, to have an early Tertiary lacustrine deposit within a prospective Tertiary basin. We would like to postulate the presence of significant sequences of both early and late Tertiary lacustrine deposits within the Great Salt Lake Basin. This hypothesis is based on surface geological and geophysical data.

Early Tertiary

Although fragmented and restricted, surface evidence suggesting the presence of early Tertiary lacustrine deposits in the Great Salt Lake is cited by several authors. McDonald (1976) suggests that: "extensive lake formation may have commenced immediately west of the Wasatch Front by Late Eocene time." He has based this statement on the presence of a Paleocene-Eocene snail collection (see also Heylmun, 1965) from a lacustrine limestone in the Salt Lake Salient north of Salt Lake City. However, McDonald restricts this deposit to the Eocene due to the presence of volcanics in the section. Mann (1974) obtained K/Ar age dates on volcanics found in the Salt Lake Salient which overlie dense, light-gray limestones. The ages of 55.7 (±2.0) million years and 50.9 (±2.0) million years indicate that local lacustrine deposition might have existed as early as Early to Middle Eocene. Larsen (1957) has assigned a Paleocene to Eocene age to a limestone unit overlying colluvial conglomerates on the east side of Antelope Island. The age assignment of these rocks is based on a lithologic correlation with the Wasatch Formation to the east. Although these deposits are not extensive, they do suggest that conditions for a lacustrine environment may have been present in the area of the Great Salt Lake in early Tertiary time. If a basin of large enough size developed during this time, then significant sequences of early Tertiary lacustrine rocks could be present.

Further evidence for early Tertiary deposition within the Great Salt Lake Basin can be extracted from geophysical evidence, although the lacustrine nature of this deposition has to be inferred from the proximity of the above mentioned outcrops on Antelope Island and the Salt Lake Salient. Seismic data were acquired in the Great Salt Lake Basin in 1973-74. Eight hundred and fifty miles of data were recorded from a barge (figure 5) using an airgun source, resulting in a 5 x 2 mile grid covering the lake. Encouragement to carry out this survey was stimulated by a similar though somewhat more shallow survey undertaken jointly by the Utah Geological and Mineralogical Survey, the University of Utah and the University of Wisconsin-Milwaukee in 1968 (Mikulich and Smith, 1974). The results of the Amoco survey are very good and indicate that a Tertiary section in excess of 15,000 feet thick may be developed within the basin.

We have difficulty in attributing a 15,000 foot sediment thickness solely to late Tertiary deposition that would have developed in a typical Basin and Range graben that began forming only 17 million years ago. Measured surface data in two of the thicker late Tertiary sections in the eastern Basin and Range grabens suggest that late Tertiary sediment thicknesses are generally less than 10,000 feet. Heylmun (1965) describes a Salt Lake Group (late Tertiary) sedimentary section in Rush

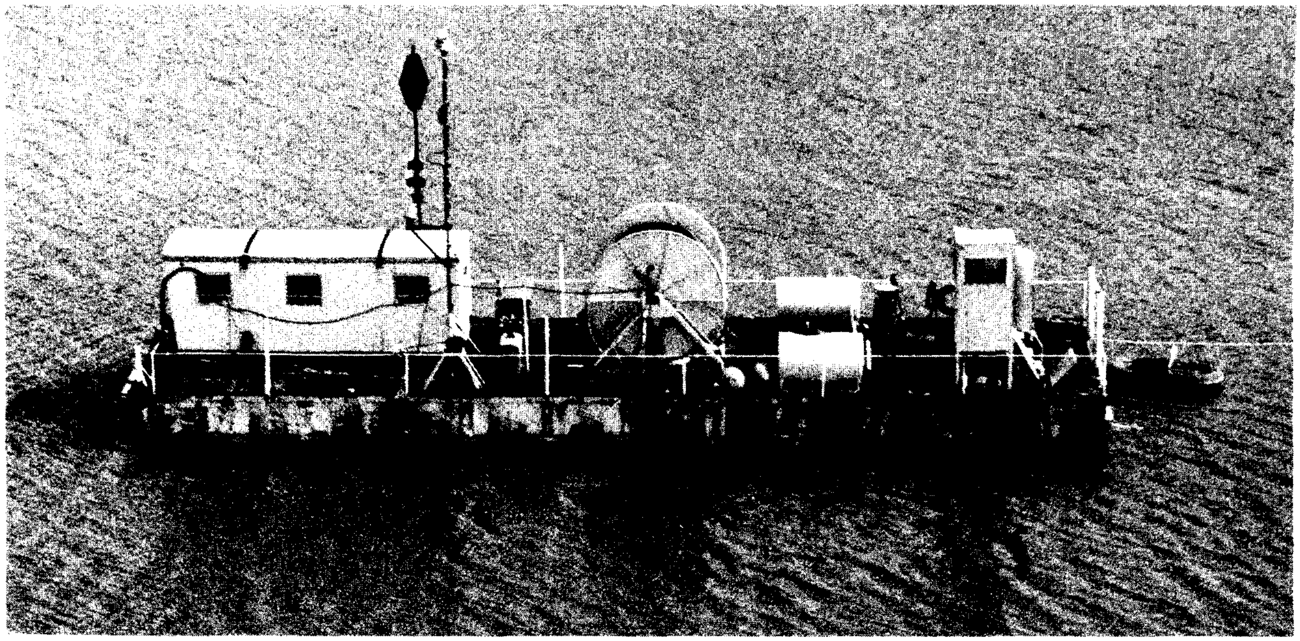

Figure 5. Geophysical barge used in the acquisition of seismic data on the Great Salt Lake in 1973-1974.

Valley in excess of 8,000 feet. This probably does not represent the true thickness for this section as it may be partially duplicated by faulting. Adamson and others (1955) describe a Salt Lake Group section in the Idaho portion of Cache Valley. This complete section of the Salt Lake Group is slightly less than 9,000 feet thick. Assuming that sedimentation rates in the late Tertiary of the Great Salt Lake basin were not markedly different from those of Cache and Rush Valleys, we can account for no more than 10,000 feet of Tertiary fill in the Great Salt Lake Basin from Salt Lake Group sedimentation. Interpreting the remaining 5,000 feet of the 15,000 foot section in the basin as early Tertiary is not inconsistent with other early Tertiary sediment thicknesses in the area, as seen from the isopach map constructed in figure 6.

The presence of early Tertiary sediments within the Great Salt Lake Basin also dictates the necessity of an early Tertiary structural basin. McDonald (1976) has suggested that north-south trending folds that developed during latest Cretaceous time may have been the site of basinal development during the early Tertiary in the Great Salt Lake area. Synclines were down-dropped relative to areas of anticlinal development as compressional stresses of the Sevier Orogeny waned. Examination of the literature reveals that there is field evidence that normal fault movements of late Mesozoic and early Tertiary age were taking place in northwestern Utah (Loring 1976). Eardley (1963a) reports Eocene age Basin and Range faults in western Utah and further suggests that these faults remained active into the Pliocene and Early Pleistocene. Schaffer (1960, 1962), based on his work in the Silver Island Mountains in northwestern Utah, considers it likely that Basin and Range topography (similar to that of today) may have existed in early Tertiary. O'Neill (1969) has documented possible early Cenozoic high-angle faults with up to 7,700 feet of displacement in the Pilot Mountains. Doelling (1964) has found Paleocene age normal faults immediately adjacent to the Great Salt Lake in the northern Lakeside Mountains.

Late Tertiary

Late Tertiary lacustrine deposition is very likely to have occurred within the Great Salt Lake Basin. The occurrence of marginal lacustrine facies at the northeastern margin of the basin (Slentz and Eardley, 1956) strongly suggests that an open lacustrine environment is to be expected toward the center of the basin. Lacustrine deposition in the Great Salt Lake Basin during the later Tertiary may have been enhanced by the presence of the Ogden-Salt Lake City Trough. This structural trough was probably well enough developed to act as a "catch basin" in Miocene to Early Pliocene time for the large volumes of clastics derived from the Wasatch Mountains.

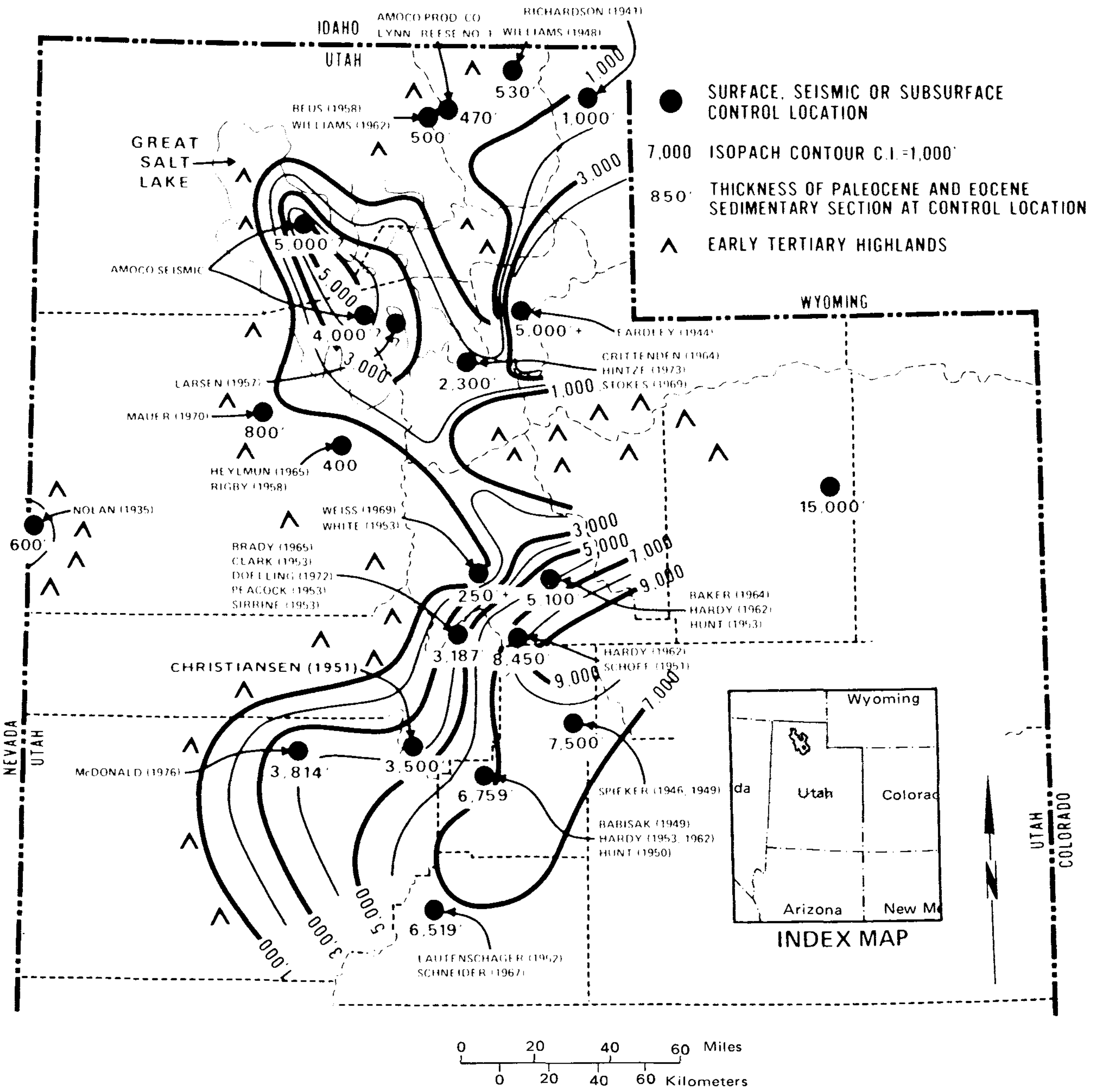

Figure 6. Isopach map of early Tertiary sedimentary deposits, Northwestern Utah. Names adjacent to control locations correspond to the references cited for that location.

Hydrocarbon Occurrences in the Great Salt Lake Area

The presence of a thick Tertiary section possibly containing sequences of lacustrine rocks is encouraging for hydrocarbon exploration in light of production from similar Tertiary lacustrine deposits in Nevada. Shows of oil and gas immediately adjacent to the Great Salt Lake Basin lend further encouragement to exploration efforts.

Numerous shows of gas occur throughout the area in the Tertiary formations. Seeps of flammable gas have been known for some time in the Great Salt Lake area and are documented and described by Richardson (1905). It is not uncommon to encounter gas in drilling shallow water wells, and there have been instances where water wells have blown out because of this gas (e. g. Ritzma, 1975; McDonald, 1976). Much of the shallow gas can probably be attributed to bacterial activity; however, gas shows reported in deeper tests are more likely of thermal origin. There has been limited gas production from two small fields in the Ogden-Salt Lake City Trough. The Farmington field produced, just before the turn of the century, from sands between 400 and 700 feet deep. The field was abandoned in 1896 after a cumulative production of 150 MMCF (million cubic feet) (Richardson, 1905). Since the 1920's intermittent production of small quantities of gas has been produced from several shallow wells in the area surrounding section 35, T. 9 N., R. 4 W., west of Brigham City (Eardley and Haas 1936; McDonald, 1976). The cummulative production from this area is unknown and is likely very small.

There have been several oil shows adjacent to the Great Salt Lake Basin. Western Petroleum's Nebeker No. 1 (section 21, T. 1 N., R. 1 W.) has been reported by Heylmum (1963) to have encountered asphaltic sands and gas at around 700 feet. The shows and asphalt seeps located at Rozel Point on the northeastern edge of the lake are extremely encouraging for Amoco's exploration effort in the lake. Early discussions and descriptions of the seeps may be found in Maguire (1904, 1905), Gibbs (1905) and Boutwell (1905). The Rozel Point oil field was drilled in association with these seeps. Intermittent production since the discovery of the seeps has resulted in a cummulative production of 2,896 barrels of oil (Stowe, 1970). Production rates of 5 to 10 barrels of oil per day are cited by Eardley (1963b).

The origin of the Rozel Point oil is yet uncertain. The characteristics of the oil are as follows:

Dark brown
Specific gravity of 1.06
A. P. I. gravity of 9.0°-9.4°
Softening point of 73°F
Non-combustible

The composition of the oil is:

32% non-oxygenated resins
50% asphaltenes
13.7% sulfur
4% isoparaffins

The character and composition of the oil, and the fact that it is recovered from depths of less than 300 feet strongly suggest that bacterial alteration has taken place. Because of this, the results of Amoco's attempts to correlate this oil with other oils in the region are indeterminate. The age of the oil, however, is suggested to be Tertiary (Hunt, 1978) and Amoco optical data on the oil tend to support this assertion.

Assuming a Tertiary age for the oil, a likely location for generation is in the Great Salt Lake Basin. We feel that generation has taken place within the basin with migration to the basin edge resulting in the seeps at Rozel Point. Hopefully drilling in the lake will encounter accumulations at sufficient depth to escape the effects of bacterial alteration.

The presence of high bottom-hole temperatures and hot springs in the area (Heylmun, 1966) suggests a high geothermal gradient, which would aid in generation from Tertiary source rocks.

Basin Configuration

Seismic data indicate that the Great Salt Lake Basin is large enough to generate significant volumes of hydrocarbons from the Tertiary. The basin is 70 miles long, 20 miles wide and in excess of 15,000 feet deep. The axis of the basin in the subsurface trends NNW following the present-day trend of the Great Salt Lake very closely. The basin may be subdivided into two subbasins composed of an asymmetric southern sub-basin and a more symmetric northern sub-basin. Good trap potential in the form of structures and wedges can be demonstrated on seismic profiles in both sub-basins.

DRILLING PROGRAM

Amoco has been mobilizing for the drilling operations on the lake since November of 1977. At the time of this writing, the first well of a proposed six well program is being drilled. The rig has been erected on a mobile, floating platform 180 feet long by 90 feet wide. This configuration allows for minimal time and expense in changing locations.

The first test (Indian Cove State Unit number 1, figure 7) is the evaluation of the Tertiary section on a structural anomaly on the North arm of the lake (location number 2, figure 1). The well will penetrate the basement (Lower Paleozoic? or Pre-Cambrian?) at a depth below 10,500 feet. We are anticipating generation and expulsion of hydrocarbons from open-lacustrine, organic-rich facies and marginal lacustrine "boghead" coals, resulting in migration into Tertiary marginal-lacustrine clastic and carbonate reservoirs. Because of the location and the depth of this first well, it is questionable as to whether or not the postulated sequence of early Tertiary rocks will be encountered. It is hoped that future tests of both the structural and

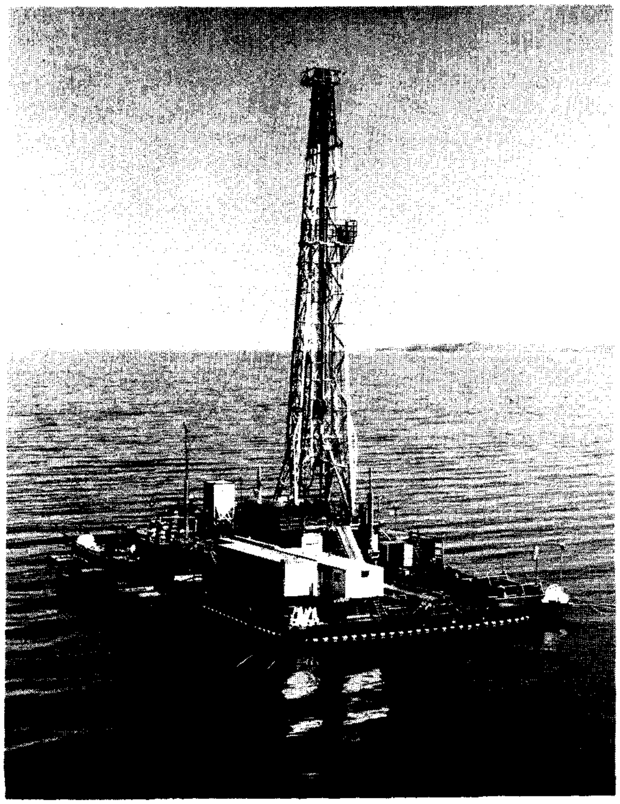

Figure 7. Amoco Production Company's Indian Cove, State Unit No. 1, drilling six miles off-shore in the Great Salt Lake.

wedge anomalies of the remaining wells of the drilling program will penetrate rocks of this age.

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BOTTOM GRAVITY METER REGIONAL SURVEY OF THE GREAT SALT LAKE, UTAH

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ABSTRACT

A bottom gravity meter regional survey of the Great Salt Lake (64 stations during 1968) resulted in the compilation of a simple Bouguer gravity anomaly map (with 5-mgal contour interval) and interpretive geologic cross sections along four east-west gravity profiles across the lake that provided information concerning the geologic structures beneath the lake. The large gravity low, that extends for a distance of about 70 miles, essentially the entire length of the lake, indicates a large north-northwestward trending graben beneath the lake, herein designated the Great Salt Lake graben. The closely spaced gravity contours, with steep gravity gradients, indicate that the graben is bounded on each side by large Basin and Range fault zones. On the northwestern side is the East Lakeside Mountains fault zone; on the southwestern side is the East Carrington-Stansbury Islands fault zone; and on the east side is the East Great Salt Lake fault zone. All fault names are newly designated. The large gravity low centers that lie north and south of the gravity saddle that extends between Bird (Hat) Island and the Promontory Point-Fremont Island area, indicate that at least two Cenozoic structural basins of deposition probably formed within the great graben between the Dolphin Island-Rozel Hills area and the Tooele Valley graben. The two basins are designated the "northern Cenozoic basin" and "southern Cenozoic basin" to the north and south, respectively, of the gravity saddle.

The geologic cross sections along the gravity profiles, based on a density contrast of 0.5 gm/cc between the bedrock and valley fill, indicate that the maximum thickness of the Cenozoic structural basins (valley fill) is more than 7,100 feet and 9,700 feet in the northern and southern Cenozoic basins, respectively. An assumed larger or smaller density contrast would result in correspondingly smaller or larger thicknesses, respectively.

The new gravity data over the Great Salt Lake, used in conjunction with the previous gravity data over the adjoining mainland (Cook and others, 1966), afforded an interpretation of the continuity and interrelationships of the geologic structures. For example, the Great Salt Lake graben is continuous with the Tooele Valley graben. Also, an arm of the northern Cenozoic basin within the Great Salt Lake graben probably extends southward, with some constriction, between the Lakeside Mountains and Carrington Island, to connect with the Cenozoic structural basin within the Lakeside-Stansbury graben.

INTRODUCTION

During July and August 1968 a regional gravity survey of the entire Great Salt Lake, Utah was made by the U. S. Defense Mapping Agency, Topographic Center (formerly designated U. S. Army Map Service) in cooperation with the Utah Geological and Mineral Survey (formerly designated Utah Geological and Mineralogical Survey). Figure 1 shows an index map of the survey area.

Sixty-four new gravity stations were taken at the bottom of the Great Salt Lake, (plate 2, in pocket) using a bottom gravity meter. The new gravity data were combined with the gravity data on land peripheral to the Great Salt Lake and along the Southern Pacific Railroad causeway across the lake that was previously published by Cook and others (1966).

The combined gravity data were used in compiling 1) a simple Bouguer gravity anomaly map of the Great Salt Lake and vicinity (plate 2) and 2) four interpretive geologic cross sections indicating the general geologic structures under and adjacent to the Great Salt Lake. A knowledge of the geologic structures will be helpful not only in deciphering the tectonic patterns and geologic

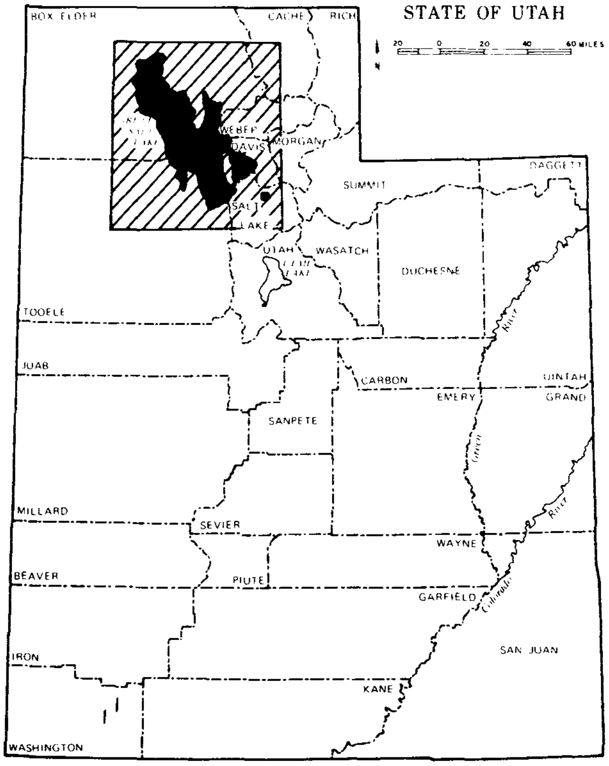

Figure 1. Index map of Utah, showing survey area.

history of the region, but also in the evaluation of the potential for natural resources. For example, the existence of deep Cenozoic (including Quaternary and Tertiary) basins beneath the Great Salt Lake makes the area favorable for the exploration of petroleum and/or natural gas.

TECHNIQUES AND BACKGROUND DATA

Using a LaCoste and Romberg bottom gravity meter, readings at 64 stations were taken along east-west profiles spaced approximately 5 miles apart. The stations were at 2- and 5-mile intervals on alternate traverses. Plate 2 shows the station coverage over the Great Salt Lake and surrounding areas. In the extreme northern part of the lake, the gravity coverage was less detailed than in other parts of the lake because of the difficulty in taking gravity readings in the shallow water. In this area, the wave action on the surface of the lake caused motion of the water at the bottom and hence instability (i.e., accelerations) of the bottom gravity meter that prevented the taking of accurate measurements. To await periods of perfectly calm surface water conditions for satisfactory gravity measurements would have prolonged the survey unduly.

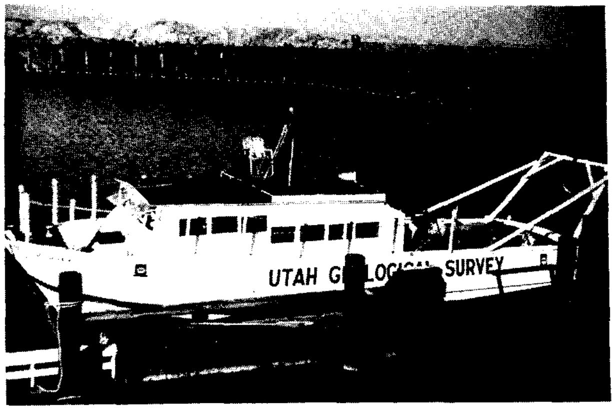

Figure 2. The boat *G. K. Gilbert* at dock in Little Valley Harbor, Great Salt Lake. Tellurometer on tripod on top of cabin. Bottom gravity meter and power winch inside boat at stern. Note cable to pulley on wooden yoke over stern of boat. Photograph taken by K. L. Cook on August 4, 1968.

The *G. K. Gilbert*, a boat owned by the Utah Geological and Mineral Survey, was used for the survey (figure 2). The boat, which was 42 feet long, 13 feet wide and 6 tons in weight, was propelled by two water-jet-type propulsion engines and had a draft of 1½ feet. The gravity meter was lowered over the stern of the boat on a cable that passed through a pulley to a power winch (figure 3).

Horizontal control was obtained to an accuracy of generally a few meters with a Tellurometer (Model MRA3). The master was mounted on top of the cabin of the boat (figure 2) and the two slave stations were either on the mainland or on the islands of the lake. Vertical control was obtained to an accuracy of half a foot with a lead line dropped over the side of the boat.

Two principal base stations on land were used for the survey (plate 2): (1) for the survey of the southern part of the lake, the station was on the breakwater forming the County Boat Harbor at Silver Sands Beach and (2) for the survey of the northern part of the lake, the station was adjacent to the wharf at Little Valley Harbor (northwest of Promontory Point). Using LaCoste and Romberg land gravity meter No. 123, these base stations were tied to the Salt Lake City K base station (at the Salt Lake City airport), which is a United States National Gravity Base Net station (Cook and others, 1971). A description of the location of each of these base stations is given in Appendix 1.

Figure 3. LaCoste and Romberg bottom gravity meter being lifted over side of boat before lowering by cable and power winch into Great Salt Lake. Note metal flanges on tripod legs of instrument housing to facilitate stability in muddy bottom of lake. Photograph taken by K. L. Cook on August 4, 1968.

The gravity data were reduced during 1968 by the Gravity Division of the U. S. Army Map Service in Washington, D.C. to give simple Bouguer gravity anomaly values. In making the Bouguer corrections, an average density of 1.22 gm/cc was used for the salt water of the lake, and a density of 2.67 gm/cc was used from the bottom of the lake to mean sea level. Listings of the elevations of the Great Salt Lake during the gravity survey, the density of the salt waters of the Great Salt Lake during the summer of 1968, and the principal facts of the bottom gravity stations are given in Appendices 2, 3, and 4, respectively.

The simple Bouguer gravity anomaly values for the bottom gravity stations were contoured on a map using a 5-milligal (mgal) contour interval. This map was then fitted to the corresponding gravity map values of Cook and others (1966) along the shores of the lake and the causeway across the lake. The resulting simple Bouguer gravity anomaly map, at a 5-mgal contour interval, is shown in plate 2. Four profiles (A-A′ through D-D′, plate 2) were selected for the construction of the interpretive geologic cross sections, which were computed using the two-dimensional modeling technique of Talwani and others (1959).

The resulting interpretive geologic cross sections, in conjunction with the characteristics and patterns on the gravity map and the mapped surface geology, were used to delineate the major geologic structures of the region. The results of the gravity studies were also compared with the results of the available seismic data to provide as reasonable a geologic interpretation as possible.

GEOLOGY

The Great Salt Lake lies along the active rift system in the eastern part of the Basin and Range province (Cook, 1969). The region is characterized by north-south trending mountains and valleys which generally are large horsts and grabens, respectively. The mountain ranges are generally bounded by major Basin and Range fault zones, many of which are seismically active today.

North-south trending mountain ranges surround the Great Salt Lake in most areas. These mountains, which are generally composed of Paleozoic rocks, include the Hogup Mountains, Terrace Mountains, Lakeside Mountains, Promontory Mountains, Oquirrh Mountains, and Stansbury Mountains (plate 2).

Several islands and peninsulas of the Great Salt Lake are composed of Precambrian and/or Paleozoic rocks (plate 2). Antelope Island, Fremont Island, Carrington Island, and Bird (Hat) Island are composed of Precambrian rocks. Stansbury Island and Promontory Point are composed of Precambrian and Paleozoic rocks. South Little Mountain is composed of Precambrian rocks.

Volcanic rocks of Tertiary age are the principal composition of (1) the Rozel Hills, (extending northwest of Rozel Point) which lie along the northeastern margin of Great Salt Lake and (2) the Wildcat Hills and Cedar

Hill, both of which lie near the northern margin of Great Salt Lake and off the map of plate 2.

Most of the surficial valley fill surrounding the Great Salt Lake is Quaternary alluvium. However, several isolated outcrops of Tertiary age (including the Salt Lake group) occur along or near the flanks of the mountain ranges adjacent to the lake.

Within several of the mountain ranges, major north-south trending faults and minor east-west trending faults have been mapped (plate 2). Examples of such faulting are found in the Stansbury Mountains, Lakeside Mountains, Terrace Mountains, and Hogup Mountains.

The Great Salt Lake is approximately 75 miles long and up to 30 miles wide. At the time of the gravity survey (1968), the lake had a maximum depth of 30 feet, and the surface elevations were 4,194 feet and 4,195 feet (i.e., a difference of 1 foot) for the north and south arms, respectively (see Appendix 2). The Great Salt Lake itself is a playa lake, the remanent of the historic Lake Bonneville which covered most of western Utah and parts of Nevada and Idaho during Pleistocene time. In modern times, the lake has receded to its present size and has no outlet.

The Southern Pacific Railroad causeway, completed during 1959 between Lakeside and Promontory Point, isolates the northern portion of the lake from the southern part, except for two small culverts between them. Because all surface water inflow is into the southern part of the lake, the southern part is much less saline than the northern part and at a higher elevation (about 1 foot during 1968). The density of the lake waters during 1968 was 1.21 to 1.23 gm/cc in the north arm and 1.14 gm/cc (shallow water) to 1.21 gm/cc (deep water) in the south arm (See Appendix 3).

INTERPRETATION

Gravity Patterns and Geologic Structures

The simple Bouguer gravity anomaly map (plate 2) of the Great Salt Lake and vicinity contains gravity patterns which correspond to geologic structures. The correspondence of the broader gravity patterns with the broader regional geologic structures of the Great Salt Lake region, especially the land region peripheral to the lake, are given in a previous publication (Cook and others, 1966), and will not be discussed in detail here. In the present paper, emphasis will be given to the correspondence of the gravity patterns and geologic structures in the Great Salt Lake area proper. However, the interrelationships of geologic structures and those of the surrounding mainland areas will be treated briefly to provide an overview.

On the gravity map (plate 2), the large elongate gravity lows indicate grabens. These are generally Cenozoic basins that contain sedimentary and/or volcanic rocks of Quaternary and Tertiary age possibly up to 12,000 feet in thickness (Cook and others, 1966, p. 69). The large elongate gravity highs indicate horsts, which generally form the mountain blocks in the region. The zones of closely spaced ("tight") gravity contours, with steep gravity gradients, generally indicate Basin and Range fault zones. These fault zones generally result in a large density contrast between the rocks in the mountain blocks and the valley fill material within the grabens.

The main trend of the gravity contours is north to north-northwest and parallel to the principal Laramide and older structures, as well as the major Basin and Range faults in the region (Cook and Berg, 1961). However, some locally pronounced trends are northeastern and are probably caused by Basin and Range or perhaps earlier faulting.

Horsts. On the northwestern end of the Great Salt Lake, the Lakeside Mountains horst (newly designated herein) is indicated by an elongate northward-trending gravity high (maximum of about -140 mgal) which is more than 40 miles long. This high overlies the Lakeside Mountains and extends northward over the lake to include Gunnison Island, Cub Island, and the lake area north thereof (plate 2). The horst is interpreted as one large block that includes the Lakeside Mountains, Gunnison Island, and Cub Island as outcrops of the horst.

On the western side of the Great Salt Lake, the Carrington-Stansbury Islands horst (newly designated herein) is indicated by the elongate northward-trending belt of gravity highs which is more than 30 miles long. This belt overlies Stansbury Island (-140 mgal) and extends northward over Carrington Island (maximum of about -130 mgal), Bird (Hat) Island (-133 mgal) and the lake area north thereof. The horst is interpreted as one large block that includes all three islands as outcrops of the horst.

Along the eastern margin of the Great Salt Lake, the continuous belt of gravity highs over the Promontory Range (maximum of about -130 mgal), Fremont

Island (-130 mgal) South Little Mountain (-135 mgal) and Antelope Island (-130 mgal) indicates a large essentially continuous fault block throughout this area. This interpretation was first suggested by Cook and others (1966, p. 60). For convenience of nomenclature, however, the newly designated "Promontory Mountains horst" and "Antelope Island horst" shown on plate 2 are used for the respective portions of the large block covered by these topographic features, and a single name is not given to the fault block as a whole. Moreover, the existence of previously mapped east-west trending faults within this large block indicates that the block is broken in places. Even as recently as Basin and Range faulting, this block has probably had internal faulting, but presumably on a minor scale. The same principle also applies to the Lakeside Mountains horst and the Carrington-Stansbury Islands horst.

Grabens. In a previous publication (Cook and others, 1966), the following grabens and their corresponding gravity features were described; that discussion will not be repeated here, except in so far as it concerns the overall tectonic interrelationships: the Strongknob graben (minimum simple Bouguer gravity anomaly value of about -155 mgal), the Rozel graben (-165 mgal), the Bear River Bay graben (-160 mgal), the Lakeside-Stansbury graben (-165 mgal), the East Antelope Island graben (-160 mgal); the Farmington graben (-195 mgal), and the Tooele Valley graben (-185 mgal) (plate 2).

The Great Salt Lake graben (newly designated, plate 2) is indicated by the large gravity low that extends for about 70 miles from the Dolphin Island-Rozel Hills area on the north to the Tooele Valley graben area on the south (Cook and others, 1969). The graben constitutes a large Cenozoic structural basin filled with thick sequences of sedimentary and/or volcanic rocks.

In the region between Bird (Hat) Island and the Promontory Point-Fremont Island area, the large Cenozoic structural basin may have been separated at times into at least two major Cenozoic structural basins of deposition within the graben during its development. This is evidenced by the gravity saddle and the constriction of the main gravity low associated with the Great Salt Lake graben. The "northern Cenozoic basin" lies north of the gravity saddle and the "southern Cenozoic basin" lies south thereof.

In that part of the northern Cenozoic basin between the Hogup Mountains and Rozel Hills, the gravity data indicate that the thickness of rocks in the basin is relatively small in comparison with the area within the same basin south thereof. The Bouguer gravity values over the lake in this area are about -150 to -153 mgal in comparison with values of about -140 mgal over the Hogup Mountains and Rozel Hills, a difference of only 10 to 13 mgal.

The gravity data indicate that the deepest part of the northern Cenozoic basin, where the rocks are the thickest, is probably in the area of the Southern Pacific Railroad causeway, at a point about midway between Lakeside and Promontory Point (plate 2). Here the Bouguer gravity anomaly values form a minimum of less than -165 mgal, in contrast with values of about -130 mgal over the Paleozoic bedrock in the Lakeside Mountains to the west and the Promontory Mountains to the east, a difference of about 35 mgal.

The gravity data further indicate that the southern Cenozoic basin, within the Great Salt Lake graben, is probably longer and deeper than the northern Cenozoic basin. South of the gravity saddle (about -160 mgal) between Bird (Hat) Island and the Promontory Point-Fremont Island area, the decrease of the Bouguer gravity values along the axis of the gravity low, to reach values of less than -185 mgal within the Tooele Valley graben, indicates southward deepening of the basin. These low values are in contrast with gravity values of about -130 mgal over Carrington Island and Antelope Island, a difference of about 55 mgal. It should be noted that along the axis of the gravity low, the values do not decrease consistently; rather, there are two subsidiary gravity low centers over the lake: 1) one (about -170 mgal) midway between Carrington Island and the northern tip of Antelope Island; and 2) another (about -175 mgal) midway between Stansbury Island and the southern part of Antelope Island. These gravity low centers are provisionally interpreted as being caused by undulations of the bedrock surface and may be related to subsidiary structural basins along the axis of the main southern Cenozoic basin.

The Great Salt Lake graben is continuous with the Tooele Valley graben, their trends departing from each other by about 45°. An interpretive geologic cross section along a gravity profile across the southern part of the Tooele Valley graben by Cook and others (1966) indicates the depth to bedrock to be 12,000 feet. A density contrast of 0.4 gm/cc between the bedrock and valley fill was assumed. A well (WG1 on plate 2) within the Tooele Valley graben and about 2 miles south of this gravity profile, was drilled to a depth of 7,993 feet without completely penetrating the valley fill of Cenozoic age (Cook and others, 1966, p. 68). The great thickness of Cenozoic valley fill penetrated in the Tooele Valley graben supports the interpretation that comparable thicknesses should occur beneath the southern Cenozoic basin of the Great Salt Lake graben.

It should be noted that the gravity trough between the Lakeside Mountains and Bird (Hat) Island, that extends southwest of the gravity low center over the northern Cenozoic basin, indicates a southern arm of the northern Cenozoic basin. This gravity trough continues southward, with some constriction between the Lakeside Mountains and Carrington Island, to join the pronounced gravity low center over the Lakeside-Stansbury graben. Such continuation indicates that this arm of the northern Cenozoic basin probably extends southward to connect with the Cenozoic structural basin within the Lakeside-Stansbury graben.

Faults. The gravity data indicate many major Basin and Range fault zones, which are shown on plate 2. The location of each fault, indicated by the gravity data was obtained from either the gravity map (plate 2) or the interpretive geologic cross sections along the four profiles (to be discussed later). Most of the faults shown on plate 2 are newly designated but will be only briefly mentioned.

The Great Salt Lake graben is bounded by the following fault zones: 1) on the northwestern margin, by the East Lakeside Mountains fault zone; 2) on the southwestern margin, by the East Carrington-Stansbury Islands fault zone; and 3) on the eastern margin, by the East Great Salt Lake fault zone, which extends continuously from the Rozel Hills south-southeastward along or near the western margin of the Promontory Range, Fremont Island, South Little Mountain, and Antelope Island.

The Strongknob graben is bounded on the east by the West Lakeside Mountains fault zone. The Bear River Bay graben is bounded on the west by the East Promontory Mountains fault zone. The Lakeside-Stansbury graben is bounded on the west by the East Lakeside Mountains fault zone and on the east by the West Carrington-Stansbury Islands fault zone. The Antelope Island horst is bounded on the east by the East Antelope Island fault zone.

Each of the Basin and Range fault zones are generally comprised of individual step faults that form a sinuous and/or braided pattern on the geologic map (plate 2). The indicated locations and throws of the faults and the configuration of the bedrock are shown in the profiles.

Profiles

Interpretive geologic cross sections were constructed along four east-west profiles (A-A′ through D-D′, figures 4 - 7) across the Great Salt Lake, using the two-dimensional modeling technique of Talwani and others (1959). Simple two-layer models were assumed in each cross section. A density contrast of 0.5 gm/cc was assumed between the bedrock (bottom layer, with rocks of pre-Tertiary age) and the top layer (valley fill, with rocks of Quaternary and/or Tertiary age); vertical or steeply dipping faults were assumed in all models. It should be noted that all interpretive geologic cross sections have a vertical exaggeration so that apparent dips are greatly exaggerated. The water in the Great Salt Lake is too shallow (less than 30 feet during 1968) to be included in the cross sections.

The figure for each profile is divided into three parts: (1) part "a", which shows the "observed" simple Bouguer gravity anomaly values, in milligals, with the assumed regional gravity trend; (2) part "b" which shows the residual gravity values, in milligals, after the assumed regional gravity trend has been removed from the observed gravity values; and (3) part "c" which shows the interpretive geologic cross section with the gravity station locations marked on the profile. In part "c" of three profiles, "contour stations" are indicated at locations along those portions of each profile for which the gravity control was based on contoured values only. These values were taken from the gravity map (plate 2).

Because of the inherent ambiguity of gravity data, the models should not be considered unique; however, based on all available information, they are believed to represent a reasonable interpretation of the structural configuration of the contact between the valley fill and the bedrock. For those faults already mapped at the surface (Stokes, 1963), the locations of the faults shown on the profiles agree with those of the mapped faults. For those faults interpreted from the shallow reflection seismic survey over the lake during 1969, reported by Mikulich (1971) and Mikulich and Smith (1974), the location of the faults shown on the profiles generally agree well with those interpreted from the seismic survey, with a few notable exceptions that will be discussed later. This seismic survey had a maximum depth of penetration of only 4,000 feet below the surface of the lake. It should be noted that the actual number of faults along each profile, especially those at great depth, may be more or less than those shown in the profile. However, for the density contrast assumed for each profile and the total thickness of the valley fill,

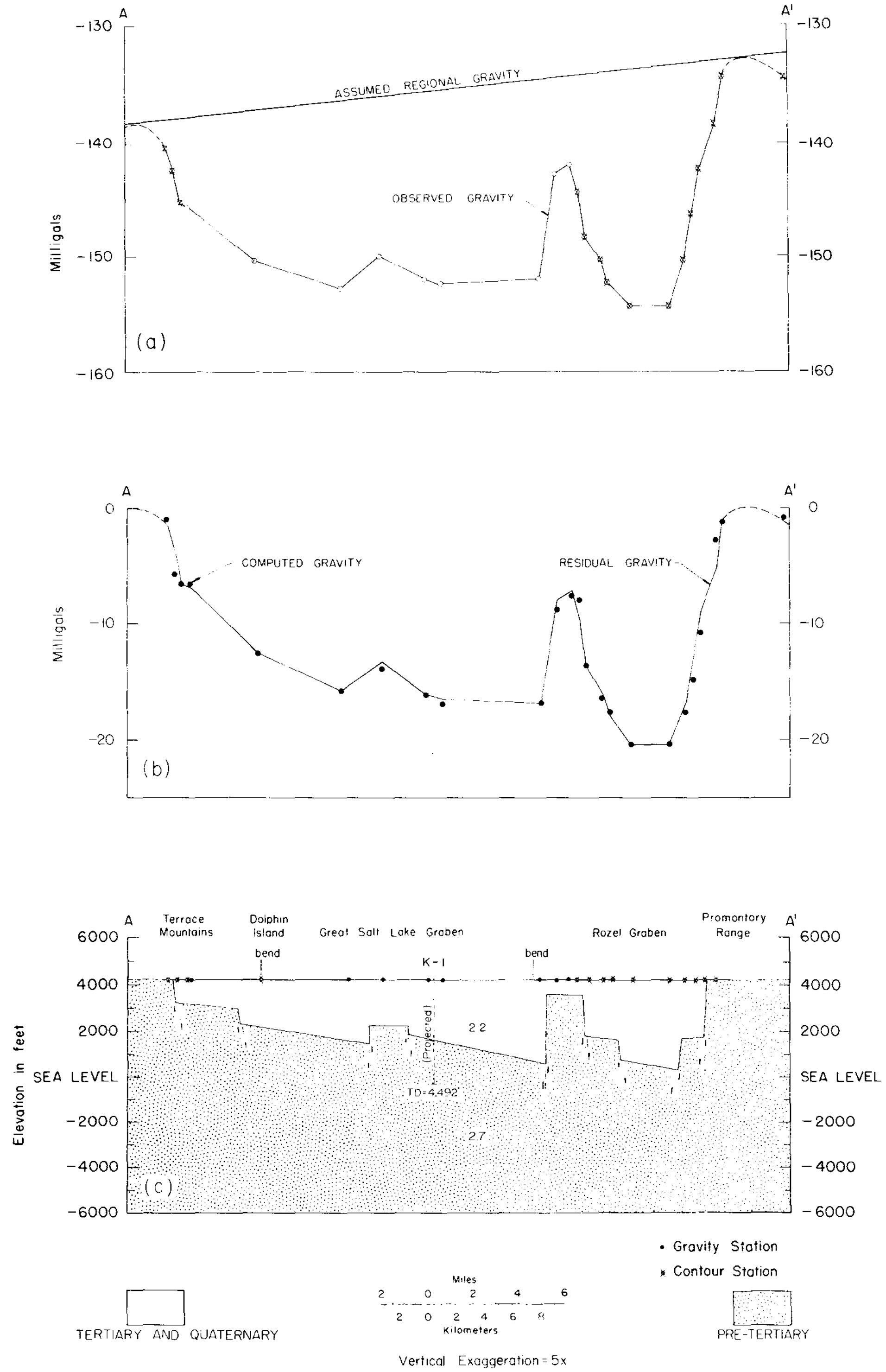

Figure 4. Gravity and interpretive geologic cross section along profile A-A' across Great Salt Lake and Rozel grabens. Assumed density contrast is 0.5 gm/cc.

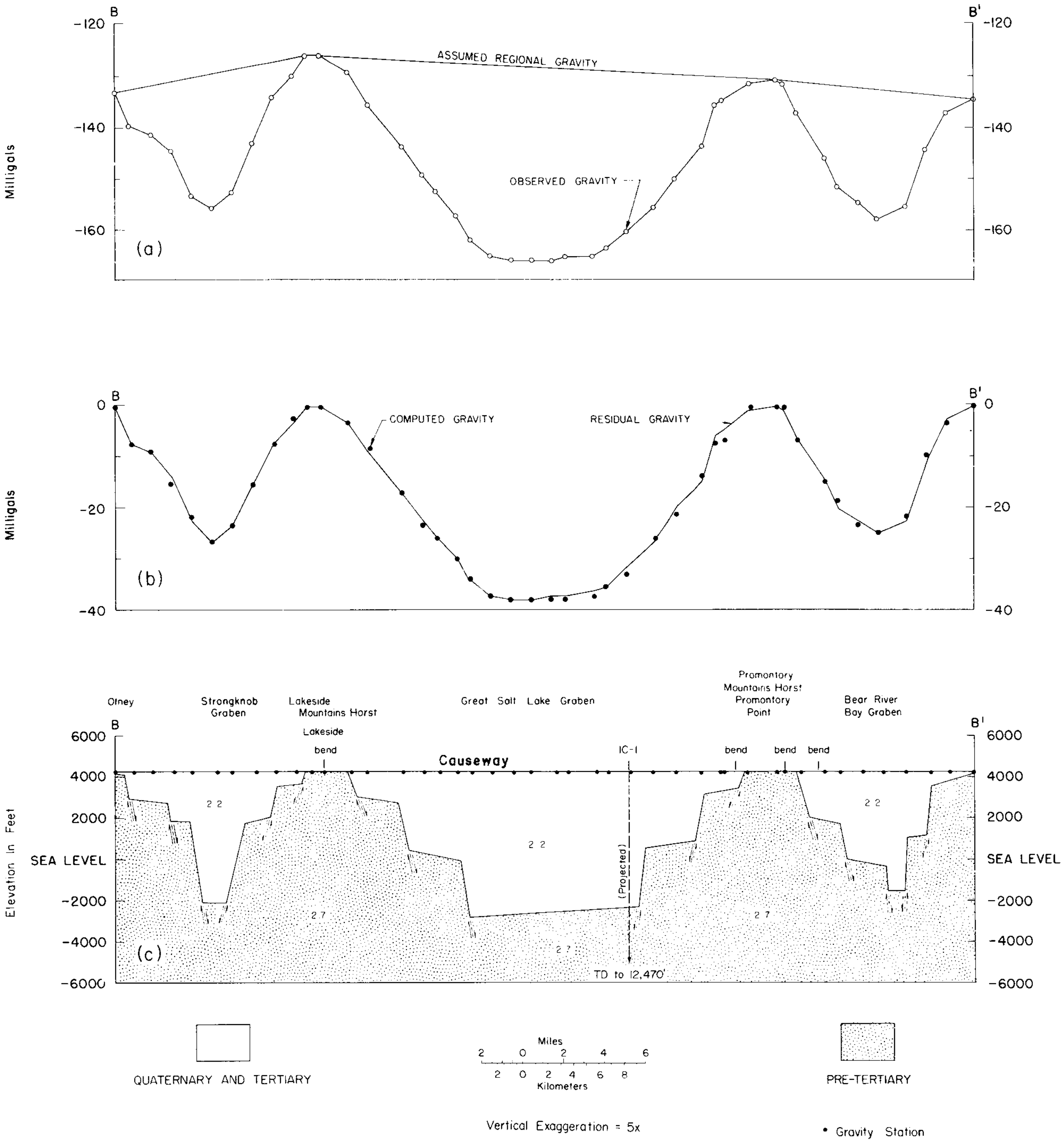

Figure 5. Gravity and interpretive geologic cross section along profile B-B′ across Strongknob, Great Salt Lake, and Bear River Bay grabens and across Lakeside Mountains and Promontory Mountains horsts. Assumed density contrast is 0.5 gm/cc.

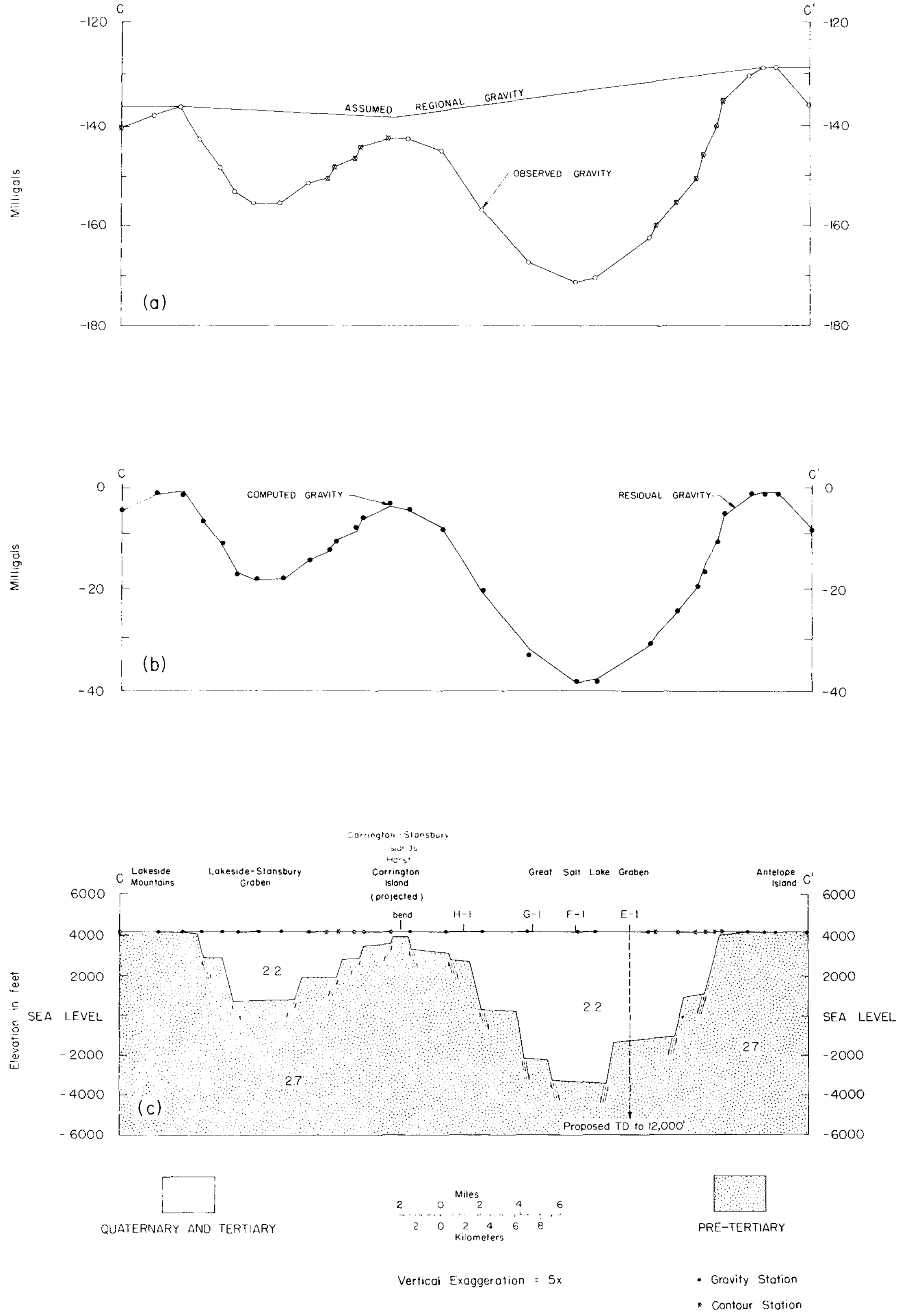

Figure 6. Gravity and interpretive geologic cross section along profile C-C′ across Lakeside-Stansbury and Great Salt Lake grabens and Carrington-Stansbury Islands horst. Assumed density contrast is 0.5 gm/cc.

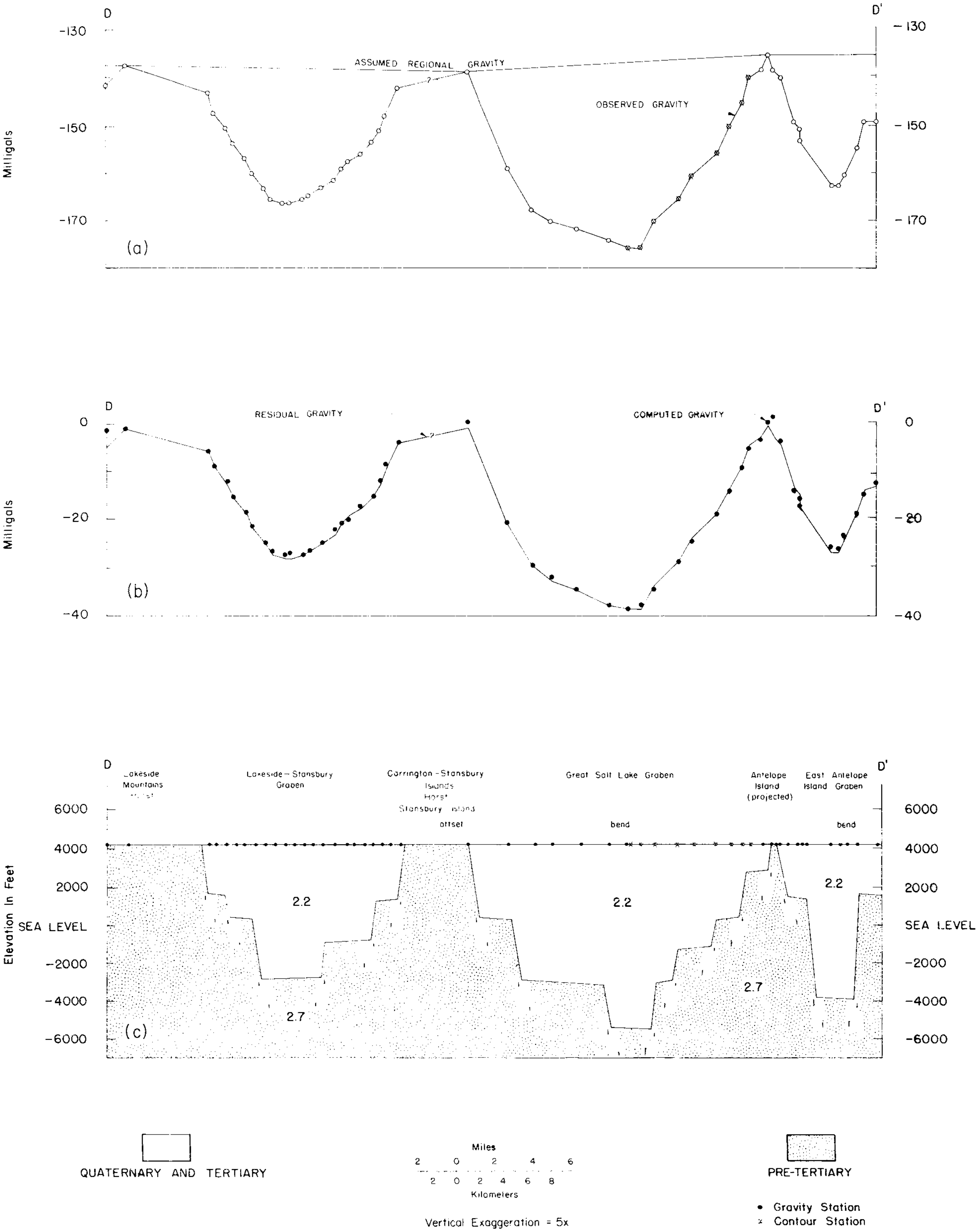

Figure 7. Gravity and interpretive geologic cross section along profile D-D′ across Lakeside-Stansbury, Great Salt Lake, and East Antelope Island grabens and across Lakeside Mountains, Carrington-Stansbury Islands, and Antelope Island horsts. Assumed density contrast is 0.5 gm/cc.

the overall configuration of the bedrock surface is considered reasonable. It should be emphasized that if the true density contrast between the top (valley fill) and bottom (bedrock) layers of rocks is less or greater than the assumed value of 0.5 gm/cc, the thickness of the top layer (valley fill) will be correspondingly greater or less, respectively, than that shown in the models.

Profile A-A'. Profile A-A' (figure 4) extends for about 29 miles along lat 41°28' N approximately across the northern Cenozoic basin between the Terrace Mountains and the western flank of the Promontory Mountains (see plate 2). The model shows the Great Salt Lake graben with a small, buried horst in the bedrock approximately midway between the Terrace Mountains and the Rozel Hills. This small, narrow horst is apparently the northern continuation of the Lakeside Mountains horst, a large block which forms the Lakeside Mountains, and Gunnison and Cub islands, as discussed earlier. The maximum depth to bedrock in the Great Salt Lake graben along profile A-A' is positioned just west of the Rozel Hills, and is indicated as being about 3,600 feet.

Just east of the Great Salt Lake graben is a small horst which comes to within about 600 feet of the surface. This horst separates the Great Salt Lake graben from the Rozel graben, which lies under the Rozel Hills. The Rozel graben has been described elsewhere in detail by Cook and others (1966).

Profile B-B'. Profile B-B' (figure 5) extends for about 38 miles at lat 41°15' N approximately along the Southern Pacific Railroad between the Olney siding, west of Strongknob Mountain, and South Little Mountain, east of Promontory Point (plate 2). The profile passes through Lakeside and Promontory Point. Approximately 19 miles of the profile lie along the causeway which crosses the lake.

On the west, the model shows the Strongknob graben, which has been described elsewhere in detail by Cook and others (1966). To the east of the Strongknob graben are successively, the Lakeside Mountains horst, the Great Salt Lake graben, the Promontory Mountains horst, and the Bear River Bay graben. Along profile B-B', the maximum depth to bedrock is apparently along the deep western margin of the Great Salt Lake graben, which corresponds with the deep eastern base of the Lakeside Mountains horst. Moreover, the northern Cenozoic basin is apparently deepest here; and the maximum basin fill is indicated as about 7,100 feet. The Bear River Bay graben has been described elsewhere in detail by Cook and others (1966).

Profile C-C'. Profile C-C' (figure 6) extends for about 34 miles along lat 40°47' N approximately between the Lakeside Mountains and Antelope Island (plate 2). The profile crosses over a narrow peninsula of Quaternary rocks extending south of Carrington Island and continues eastward for about 20 miles over the lake itself. Beneath the western part of the profile is the Lakeside-Stansbury graben, which has been described elsewhere in detail by Cook and others (1966). Beneath the central part of the profile is the Carrington-Stansbury Islands horst, the top of which is buried beneath a thin cover of Quaternary rocks. The Great Salt Lake graben lies between Stansbury Island and Antelope Island. The maximum depth to bedrock along the profile is approximately midway between the two islands and is indicated as 7,600 feet. It should be noted that this part of the Great Salt Lake graben is in the southern Cenozoic basin.

Profile D-D'. Profile D-D' (figure 7) extends for about 41 miles along lat 40°50' N approximately from the Lakeside Mountains eastward across Stansbury Island (with a slight offset in the profile), the southern part of the Great Salt Lake (with a slight bend in the profile in the central part of the lake), the southern tip of Antelope Island, and along the road causeway between Antelope Island and the mainland (plate 2). The profile crosses the following structures, successively from west to east: Lakeside Mountains horst, Lakeside-Stansbury graben, Carrington-Stansbury Islands horst, Great Salt Lake graben, Antelope Island horst, East Antelope Island graben, and Farmington Bay horst. The East Antelope Island graben and Farmington Bay horst have been described elsewhere in detail by Cook and others (1966).

Along profile D-D', the basement configuration is strikingly asymmetrical. In particular, the Great Salt Lake graben is deepest toward Antelope Island where the maximum depth to bedrock is indicated as about 9,700 feet. It should be noted that although the maximum depth to bedrock within the Great Salt Lake graben is greater along profile D-D' than profile C-C', the deepest part of the southern Cenozoic basin lies south of profile D-D', where the Great Salt Lake graben joins the Tooele Valley graben (plate 2). Consequently the maximum thickness of the valley fill in the southern Cenozoic basin probably exceeds 9,700 feet.

Summary of profiles

The maximum depths to bedrock indicated within the various grabens along the four profiles A-A' through

D-D′ are summarized in table 1. Also in the table, a comparison between the maximum depth to bedrock indicated in this paper with depth estimates given by Cook and others (1966) shows good agreement. The discrepancy in the estimated depths to bedrock for the East Antelope Island graben can be explained partly because an assumed regional gravity trend is removed in this paper, whereas none was removed by Cook and others (1966).

Although the structures shown in the interpretive geologic cross sections are considered a reasonable interpretation, based on the available gravity and geologic control, they should not be considered a unique interpretation. An equally good fit of the computed and residual gravity could be obtained by assuming a larger number of step faults than those actually shown. Also, the angle of dip shown on the faults is subject to much uncertainty, but the values assigned are considered reasonable. For an assumed density contrast greater or less than the value of 0.5 gm/cc used, the interpreted locations of the inferred faults would not have changed appreciably. However, the total throw of the postulated faults would be correspondingly less or greater, respectively, and the maximum thickness of the Cenozoic valley fill in the central part of the grabens would be correspondingly less or greater, respectively, than that shown in the profiles.

A significant result of the interpretive geologic cross sections is that within the Great Salt Lake graben, the maximum thickness of the Cenozoic valley fill in the southern Cenozoic basin (indicated as about 9,700 feet on profile D-D′) is much greater than that in the northern Cenozoic basin (indicated as about 7,100 feet on profile B-B′).

COMPARISON OF RESULTS OF SEISMIC AND GRAVITY SURVEYS

During 1969, an extensive seismic reflection survey was made over the Great Salt Lake (Mikulich, 1971; Mikulich and Smith, 1974). The maximum depth of penetration of the Bolt air gun used for this survey was only 4,000 feet.

A comparison of the results of the seismic and gravity surveys shows that most of the faults that were indicated by the seismic data (not shown on plate 2) correspond well with the faults interpreted from the gravity data (shown on plate 2). In particular, the best correspondence is noted for the larger, elongate, north-south trending Basin and Range faults that delineate the east and west margins of the complexly faulted Great Salt Lake graben. Some of the individual step faults along fault zones marginal to the graben probably have vertical throws of 1,000 feet or more, and are indicated

Table 1. Summary of indicated maximum depths to bedrock along profiles.

Name of graben	Profile	Maximum depth to bedrock -- this paper (feet) [1]	Estimated depth to bedrock (Cook and others, 1966) (feet)[2]
Great Salt Lake (Northern basin)	A-A′	3,600	– –
Rozel	A-A′	3,900	>2,350
Strongknob	B-B′	6,400	>1,500
Great Salt Lake (Northern basin)	B-B′	7,100	– –
Bear River Bay	B-B′	5,800	>1,500
Lakeside-Stansbury	C-C′	3,500	>1,500
Great Salt Lake (Southern basin)	C-C′	7,600	– –
Lakeside-Stansbury	D-D′	7,000	>2,500
Great Salt Lake (Southern basin)	D-D′	9,700	– –
East Antelope Island	D-D′	8,100	6,100[3]
Tooele Valley	[4]	– –	12,000[4]

[1] Based on an assumed density contrast of 0.5 gm/cc between the bedrock and valley fill.

[2] Estimated from the Bouguer approximation and an assumed density contrast of 0.4 gm/cc or 0.5 gm/cc between the bedrock and valley fill – – unless otherwise noted.

[3] Value along profile B-B′, figure 4, Cook and others, 1966, p. 70. Based on an assumed density contrast of 0.5 gm/cc. Also depths to bedrock of 4,600 feet and 7,900 feet are indicated for assumed density contrasts of 0.6 gm/cc and 0.4 gm/cc, respectively.

[4] Value along profile A-A′, figure 3, Cook and others, 1966, p. 66. Based on an assumed density contrast of 0.4 gm/cc between the bedrock and valley fill.

by both gravity and seismic data at approximately the same locations. The faults that show good correspondence are in the following areas: 1) along the East Great Salt Lake fault zone west of Antelope Island (along profile D-D') and west of Promontory Point (along profile B-B') and 2) along the East Lakeside Mountains fault zone east of Lakeside (along profile B-B').

As expected, several faults interpreted from the seismic data were not indicated by the gravity data because the faults were in either Quaternary or Tertiary sediments with insufficient density contrast on either side of the fault. Also some faults interpreted from the seismic data were of insufficient vertical throw to be resolved in a regional-type bottom gravity survey.

SUMMARY AND CONCLUSIONS

The bottom gravity meter survey of the Great Salt Lake made possible the compilation of a simple Bouguer gravity anomaly map and interpretive geologic cross sections along four east-west gravity profiles across the lake that provided helpful information concerning the geologic structures beneath the lake. The large gravity low, that extends for a distance of about 70 miles, essentially the entire length of the lake, indicates a large north-northwestward trending graben beneath the lake. The closely spaced gravity contours, with steep gravity gradients, indicate that the graben is bounded on each side by large Basin and Range fault zones. On the northwestern side is the East Lakeside Mountains fault zone; on the southwestern side is the East Carrington-Stansbury Islands fault zone; and on the east side is the East Great Salt Lake fault zone. All fault names are newly designated. The large gravity low centers that lie north and south of the gravity saddle that extends between Bird (Hat) Island and the Promontory Point-Fremont Island area, indicate that at least two Cenozoic structural basins of deposition probably formed within the large graben between the Dolphin Island-Rozel Hills area and the Tooele Valley graben. The two basins are designated the "northern Cenozoic basin" and "southern Cenozoic basin" to the north and south, respectively, of the gravity saddle.

The geologic cross sections along the gravity profiles, based on a density contrast of 0.5 gm/cc between the bedrock and valley fill, indicate that the maximum thickness of the Cenozoic structural basins (valley fill) are 1) about 7,100 feet in the northern Cenozoic basin, along profile B-B' and 2) about 9,700 feet in the southern Cenozoic basin, along profile D-D'. An assumed larger or smaller density contrast would result in correspondingly smaller or larger thicknesses, respectively.

The new gravity data over the Great Salt Lake, used in conjunction with the previous gravity data over the adjoining mainland (Cook and others, 1966), afforded an interpretation of the continuity and interrelationships of the geologic structures. For example, the Great Salt Lake graben is continuous with the Tooele Valley graben. Also, an arm of the northern Cenozoic basin within the Great Salt Lake graben probably extends southward, with some constriction, between the Lakeside Mountains and Carrington Island to connect with the Cenozoic structural basin within the Lakeside-Stansbury graben.

ADDENDUM

Since the final draft of the simple Bouguer gravity anomaly map (Plate 2) and interpretive geologic cross sections along the four gravity profiles across the Great Salt Lake were completed (during April 1975), in preparation for oral presentation at scientific meetings during 1975 (Cook and others, 1975; Cook and others, 1976), the Amoco Production Company initiated a test drilling program of the Great Salt Lake during May, 1978. Nine drill holes were planned, five in the north arm of the lake and four in the south arm. The locations of the test holes were apparently based on the results of a deep reflection seismic survey started on July 25, 1973, by the Amoco Production Company.[1] This survey used a specially constructed barge 60 feet long, with a total of 14 air guns (7 air guns mounted on each side of the barge). The depth of penetration was at least 12,000 feet.

The locations of all 9 Amoco test holes, presently drilled or proposed, in the Great Salt Lake are shown on plate 2. Some of the test holes are projected into the appropriate nearest interpretive geologic cross sections along the gravity profiles. At the time of submittal of

[1] The information herein concerning the deep reflection seismic survey by the Amoco Production Company is based on notes taken by K. L. Cook during a joint lecture by Craig Hansen and Charles (Bud) Ervin, geophysicists of the Amoco Production Company, Denver, Colorado. The lecture was presented on December 3, 1974, as part of a Great Salt Lake Seminar conducted at the University of Utah, under the supervision of Professor James A. Whelan, Department of Geology and Geophysics.

Table 2. Amoco Production Company, State of Utah drilled or proposed well locations in Great Salt Lake (Source - Utah Geological and Mineral Survey, August 1979 and Survey Notes, August 1979).

Well Designation	Section, Township, Range	Latitude N[8]		Longitude W[8]		Total Depth (TD) (feet) and Status[1]	Lithology at TD
		deg	min	deg	min		
NORTH BASIN							
J-1 (South Rozel)	C-NE-SW Sec. 21-8N-7W	41°	24.36′	112°	39.24′	6,802 (D)	Paleozoic carbonates[4]
K-1 (North Gunnison)	C-NE-SE Sec. 11-8N-9W	41°	26.04′	112°	49.21′	4,492 (D)	Paleozoic carbonates
D-1 (West Rozel)	C-NW-SW Sec. 23-8N-8W	41°	24.36′	112°	44.04′	8,503 (T)	[2]
Indian Cove No. 1 (IC-1 on plate 2)	C-SW-SE Sec. 23-7N-7W	41°	19.06′	112°	36.59′	12,470 (D)	Precambrian schist[5]
West Rozel No. 2 (WR-2 on plate 2)	S-NW-SW Sec. 15- 8N-8W	41°	25.25′	112°	45.18′	2,700 (approx.) (T)	Rozel Point basalt[3]
SOUTH BASIN[6] E-1	C-NW-SW Sec. 19-3N-4W	40°	58.56′	112°	21.09′	Proposed to 12,000[7]	– –
F-1	C-NW-SW Sec. 15-3N-5W	40°	59.42′	112°	24.59′	Proposed	– –
G-1	C-SE-NW Sec. 29-3N-5W	40°	57.97′	112°	26.66′	Proposed	– –
H-1	C-NW-SW Sec. 11-3N-6W	41°	00.28′	112°	30.36′	Proposed	– –

[1] (T) = Temporarily abandoned.
(D) = Dry and abandoned.
Source – Survey Notes, August 1979.

[2] Paleozoic carbonates at about 6,325 feet. Tested heavy oil from basalt at 2,300 feet depth. (Survey Notes, August 1979).

[3] Pump tests recovered 8,000 barrels of heavy oil at rates as high as 1,500 barrels per day from 2,300 feet to total depth. (Survey Notes, August 1979).

[4] Paleozoic carbonates at 6,000 feet (Survey Notes, August 1979).

[5] No Paleozoic rocks penetrated. Precambrian at 12,450 feet (Survey Notes, August 1979).

[6] Drilling operations are scheduled to begin in late summer of 1979 (Survey Notes, August 1979).

[7] Survey Notes, August 1979.

[8] Coordinates of latitude and longitude of the wells were determined from a map (on which the well locations had been determined from the citation by section, township, and range) kindly furnished by Howard R. Ritzma, Utah Geological and Mineral Survey.

this paper for publication (August, 1979), the five test holes on the north arm of the lake had been completed, and the first test hole on the south arm of the lake was still in preparation to be drilled. No well logs were available because, under the terms of the state of Utah land leases to the Amoco Production Company, these data are to be considered proprietary until 7 months following the completion of each well.

Table 2 gives 1) the names and locations (both by section, township, and range and also by latitude and longitude) of all 9 Amoco test holes in the Great Salt Lake (both those already drilled and those proposed); 2) the total depth of each test hole drilled to date (August 1979); and 3) miscellaneous lithologic information that has been released by the Amoco Production Company.

It should be emphasized that in projecting the Amoco test holes into the appropriate nearest geologic cross sections along the gravity profiles, the projection was made along the trend of the gravity contours (plate 2), and hence along the indicated trend of the geologic structure (i.e., Basin and Range fault zones). Because the distances of the projections were necessarily large for the two profiles (A-A′ and B-B′) along which the Amoco test holes have been completed, and especially because the complete well logs are not yet available, any comparison between the available drilling data and the indicated maximum depth to bedrock, as shown on the profiles, is of limited value.

For example, test hole K-1, which is projected onto profile A-A′ (figure 4), actually lies about 3 miles south-southeast of profile A-A′ at a point within the north Cenozoic basin where the lower gravity values indicate a somewhat larger thickness of valley fill than along profile A-A′. Similarly, test hole IC-1, which is projected onto profile B-B′, (figure 5), lies about 7 miles north-northwest of profile B-B′; but here a comparison is more difficult. In particular, it is reported (Survey Notes, August 1979) that in test hole IC-1 (1) no Paleozoic rocks were penetrated and (2) Precambrian rocks were penetrated at a depth of 12,450 feet.

These early drilling results indicate that the maximum depth to bedrock shown along profile B-B′ (figure 5) is probably too small and that therefore the assumed average density contrast of 0.5 gm/cc between the bedrock and valley fill is probably too large for the northern Cenozoic basin. This indication has been corroborated by the measurement of the density of a dense gray siltstone core sample from Amoco test hole IC-1 (the one projected into profile B-B′, figure 5) from a depth of approximately 5,500 feet. The density was 2.54 gm/cc (J. W. Gwynn, Utah Geological and Mineral Survey, August 14, 1979, personal communication).

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The U. S. Army Map Service personnel, who performed the bottom gravity meter survey, consisted of: 1) Supervisor - R. M. Iverson; 2) Party Chiefs and bottom gravity meter instrument operators - Lawrence Hunt, during the early part of the survey and M. T. Strohmeier, during the latter part of the survey; 3) Electronic Technician (for repairs and maintenance of gravity meter) - Glen Cobb, 4) Tellurometer operators - Lewis Phillips, in charge, assited by Ronald Creel, James D. Hutchison, Carl Kaywood, and Don Zeal.

The *G. K. Gilbert* was operated for the Utah Geological and Mineralogical Survey by Leonard Hedberg, captain, and Dave Sekino, first mate.

Robert H. Brown, a graduate student in Geophysics at the University of Utah, made the gravity ties between the Salt Lake City airport base station K and the Little Valley and Silver Sands base stations.

The gravity data were reduced under the immediate supervision of Robert Ziegler, Gravity Division, Army Map Service, Corps of Engineers, Department of the Army, Washington, D. C.

Appreciation is expressed to the Gravity Division, Army Map Service, Corps of Engineers, Department of the Army, Washington, D. C., for the loan of LaCoste and Romberg land gravity meter No. 123, which was used to make the ties of the various gravity base stations on land.

Leonard Hedberg and J. A. Whelan provided density values of the waters of the Great Salt Lake given in Appendix 3.

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APPENDIX 1

DESCRIPTION OF GRAVITY BASE STATIONS

1 Little Valley Gravity Base Station

The station is located on U. S. government benchmark "BM 4205" on the land surface at Little Valley

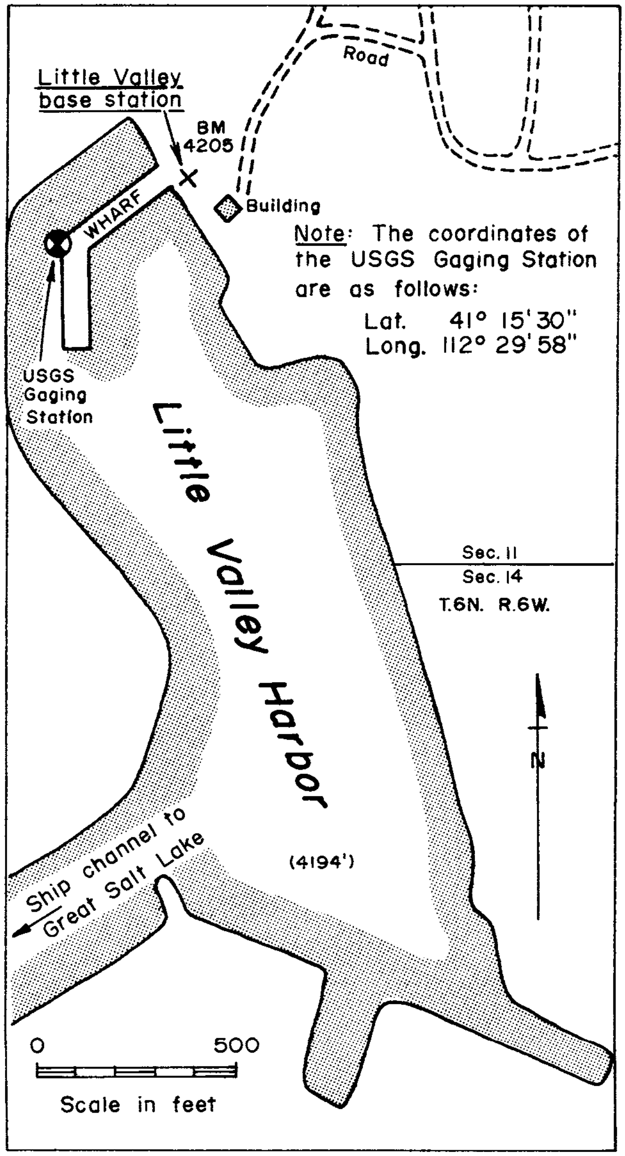


Figure 8. Sketch map showing location of Little Valley gravity base station.

Harbor northwest of Promontory Point (figure 8). The benchmark is shown on 1) the U. S. Geological Survey 7-1/2 minute topographic quadrangle map "Pokes Point, Utah" and 2) the map entitled "Great Salt Lake and Vicinity, Utah" published in 1974 jointly by the U. S. Geological Survey and the Utah Geological and Mineral Survey. The coordinates of the station are: lat 41°15.53′ N and long 112°29.90′ W.

2. Silver Sands Gravity Base Station

The station is located at Silver Sands Beach near the southwest end of the 60-foot-wide breakwater that forms the County Boat Harbor about 0.12 mile (0.2 km) southwest of U. S. government benchmark "BM 4209" that is shown on the 1) Garfield, Utah (1952) 7-1/2 minute topographic quadrangle map of the U. S. Geological Survey and 2) the map entitled "Great Salt Lake and Vicinity, Utah," published in 1974 jointly by the U. S. Geological Survey and the Utah Geological and Mineral Survey. The station is located on top of a sand bar that lies immediately southeast of the breakwater about 120 feet northeast of the southwest end of the breakwater (figure 9). The elevation of the top of the sand bar is about 5 feet below that of the top of the breakwater and was about 2 feet above the level of the south arm of the Great Salt Lake on July 28, 1968 during the time of the gravity survey. The station, which was marked in 1968 by a metal stake driven onto the sand bar, is 15 feet southeast of the bottom of the breakwater and 30 feet northeast of the northeast side of the boathouse which in 1968 contained the water-level marker for the Great Salt Lake in this area. The coordinates of the station are: latitude 40° 44.11′ N and longitude 112° 12.81′ W.

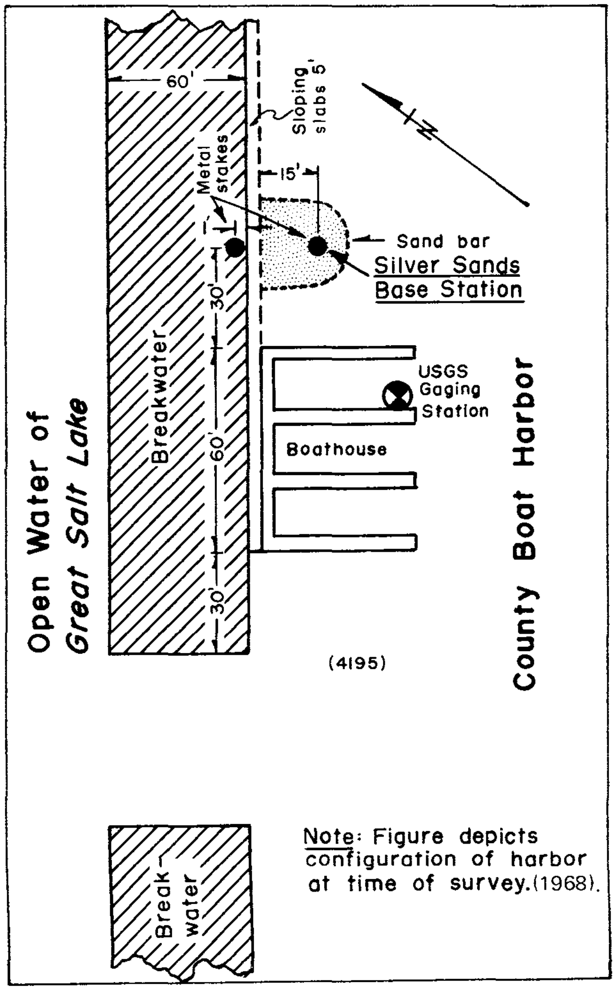


Figure 9. Sketch map showing location of Silver Sands gravity base station.

APPENDIX 2

Elevations of the Great Salt Lake during the gravity survey (data supplied by Leonard Hedberg, Utah Geological and Mineralogical Survey, August 1968).

Elevation of Great Salt Lake –South Arm (Boat Harbor Gage) For Period July 1-27, 1968

Date	Elevation (Ft.) Above MSL
July 1	4,195.48
2	4,195.45
3	4,195.45
4	4,195.40
5	4,195.40
6	4,195.40
7	4,195.38
8	4,195.38
9	4,195.38
10	4,195.35
11	4,195.33
12	4,195.33
13	4,195.33
14	4,195.28
15	4,195.25
16	4,195.25
17	4,195.28
18	4,195.22
19	4,195.18
20	4,195.18
21	4,195.13
22	4,195.05
23	4,195.05

24	4,195.05
25	4,195.05
26	4,195.03
27	4,195.00

Considerable storm activity occurred during July 22-23.
Maximum elevation: 4,195.42
Minimum elevation: 4,194.05

Elevation of Great Salt Lake — — North Arm (Saline Gage) For Period July 28–August 9, 1968

July	28	4,194.30
	29	4,194.28
	30	4,194.30
	31	4,194.30
Aug.	1	4,194.25
	2	4,194.23
	3	4,194.23
	4	4,194.20
	5	4,194.20
	6	4,194.15
	7	4,194.15
	8	4,194.15
	9	4,194.13

Large storm occurred on August 3, from about 6:00 p.m., until midnight.
Maximum elevation 4,195.25
Minimum elevation: 4,193.32

APPENDIX 3

Data on density of waters of the Great Salt Lake during the summer of 1968 (data supplied by James A. Whelan, Department of Geological and Geophysical Sciences, University of Utah, and Leonard Hedberg, Utah Geological and Mineral Survey, September 1968).

North Arm

Density varies from 1.21 to 1.23 gm/cc.
Average density is 1.22 gm/cc.

South Arm

Density of water from surface of lake to a depth of 20 feet is 1.14 gm/cc.
Density of water layer between this depth (20 feet) and bottom of the lake is 1.21 gm/cc.

APPENDIX 4

Principal facts of gravity stations for the bottom gravity meter survey of the Great Salt Lake (as compiled by the U. S. Army Map Service during December 1968) are shown on table 3.

EXPLANATION

The listing contains consecutively, from left to right:
Station name.
Station number.
Latitude, in degrees and minutes.
Longitude, in degrees and minutes.
Elevation of Great Salt Lake, in meters, when station was taken.
Depth to bottom of lake, in meters, at location of station.
Observed gravity, in milligals.
Free-air gravity anomaly value, in milligals.
Simple Bouguer gravity anomaly value, in milligals (using, for the Bouguer correction, an average density of 1.22 gm/cc for the lake water and 2.67 gm/cc for the material between the lake bottom and mean sea level).
Theoretical gravity at mean sea level, using the International Gravity Formula, in milligals.

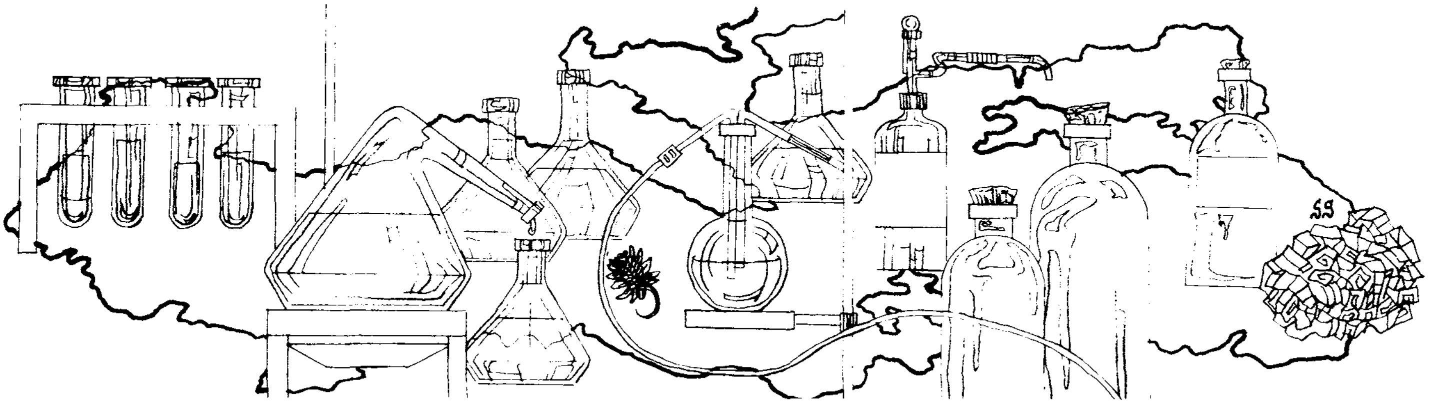
Notes: The observed gravity value at Salt Lake City airport base station K was taken as 979,815.444 mgal (Cook and others, 1971). Using this value, the ties to the Little Valley and Silver Sands gravity base stations, which were made with the LaCoste and Romberg land gravity meter No. 123, resulted in observed gravity values of 979,906.540 mgal and 979,825.407 mgal, respectively, for these base stations. It should be noted that the arbitrary (and incorrect) values given in the listing for the latitudes and longitudes of these two base stations only do not affect the accuracy of the values of the observed gravity of these base stations.

The simple Bouguer gravity anomaly values used in contouring the map shown on plate 2 over the Great Salt Lake itself (i.e., for the bottom gravity meter stations only) were obtained by adding algebraically 4.36 mgal to the simple Bouguer gravity anomaly values shown in the listing. This adjustment was made so that the gravity contours over the Great Salt Lake would fit smoothly with the simple Bouguer gravity anomaly contours (obtained from the land gravity meter surveys) over the land adjacent to the lake published by Cook and others (1966). For these land gravity meter surveys (Cook and others, 1966, p. 59), the reference for observed absolute gravity was the U. S. Coast and Geodetic Survey pendulum station No. 49, in the Temple Grounds in Salt Lake City, for which the absolute gravity value was accepted as 979,806 mgal (Duerksen, 1949, p. 8).

PRINCIPAL FACTS AT GRAVITY STATIONS

STA NAME AND NUM		LATITUDE NORTH +	LONGITUDE EAST +	ELEVATION METERS	SUPP ELEV METERS	OBSERVED G MGAL	FREE AIR MGAL	BOUGUER MGAL	THEOR G MGAL
SILVER SANDS	3000	40 60.00	-111 60.00	1278.715	1.524	979826.260	-49.173	-192.156	980269.574
N-1	1	40 44.96	-112 23.38	1278.715	1.067	979826.017	-26.895	-169.910	980247.194
P-1	2	40 42.36	-112 22.07	1278.715	2.134	979803.983	-45.393	-188.335	980243.328
N-2	3	40 45.69	-112 15.10	1278.715	7.010	979815.710	-40.122	-182.727	980248.281
M-1	4	40 49.60	-112 26.00	1278.715	2.591	979840.408	-19.877	-162.786	980254.096
M-2	5	40 49.80	-112 24.40	1278.715	4.724	979832.444	-28.796	-171.559	980254.394
M-3	6	40 49.70	-112 23.30	1278.715	6.096	979830.194	-31.321	-173.989	980254.245
M-4	7	40 49.70	-112 21.60	1278.715	6.248	979828.221	-33.341	-175.998	980254.245
M-5	8	40 49.80	-112 20.00	1278.715	7.010	979826.163	-35.784	-178.389	980254.394
M-6	9	40 49.70	-112 18.80	1278.715	7.772	979824.890	-37.142	-179.695	980254.245
L3	10	40 53.66	-112 18.73	1278.724	7.925	979838.544	-29.425	-171.968	980260.137
L2	11	40 53.72	-112 21.92	1278.724	7.772	979827.201	-40.810	-183.364	980260.226
L1	12	40 54.54	-112 23.31	1278.724	5.639	979841.303	-27.269	-169.970	980261.447
SILVER SAND	4000	40 60.00	-111 60.00	1278.724	3.048	979825.407	-50.493	-193.373	980269.574
SS2 HBR LND	20000	40 60.00	-111 60.00	1278.678	.000	979825.596	-49.379	-192.463	980269.574
K-1	13	40 57.37	-112 31.87	1278.654	1.829	979865.762	-5.868	-148.824	980265.660
K-2	14	40 57.88	-112 27.27	1278.654	6.248	979845.349	-28.405	-171.056	980266.418
K-3	15	40 58.19	-112 23.43	1278.654	8.077	979842.448	-32.331	-174.856	980266.880
J-5	16	41 .86	-112 21.52	1278.654	7.925	979852.737	-25.971	-168.507	980270.855
K-4	17	40 57.63	-112 29.83	1278.654	4.724	979855.371	-17.540	-160.296	980266.047
K-5	18	40 58.24	-112 24.39	1278.654	7.772	979841.432	-33.328	-175.874	980266.955
K-6	19	40 58.66	-112 19.26	1278.654	7.772	979851.332	-24.053	-166.599	980267.579
J-4	20	41 2.02	-112 26.55	1278.654	8.077	979848.140	-32.343	-174.868	980272.582
I-12	21	41 7.80	-112 18.30	1278.654	1.676	979894.963	7.846	-135.120	980281.193
I-11	22	41 7.40	-112 20.70	1278.654	4.724	979886.563	-.899	-143.655	980280.597
I-10	23	41 7.20	-112 22.50	1278.654	6.096	979878.225	-9.362	-152.024	980280.298
I-5	24	41 5.40	-112 35.10	1278.654	2.286	979886.642	2.912	-140.012	980277.617
H-4	25	41 11.60	-112 29.00	1278.648	1.981	979885.738	-7.138	-150.082	980286.856
H-3	26	41 11.40	-112 32.80	1278.648	7.468	979870.846	-23.425	-165.991	980286.557
H-2	27	41 11.60	-112 37.60	1278.648	8.687	979866.515	-28.431	-170.913	980286.856
H-1	28	41 11.60	-112 43.30	1278.639	6.858	979878.335	-16.049	-158.656	980286.856
H-1A	29	41 11.60	-112 47.70	1278.639	1.524	979896.121	3.383	-139.592	980286.856
I-3	30	41 6.10	-112 37.60	1278.639	1.676	979878.929	-5.660	-148.624	980278.660
I-4	31	41 8.10	-112 41.50	1278.639	7.163	979864.605	-24.658	-167.244	980281.640
J-2	32	41 3.90	-112 41.50	1278.639	5.334	979863.455	-18.986	-161.698	980275.383
I-6	33	41 5.90	-112 33.10	1278.639	3.505	979882.202	-2.654	-145.492	980278.362
I-7	34	41 6.00	-112 31.10	1278.639	6.096	979874.893	-10.912	-153.572	980278.511
I-8	35	41 6.00	-112 29.30	1278.639	7.010	979866.236	-19.849	-162.446	980278.511
I-9	36	41 6.10	-112 27.20	1278.639	8.230	979860.136	-26.475	-168.988	980278.660
J-3	37	41 3.50	-112 31.00	1278.639	2.591	979870.939	-10.059	-152.961	980274.788
LITTLE VALLY	50000	40 60.00	-111 60.00	1278.407	.000	979906.540	31.481	-111.573	980269.574
F1	38	41 20.33	-112 50.48	1278.395	1.097	979914.838	9.141	-133.836	980299.871
F2	39	41 19.73	-112 43.72	1278.395	8.534	979887.035	-20.063	-162.528	980298.976
F3	40	41 20.34	-112 39.03	1278.395	7.468	979881.515	-26.163	-168.701	980299.886
F4	41	41 20.09	-112 31.05	1278.395	4.877	979904.792	-1.713	-144.430	980299.513
G-1	42	41 14.11	-112 32.42	1278.395	1.219	979882.121	-14.339	-157.308	980290.597
G-2	43	41 14.93	-112 34.84	1278.395	7.620	979876.434	-23.224	-165.751	980291.819
G-3	44	41 14.97	-112 37.76	1278.395	8.230	979873.605	-26.301	-168.787	980291.679
G-4	45	41 15.14	-112 40.29	1278.395	8.230	979873.207	-26.952	-169.438	980292.132
G-5	46	41 15.40	-112 43.21	1278.395	8.839	979877.052	-23.683	-166.126	980292.520
G-6	47	41 15.54	-112 45.75	1278.395	6.096	979885.210	-14.887	-157.520	980292.729
G-7	48	41 15.63	-112 47.89	1278.395	3.048	979899.812	.523	-142.320	980292.863
E-1	49	41 24.61	-112 39.38	1278.380	3.353	979894.952	-17.831	-160.651	980306.257
E-6	50	41 26.26	-112 48.08	1278.380	4.267	979906.066	-9.461	-152.218	980308.717
E-7	51	41 26.23	-112 49.43	1278.380	3.658	979908.345	-6.948	-149.747	980308.674
E-2	52	41 24.74	-112 41.41	1278.380	5.486	979895.049	-18.586	-161.259	980306.450
E-3	53	41 24.80	-112 43.03	1278.380	6.706	979896.747	-17.353	-159.942	980306.540
E-4	54	41 25.01	-112 44.94	1278.380	5.639	979900.797	-13.287	-155.950	980306.853
E-5	55	41 25.29	-112 47.41	1278.380	4.724	979902.967	-11.253	-153.979	980307.270
E-8	56	41 25.00	-112 53.12	1278.380	2.286	979914.325	1.289	-141.604	980306.837
D-1	57	41 28.41	-112 45.93	1278.380	5.029	979905.697	-13.273	-155.977	980311.926
D-2	58	41 28.58	-112 51.77	1278.380	4.877	979905.798	-13.378	-156.093	980312.180
D-3	59	41 28.61	-112 55.86	1278.380	1.829	979904.732	-13.549	-156.474	980312.224
C-1	60	41 33.71	-112 52.32	1278.380	2.743	979916.163	-10.013	-152.875	980319.837
C-2	61	41 33.80	-112 50.16	1278.380	2.896	979916.963	-9.394	-152.245	980319.971
B-1	62	41 39.01	-112 48.72	1278.380	.914	979920.761	-12.764	-155.752	980327.751
D-4	63	41 28.41	-112 54.04	1278.374	2.743	979907.162	-11.104	-153.965	980311.926
D-5	64	41 28.62	-112 50.99	1278.374	3.962	979905.441	-13.514	-156.291	980312.239

CHEMISTRY



CONTENTS

THE GREAT SALT LAKE BRINE SYSTEM

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INTRODUCTION

The Great Salt Lake, a dessicated remnant of Pleistocene Lake Bonneville, is a very complex saline body of water. The interrelationships of the various facets of the Great Salt Lake brine system are described in the following sections:

1. History of Great Salt Lake Brines
2. Physical Characteristics of the Lake Brines
3. Composition of the Lake Brines
4. Dissolved Solids Inflow to the Lake
5. Dissolved Solids Load (Salt Load) in the Lake
6. Brine Concentration Changes
7. UGMS – Great Salt Lake Research Programs

HISTORY OF GREAT SALT LAKE BRINES

Introduction

The dissolved solids present in the brines of the Great Salt Lake were derived, in part, from those salts that were contained in the waters of Pleistocene Lake Bonneville. Evaporation concentrated those dissolved solids into what is now Great Salt Lake brine. Additional dissolved solids were then and are still being brought into the lake by inflow (i.e., rivers, groundwater, rainfall).

The Great Salt Lake is one of the most saline lakes in the world. Table 1 shows the concentration in weight percent (wt.%) and the percent of dissolved solids of a Great Salt Lake (GSL) brine compared to brines of the Dead Sea and the ocean. The dissolved solids data show that the Great Salt Lake is quite similar in composition to the ocean, while both of these brines vary significantly from Dead Sea brine in their proportions of chloride, sodium, and sulfate.

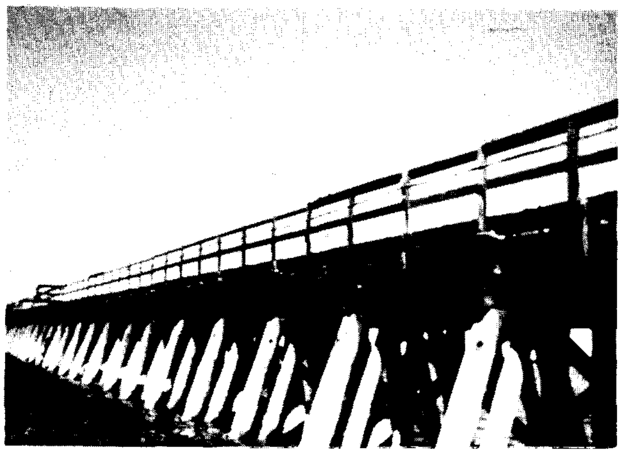
Table 1. Typical brine compositions

	Concentration in brine, Wt.%			g/100 g dissolved solids		
Constituent	GSL	Dead Sea	Ocean	GSL	Dead Sea	Ocean
chloride	14.1	17.5	1.94	55.2	65.1	55.4
sodium	7.6	3.3	1.08	29.8	12.3	30.8
sulfate	2.0	0.7	0.27	7.8	2.6	7.7
magnesium	1.1	3.4	0.13	4.3	12.6	3.7
calcium	0.02	1.4	0.04	0.06	5.2	1.1
Total Wt. %	25.52	26.9	3.50			

From Flint, 1971

Precauseway (1960) Conditions

Prior to the completion of the Southern Pacific Railroad (SPRR) causeway in 1959, which replaced a 12 mile long wooden trestle, the Great Salt Lake was a continuous, relatively homogeneous saline body of water. Changes in concentration were dependent only on inflow and evaporation. Somewhat more concentrated brine was present in the western and northern portions of the lake, where higher evaporation rates were experienced than on the remainder of the lake because of the hot, dry summer winds coming from the arid regions directly to the north and west. Precipitation, in contrast, is heaviest on the eastern and southern portions of the lake, which reduces brine concentration in those areas. (A more complete discussion of precipitation and evaporation patterns over the Great Salt Lake is contained in Gwynn and Sturm, Solar Ponding Adjacent to the Great Salt Lake and other papers, this volume). The concentration of brine is also diminished by the fresh water near the areas of major surface inflow, located on the southern and eastern portions of the lake.



Wooden railroad trestle across Great Salt Lake that was constructed in 1902 and replaced by a rockfill causeway in 1959.

Post Causeway (1960) Conditions

The central twelve mile portion of the SPRR causeway was designed as a permeable rockfill structure with two concrete box culverts to permit brine transfer through the structure. The causeway has essentially divided the lake into two bodies of water, the north arm and the south arm, with each arm developing its own physical and chemical characteristics.

PHYSICAL CHARACTERISTICS OF THE LAKE BRINES

Color, turbidity, head difference, density, and south arm stratification are the major differences that have been noted between the north and south arms since the causeway's construction.

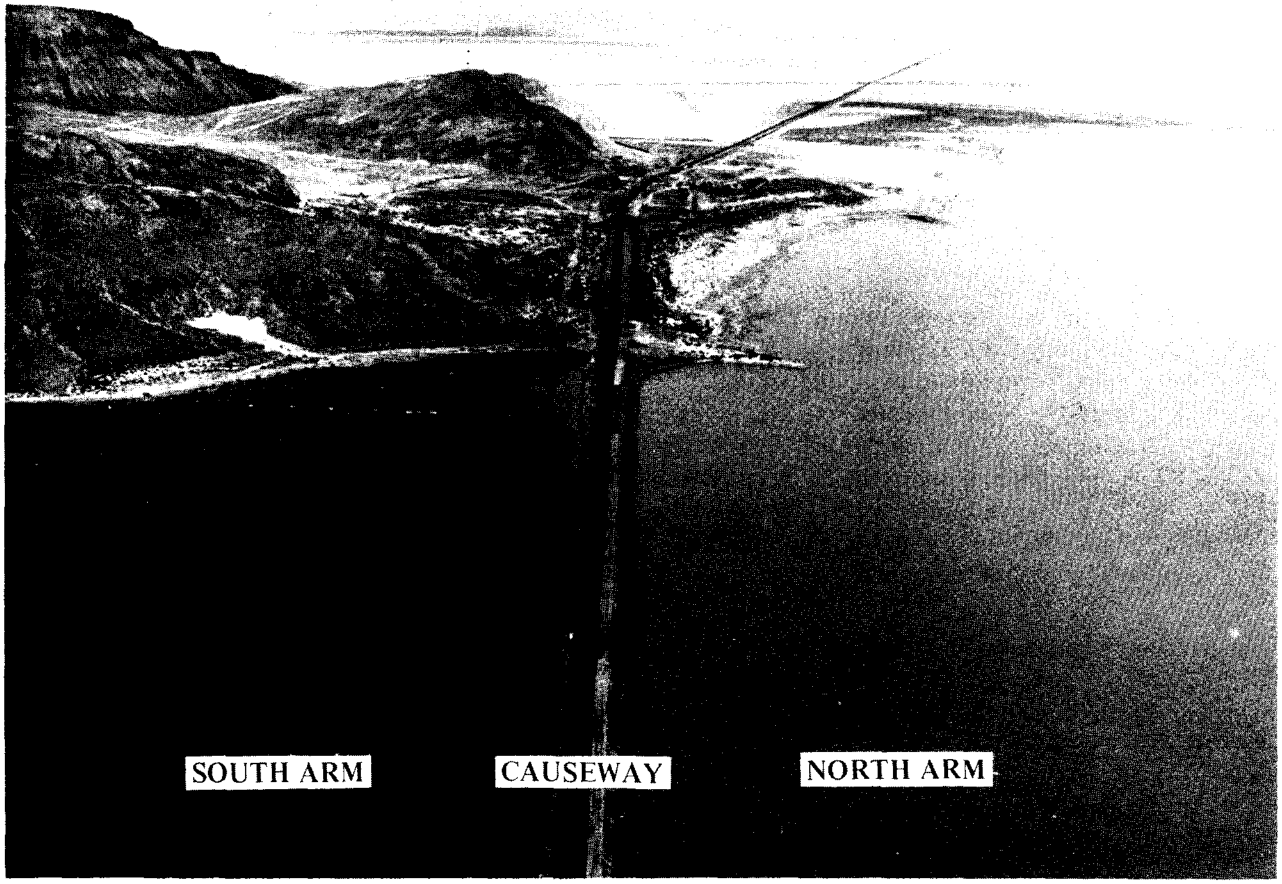
Color

The color of the brine is the first and most dramatic difference that can be seen between the north and south arms of the lake. The north arm brine appears reddish-pink in color, whereas the south arm brine is blue-green. The coloration in both arms is the result of innumerable algae and bacteria of the few species which are able to survive in these saline lake waters. The blue-green species of algae are more suited to the lower salinity of the south arm, and the red algae to the greater salinity of north arm.

Turbidity

The turbidity or lack of clarity of the lake's brines is measured by the depth at which a secchi disk, a 12 inch diameter white plastic disk, is no longer visible in the brine. In the north arm, turbidity is mainly due to the algae, etc. which cause the reddish-pink color of the brine. The turbidity measurements throughout the north arm vary from as much as three feet during the spring to less than one foot during the fall.

The turbidity of the south arm varies both with location and time. The inflow areas of the south arm have the greatest turbidity due to finely divided suspended sediments from the rivers. In general, the eastern side of the lake is more turbid than the western side. The turbidity of the south arm varies from four feet during the winter to twenty-four feet during the spring and into the summer. The high turbidity of the south arm in the late winter is a result of suspended mirabilite



Looking west at the western end of SPRR causeway, near lakeside. Note darker coloration of south arm (blue-green) versus lighter coloration of north arm (reddish-pink).

(table 2) and algae population. As the mirabilite dissolves during the spring and the newly hatched brine shrimp consume the algae, the turbidity of the brine suddenly decreases.

Density

The density (which is directly related to and is a measure of ion concentration) differences that have developed between the north and south arm brines of the Great Salt Lake, since the construction of the SPRR causeway, are an enhancement of precauseway conditions, as previously discussed. The density of the lake brine varies inversely with seasonal, yearly and long term fluctuations in lake levels.

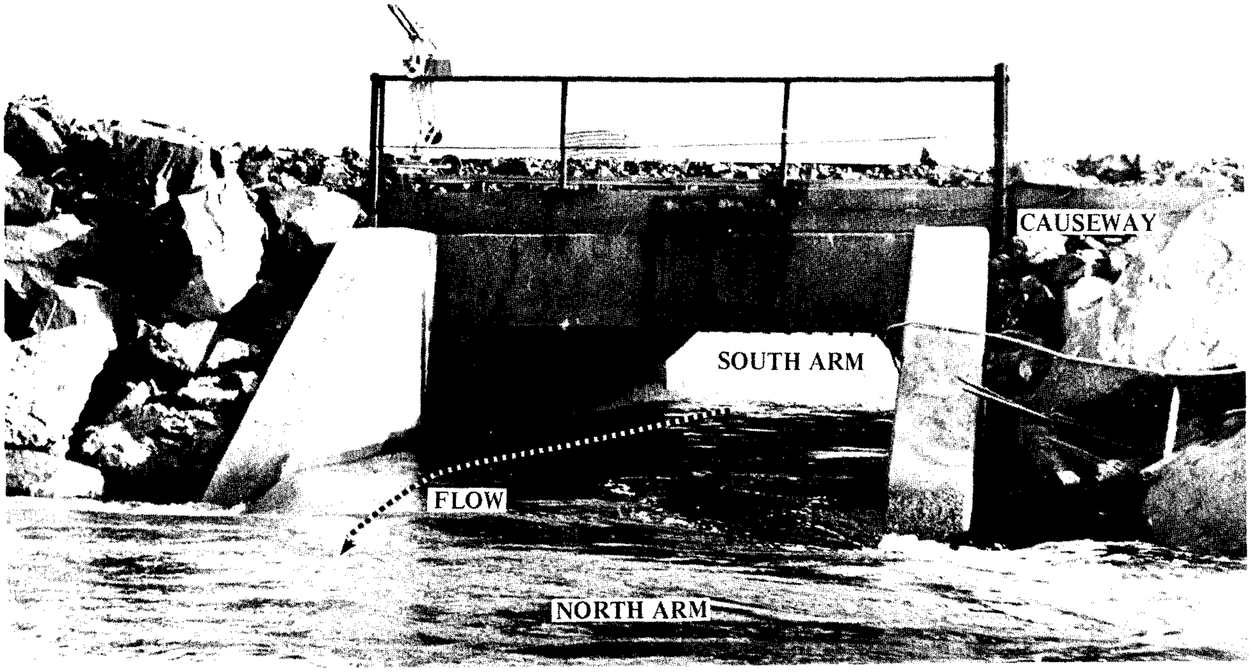
Head Difference

The head difference, or difference in surface elevations between the north and south arms of the lake, is most visible along the causeway. This difference is caused by two factors. First, and most important, approximately 90% of the surface inflow to the lake enters the south arm and causes an increase in volume which is not immediately transferred through the causeway to the north arm. Second, the difference in brine density between the two separated arms of the lake causes the less dense south arm brine to be maintained at a higher level than the more dense north arm brine.

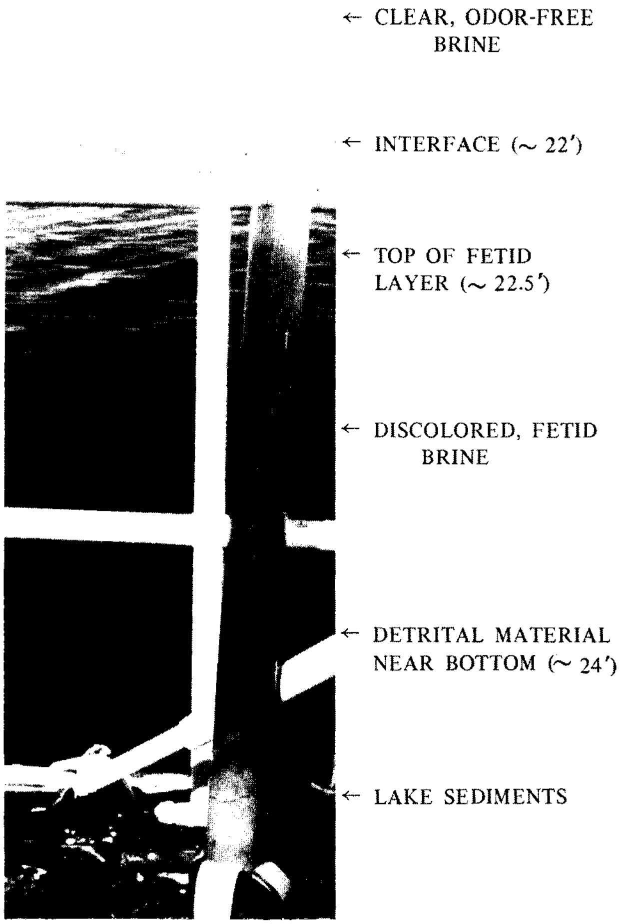
South Arm Stratification

A density stratification or layering of the brine in the south arm of the lake was first observed in 1965 (Hahl and Handy, 1969). Data prior to the construction of the causeway, are insufficient to indicate whether or not a density stratification was prevalent at that time.

The brine in the south arm is stratified into two distinct layers. The top 20-23 feet is relatively clear and odorfree. During 1979, the density at the 10 foot depth varied from 1.089 to 1.110 g/cc. Below 20-23 feet, however, a sudden increase in density is measured. Slightly below that increase, a discolored and fetid (hydrogen sulfide-laden) brine is encountered which continued downward to the bottom of the lake. The density, at the 25 foot depth in the south arm varied from 1.166 to 1.170 g/cc during 1979.



North end of east culvert on SPRR causeway. Note drop in surface elevation (head difference) as the south arm brine flows into the north arm.



Stratified column of lake brine and sediments. Note decreasing clarity with increasing depth.

Table 2. Common minerals from the GSL brine system (natural and processed).

Common Name	Formula
Anhydrite	$CaSO_4$
Aragonite	$CaCO_3$
Arcanite (Potassium Sulfate)	K_2SO_4
Astrakanite (Bloedite)	$Na_2SO_4 \cdot MgSO_4 \cdot 4H_2O$
Bischofite	$MgCl_2 \cdot 6H_2O$
Carnallite	$KCl \cdot MgCl_2 \cdot 6H_2O$
Epsomite (Bitter Salts)	$MgSO_4 \cdot 7H_2O$
Glaserite (Apthitalite)	$Na_2SO_4 \cdot 3K_2SO_4$
Mirabilite (Glauber's Salt)	$Na_2SO_4 \cdot 10H_2O$
Halite	$NaCl$
Hexahydrite	$MgSO_4 \cdot 6H_2O$
Kainite	$KCl \cdot MgSO_4 \cdot 2.75\ H_2O$
Langbeinite	$2MgSO_4 \cdot K_2SO_4$
Leonite	$MgSO_4 \cdot K_2SO_4 \cdot 4H_2O$
Magnesium Sulfate	$MgSO_4$
Salt Cake (Thenardite)	Na_2SO_4
Schoenite	$MgSO_4 \cdot K_2SO_4 \cdot 6H_2O$
Vanthoffite	$3Na_2SO_4 \cdot MgSO_4$

COMPOSITION OF THE LAKE BRINES

Major Ions

The major cations (positively charged ions) in the Great Salt Lake brines, in decreasing order of abundance, are sodium (Na), magnesium (Mg), potassium (K), and calcium (Ca). The major anions (negatively charged ions), in decreasing order of abundance, are chloride (Cl) and sulfate (SO_4). Each of these ions, in its relative proportion to the other ions, forms an important link in the brine chemistry of the lake. The minerals, most of which contain waters of hydration, are formed from these ions upon precipitation from the brine. The most common minerals are listed in table 2.

Cations

Sodium: Sodium is the second most abundant ion in the waters of the Great Salt Lake. During water year 1979 its concentration varied from a low of 40.0 g/l (3.7%), to a high of 106.5 g/l (8.7%). Sodium chloride, or common table salt, is the first and most common mineral to precipitate from evaporating Great Salt Lake brines. If brine is sufficiently concentrated, sodium sulfate, in the form of glaubers salt (mirabilite), will precipitate naturally as a result of winter cooling. More dilute brine requires colder temperatures for precipitation of mirabilite. Other sodium bearing minerals that can be produced through solar evaporation are astrakainite, glaserite, and vanthoffite.

Magnesium: Magnesium is the fourth most abundant ion. The lowest magnesium concentration determined during water year 1979 was 5.4 g/l (0.50%) and the highest was 11.9 g/l (0.97%). Magnesium minerals begin to precipitate in industrial solar ponds after approximately 65% of the water has been evaporated from present north arm brine. The first magnesium mineral to precipitate upon concentrating the brine is epsomite, while other typical magnesium minerals, that can precipitate after further concentration of the brine, are kainite, schoenite, hexahydrite, and carnallite. Magnesium chloride brine is the last major component in the normal concentration path of Great Salt Lake brine.

Potassium: Potassium is the fifth most abundant ion. During water year 1979, the potassium content of the lake varied from a low of 2.9 g/l (0.26%) to a high of 8.82 g/l (0.72%). Potassium minerals begin to precipitate in industrial solar ponds after approximately 75% of the water contained in present north arm brine has been evaporated. Typical potassium bearing minerals produced through solar evaporation are kainite, schoenite, and carnallite.

Calcium: Calcium is the least abundant of the six major ions. It varied in concentration from a low of 0.28 g/l (0.026%) to a high of 0.45 g/l (0.036%) during water year 1979. The calcium level in Great Salt Lake brine is low as compared to the proportion of calcium in surface inflow, because it readily reacts with carbonate and sulfate ions to form nearly insoluable compounds.

Anions

Chloride: Chloride is the most prevalent of all the ions. It varied in concentration from a low of 76.0 g/l (7.0%) to a high of 190.7 g/l (15.59%) during water year 1979. Besides with sodium, the chloride ion also precipitates with potassium and magnesium ions to form complex salts in industrial solar ponds. Sodium chloride co-precipitates with all other minerals as the pond brines concentrate further. Other chloride salts that are found in solar ponds are kainite, carnallite, and bischofite.

Sulfate: The sulfate ion is the third most abundant ion in the Great Salt Lake brine system. Its concentration varied from a low of 10.2 g/l (0.94%) to a high of 25.0 g/l (2.0%) duirng water year 1979. The sulfate ion is particularly temperature sensitive, and will precipitate readily with any of the major cations, especially upon cooling of the brine. The most common sulfate salt is mirabilite. A multitude of sulfate minerals can be precipitated within solar ponds. The most common salts are epsomite, hexahydrite, kainite, and schoenite.

Waters of Hydration

The majority of the minerals precipitated from Great Salt Lake brine contain waters of hydration, or water molecules that are incorporated into the molecular structure of minerals. Mirabilite ($Na_2SO_4 \cdot 10H_2O$), has a very high degree of hydration. When warmed mirabilite will completely dissolve in its own hydration waters.

Waters of hydration are a major concern when considering the minerals from Great Salt Lake brine. Water, thus incorporated into minerals, is effectively removed from solution, and, depending upon the degree of hydration, the type of minerals that will sequentially precipitate from the brine are affected. Waters of hydration also effect the physical characteristics of some types of minerals. When Great Salt Lake brine is acted upon by either natural or man-induced forces, i.e., evaporation, heating, cooling, etc., a great variety of minerals can be produced. Table 2 lists some of these minerals.

Minor Ions

The Great Salt Lake brine system contains many minor or trace ions. Table 3 shows some of these ions and their approximate concentrations in the three brine types within the lake. The concentrations of these ions are dependent on 1) the solubilities of potential compounds containing these ions and 2) the supply of trace ions to the lake. The solubilities of these ions are related to both the composition and the concentration of the lake brine.

Table 3. Approximate concentrations of trace ions in Great Salt Lake brines[1].

Values in mg/l

BRINE TYPES	Br*	Li*	B*	NH_4 as N	HCO_3	CO_2	CO_3	CO_3 Solids	F	OH	NO_3 as N	NO_2 as N	P as Ortho
South Arm Shallow	60	20	20	0.3	650	5	0	310	1.8	0	1.6	<0.05	0.6
South Arm Deep	105	33	33	4.5	500	50	0	250	2.0	0	1.3	<0.05	1.9
North Arm	150	50	50	0.5	450	25	0	240	2.2	0	0.7	<0.05	0.5

Values in $\mu g/l$

	As	Ba	Cd	Cr	Cr as Hex	Cu	Pb	Fe	Mn	Ni	Se	Zn
South Arm Shallow	150	<500	<50	<100	25	170	<200	200	<50	<200	<5	50
South Arm Deep	250	<500	<50	<100	12	170	<200	<100	<50	<200	<5	60
North Arm	225	<500	<50	<100	12	170	<200	<100	<50	<200	<5	60

[1] From Utah State Division of Health Analysis Reports – Water Year 1979

* From UGMS Analyses

The inflow waters to the Great Salt Lake contain concentrations of some ions, on a dry weight ratio, that are greater than the dry weight ratio that exists in the lake. This condition occurs when the cations in the inflow waters, such as calcium, react readily with sulfate, sulfide, and carbonate anions and precipitate from the brine (i.e., $CaSO_4$, $CaCO_3$, etc.). The maximum concentration at which these ions exist, as a dissolved species, is dependent upon the solubility of the least soluble compound of that ion in the brine of a particular concentration. The concentration of those ions that do not readily react to form precipitates, such as lithium (Li), boron (B), and Bromine (Br), is directly proportional to the concentration of the brine. Such ions can be used to monitor brine concentration because of their linearity of concentration and because of their ease of analysis. Other trace ions may be precipitated, or become more soluable with increasing brine concentration, such as iron (Fe) and zinc (Zn) respectively (table 3).

Radiochemistry

The radiochemistry, or naturally occurring very low-level, low-intensity radioactivity that occurs within the lake has only recently been investigated. A very rudimentary investigation of several samples, utilizing highly sophisticated radiation detectors, has shown vertical stratification of various low-level radioactive species in the lake brines. Further research is anticipated and warranted to investigate this phenomena.

DISSOLVED SOLIDS INFLOW TO THE LAKE

The three types of inflow to the lake, surface inflow, subsurface inflow, and precipitation, each contribute dissolved solids to the lake.

Surface Inflow

The Bear, Weber, and Jordan River systems, the major sources of surface inflow to the Great Salt Lake, contribute approximately 90% of the surficial inflow and approximately 60-80% of the surficial dissolved solids load entering the lake. The remaining surface inflow and dissolved solids come from small streams and canals. Arnow and Mundorff (1972) state:

> "The water that enters Great Salt Lake in the three main streams is quite different in chemical quality from the water in the headwaters of these streams. Most of the runoff in the three streams originates as snowmelt or rainfall on the Uinta Mountains and Wasatch Range, and this runoff is low in dissolved solids and of the calcium bicarbonate type – suitable for most any use.
>
> In the lower reaches of the Bear and Jordan Rivers, however, the dissolved solids increase because of evapotranspiration, return flow from irrigated lands, discharge of industrial and municipal wastes, and groundwater inflow; and the water type changes in these two streams as the major dissolved constituents become sodium, chloride, and sulfate. In the Weber River, however, the dissolved solids do not greatly increase and the water type remains the same."

An approximate breakdown of the total surficial inflow volume and contributed dissolved solid load for water year 1964 is shown in table 4. The three major river systems contributed 87% of the total surficial inflow but only 59% of the total dissolved solids load during that time. The other sources of surficial inflow, springs, drains, and canals represented the remaining 13% of the inflow volume while contributing the remaining 41% of the dissolved solids load.

Table 5 shows the quality of water entering the Great Salt Lake from the three major tributaries during water year 1975, and illustrates the ranges of some of the more common ion constituents. The total surface inflow volume (table 4) represents 16% of the lake volume. The total dissolved solids contained represent only 0.05% of the dissolved solids load of the entire lake. A standard surface elevation of 4200′ is assumed.

Table 4. Great Salt Lake surface inflow data.

Source	Drainage Area (mi^2)	Percent of Discharge	Percent of Dissolved Load	Acre Feet (Thousands)	Tons Load (Thousands)
Bear River	6,800	53	37	940	795
Weber River	2,060	23	9	412	189
Jordan River	3,490	11	13	199	287
Other	9,150	13	41	219	878
Total	21,500	100	100	1,770	2,149

From Hahl, 1968 – Data for Water Year 1964

Table 5. Ranges of some dissolved solids constituents of major tributaries entering the Great Salt Lake (Water Year 1975).

Values in mg/l

Tributary	Silica		Calcium		Magnesium		Sodium		Potassium		Bicarbonate		Sulfate		Chloride	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Bear River at Corrine	16	8	69	51	65	20	300	59	22	7	372	211	67	31	460	85
Weber River at Plain City	12	8	65	35	23	9	49	12	7	2	303	135	34	15	64	16
Jordan River at 5800 So. SLC	31	20	180	83	74	54	220	140	21	13	354	251	460	240	310	190

Data From: Water Resources Data for Utah
U. S. Geological Survey Water Data
Report UT-75-1
October 1974 - September 1975

An average composition of surficial inflow to the lake during 1960-61 is shown in the following listing. It is presented as dry weight percentages of the various chemical constituents. Note that approximately 60% of the dissolved solids load is sodium and chloride.

Dry Weight Percentages of Surficial Inflow Dissolved Solids Constituents:

Silica	1.3	Bicarbonate	12.8	Sodium	22.7
Potassium	1.5	Magnesium	3.7	Chloride	36.3
Nitrate	.3	Sulfate	14.3		(59.0)
Calcium	7.1				

From Hahl and Lanford, 1964

Subsurface Inflow

Very little is known concerning the amount or the composition of dissolved solids in the groundwater inflow to the Great Salt Lake. The estimates of subsurface inflow volume vary from 275,000 acre feet, reported by Peck and Richardson (1966) as the average for the years 1937-1961, to an average of 75,000 acre feet for the years 1937-1973, reported by Arnow in 1977. Handy and Hahl (1966) reported a dissolved solids load of 1.2 million tons contained in 200,000 acre feet of subsurface inflow during 1964. This flow for 1964 would have an average concentration of 700 ppm total dissolved solids.

The volume of subsurface inflow to the lake and the dissolved load are very small compared to the total volume and load of the lake. The estimated water volume contributions to the lake, of 75,000 to 275,000 acre feet represent only .68 to 2.48% of the total lake volume, based on a surface elevation of 4200 feet. The 1.2 million tons of dissolved solids reported by Handy and Hahl (1966), represent only 0.03% of the total dissolved solids load in the Great Salt Lake.

Precipitation (Rainfall)

The climate and precipitation patterns over the Great Salt Lake are complex. Whelan (1973) states: "The climate of the area ranges from temperate-arid west of the lake, with an annual precipitation of 4.5 inches, to temperate semi-arid east of the lake, with an annual precipitation of 16 inches" (see Eubank and Brough, this volume). Precipitation on the surface of the Great Salt Lake is estimated to contribute 25 to 30% of the total inflow to the lake. This represents approximately 6% of the lake volume as calculated for a lake surface elevation of 4200 feet. Very little is known about the dissolved solids contributed to the lake by rainfall, however, windblown salts from the desert areas west of the lake are possibly brought into the lake by precipitation.

DISSOLVED SOLIDS LOAD (Salt Load) IN THE GREAT SALT LAKE

The dissolved solids load or "salt load" of the Great Salt Lake, the total weight of the ions dissolved in the lake waters, is commonly expressed in terms of billions of tons. The salt load varies through time as mineral salts precipitation and dissolution occur. Some precipitated salts may be prevented from dissolving for extended periods of time if they are covered by a layer of sediments.

The total dissolved solids content of lake brine is a measure of the total amount of ions dissolved in a given quantity of water. This value is commonly expressed either in terms of weight percent (wt.%, i.e. weight of ions per weight of brine) or as a ratio of ion weight to brine volume, such as grams per liter (g/l). The total dissolved solids content of the lake, has fluctuated greatly during historic times due to changes in the lake's surface elevation, and therefore its volume. The reported dissolved solids content of the lake has varied from 15% in the 1870's (elevation 4212 feet above mean sea level (MSL)) to approximately 28% in the early 1900's and 1960's (elevation 4191 MSL), (Hahl and Langford, 1964).

Prior to 1966 no continuous lake brine monitoring program was conducted, and very little can accurately be said concerning any changes in brine concentrations. In fact, very few samples, if any, of north arm brine were analyzed before 1966.

Table 6 shows the lake sampling dates, lake elevation and volumes near the annual low lake level for each water year from 1966 to 1979. These samples are considered the best for yearly comparisons because lake brines are in their most homogenous state at this time of year. Table 7 is a tabulation of total dissolved solids concentration and total weight percent for the three brine types, south arm shallow, south arm deep, and north arm, and the load distribution between the north and south arms of the lake from 1966 to 1979.

Prior to the completion of the SPRR causeway, in 1959, the lake reached saturation with respect to sodium chloride when its elevation fell to, or below, 4196 feet (Whelan, 1973). Near this elevation, the weight percent dissolved solids in the lake remained fairly constant, near 28%. Data from 1966 to 1970 show a decrease in the dissolved solids load present in the Great Salt Lake as a result of the precipitation of halite. Even though the annual high lake levels were above 4196 feet, for several of these years, the rate of dissolution of the halite was not sufficient to redissolve the halite precipitated during those annual low lake levels. Lake volume is directly related to lake elevation and is the single greatest influence on the brine concentrations of the lake. Brine concentrations can be directly related to volume changes until that point where the brine becomes saturated with sodium chloride. Beyond that point, concentration is not always directly related to volume changes, because of the physical limitations of halite dissolution rates as compared to halite precipitation rates from the brine.

From 1971 to 1976 the total tons of dissolved solids increased. Salt that had been precipitated on the

Table 6. North and south arm sampling[1] dates near the end of Water Years 1966-1979 with respective lake elevations and volumes.

	NORTH ARM			SOUTH ARM			
Water Year	Sampling Date	Elevation(2) (MSL)	Volume(3) (A.F. x 10^3)	Sampling Date	Elevation (MSL)	Shallow (<23') Volume(4) (A.F. x 10^3)	Deep (>23') Volume (A.F. x 10^3)
1966	9-23	4193.0	3,640	10-27, 28	4193.4	6,691	164
1967	10-19	4193.4	3,740	10-7	4193.9	6,759	297
1968	9-28	4193.8	3,841	9-28	4194.4	6,831	421
1969	10-25	4194.2	3,946	10-24	4195.3	7,048	617
1970	10-25	4194.0	3,893	11-12	4195.2	7,043	595
1971	11-9	4196.0	4,450	11-3	4197.2	7,435	1,025
1972	10-25	4196.7	4,665	10-27	4198.3	7,786	1,291
1973	10-10, 11	4197.5	4,926	10-5	4199.3	7,964	1,521
1974	10-4	4197.8	5,027	10-1	4199.2	7,936	1,501
1975	10-10	4198.6	5,308	10-15	4199.9	8,123	1,641
1976	10-21	4199.2	5,535	10-13	4200.4	8,316	1,756
1977	10-17	4198.0	5,096	10-8	4198.8	7,800	1,414
1978	10-27	4197.3	4,859	10-6	4198.6	7,750	1,366
1979	10-17	4196.6	4,633	11-1, 6	4197.6	7,584	1,118

[1] UGMS Great Salt Lake Sampling Program

[2] Taken from nearest semi-monthly reading as reported by USGS. All elevations are given in feet.

[3] Volume readings are total for a particular elevation. The volume displaced by precipitated halite is unknown and is therefore not taken into consideration. The greatest effect will be in the north arm and south arm deep values.

[4] Does not include volume of bays.

Table 7. Total dissolved solids tabulation[1] 1966-1979 near the end of the Water Years.

Water Year	SOUTH ARM BRINE Shallow (<23') g/l[2]	SOUTH ARM BRINE Shallow (<23') Tons[3]	SOUTH ARM BRINE Deep (>23')[4] g/l	SOUTH ARM BRINE Deep (>23')[4] Tons	NORTH ARM BRINE g/l	NORTH ARM BRINE Tons	Total Tons Dissolved	Percent Distribution North	Percent Distribution South
1966	277.95	2,528.7	340.4	75.9	333.01	1,648.2	4,252.8	38.8	61.2
1967	255.80	2,350.9	323.79	130.8	339.18	1,724.8	4,206.5	41.0	59.0
1968	232.52	2,159.7	270.74	155.0	334.47	1,746.8	4,061.5	43.0	57.0
1969	212.25	2,034.0	272.20	228.4	334.47	1,794.6	4,057.0	44.2	55.8
1970	199.14	1,907.0	288.64	233.5	336.28	1,780.0	3,920.0	45.4	54.6
1971	164.63	1,664.3	258.95	360.9	315.68	1,910.1	3,935.2	48.5	51.5
1972	148.60	1,573.2	260.95	458.1	334.47	2,121.5	4,152.8	51.1	48.9
1973	138.35	1,498.1	259.77	537.2	339.62	2,274.7	4,310.0	52.8	47.2
1974	127.99	1,381.1	254.35	519.1	326.77	2,233.5	4,133.7	54.0	46.0
1975	125.51	1,386.2	261.08	582.5	338.80	2,445.2	4,413.9	55.4	44.6
1976	120.38	1,361.2	272.67	651.0	343.44	1,584.7	4,596.9	56.2	43.8
1977	141.11	1,496.6	269.03	517.2	343.08	2,377.2	4,391.0	54.1	45.9
1978	143.08	1,507.7	255.29	474.1	334.72	2,211.4	4,193.2	52.7	47.3
1979	160.12	1,651.1	258.82	393.4	341.44	2,150.9	4,195.4	51.3	48.7

[1] Sampling dates and volume data are from Table 6.

[2] Averaged values for all samples. (g/l = grams per liter)

[3] Tonnages: a) Actual tons are x10^6

b) Due to unknown volume of precipitated halite south arm shallow tonnages may be slightly high.

c) Due to unknown volume of precipitated halite south arm deep and north arm tonnages may be high.

d) Tons = χ g/l x volume (A.F.) x 1.3597 tons/A.F.

[4] South arm deep g/l values may be unduely high because of sampling technique and relative depth of lake at sampling locations.

lake bottom in prior years slowly redissolved as the lake level rose above 4196 feet. The rate of rise in lake elevation and the degree of mixing determined the short-term or yearly concentrations of the lake brines. It is believed that all of the sodium chloride capable of being dissolved from the bottom of the north arm was in solution during June 1976, a recent high lake level. The salt from the bottom of the south arm was dissolved sometime prior to this date because of the lower brine concentration in that arm. Table 8 shows the tons of dissolved ions in the Great Salt Lake and their distribution during June 1976 when the total dissolved load was 4.66 billion tons. From 1977 to 1979 the lake level lowered and the total dissolved load decreased (see table 7), as the result of sodium chloride being precipitated in the north arm of the lake.

The precipitation of halite in the north arm, at present lake elevations, is a result of several factors. First, the causeway restricts the lake currents that existed prior to its construction, and thus diminished the mixing between the two arms of the lake. Second,

Table 8. Dissolved ion tonnages in the Great Salt Lake high lake level – June 1976.

ION	SOUTH ARM BRINE Shallow (<23') g/l	SOUTH ARM BRINE Shallow (<23') Tons	SOUTH ARM BRINE Deep (>23') g/l	SOUTH ARM BRINE Deep (>23') Tons	NORTH ARM BRINE g/l	NORTH ARM BRINE Tons	Percent Distribution S.A.S.	Percent Distribution S.A.D.	Percent Distribution N.A.	Total Tons Dissolved
K	2.92	35.1	6.29	18.4	8.48	68.4	28.8	15.1	56.1	121.9
Na	34.33	412.5	75.03	219.1	105.12	847.9	27.9	14.8	57.3	1,479.5
Mg	3.81	45.8	7.78	22.7	10.40	83.9	30.0	14.9	55.1	152.4
Ca	0.185	2.2	0.381	1.1	0.421	3.4	32.8	16.4	50.8	6.7
Cl	60.46	726.5	131.78	384.9	181.73	1,465.8	28.2	14.9	56.9	2,577.2
SO_4	7.92	95.2	17.30	50.5	21.73	175.3	29.7	15.7	54.6	321.0
Li	.0181	.217	.0387	.113	.0520	.419	29.0	15.1	55.9	.749
Br	.0409	.491	.0912	.266	.1150	.928	29.1	15.8	55.1	1.685
B	.0139	.167	.0296	.086	.0400	.323	29.0	14.9	56.1	.576
Total	109.70	1,318.18	238.72	697.16	328.09	2,646.37	29.4	15.3	55.3	4,661.71
							Average % Distribution			

Lake Volumes: South Arm Shallow (S.A.S.) 8,837,000 A.F.
South Arm Deep (S.A.D.) 2,148,000 A.F.
North Arm (N.A.) 5,932,000 A.F.

surface inflow to the north arm is primarily south arm brine, not fresh water. Third, weather patterns over the north arm result in low rainfall and high evaporation rates. All of these factors tend to increase brine concentration.

Precipitation of sodium chloride does not occur in the south arm of the lake at the present time, because of its diluted state, which is due to two main factors. First, the inflow to the south arm comes as fresh water, and second, weather patterns are not as favorable for high evaporation rates as they are in the north arm. Thus, concentration of lake brines to halite saturation, through evaporation, will occur more quickly in the north arm than in the south arm.

There was a steady increase in the percent of the dissolved solids load in the north arm as compared to the south arm for the entire period from 1966 to 1976 as shown in the "percent distribution" data in table 7. This corresponds to the overall increase in lake volume, and the accompanying dissolution of halite from the north arm along with south arm dilution from inflow. The "total tons dissolved" and "percent distribution" data for both north and south arms are almost identical for years 1972 and 1979, which have nearly the same surface elevation. The total tons dissolved in 1972 is slightly lower than that in 1979 possibly because, in 1972, dissolution of precipitated halite was occurring at a slower rate than the precipitation of halite in 1979.

The reader should keep in mind that many potential sources of error exist in the calculation of the data shown in table 7, such as the chemical analyses themselves, the volume computations for the lake, and the assumption of overall homogeneity of lake brines within the brine types designated.

BRINE CONCENTRATION CHANGES

Seasonal Changes

The concentrations of the lake brines vary on a seasonal basis with changing lake levels (see figure 1), which are influenced by annual inflow and weather cycles. Brine concentrations are lowest during the annual high lake level which normally occurs between May 15 and June 15. During this time of year, inflow to the lake far exceeds evaporation and the lake volume increases, thus raising the lake elevation. Brine concentrations are highest during the annual low lake level which normally occurs between October 15 and November 15, when evaporation far exceeds inflow and the lake volume decreases. Table 9 illustrates the effects of high and low lake levels, as well as the effect of cold weather on the various ion concentrations.

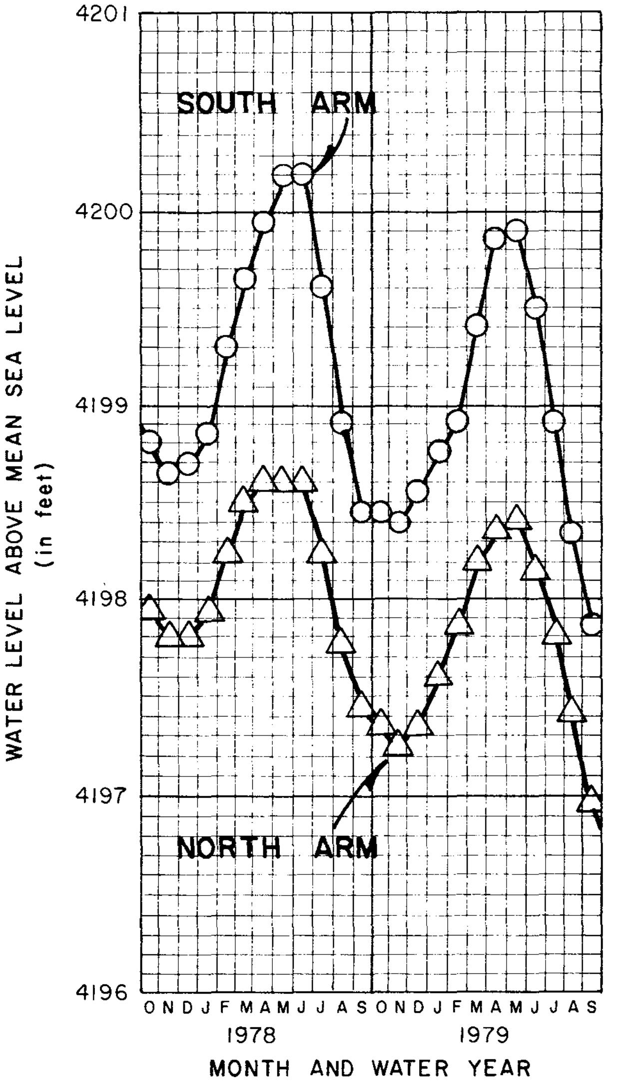


Figure 1. Great Salt Lake Hydrograph for Water Years 1978 and 1979.

After June, when evaporation from the lake normally exceeds inflow (i.e., rivers and rain) and the concentrations of the brines increase with decreasing lake elevations. This cycle ends approximately October 15 to November 15. The concentrations values listed under *Low* (table 9) represent typical brines near that time. A comparison of *High* versus *Low* values for the three brine types; north arm, south arm shallow, and south arm deep, show the increase in concentrations experienced by the lake brines due to evaporation during the summer of 1978. Exceptions are the sodium and sulfate values for the south arm deep samples. Excess

Table 9. Typical seasonal changes in brine composition.

Location	NORTH ARM CONCENTRATIONS$^{(1)}$			SOUTH ARM CONCENTRATIONS					
	at 10′			South Arm Shallow 10′			South Arm Deep 25′		
Condition$^{(2)}$	High	Low	Cold	High	Low	Cold	High	Low	Cold
Date	6-21-78	10-27-78	3-9-79	7-14-78	10-6-78	2-6-79	7 -14-78	10-6-78	2-6-79
Parameter									
K	7.33	8.44	7.75	2.99	3.60	3.27	5.45	6.30	5.15
Na	101.75	103.80	97.00	40.70	47.40	44.50	79.60	79.50	79.80
Mg	10.99	12.02	11.37	4.57	5.04	4.87	8.52	8.62	8.33
Cl	183.63	184.34	179.02	73.58	80.12	78.70	140.03	145.34	141.80
SO_4	21.72	21.81	13.25	9.71	9.87	9.59	17.44	16.46	17.61
Density	1.216	1.225	1.203	1.090	1.102	1.098	1.167	1.175	1.170

[1] Concentrations are given in grams per liter.
[2] Condition – High - High lake level brine
Low - Low lake level brine
Cold - Winter cooled lake brine

sodium and sulfate present in the *High* sample, are probably due to the redissolving and remixing of the small amount of mirabilite which precipitated during the previous winter from the south arm shallow brines.

As the lake level completes its annual cycle from November to May, a dilution of the *Low* lake brines occurs, as inflow to the lake exceeds evaporation. The lake brines also cool during the latter part of this time with the coming of winter. The *Cold* data represent the winter cooled lake brines. The coldest lake brines are normally encountered in February.

A comparison of *Low* versus *Cold* data (table 9) reveals a slight dilution of all the *Cold* brines with respect to all parameters except sodium and sulfate. These two ions, sulfate in particular, show a greater drop in concentration in the north arm and south arm shallow brines during the winter cooling process when mirabilite is formed at the surface. Once again the south arm deep concentration values do not show a decrease with respect to the concentrations of sodium and sulfate. Some mirabilite, which was precipitated from the south arm shallow brines, was redissolved in the warmer south arm deep brines, and thus the concentrations of both sodium and sulfate increased. The precipitation and subsequent dissolution of mirabilite effect the concentrations of the lake brines fourth only to dilution, evaporation, and halite precipitation.

Long Term Changes

The factors which have and will effect long term changes in lake brine concentrations are changes in lake elevation and the SPRR causeway. Both factors have already been discussed to some extent in this paper. A comprehensive discussion of historical lake elevations by Arnow is contained in this volume.

The long term effects of the Southern Pacific Railroad causeway on brine concentration are not known completely, but preliminary data indicate that, at present lake elevations, the causeway 1) permits the migration of dissolved salts from the south arm to the north arm and 2) will continue to maintain the concentration of the north arm at a higher level than that of the south arm. These conditions will most likely diminish when the lake elevation decreases to a point where south arm brines become saturated with respect to halite.

UGMS–GREAT SALT LAKE RESEARCH PROGRAMS

The Utah Geological and Mineral Survey (UGMS) has conducted and is now conducting research programs to investigate various facets of the lake's environment and its brines. The three research programs currently active are: the quarterly sampling program, the temperature monitoring program, and the incremental sampling program.

Quarterly Sampling Program

UGMS began the first comprehensive study of the chemical variations within the Great Salt Lake in June 1966. For several years, the lake was sampled at specified locations (see figure 2) at nearly monthly intervals. Since this sampling program proved to be excessive, the sampling interval was reduced to four times a year representing the high and low lake levels, and the approximate mid-points inbetween. The number of sampling locations was also reduced and optimized.

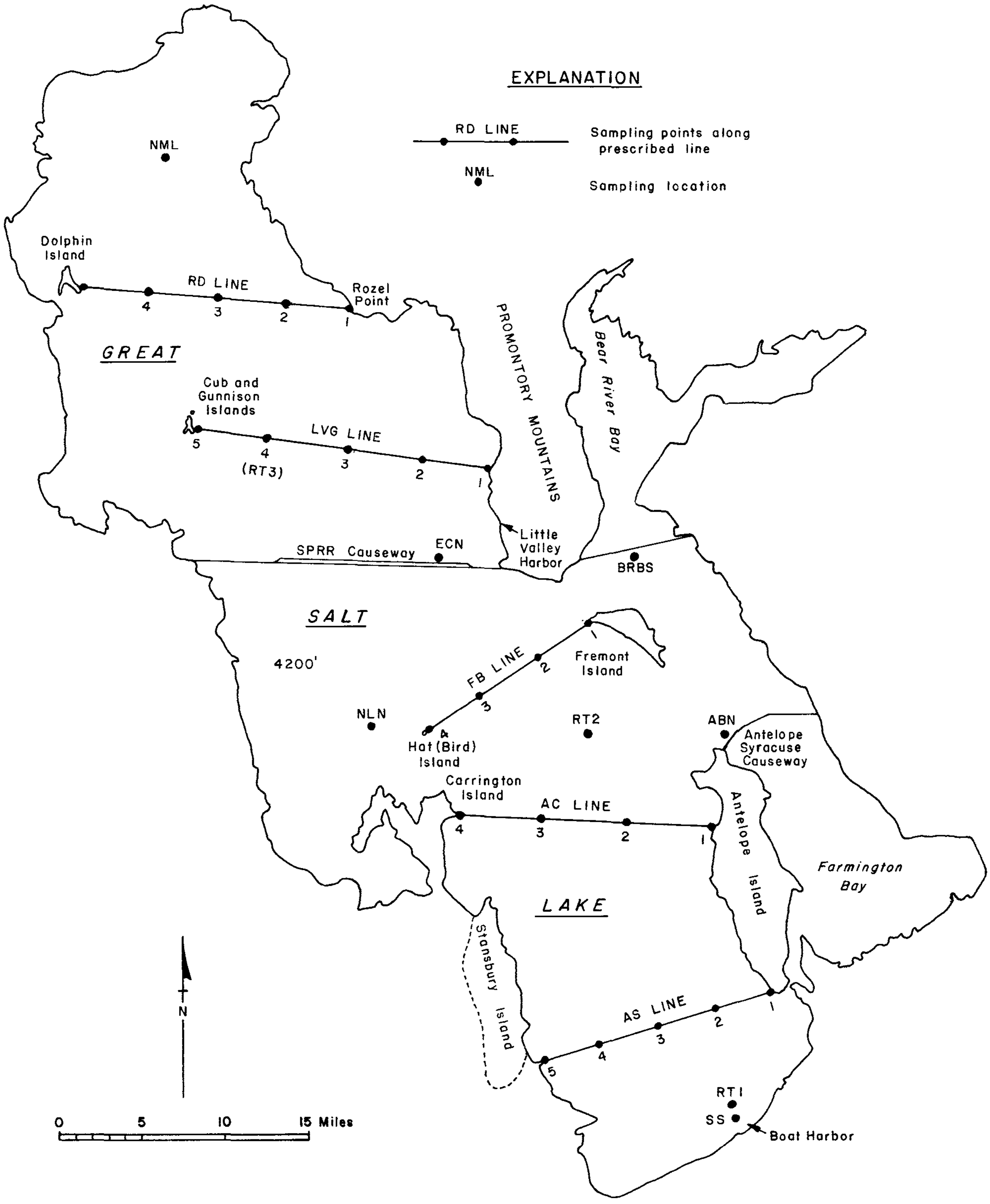


Figure 2. UGMS - Great Salt Lake sampling location map.

Established sampling sites are located by either dead reckoning or a marker bouy. Samples are taken with a 12 volt DC electric pump connected to a weighted hose which is marked at one foot intervals. Several hose-volumes of brine are pumped to flush the hose at each sampling depth to prevent contamination between samples. The brine samples are collected in a one liter polyethylene bottle and temperature and specific gravity reading are taken and recorded for each sample depth.

Before 1967, samples were taken systematically from the surface to the bottom; the vertical sampling depth interval was either 3, 4, or 5 feet. By 1967-68 the sampling depth interval was standardized at 5 feet. The present satndard sampling depths are now .5′ (surface), 5′, 10′, 15′ . . . bottom.

Samples are analyzed for potassium (K^+), sodium, (Na^+), magnesium (Mg^{++}), calcium (Ca^{++}), chloride (Cl^-), sulfate ($SO_4^{=}$), bromide (Br^-), boron (B^{+++}), lithium (Li^+), and specific gravity (g/cc). Analyses prior to 1975 were conducted by UGMS presonnel, since then the analyses have been contracted to private laboratories.

The analytical methods history used for the UGMS brine samples are given in table 10 , and are discussed in more detail in a later article on analytical procedures.

The shear volume of data necessary to determine trends and profiles within the lake is staggering. In the thirteen years of gathering lake brine samples, Utah Geological and Mineral Survey has had over 4,000 samples analyzed, and is now using a computer to file and manipulate this information. Programmers are currently working on new programs to fully utilize this data.

Temperature Monitoring Program

Brine temperature data is collected during normal UGMS quarterly lake sampling to monitor seasonal changes. Table 11 shows selected data from water year 1979. The surface brines of the south arm varied from a low of 29° to a high of 74°F, a variation of 45°F, whereas the bottom brines varied only from 46° to 66°F a variation of only 20°F. Overall, the south arm deep brines remain warmer during the winter and cooler during the summer than do the south arm shallow brines. This data show the insulative properties of the lake brines. The north arm "Winter" brines data in table 11 are not representative of what might be expected had the samples been taken during the coldest portion of the winter. Normally, brines below 10 to 15 feet would be warmer than surficial brines, similar to the temperature profile noted in the south arm. These data for the north arm "Winter" brines show the temperature profile reversal generally noted in lake brines during early spring.

The Utah Geological Survey is also conducting a program to monitor a vertical temperatures profile in the south arm of the lake. A fifty channel digital recorder was connected to thermocouple temperature probes placed at four inch intervals from the bottom to one foot up, two inch intervals from one foot to five feet from the bottom, and one foot intervals from five feet to twenty-five feet, the approximate brine depth at the monitoring site. Additionally, two temperature sensors were placed in the air at distances of four and eight feet above the lake brine surface. Each thermocouple probe was measured every two hours. Over one years data were collected prior to the systems removal, due to thermocouple lead malfunctions. The data collected not only demonstrated the overall characteristics mentioned in the preceeding paragraph but also demonstrated the

Table 10. Analytical procedures used for UGMS Great Salt Lake brine samples 1966 - 1979.

Laboratory	Utah Geological Survey	Chemical & Mineralogical Services	American Chemical & Research
Years	1966 - 1974	1975 - 1978	1979 -
Ions			
K	Atomic Absorption	Flame Emission	Atomic Absorption
Na	Atomic Absorption	Flame Emission	Atomic Absorption
Mg	Atomic Absorption	Titratrametric (EDTA)	Titrametric (EDTA)
Ca	Atomic Absorption	Atomic Absorption	Atomic Absorption
Cl	Titrametic ($AgNO_3$)	Titrametric ($AgNO_3$)	Titrametric ($AgNO_3$)
SO_4	Gravimetric ($BaCl_2$)	Gravimetric ($BaCl_2$)	Gravimetric ($BaCl_2$)
Li	Atomic Absorption	Atomic Absorption	Atomic Absorption
Br	Titrametric ($Na_2S_2O_3 \cdot 5H_2O$)	Titrametric ($Na_2S_2O_3 \cdot 5H_2O$)	X-Ray Fluoresence
B	Colorimetric (Quinalizarin)	Colorimetric (Quinalizarin)	Colorimetric (Quinalizarin)

From Whelan, 1973; and Whelan & Peterson, 1979

Table 11. Great Salt Lake temperature (°F) data from UGMS quarterly samplings (Water Year 1979).

Season	FALL		WINTER		SPRING		SUMMER	
Date	10-6-78	10-27-78	2-6-79	3-9-79	5-15-79	5-25-79	8-19-79	9-1-79
Location	SA-RT2(1)	NA-RT3(2)	SA-RT2	NA-RT3	NA-RT3	SA-RT2	NA-RT3	SA-RT2
Depth (Ft.)								
5	66	60	29	40	66	69	76	74
5	65	60	27	40	64	68	76	74
10	65	60	27	40	62	67	76	73
15	64	60	27	37	60	67	76	73
20	64	61	28	32	47	66	76	73
25	66	61	39	32	48	58	58	66
Bottom (Ft.)	66 (30.5)	61 (29)	46 (31)	32 (27)	48 (29)	48 (31.5)	55 (29)	62 (30)

[1] SA-RT2 - South Arm Sample - Research Tower Two

[2] NA-RT3 - North Arm Sample - Research Tower Three

more subtle day/night temperature cycles experienced by the lake. These data, as a data base for the lakes temperatures, is invaluable. The data to date have proved to be of sufficient worth that a more comprehensive program with improved equipment is anticipated to start in 1980.

Incremental Sampling Program

During October, 1978 a new monthly sampling program was initiated to monitor the vertical concentration gradations and other phenomenon noted in the south arm of the lake. This program was later expanded to include a monthly monitoring program for the north arm to observe, among other things, the mirabilite formation during the winter and its dissolution during the summer. The incremental sampling program is set up as follows:

General: Monthly samplings are taken at Amoco Production Company's south arm weather tower (RT2), and their north arm tower (RT3) (see figure 2). The towers themselves are used by UGMS as a stationary incremental sampling base. Once samples have been collected they are allowed to equilibrate to laboratory temperature before specific gravity measurements are made. Selected samples are submitted for chemical analysis. The density and chemical results have not been fully analyzed as of this date.

South Arm Incremental Sampling: South arm samples are collected at six inch increments from the following intervals; from the surface to six feet, from eight feet to twelve feet, from fourteen feet to twenty feet, and from twenty-five to the bottom. The intervening intervals, from six to eight feet, from twelve to fourteen feet, and from twenty to twenty-five feet are sampled at three inch increments. These last intervals are sampled more closely because they are known or suspected to have density changes. This method of sampling insures a close monitoring of both subtle and dramatic changes in brine composition. Figure 3 demonstrates the gradations of density that occur in the south arm of the lake.

Besides density changes, another phenomenon that has been observed in the south arm deep brine (below 20-23') is the existence of a fetid layer (discussed earlier) within the deep brine. This fetid layer is noted by a foul smell and brown discoloration of the brine. The fetid layer is found to exist, beginning from six to twenty-four inches below the sudden increase in brine density (interface) as shown in figure 3, and continues, along with the increasing specific gravity, to the bottom of the lake. (Also see Taylor, Hutchinson, and Muir, this volume).

North Arm Incremental Sampling: North arm samples are collected at six inch intervals from surface to the bottom. Figure 4 shows two types of profiles that have been encountered to date. The profile dated December 20, 1978 shows what may be considered a typical north arm brine concentration profile, characterized by a relatively homogeneous brine. The profile dated July 20, 1979 demonstrates a brine composition that is relatively homogeneous from the surface to twenty feet. From twenty feet to the bottom, however, the influence on the density of the brines by the dissolution of mirabilite, is readily seen. When comparing the north arm and south arm profiles, please note the different specific gravity scales used.

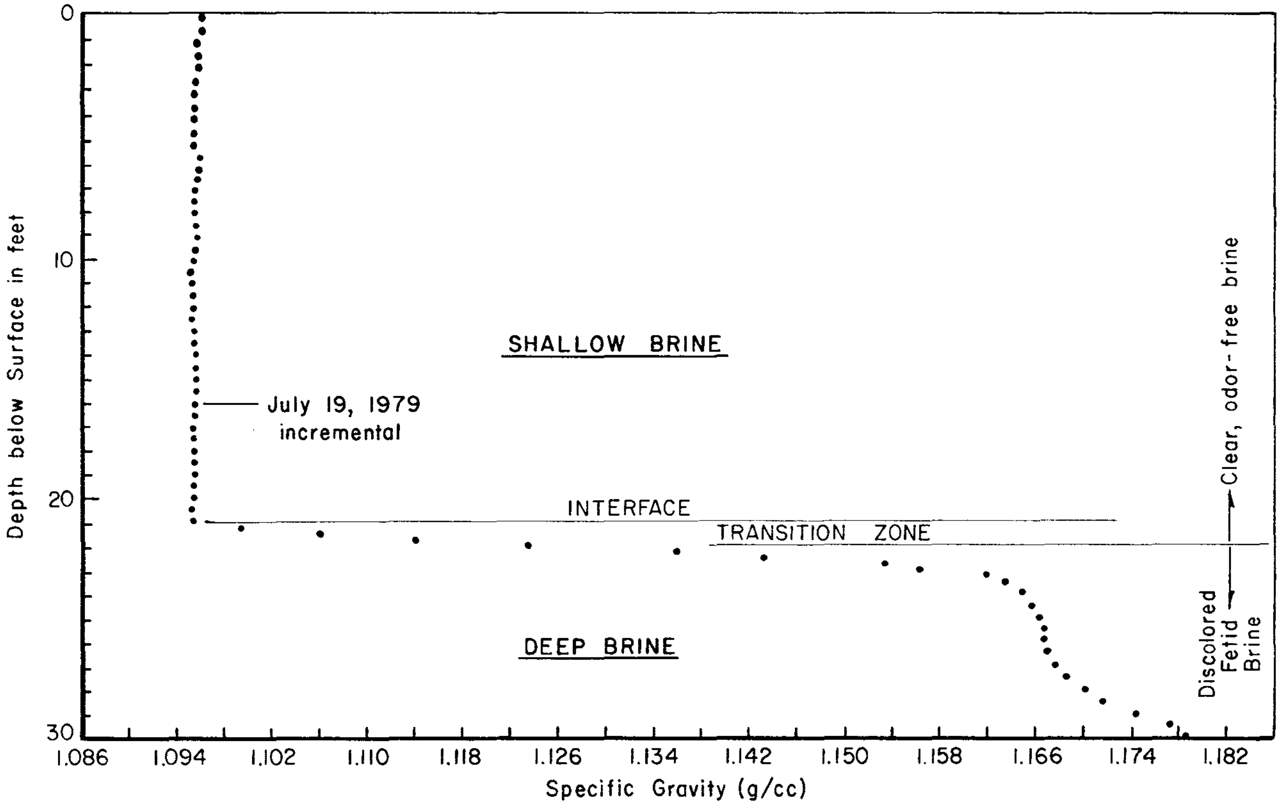


Figure 3. South arm density profile from incremental sampling program.

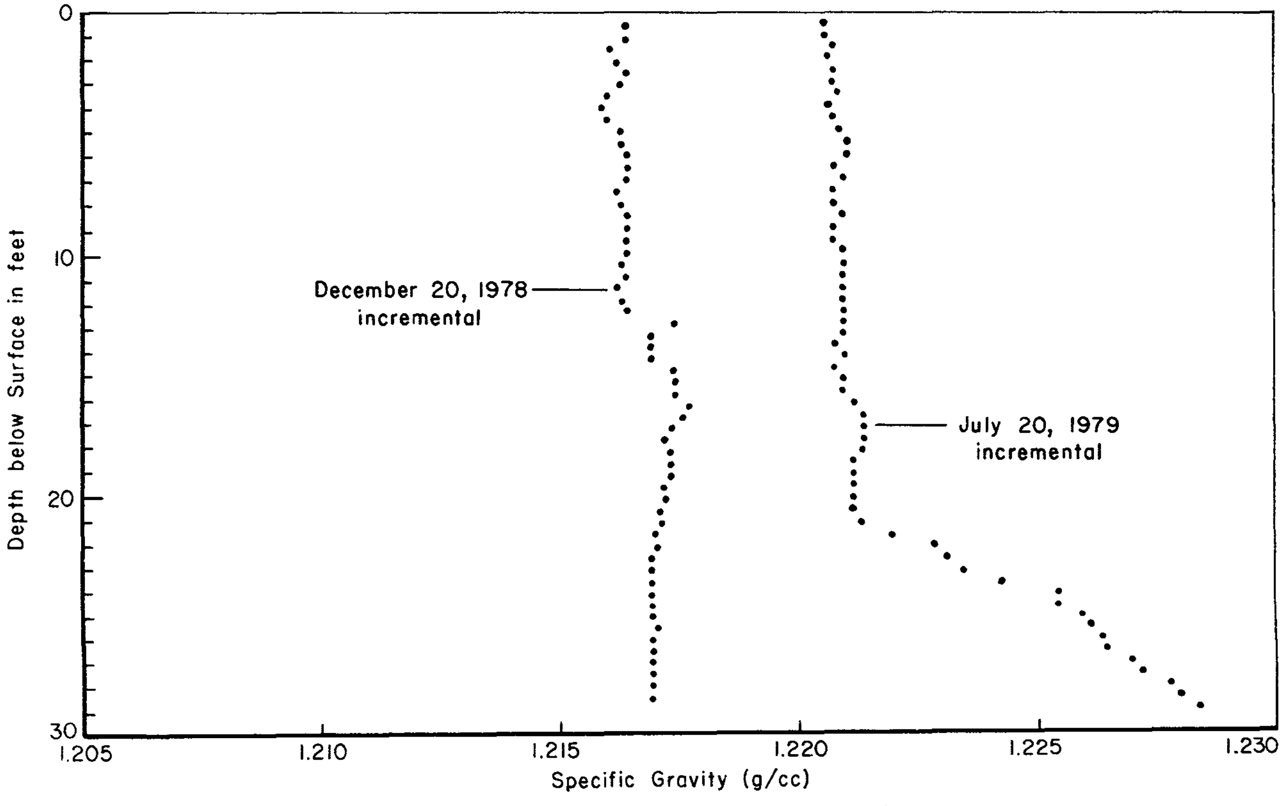


Figure 4. North arm density profiles from incremental sampling program.

CONCLUSION

The preceeding discussions have shown the complexities of the various aspects of Great Salt Lake brine, and have noted, to some degree, the interrelationships that exist within the brine system. The considerable amount of information that has been collected during the past thirteen years will permit more accurate evaluation of the Great Salt Lake brine system. Further research efforts will only continue to broaden the horizons of understanding about this unique saline body of water, the Great Salt Lake.

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FACTORS AFFECTING THE CONCENTRATION
OF
GREAT SALT LAKE BRINES

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ABSTRACT

The principal factors that affect and control the concentrations of the brines within the Great Salt Lake are 1) the Southern Pacific Railroad Causeway, which essentially creates a two lake system, 2) water inflow (from streams, springs and rainfall), 3) evaporation 4) lake currents, and 5) mirabilite precipitation.

INTRODUCTION

The Great Salt Lake, located in northwestern Utah, is a terminal body of water, (it has no outlet). The Great Salt Lake has become saline with 1) salts that were concentrated from the evaporated waters of Pleistocene Lake Bonneville, 2) dissolved salts that are brought into the lake by its tributaries; and 3) wind transported salts. The concentration of the lake's brines depends on the balance between inflow into the lake, evaporation from the lake, precipitation of salts, and factors which control the movement or confinement of the lake brines.

PRE-CAUSEWAY FACTORS EFFECTING BRINE CONCENTRATION

Prior to the construction of the Southern Pacific Railroad Causeway across the lake in 1959, the salt concentration of the north and south sections were similar. Long term and seasonal lake level fluctuations played, and still play, an important role in affecting the concentration of the lake's brine. At the time of the historic high lake level of 4212′ in 1873, the quantity of water in the lake was much greater, with a lower salt concentration than it had just prior to the completion of the causeway in 1959, when the level of the lake was at about 4195′. Seasonal lake level fluctuations, though only of a magnitude of up to three feet, also cause cyclical changes in the concentration of the lake brines. The high seasonal lake elevations, with correspondingly lower concentrations of salt, occur during the months of May or June, and the low elevations, with higher concentrations of salt, during October or November.

Observers noted, however, that the pre-causeway brines were more concentrated along the western side of the lake and at its northern end than they were along its eastern side and southern end. The most important cause for this difference in concentration was dilution of the lake brines by the fresh water of the tributaries which entered the lake from the east and south.

Other factors which likely contribute to the variations in concentration throughout the lake are differences in the precipitation and evaporation patterns across the lake, prevailing wind directions, and lake current patterns.

POST-CAUSEWAY FACTORS EFFECTING BRINE CONCENTRATION

Southern Pacific Railroad Causeway

In 1902, the Southern Pacific Railroad completed a rail line across the central portion of the Great Salt Lake (see figure 1). The structure was constructed as a rock fill across the mouth of Bear River Bay (with one opening provided) and into the Great Salt Lake proper from both the east and west until structural failure of the fill occurred. This left a section of open water between the east and west fill sections of approximately 12 to 13 miles. An open, wooded trestle structure across this distance was constructed. The trestle structure, while supporting the railroad, did not significantly block or alter the free movement of the lake brines. The trestle structure eventually became in need of repair or replacement, and in 1959 a rock fill structure was constructed some 1500 feet north of the trestle. The rock fill causeway was designed to allow free movement of brines. The rising level of the lake and the resulting increase in concentration of brines of the north arm have resulted in a higher brine level, or head, in the south.

This causeway has created a two-lake system, each with its own characteristics. The north arm has become a pink colored, very concentrated body of brine and the south arm a less concentrated blue-green body of brine.

There is some mixing, however, through the causeway structure itself, and through the two culverts (which are 15 feet wide by about 22 feet in depth) that were built into the causeway structure. Figure 2 illustrates the bidirectional flow that occurs through the two culverts, provided that the flow is not blocked by debris.

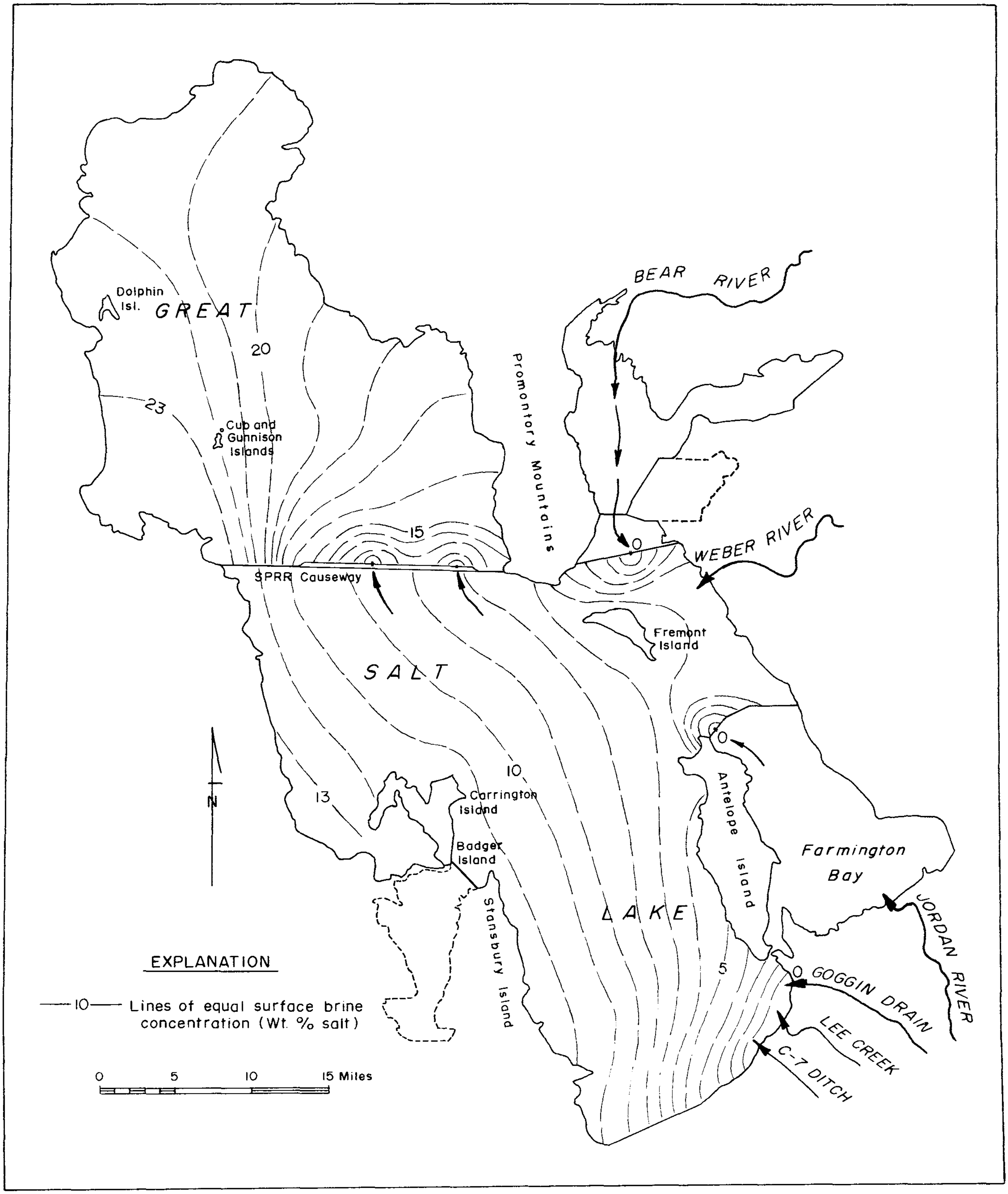

Figure 1. Map of lake showing hypothetical distribution of surface brine concentrations.

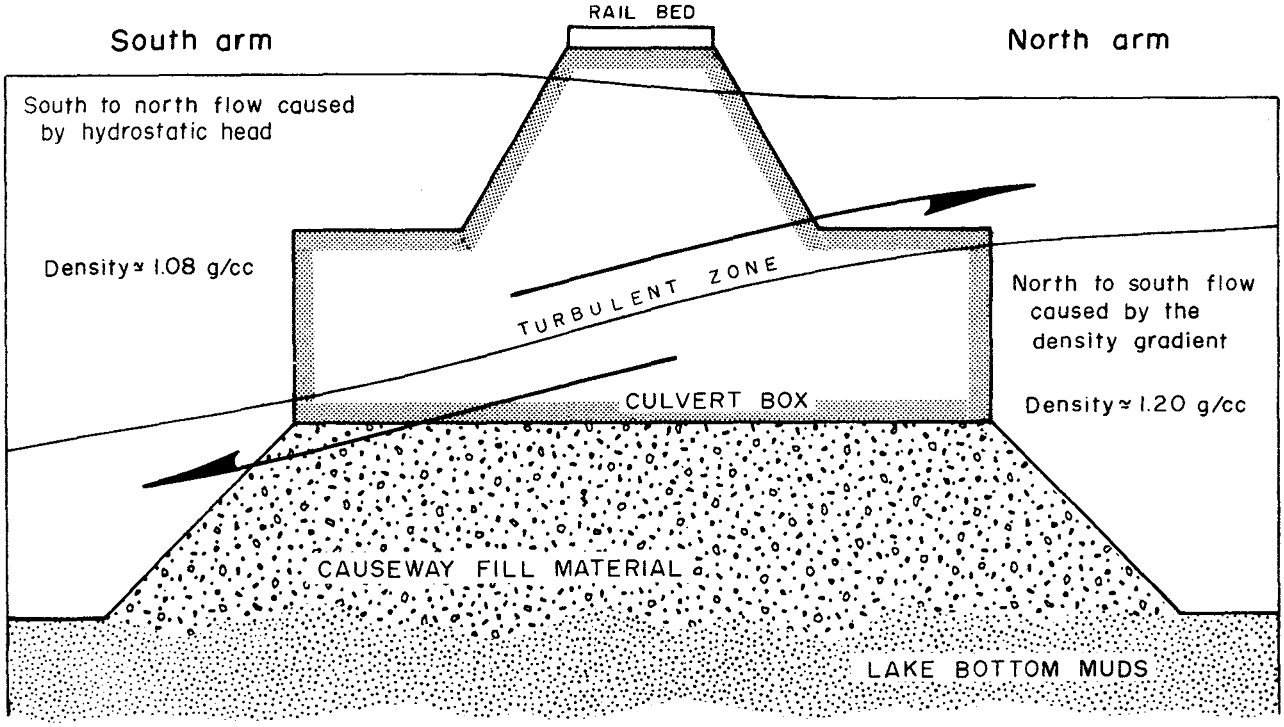

Figure 2. Bidirectional flow through the Southern Pacific Railroad causeway.

Figure 1 illustrates a hypothetical distribution of the brine concentrations in the lake and shows the effect of the causeway. The causeway acts as a barrier to winds, reducing their fetch down the long axis of the lake. The causeway also acts as a barrier to wind-blown brines, reducing the amplitude of brine moving back and forth in the lake (this movement is known as a seiche). In addition, there exists a brown, dense, fetid layer of brine beneath the southern brine body. It is not known if this layer existed before the construction of the causeway, or the reasons why it exists.

Water Inflow

Tributaries

There are no substantial tributaries that flow into the north arm of the lake. In the south arm the concentration of the brine is effectively diluted by the inflow of fresh water tributaries that enter the eastern side and southern end of the lake (see figure 1). The main tributaries that enter the south arm are the Bear, Jordan and combined Weber and Ogden Rivers. Numerous other small tributaries enter within the same general areas. During the spring months, when the winter snow pack is melting, the rate of inflow is at its highest, and the south arm brines become diluted as the lake approaches its high seasonal elevation. At the end of the summer the rate of tributary inflow diminishes, the level of the surface elevation lowers, and the brines become more concentrated.

The north arm, however, has no significant tributaries and receives the majority of its inflow as brine from the south arm. This inflow is limited by the causeway. As a result the north arm experiences smaller seasonal water level fluctuations.

Ground Water

The amount of groundwater inflow, as compared to other sources of inflow into the lake, is relatively small. The greater portion of the ground water that enters the lake basin as a whole, enters mainly from aquifers south and east of the lake. The quantity of ground water inflow into the north arm, is much less than that to the south arm, and comes mainly from areas north of the lake.

Rainfall

Precipitation, as rain and snow, accounts for approximately 25 percent of all water entering the lake and precipitation, as rain during the summer and snow during the winter, acts to dilute the concentration of the lake brines. The heaviest precipitation on the Great Salt

Lake occurs from March through May of each year, with a secondary high during October and November. The average annual precipitation over the lake ranges from 10 to 15 inches. The amount of precipitation which falls on the lake is not uniform. Waddell and Fields (1977, p. 5) show that the amount of precipitation received by the north arm is less than that received by the south arm. This not only enhances the concentration differences between the two portions of the lake, but helps to increase the head difference between them.

Evaporation

Amount of Evaporation

The Great Salt Lake is a terminal lake and evaporation is the only major means by which water may be removed; salts can be removed only by precipitation or by industrial use. Salts are thus retained in the basin. Evaporation of the lake brines tends to balance the water added by total water inflow. The balance between total water inflow to the lake and evaporation determine not only the seasonal fluctuations of the lake, but also the long term levels, which in turn effect the concentration of the brines within the lake. If large amounts of water are evaporated from the lake, for a given quantity of inflow, i. e. evaporation exceeds inflow, the level of the lake will drop and the brines, of both the north and south arms will increase in concentration.

Rate of Evaporation

The greatest rate of evaporation from the lake occurs during the hot summer months from June to September and is aided by the hot dry winds crossing the desert from the northwest and southwest. As with rainfall evaporation is not uniform throughout the area of the lake. Waddell and Fields (1977, p. 8) show that the average annual freshwater-lake evaporation over the north arm area of the lake is greater than that over the south arm of the lake. (See Gwynn and Sturm, Solar Ponding Adjacent to the Great Salt Lake, this issue).

The rate of evaporation, under a given set of climatic conditions is effected by the concentration of the brines. The more concentrated the brine, the lower its evaporation rate will be. It would be expected then, that under similar climatic conditions, south arm brine would evaporate at a greater rate than the more concentrated north arm brine.

Lake Currents

The water currents which move throughout the lake have been discussed by Katzenberger and Whelan (1975, p. 103-107). Tributary inflow, winds and possibly the Coriolis force contribute to the currents in the lake caused by tributary inflow.

Tributary Inflow

Lake currents circulate the less concentrated lake brines in a counter clockwise direction from the inflow source areas. During their journey around the lake, the brines evaporate and concentrate, resulting in more concentrated brines on the west side.

In the south arm of the lake, tributaries enter through Farmington Bay; along the south shore, west of Antelope Island; and out of Bear River Bay, just north of Fremont Island. The water entering the south end of Farmington Bay moves generally to the north where it enters the south arm proper through the bridged opening in the Antelope Island Syracuse causeway. This fresh water flow dilutes the concentration of Farmington Bay and then dilutes the south arm brine with the less concentrated bay water. The water entering the south arm moves the water in the lake to the north.

The water entering the south end of the lake proper through the C-7 ditch, Lee's Creek and the Goggin Drain (figure 1) not only dilutes the water of the south end of the lake, but also initiates a northerly flow along the west side of Antelope Island.

The water entering the lake from Bear River Bay and the Weber River mixes with and dilutes the lake brines north and east of Fremont Island, this added volume of water moves the lake brines westward along the causeway. The net effect of the principal tributary inflow into the south arm is to produce the potential for a counter-clockwise current.

In the north arm of the lake, the south to north flow of water through the two culverts initiates a northward flow of water along the west side of the Promontory Mountains, as well as dilutes, to some degree, the north arm brines.

Winds

Surface currents and waves on both arms of the lake can be caused by prevailing winds from the north and south as well as by canyon winds from the east. It is possible that these winds could provide a portion of the force required to drive the south arm and the north arm brines in a counter-clockwise direction within the lake, but their effects are temporary.

Coriolis Forces

Any movement of brine in the north or south arms of the lake must be effected by Coriolis force, the resultant effect of which is to force the brine in a counter clockwise direction along the east side of the lake towards the north, and then down the west side towards the south. During its journey around the lake, the brine evaporates and concentrates, resulting in more concentrated brines on the west side of the lake.

Mirabilite Precipitation

During the cold winter months, mirabilite ($Na_2SO_4 \cdot 10\ H_2O$) precipitates from the lake brines. At the present time, only the north arm of the lake is sufficiently concentrated to allow formation of appreciable amounts of this salt. Mirabilite requires 10 waters of hydration, which effectively removes water from the lake and effects, to a minor degree, the concentration of the lake brines. As the lake waters warm in the spring time, the layer of mirabilite on the bottom of the lake goes back into solution and forms a highly concentrated sulfate-rich layer of deep brine which may lie dormant near the bottom of the lake for several months.

CONCLUSIONS

The Southern Pacific Railroad causeway, water inflow, evaporation, lake currents and the crystallization of mirabilite all influence the concentration of Great Salt Lake brines. The causeway acting with increased lake level (inflow greater than evaporation) has resulted in a lake with two essentially differing bodies of water.

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CHEMISTRY OF GREAT SALT LAKE BRINES IN SOLAR PONDS

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INTRODUCTION

The chemistry of the brines taken from the Great Salt Lake and evaporated in solar ponds is both simple and complex. The crystallization of sodium chloride is a relatively simple process, but if other salts containing magnesium, potassium, and sodium are desired, then it becomes essential to understand the chemistry of the brines and the environmental influences on the solar pond that affect the chemistry.

SOLAR POND CHEMISTRY

Chemical reactions in solar ponds are subject to the effects of winds, rain, and temperature variations not even considered in chemical handbooks or in classical phase chemistry. Companies which produce only sodium chloride, which is stable over a wide range of temperatures, are not troubled greatly by erratic weather. Production of other and more complex salts, however, is greatly effected by weather conditions.

The main parameters which affect the crystallization of minerals in solar ponds are:

- Evaporation rate
- Brine temperature
  - Average brine temperature
  - Brine day-night temperature cycles
  - Seasonal temperature changes
- Brine depth
- Brine sequencing
- Residence time
- Pond leakage and brine capture (entrainment)

Evaporation Rate

The general concentration path of Great Salt Lake brines is shown in figure 1. As water is removed, saturated ions crystallize as salts, bringing with them oppositely charged ions and sometimes waters of hydration. At the top of the figure are listed some of the salts that are precipitated during evaporation. The approximate brine concentrations at which these various salts can precipitate are given. Since evaporation must occur at the brine surface, crystallization of the salts also occurs there. The higher the evaporation rate, the higher the probability for supersaturation and salt formation. These salt crystals eventually fall from the surface of the brine and settle to the pond floor. The main points to be noted are: 1) that the surface crystals are in equilibrium with the surface brines, and 2) they may vary considerably from predicted crystals based on variations in the chemistry of the brine proper. Figure 2 shows a plot of moles of magnesium chloride per 1000 moles of water compared with other dissolved salts in the brine. Analysis of the solar pond brine for concentration of magnesium chloride, or magnesium, can be used by the pond operator to show where a brine is along its concentration path, and what total brine and individual salt chemistries can be expected.

Figure 3 is a portion of the 25°C triangular sulfate-potassium-magnesium phase diagram for the Great Salt Lake brine system, and shows the minerals that are in equilibrium with a brine at a particular concentration. Both figures 2 and 3 represent typical brine concentration paths at summer time temperatures. Note that these figures do not represent the entire brine concentration picture. All of the factors previously mentioned will cause modifications to these diagrams. The total effect on the chemistry of the brine by the specific day-by-day and season-by-season variations of concentration and temperature which arise in a solar ponding operation would require a lengthy discussion beyond the scope of this paper.

Brine Temperature

Fluctuations in temperature result in changes in ion saturation which cause selective precipitation or dissolution of salts in a brine body.

Average brine temperature

Some of the crystals that are formed at the brine surface by evaporation will tend to decompose or dissolve once they drop to the pond floor. The decomposition rate of these salts is dependent on factors such as changes in both brine temperature and concentration. The actual temperature range experienced by pond brines is normally .60 to .80 times that of the air temperature and may vary from top to bottom in a pond. Many salt crystals are never at equilibrium with the

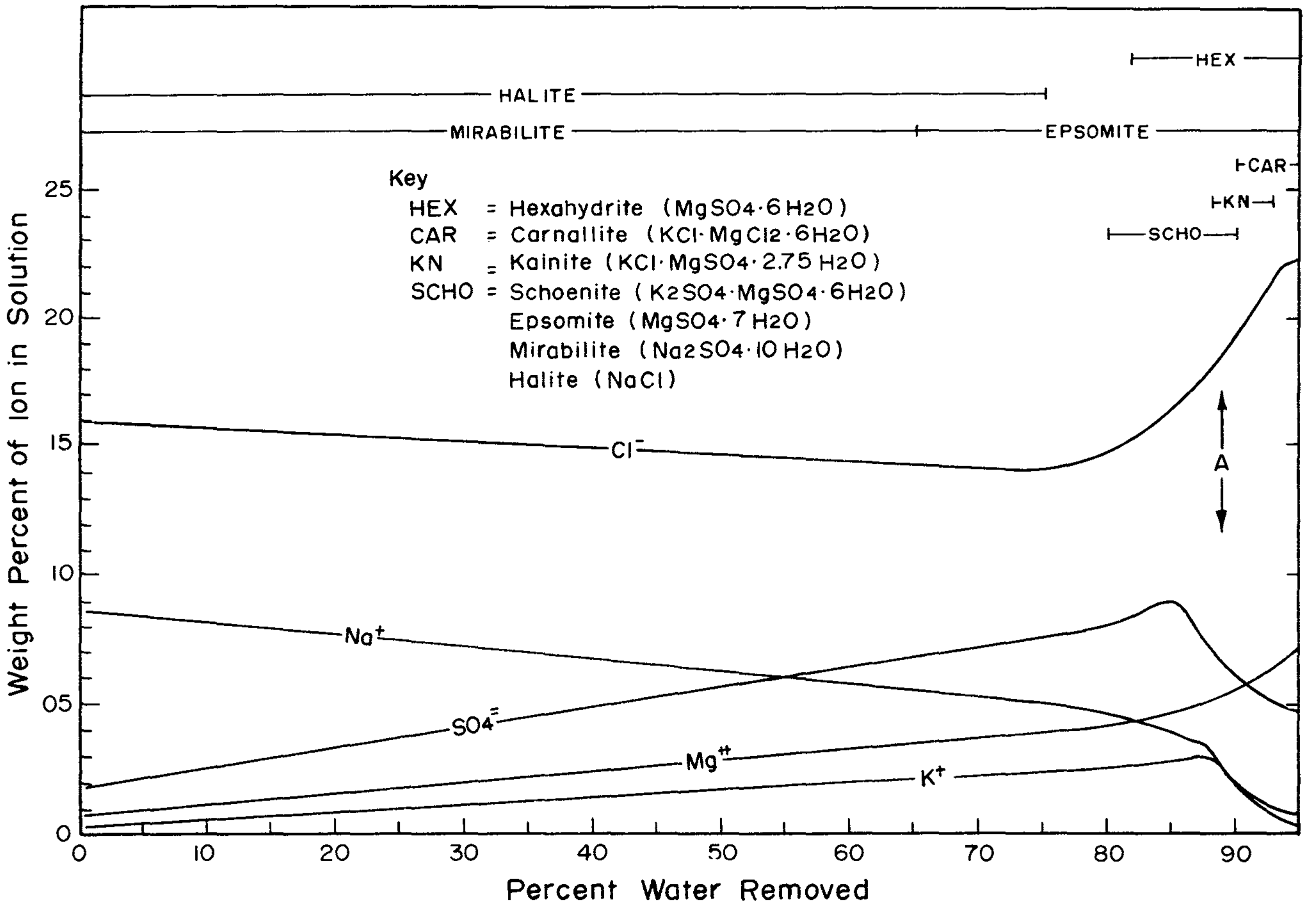

Figure 1. Concentration path of some Great Salt Lake brines.

brines in which they are situated because of the temperature changes they encounter as they develop. The average brine temperature is generally the best criteria in predicting the type of crystals that will be precipitated on the pond floor.

Brine day-night temperature cycles

Under natural solar pond conditions the brine temperature fluctuates with the air temperature, although there is a lag time for temperature response in the brine. This fluctuation in temperature results in changes in ion saturation which causes selective precipitation or dissolution of salts in the brine body.

For example, the air temperature may be 35°C during the day and 15°C at night. Brine at Point A on figure 1 may favor the formation of kainite ($MgSO_4 \cdot KCl \cdot 3H_2O$) during the daytime and schoenite ($MgSO_4 \cdot K_2SO_4 \cdot 6H_2O$) at night. The sulfate ion is particularily temperature sensitive and salts containing it tend to precipitate at cooler temperatures. The result is a mixture of both salts in a single pond from the same brine. Another example is that under controlled laboratory conditions, brine from the north arm of the Great Salt Lake will not crystallize mirabilite ($Na_2SO_4 \cdot 10H_2O$) until the brine temperature reaches 2°C or lower. In solar ponds, however, this salt has been observed to crystallize at brine temperatures above 7°C. During the winter, as the surface temperature of the brine becomes very cold (2°C or lower) at night, especially on clear nights, mirabilite will form on and just below the surface and subsequently drop to the somewhat warmer brine at the floor of the pond. Because there is insufficient activation energy in this brine to redissolve the mirabilite, it remains on the floor.

Surficial cooling during the summer nights also causes salts to precipitate, but the next day's heat generally provides sufficient activation energy to cause total dissolution of those salts precipitated just a few hours before. It is not unusual to find a quarter inch layer of hexahydrite ($MgSO_4 \cdot 6\ H_2O$) at the bottom of a solar pond in the morning redissolved by late afternoon.

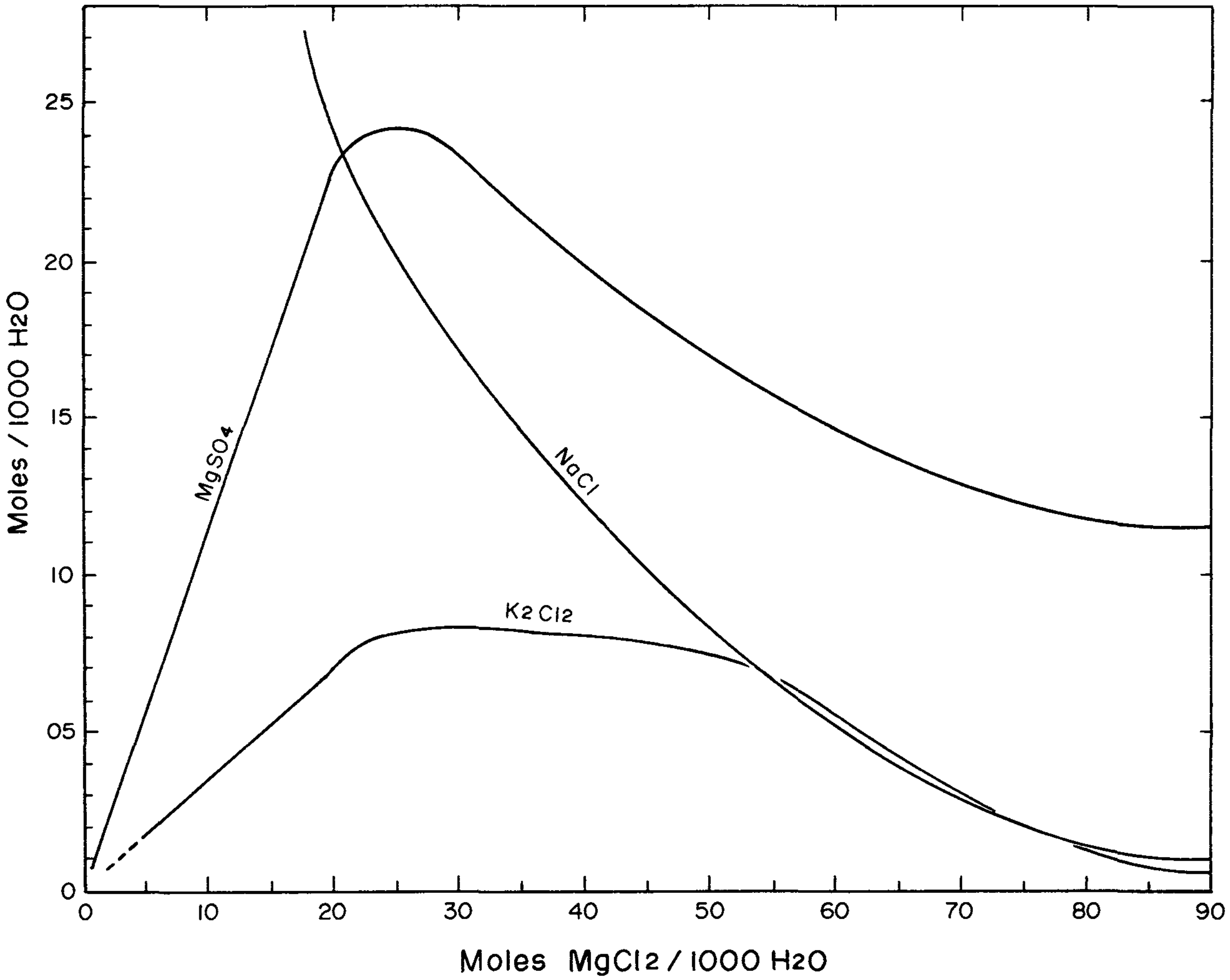

Figure 2. Typical concentration path of evaporated Great Salt Lake brines as a function of magnesium chloride concentration.

However, it is also possible for salts precipitated by cooling to be later covered by salts precipitated by evaporation, which effectively prevents dissolution of those salts that would normally redissolve.

Seasonal Temperature Changes

Some salts deposited in June, July, and August will convert to other salts, with a possible total change in chemistry, when they are exposed to colder winter temperatures, and rainfall. Kainite, for example, may convert to sylvite and epsomite, and become a hardened mass; or if it is in contact with a sulfate rich brine, it can convert to schoenite. Conversely, glaubers salt will precipitate in the winter, but redissolve during the hot summer months.

Brine Depth

The depth of brine within a solar pond can effect the mineralogy of the precipitated salts. Even with stiff winds, the highly saturated brines at the pond surface do not mix easily with the brines next to the pond floor. This is equally true in deep and in very shallow ponds (less than three inches). Since crystals can only grow in the supersaturated brines, unless the super saturated brines extend to the pond floor, all new floor growth will normally depend on crystals precipitated from the surficial brine.

Crystals formed at or near the surface of the brine are usually much different in both size and mineralogy from those allowed to grow from the floor up. If the supersaturated surface brines do not come in contact

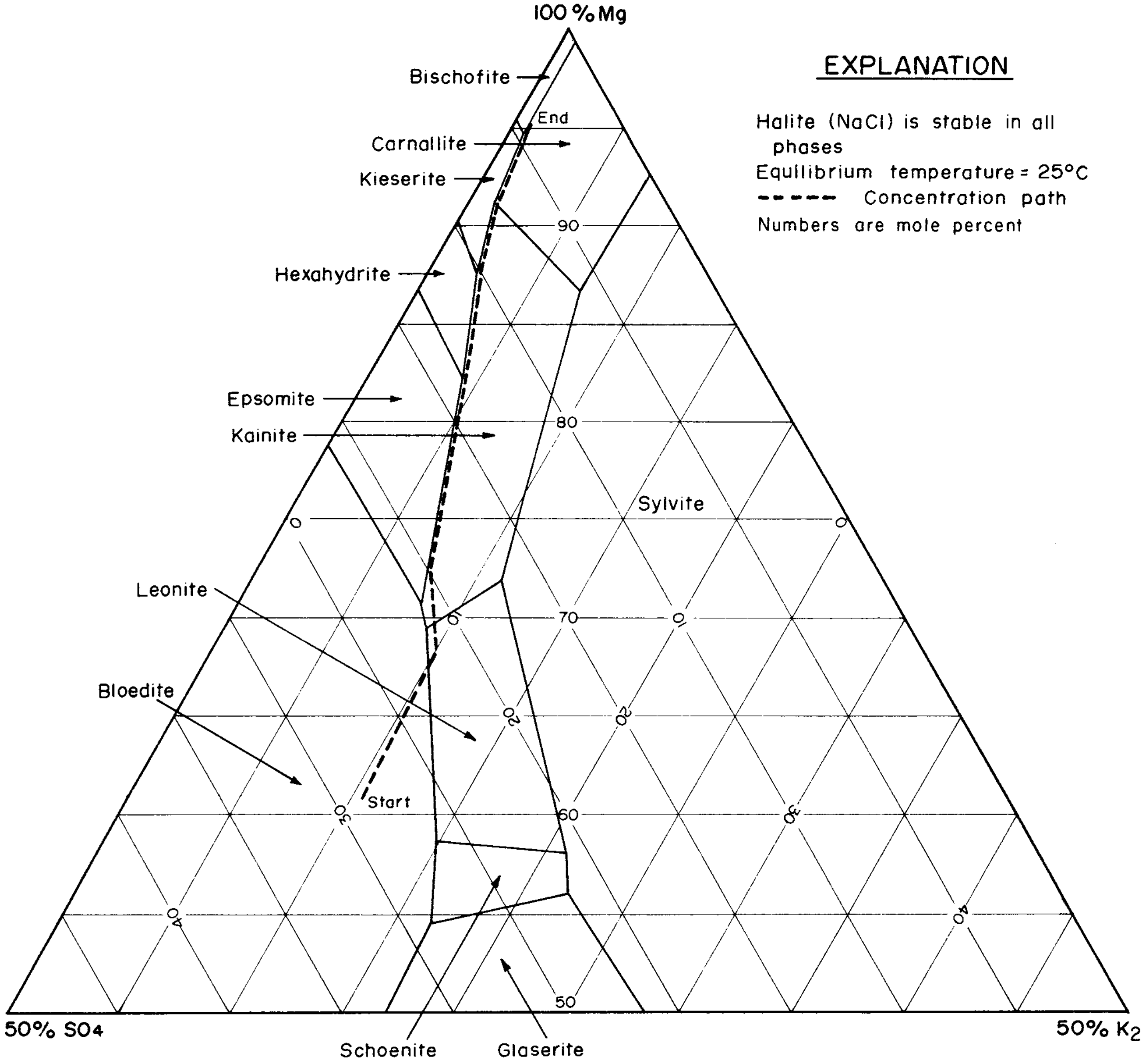

Figure 3. Typical concentration path of evaporated Great Salt Lake brine.

with the pond floor, the mineralogy of the pond deposit will be far from uniform.

The depth of a solar pond also controls the size of the crystals produced. Halite (NaCl) for example, when precipitated in a pond under three inches or over twelve inches in depth, will have a smaller crystal size than when precipitated in a pond three to twelve inches deep. The smaller crystals of halite are undesirable since a premium price is paid for larger crystals.

Brine Sequencing

Whether a brine is concentrated in a single pond, or in numerous ponds connected in series, has a profound effect on the minerals that are formed. A single pond fed raw brine from the lake, but held at a concentration of seven percent magnesium, will only produce halite, carnallite and hexahydrite. Four ponds operated in series, however, will also produce epsomite, schoenite, leonite and kainite. The differences between the mineral suites formed are because the minerals that are found in the single pond, held at seven percent magnesium, are those that are in equilibrium with that brine, as established by the brine's phase chemistry. In a series of ponds, each progressively more concentrated, minerals in equilibrium with the various concentration stages will form and be stable in those brines. Thus, a greater number of mineral species can be produced. Once halite has precipitated, it is stable in all greater concentrations of brine.

Residence Time

Some salts require more time than others to crystallize. Brine that is not given sufficient time for crystallization before it is moved into another pond which has brine of a different concentration will produce a different suite of salts. For example, if a brine supersaturated in ions that will produce kainite, epsomite, and halite (reaction 1), is moved to another pond, in which the resulting brine mixture favors carnallite (reaction 2), then the kainite salts will be eliminated. These chemical reactions are:

Reaction 1:

$$9.75H_2O + Na^+ + 2Cl^- + 2Mg^{++} + K^+ + 2SO_4^{=} \Rightarrow$$

$$\underset{\text{(Kainite)}}{MgSO_4 \cdot KCl \cdot 2.75\,H_2O} + \underset{\text{(Epsomite)}}{MgSO_4 \cdot 7H_2O} + \underset{\text{(Halite)}}{NaCl}$$

Reaction 2:

$$12H_2O + Na^+ + 4Cl^- + 2Mg^{++} + K^+ + SO_4^{=} \Rightarrow$$

$$\underset{\text{(Carnallite)}}{MgCl_2 \cdot KCl \cdot 6H_2O} + \underset{\text{(Hexahydrite)}}{Mg\,SO_4 \cdot 6H_2O} + \underset{\text{(Halite)}}{NaCl}$$

Reaction one retains more magnesium as $MgCl_2$ in the brine; reaction two retains more sulfate. In reaction two, it is also interesting to note the effect of waters-of-hydration on crystallization; forcing out salts with high waters of crystallization results in higher rates of crystallization. The hydrated salts remove waters from the brine and further concentrate the brine in much the same way as does evaporation.

Pond Leakage and Brine Capture (Entrainment)

Regardless of brine depth or ponding area, the time required to evaporate nearly ninety percent of the water from the present north arm Great Salt Lake brine in a solar pond complex, under natural steady state conditions, is approximately eighteen months. It is necessary to evaporate nearly ninety-eight percent of the water from present north arm brine to precipitate bischofite ($MgCl_2 \cdot 6\,H_2O$). If pond leakage causes the level of the ponding area to drop too quickly, it would be impossible to reach saturation for bischofite because of brine loss. Control of leakage is essential to assure that the precipitated salts contain the greatest quantity of the desired minerals for successful pond operation.

Entrainment also affects pond brine chemistry. Brine entrained (or trapped) in the voids between salt crystals in the pond floor is effectively removed from salt production and affects the chemistry of salts that will be precipitated as concentration proceeds.

CONCLUSION

The important chemical parameters that directly or indirectly affect the chemistry of Great Salt Lake brines are interrelated. Solar ponding control becomes more complex as the brine concentration is taken past the saturation point of sodium chloride to include the precipitation of potassium and magnesium salts. A thorough understanding of the brine chemistry, as it relates to solar ponding, can be used to an advantage to produce a desired product or products from the waters of the Great Salt Lake.

ANALYTICAL PROCEDURES FOR GREAT SALT LAKE BRINE

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INTRODUCTION

Since the discovery of the Great Salt Lake by James Bridger in 1824, the salinity of the lake has been a subject of continued interest. Not until John Fremont came to the Great Salt Lake in 1843 was any investigation performed on the lake's brine to determine its salt content. At that time, he boiled five gallons of the brine to dryness and produced fourteen pints of "salt". Although quite unsophisticated, it was the first reported analysis of the lake water. With the settlement of the Salt Lake Valley came an increase in the advancement of scientific knowledge about the lake and its chemical makeup.

The methods first used to analyze the lake brines were the standard procedures employed for nonsaline waters. During the 1960's, however, with the beginning of active mineral extraction from the lake (beyond the extraction of sodium chloride), it was found that the standard water analytical procedures then being used were not suitable for the analysis of lake brine because the brine masked, enhanced or otherwise interfered with the analyses, causing errors. To overcome these problems, industrial chemists developed either totally new procedures or modified existing procedures.

Today, the procedures used for analysis of Great Salt Lake brines have been greatly improved, as have the analytical instruments that are employed. To follow are the various state-of-the-art procedures that are used or can be used for the analysis of the major ionic components of Great Salt Lake brine. Basic procedures are given for the analysis of potassium (K), sodium (Na), magnesium (Mg), calcium (Ca), chloride (Cl), sulfate (SO_4), lithium (Li), boron (B), bromide (Br), sulfide (S) ions and pH. The selection of the analytical procedure to be used for a particular ion is dependent upon the instrumentation that is available, the degree of accuracy required, and of course the availability of laboratory funding. The following notes apply to some or all of the analytical procedures listed:

1. Some of the following analytical procedures make reference to "prediluted Great Salt Lake brine". This is a forty gram sample of brine diluted to 500 milliliters with deionized water.

2. If Great Salt Lake brine more concentrated than that naturally found in the lake, i.e. concentrated solar pond brines, is to be analyzed, then further dilutions will be required.

3. The following are not necessarily cookbook analytical procedures but are generalized and will need to be developed and refined by those using them. Expertise with any of these procedures comes only with practice.

4. All dilutions made in the following procedures use distilled or deionized water unless otherwise stated.

DETERMINATION OF MOLE BALANCE FOR CHEMICAL ANALYSIS

1. Summary of Procedure

After a complete chemical analysis of Great Salt Lake brine has been completed, a cross check of the accuracy of analysis is calculated. Only the major five ions are considered in this calculation, i. e., K, Na, Mg, Cl, and SO_4. The number of moles of each ion is calculated and the totals of the anion and cation moles are compared. The current acceptable total deviation limit for the lake industries and commercial laboratories is plus or minus .0055 moles.

2. Procedure

This example, a determination of the mole balance on an analysis of south arm brine collected October, 1978, is given to illustrate the procedure.

Ion	Weight Percent Analyzed	÷	Divalent Molecular Weight of Ion	=	Moles of Ion
K	0.32		78.20		.0041
Na	4.10		45.96		.0892
Mg	0.47		24.91		.0193
			Total Moles Cation		.1126
Cl	7.20		70.90		.1016
SO_4	1.00		96.08		.0104
			Total Moles Anion		.1120

3. Calculation

Total Moles Cation (.1126)–Total Moles Anion (.1120)=
Moles Imbalance (.0006)

If the mole imbalance is greater than plus or minus .0055, then a reanalysis or restandardization of the analytical standards is in order.

POTASSIUM (K^+)

DETERMINATION OF POTASSIUM BY FLAME EMISSION

1. Summary of Procedure

A prediluted sample of Great Salt Lake brine is mixed with a standard lithium solution and aspirated into a flame photometer which measures the emission of the potassium ion versus the standard lithium source.

2. Reagents

   A. Three molar lithium nitrate standard
   B. Standard potassium solutions of 2,000, 4,000, 6,000 and 8,000 ppm.

3. Apparatus

   A. Flame photometer with internal lithium standardization.
   B. Miscellaneous labware

4. Procedure

   A. Zero lithium standard while aspirating water
   B. Zero potassium readout
   C. Aspirate, 8,000 ppm standard and maximize readout and record
   D. Aspirate the 6,000, 4,000 and 2,000 ppm standards and record
   E. Aspirate the sample and record the reading.

5. Calculation

   A. Plot the readings of the four standards on graph paper
   B. Plot the sample value on the graph and determine the potassium value (ppm K)
   C. Calculate the weight percent potassium as follows:

$$\frac{\text{ppm K x (internal dilution factor) x (predilution factor)}}{\text{Sample weight (g) x 10,000}} = \text{WT. \% K}$$

DETERMINATION OF POTASSIUM BY AN ION PROBE METHOD

1. Summary of Procedure

A one ml aliquot of Great Salt Lake brine is diluted to 100 ml and two ml of ionic strength adjuster (ISA) is added. A potassium specific ion probe and single junction reference electrode are placed in the solution and the reading taken.

2. Reagents

   A. 1000 γ* potassium standard (1.9068g KCl, dilute to 1000 ml)=1.00g/l K)
   B. Ionic strength adjuster (6M NaCl) (35.1g NaCl, dilute to 100 ml)
   C. 0.1 normal $AgNO_3$ solution

* γ = Micrograms per milliliter

D. Reference electrode filling solution (2 ml ISA, dilute to 100 ml, add $AgNO_3$ solution dropwise until cloudiness persists)

3. Apparatus

A. Potassium specific ion electrode
B. Single junction reference electrode
C. Digital ionanalyzer
D. Miscellaneous labware

4. Procedure

A. Calibrate ionanalyzer
  1. Fill reference electrode with filling solution
  2. Prepare standards
    a. 100 γ K standard (1 ml 1000 γ K solution, dilute to 100 ml, add 2 ml ISA)
    b. 100 γ K standard (10 ml 1000 γ K solution, dilute to 100 ml, add 2 ml ISA)
  3. Standardize ionanalyzer with 10 γ and 100 γ standards, millivolt reading difference should be 54 plus or minus 1. Record readings.

B. Dilute a one ml aliquot of Great Salt Lake brine to 100 ml and add 2 ml ISA.
C. Read the sample value on the ionanalyzer (reponse time about 2 min.)
D. Monitor the laboratory temperature; a 1°C change equals about 2% error. Recalibrate if necessary.

5. Calculation

A. The grams per liter potassium is plotted (10 γ standard equals 1.0 g/l K; 100 γ standard equals 10.0 g/l K) versus mv out put.
B. The weight percent potassium is calculated as follows: g/l K ÷ (brine density x 1000) = %K

DETERMINATION OF POTASSIUM
BY TITRATION

1. Summary of Procedure

An aliquot of prediluted Great Salt Lake brine containing 20 to 25 milligrams potassium is precipitated with an excess of sodium tetraphenyl boron (STPB). The solution is filtered; the filtrate is titrated with Zephiran Chloride to determine the excess STPB present.

2. Reagents

A. STPB stock solution (74.0g STPB + 2 liters H_2O + 125.0g $Al(OH)_3$, agitate 10 to 15 minutes) (28 mls 20% NaOH + 10 liters H_2O), filter STPB solution into the 10 liters of NaOH solution, dilute to 14 liters and let stand 48 hours).
B. Sodium hydroxide solution - 20%
C. Zephiran Chloride solution (20 mls of 17% Zephiran Chloride, dilute to 1 liter)
D. Titan Yellow (Clayton Yellow) indicator .05%

E. Formaldehyde solution - 37%
F. Standard potassium solution (69.000g KH_2PO_4 dilute to 1 liter)

3. Apparatus

A. 10 ml microburet, pipets, erlenmeyer flasks
B. Miscellaneous labware

4. Procedure

A. Determine the ratio of STPB to Zephiran Chloride
   1. STPB solution (50 ml STPB stock solution + 25 ml 20% NaOH, dilute to 500 ml)
   2. Titrate STPB solution with Zephiran Chloride (25 ml STPB solution, dilute to 50 ml, + 5 drops Titan Yellow indicator, titrate to pink endpoint)

B. Determine the standard factor for STPB in terms of potassium.
   1. 1.0 ml standard potassium solution + 50 ml STPB + 5 ml 20% NaOH + 2 ml formaldehyde solution, dilute to 100 ml, mix thoroughly, and let stand for five minutes.
   2. Filter on No. 1 Whatman into a dry beaker
   3. Pipet 25 ml of clear filtrate, dilute to 50 ml, add 5 drops Titan Yellow indicator, titrate to pink endpoint with Zephiran Chloride and record volume.

C. Pipet an aliquot of prediluted sample + 50 ml STPB + 2 ml formaldehyde, dilute to 100 ml, mix thoroughly and let stand 5 minutes.
D. Filter the solution, pipet a 25 ml aliquot of clear filtrate, dilute to 50 ml, add 5 drops Titan Yellow indicator.
E. Titrate to pink endpoint with Zephiran Chloride solution.

5. Calculations

A. Calculate standard potassium factor: grams KH_2PO_4 x purity x .2873 = mg K/ml
B. Calculate STPB to Zephiran Chloride ratio: 10.0 ÷ ml Zephiran Chloride used in titration = ratio
C. Calculate standard STPB factor for potassium: mg K/ml ÷ (50 ml Zephiran Chloride) x ratio = Standard Factor
D. Calculate percent potassium in sample

$$\frac{(50.00 - \text{ml Zephiran Chloride x Ratio) x Standard Factor x Dilution}}{\text{Sample Weight (g) x 10}} = \%\ K$$

SODIUM (Na^+)

DETERMINATION OF SODIUM
BY FLAME EMMISSION - METHOD I

1. Summary of Procedure

A prediluted sample of Great Salt Lake brine is mixed with a standard lithium solution, and aspirated into a flame photometer which measures the emission of the sodium ion versus the standard lithium source.

2. Reagents

A. Three molar lithium nitrate standard
B. Standard sodium solutions of 2000, 4000, 6000 and 8000 ppm.

3. Apparatus

    A. Flame photometer with internal lithium standardization
    B. Miscellaneous labware

4. Procedure

    A. Zero lithium standard while aspirating water
    B. Zero sodium readout
    C. Aspirate 8000 ppm standard and maximize readout and record the reading
    D. Aspirate the 6000, 4000 and 2000 ppm standards and record the readings
    E. Aspirate the sample and record the reading

5. Calculation

    A. Plot the readings of the four standards on graph paper
    B. Plot the sample value on the graph and determine the sodium value (ppm)
    C. Calculate the weight percent sodium as follows:

$$\frac{\text{ppm Na x (internal dilution factor) x (predilution factor)}}{\text{Sample Weight (g) x 10,000}} = \%\ \text{Na}$$

DETERMINATION OF SODIUM BY AN ION PROBE METHOD

1. Summary of procedure

A one ml aliquot of Great Salt Lake brine is diluted to 100 ml and two ml of ionic strength adjuster (ISA) is added. A sodium specific ion probe and a single junction reference electrode are placed in the solution and the reading taken.

2. Reagents

    A. 1000 γ sodium standard (2,542g NaCl, dilute to 1000 ml) = 1.00 g/l Na)
    B. Ionic strength adjuster (20.0g NH_4Cl, 50 mls H_2O, 5 mls concentrated NH_4OH, dilute to 100 mls)
    C. Reference electrode filling solution - manufactured lithium trichloroacetate solution.

3. Apparatus

    A. Sodium specific ion electrode
    B. Single junction reference electrode
    C. Digital ionanalyzer
    D. Miscellaneous labware

4. Procedure

    A. Calibrate ionanalyzer
        1. Fill reference electrode with filling solution
        2. Prepare standards
            a. 10 γ Na standard (1 ml 1000 γ Na solution, dilute to 100 ml, add 2 ml ISA)
            b. 100 γ Na standard (10 ml 1000 γ Na solution, dilute to 100 ml, add 2 ml ISA)
        3. Standardize ionanalyzer with 10 γ and 100 γ standards, millivolt reading difference should be 57 plus or minus 1; record readings.

B. Dilute a one ml aliquot of Great Salt Lake brine to 100 ml and add 2 ml ISA.
C. Read the sample value on the ionanalyzer (response time is about two minutes).
D. Monitor the laboratory temperature, as a 1°C change equals about 2% error. Recalibrate if necessary.

5. Calculation

A. The grams per liter sodium is plotted (10 γ standard equals 1.0 g/l Na, 100 γ standard equals 10.0 g/l Na) versus mv output.
B. The weight percent sodium is calculated as follows: g/l Na ÷ (brine density x 1000) = % Na

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DETERMINATION OF SODIUM BY FLAME EMISSION - METHOD II

1. Summary of Procedure

A prediluted sample of Great Salt Lake brine is prepared to contain from two to twenty ppm sodium and is analyzed by the flame emission technique versus known standards.

2. Reagents

A. Standard sodium solution - 1000 ppm
B. Working standard sodium solutions, made from 1000 ppm standard, at the following concentrations: 2, 4, 6, 8, 10, 12, 14, 16, 18, 20 ppm.

3. Apparatus

A. Flame emission spectrophotometer (AA/ AE)
B. Miscellaneous labware

4. Procedure

A. Dilute the brine sample one to five thousand or greater, if necessary, to obtain the proper concentration range (less than 20 ppm), record.
B. Using the 20 ppm standard, setup and calibrate the flame emission spectrophotometer.
C. Aspirate the 2 through 20 ppm standards and record the readings.
D. Aspirate the test sample and record the reading.

5. Calculation

A. Plot the readings of the ten standards (ppm Na versus transmittance)
B. Plot the sample value and determine the ppm Na value
C. Calculate the weight percent sodium as follows:

$$\frac{\text{ppm Na x dilution factor}}{\text{Sample weight (g) x 10,000}} = \text{Wt. \% Na}$$

MAGNESIUM (Mg^{++})

DETERMINATION OF TOTAL MAGNESIUM AND CALCIUM BY TITRATION

1. Summary of Procedure

An aliquot of prediluted Great Salt Lake brine containing 15 to 50 milligrams of magnesium is diluted and buffered to pH 10. The sample is titrated with a standard Disodium Ethylenediaminetetraacetate (EDTA) using Calmagite as an endpoint indicator

2. Reagents

A. .0529 molar magnesium iodate tetrahydrate standard (1.28 mg mg/ml)
B. pH 10 buffer (67.5g NH_4Cl + 300 ml H_2O + 570 ml NH_4OH, dilute to 1 liter)
C. Calmagite indicator 0.05%
D. .0430 molar EDTA standard (16.0g EDTA + 0.4g $MgCl_2^2 \cdot 6H_2O$, dilute to one liter)

3. Apparatus

A. Buret, pipets, erlenmeyer flask (250 ml)
B. Miscellaneous labware

4. Procedure

A. Standardization of EDTA
    1. Titrate a 25 ml aliquot of the magnesium standard with the EDTA standard.
    2. Calculate EDTA value (25 x 1.286/ ml EDTA = mg Mg/ml EDTA)
B. Pipet an aliquot of sample into an erlenmeyer flask and add 75 mlH_2O.
C. Add 5 ml of pH 10 buffer and 5 drops of Calmagite indicator.
D. Titrate the solution with the standard EDTA, swirling continuously, until a permanent blue endpoint is obtained. Record EDTA volume.

5. Calculation

A. The percent total magnesium and calcium is calculated as magnesium as follows:

$$\frac{\text{EDTA titration volume (ml) x EDTA standard value (mg/ml) x dilution volume (ml)}}{\text{sample aliquot size (ml) x sample weight (g) x 10}} = \text{Wt. \% Mg}$$

Note: If calcium has also been determined on the same sample, then the actual percent magnesium can be calculated as follows:

$$\left[\frac{\%\text{ Mg total}}{24.312} - \frac{\%\text{ Ca}}{40.08}\right] \text{x } 24.312 = \text{Wt. \% Mg}$$

CALCIUM (Ca^{++})

DETERMINATION OF CALCIUM BY FLAME EMMISSION

1. Summary of procedure

A prediluted sample of Great Salt Lake brine is analyzed by flame emission using the standard addition technique.

2. Reagents

   A. 200 ppm calcium standard (0.499g $CaCO_3$ + 100 ml H_2O + HCl (to dissolve the $CaCO_3$), dilute to one liter.

3. Apparatus

   A. Flame photometer capable of using nitrous oxide/acetylene flame.
   B. Eppendorf pipet (200 microliter), disposable cups (25 ml)
   C. Miscellaneous labware.

4. Procedure

   A. Pipet 200 microliters of calcium standard into a plastic disposable cup.
   B. Pipet 200 microliters of water into a second plastic disposable cup.
   C. Pipet 20 ml of sample into each cup.
   D. Zero flame photometer
   E. Aspirate each cup and record the readings.

5. Calculations

   A. Calculate the ppm calcium in the diluted samples as follows:

$$\frac{\text{(Intensity of sample) x 1.98}}{\text{(Intensity of sample plus addition) – Intensity of sample}} = \text{diluted Ca ppm}$$

   B. Calculate the ppm calcium in the lake brine

$$\frac{\text{Diluted ppm calcium x dilution volume}}{\text{Sample weight (g)}} = \text{ppm Ca}$$

   C. Calculate weight per cent calcium as follows: ppm Ca ÷ 10,000 = Wt % Ca

Note: A word of caution should be given as nitrous oxide/acetylene flame is extremely hot and potentially explosive.

DETERMINATION OF CALCIUM BY ATOMIC ABSORPTION

1. Summary of Procedure

A one ml aliquot of Great Salt Lake brine is diluted with water and further diluted with a lanthanum oxide solution which reduces sulfate interference. The test solution is aspirated and correlated with known standards.

2. Reagents

   A. 1000 ppm calcium standard (2.77g $CaCl_2$, dilute to one liter)
   B. Lanthanum oxide stocks solution (29.3g La_2O_3, add 250 ml HCl, dissolve, dilute to 500 ml with H_2O)
   C. 20% La_2O_3 solution

3. Apparatus

   A. Atomic absorption instrument with calcium lamp.
   B. Miscellaneous labware

4. Procedure

   A. Prepare working standards of 1, 5 and 10 ppm using the 1000 ppm standard, diluting with 20% La_2O_3 solution.
   B. Run a calibration curve on the atomic absorption unit, record.
   C. Prepare the brine sample
      1. Dilute 1 ml Great Salt Lake brine to ten ml with water to make sample D-1
      2. Dilute 1 ml of D-1 to ten ml with 20% La_2O_3 solution.
   D. Run the brine sample on the Atomic Absorption unit and record.

5. Calculation

   A. Plot the standard calibration curve.
   B. Determine the value for the unknown as follows: ppm Ca ÷ 10,000 = Wt % Ca

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CHLORIDE (Cl^-)

DETERMINATION OF CHLORIDE BY TITRATION

1. Summary of Procedure

An aliquot of prediluted Great Salt Lake brine containing 35 to 160 milligrams of chloride is diluted and titrated with a standard silver nitrate solution using the Mohr method.

2. Reagents

   A. 0.1000 molar sodium chloride standard solution
   B. Potassium chromate indicator, 5%
   C. Methyl red indicator, 0.1%
   D. Sodium Bicarbonate solution, 10%
   E. Nitric acid solution, 20% by volume
   F. 0.1000 molar silver nitrate standard solution.

3. Apparatus

   A. Buret, pipetes, 250 ml erlenmeyer flask
   B. Miscellaneous labward

4. Procedure

   A. Standardization of silver nitrate standard
      1. Titrate a 25 ml aliquot of the sodium chloride standard with the silver nitrate standard.
      2. Calculate the standard factor as follows:

$$\frac{35.46 \times 25}{\text{Titration volume} \times 10} = \text{mg Cl/ml } AgNO_3$$

   B. Pipet an aliquot of the sample into the erlenmeyer flask and add 75 ml water.
   C. Add one drop of methyl red indicator.
   D. Add the nitric acid dropwise until the test solution turns red, while swirling.
   E. Add the sodium bicarbonate solution dropwise until the test solution just turns yellow, while swirling.

F. Add 10 drops potassium chromate indicator.
G. Titrate the solution with the standard silver nitrate, swirling continuously, until the first permanent color change of the suspension from yellow, and record the volume.

5. Calculation

A. The percent chloride is calculated as follows:

$$\frac{\text{Titration volume (ml)} \times \text{AgNO}_3 \text{ standard factor} \times \text{dilution vol.}}{\text{Aliquot size (ml)} \times \text{sample weight (g)} \times 10} = \text{Wt. \% Cl}$$

DETERMINATION OF CHLORIDE BY A GRAVIMETRIC METHOD

1. Summary of Procedure

To a 25 ml aliquot of prediluted Great Salt Lake brine is added 75 ml water and 50 ml of silver nitrate solution. The precipitate is filtered, washed, dried and weighed.

2. Reagent

A. 0.250 molar silver nitrate solution

3. Apparatus

A. Sintered glass filtering crucible, 250 ml beaker
B. Analytical balance
C. Miscellaneous labware

4. Procedure

A. Pipet a 25 ml aliquot of the prediluted brine into the beaker
B. Add 75 ml water
C. Stirring continuously, add 50 ml silver nitrate solution
D. Allow the solution to digest for two hours
E. Filter the precipitate with the preweighed filtering crucible
F. Wash the precipitate liberally to flush excess silver nitrate
G. Dry the crucible at 110°C for one hour
H. Allow the crucible to cool in a dessicator and reweigh

5. Calculations .

A. Calculate the weight of precipitate
B. Calculate the weight percent chloride in the sample

$$\frac{.247 \times \text{precipitate weight} \times \text{dilution volume}}{\text{Aliquot size (ml)} \times \text{Sample weight (g)}} = \text{Wt. \% Chloride}$$

DETERMINATION OF CHLORIDE BY A COULOMETRIC METHOD

1. Summary of Procedure

A 25 ml aliquot of prediluted Great Salt Lake brine is further diluted to 100 ml. A 100 microliter sample is then placed in a chloride meter and the milliequivalents (meq) of chloride determined.

2. Reagents

   A. Acid buffer with chloride (9g polyvinyl alcohol + .04g sodium chloride + 500 mls water + 6.4g nitric acid + 100 mls glacial acetic acid, heat and stir until dissolved, cool and dilute to one liter).
   B. 100 meq chloride standard (5.849g sodium chloride, dilute to one liter).

3. Apparatus

   A. Coulometric Chloride meter
   B. 100 microliter pipet (eppendorf)
   C. Plastic sample cups - 25 ml
   D. Miscellaneous labware

4. Procedure

   A. Pour 15 ml of acid buffer into sample cup and immerse electrodes
   B. Activate conditioning switch
   C. Calibrate meter
      1. Add 100 microliters of 100 meq standard
      2. Activate the titrate switch
      3. Take reading and adjust if necessary and rerun.

   D. Dilute 25 ml of prediluted brine to 100 ml
   E. Add 100 microliters of this sample to the sample cup
   F. Activate the titrate switch and record the reading (meq chloride).

5. Calculation

   A. The precent chloride is calculated as follows:
      meq chloride x .17725 = Wt. % Chloride

SULFATE (SO_4=)

DETERMINATION OF SULFATE
BY TITRATION

1. Summary of Procedure

An aliquot of prediluted Great Salt Lake brine containing 200 to 400 milligrams (mg) sulfate is titrated with a standard barium chloride solution to an endpoint indicated by Alizarin Red S indicator.

2. Reagents

   A. 0.1000 molar ammonium sulfate (NH_4SO_4) standard solution
   B. 0.1000 molar barium chloride ($BaCl_2$) solution
   C. Alizarin Red S indicator - .2% (ARS)
   D. Sodium hydroxide solution - 20%
   E. 0.10 molar perchloric acid solution
   F. Methanol

3. Apparatus

   A. Buret, pipet, beakers
   B. pH meter with glass electrode
   C. Miscellaneous labware

4. Procedures

   Standardize the barium chloride solution.

   A. Titrate 25 ml .1 molar NH_4SO_4, diluted to 50 ml with water, with $BaCl_2$ as per procedure steps C - G. Determine the sulfate in sample.
   B. Pipet an aliquot of the prediluted brine into a beaker, dilute to 50 ml.
   C. Add 50 ml methanol and adjust solution to pH 3.0 to 3.5 with perchloric acid
   D. Add 5 drops ARS and titrate the solution to the first appearance of pink, while stirring.
   E. Continue stirring for five minutes and the color will revert to yellow
   F. Continue the titration dropwise to the first permanent pink, (a completed titration is indicated by a pink color to the precipitate).
   G. Record the volume of barium chloride used.

5. Calculations

   A. Calculate the barium chloride standard factor
   $240.25 \div \text{ml of } BaCl_2 \text{ titrated} = \text{mg } SO_4 \ / \ \text{ml } BaCl_2$
   B. Calculate the percent sulfate in the sample

$$\frac{\text{Titration volume x } BaCl_2 \text{ factor x Dilution volume}}{\text{Aliquot size (ml) x sample weight (g) x 10}} = \text{percent sulfate}$$

Note: Because Great Salt Lake brine contains potassium, a correction factor must be used to accurately determine the percent sulfate. See the accompanying table.

Table 1. Method for calculating corrected percent sulfate.

A. Calculate the ratio of % K / % SO_4
B. Read the % SO_4 error from the body of the table
C. Multiply % error by determined % SO_4 to get correction
D. Add correction to determined % SO_4 to get corrected % SO_4

RATIO % K / % SO_4 VERSUS % SO_4 ERROR

Ratio	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
.0	.00	.50	.68	.72	.95	1.08	1.18	1.27	1.34	1.43
.1	1.50	1.59	1.62	1.70	1.76	1.82	1.88	1.94	1.99	2.04
.2	2.09	2.14	2.20	2.24	2.39	2.35	2.39	2.43	2.48	2.52
.3	2.55	2.60	2.63	2.68	2.72	2.76	2.80	2.83	2.88	2.91
.4	2.95	2.99	3.02	3.06	3.10	3.12	3.16	3.19	3.23	3.26
.5	3.30	3.33	3.36	3.39	3.43	3.45	3.48	3.52	3.55	3.58
.6	3.60	3.62	3.66	3.69	3.72	3.74	3.77	3.79	3.82	3.85
.7	3.87	3.90	3.92	3.95	3.98	4.00	4.02	4.04	4.06	4.09
.8	4.11	4.14	4.16	4.18	4.20	4.22	4.24	4.27	4.29	4.30
.9	4.32	4.34	4.36	4.38	4.40	4.41	4.44	4.46	4.48	4.50
1.0	4.51	4.53	4.54	4.56	4.58	4.60	4.62	4.63	4.64	4.66
1.1	4.69	4.70	4.71	4.73	4.74	4.75	4.77	4.79	4.80	4.81
1.2	4.82	4.83	4.85	4.87	4.88	4.90	4.92	4.93	4.94	4.95
1.3	4.97	4.98	4.99	5.00	5.01	5.02	5.02	5.03	5.04	5.06
1.4	5.08	5.09	5.10	5.11	5.12	5.12	5.13	5.14	5.15	5.18
1.5	5.19	5.20	5.20	5.20	5.21	5.22	5.23	5.23	5.24	5.26

DETERMINATION OF SULFATE BY A GRAVIMETRIC METHOD

1. Summary of procedure

A five ml aliquot of Great Salt Lake brine is diluted, acidified, reacted with excess barium chloride solution, digested, filtered, dried and weighed. The percent sulfate is calculated from the barium sulfate precipitate.

2. Reagents

   A. Hydrochloric acid, concentrated (HCl)
   B. 20% barium chloride solution
   C. 10% HCl solution

3. Apparatus

   A. Filter funnel and paper (No. 42 Whatman)
   B. Porcelain crucible, tared
   C. Muffle furnace and hot plate
   D. Miscellaneous labware

4. Procedure

   A. Dilute a five ml aliquot of Great Salt Lake brine to 150 ml
   B. Add 8 ml concentrated HCl and bring to a boil
   C. Add 10 ml of 20% $BaCl_2$ solution and bring to a boil
   D. Allow sample to cool and digest for at least twelve hours
   E. Filter the precipitate through No. 42 Whatman filter paper
   F. Wash the precipitate on the filter paper as follows:
      1. Two distilled water washes
      2. One hot 10% HCl wash
      3. One final distilled water wash

   G. Place the filter paper and precipitate in a preweighed porcelain crucible and ash the filter paper in the muffle furnace at 800 to 900°C until ashing is complete.
   H. Weight the crucible and barium sulfate precipitate

5. Calculation

   A. Subtract the weight of the crucible from the total weight to determine the weight of barium sulfate precipitate as follows: grams $BaSO_4 \times 82.32 = g/l\ SO_4$
   B. Calculate weight percent sulfate as follows: $g/l\ SO_4 \div (\text{specific gravity} \times 1000) = \text{Wt. } \%\ SO_4$

LITHIUM (Li^+)

DETERMINATION OF LITHIUM BY FLAME EMISSION

1. Summary of procedure

A prediluted sample of Great Salt Lake brine is analyzed with a flame photometer using the standard addition technique.

2. Reagents

A. 200 ppm lithium standard (1.987 g $LiNO_3$, dilute to 1000 ml)

3. Apparatus

A. Flame photometer
B. Eppendorf pipet - 200 microliter
C. Miscellaneous labware

4. Procedure

A. Pipet 200 microliters of 200 ppm lithium standard into a plastic disposable cup.
B. Pipet 200 microliters of water into a second cup
C. Pipet 20 ml of prediluted brine sample into each cup
D. Aspirate water into the flame photometer and zero output
E. Aspirate sample without lithium spike and record reading
F. Aspirate water and zero output
G. Aspirate sample with lithium spike and record reading

5. Calculations

A. Calculate ppm lithium in original dilution as follows:

$$\frac{\text{emission intensity of sample x 1.98}}{\text{emission intensity of sample and spike} - \text{emission intensity of sample}} = \text{ppm Li (in original dilution)}$$

B. Calculate ppm lithium in sample

$$\frac{\text{ppm Li (in original dilution) x 500}}{\text{Sample weight (g)}} = \text{ppm lithium}$$

DETERMINATION OF LITHIUM BY ATOMIC ABSORPTION

1. Summary of procedure

A one ml aliquot of Great Salt Lake brine is diluted to 100 ml and aspirated into an atomic absorption instrument with lithium lamp. The lithium concentration is determined versus known standards.

2. Reagents

A. 1000 ppm lithium standard (9.936g $LiNO_3$, dilute to 1000 ml)

3. Apparatus

A. Atomic absorption instrument (AA) with lithium lamp
B. Miscellaneous labware

4. Procedure

A. Prepare working standards of 1, 3, 5, 7, 10 ppm Li using the 1000 ppm solution.
B. Run a calibration curve on the AA with the standards
C. Dilute a one ml aliquot of the Great Salt Lake brine to 100 ml with water
D. Run the brine sample on the AA and record reading

5. Calculation

   A. Plot the standards calibration curve from the recorded values
   B. Determine the value of the unknown in ppm lithium

BORON (B^{+++})

DETERMINATION OF BORON BY A COLORIMETRIC METHOD

1. Summary of procedure

A prediluted sample of Great Salt Lake brine is added to a quinalizarin-in-sulfuric acid reagent, the color is allowed to develop, and an absorbance reading is taken with a spectrophotometer versus known standards.

2. Reagents

   A. Quinalizarin stock solution (0.1g quinalizarin in 100 mls concentrated H_2SO_4)
   B. Quinalizarin test solution (10 mls stock solution in 500 mls of concentrated H_2SO_4)
   C. Boron standards (boric acid solutions of 0, 1, 3, 5, 7, 10, 15 and 20 ppm B in H_2O in 500 ml volumetrics each with 10g of $MgCl_2 \cdot 6H_2O$, 10g KCl and 10g Na_2SO_4)

3. Apparatus

   A. Spectrophotometer (optimized between wavelengths 615 and 650)
   B. Pipets, pipet bulb
   C. Miscellaneous glassware

4. Procedure

   A. Prepare a standard boron curve
      1. to 2 ml of 20 ppm boron standard in a cuvette, carefully add 15 ml of quinalizarin test solution to avoid splattering.
      2. Proceed similarly with the other standards
      3. Allow the color of the standards to develop for twenty minutes, stirring occasionally.
      4. Standardize the spectrophotometer with the high and low standards.
      5. Read the values of all standards and plot the results.

   B. Unknown sample determination
      1. Prepare the unknown solution as in A above.
      2. Record the reading and plot the result to determine the ppm B.

5. Calculations

   A. The ppm B present in the original sample is calculated as follows:

$$\frac{\text{ppm Boron reading x 500}}{\text{Sample Weight}} = \text{ppm Boron}$$

DETERMINATION OF BORON BY TITRATION

1. Summary of procedure

An aliquot of prediluted Great Salt Lake brine containing .3 to 1.0 milligrams (mg) boron is acidified and boiled to remove CO_2. The pH is adjusted, manitol is added, and the excess manitol-boron complex is titrated.

2. Reagents

   A. Standard boron solutions 200 and 20 micrograms Boron/ml
   B. 0.01 molar sodium hydroxide standard solution
   C. 1 molar hydrochloric acid
   D. Mannitol, reagent grade
   E. pH 7.0 buffer
   F. Methyl red indicator - .1%

3. Apparatus

   A. Buret, pipets, beakers
   B. pH meter with glass electrode
   C. Miscellaneous labware

4. Procedure

   A. Pipet an aliquot of sample into a 250 ml beaker and dilute to 150 m.l.
   B. Pipet 5 mls of 20 micrograms Boron solution into a beaker and dilute to 150 mls
   C. Pipet 10 mls of 20 micrograms Boron solution into a beaker and dilute to 150 mls.
   D. A blank of 150 ml water is also made.
   E. Add 2 drops methyl red indicator to each beaker and boil for two minutes.
   F. Cool to room temperature
   G. Calibrate the pH meter to 7.0 with the buffer solution
   H. Adjust the test solution and standards to pH 7.0 with .01 molar Na OH solution
   I. Add 5 to 10g mannitol to the solution.
   J. Titrate the blank, standards, and sample immediately with .01 molar NaOH to pH 7.0 and record the quantities used.

5. Calculation

   A. Calculate standard boron value (micrograms B/ml NaOH): 100 micrograms B÷ (ml NaOH – ml for blank) + 200 micrograms B ÷ (ml NaOH – m.l for blank) ÷2 = Standard value
   B. Calculate ppm boron in sample

$$\frac{\text{(Titration ml – blank ml) x Standard factor}}{\text{Sample aliquot x sample weight} \div \text{dilution volume}} = \text{ppm Boron}$$

BROMIDE (Br^-)

DETERMINATION OF BROMIDE BY TITRATION

1. Summary of procedure

A twenty gram sample of Great Salt Lake brine is diluted to 50 ml and buffered with calcium carbonate. Bromide is oxidized to bromate by heating the sample with excess lithium hypochlorite. The excess lithium hypochlorite is reduced with sodium formate. The bromate is titrated with sodium thiosulfate.

2. Reagents

   A. 50% hydrochloric acid solution (50 mls HC1, dilute to 100 mls)
   B. .8 N lithium hypochlorite solution (12g LiOC1, dilute to 500 mls)
   C. 2 M sodium formate solution (13.6g $NaCHO_2$, dilute to 100ml)
   D. 1% sodium molybdate solution (1 g $NaMoO_4 \cdot 2H_2O$, dilute to 100 ml)
   E. 25% sulfuric acid solution (100 mls H_2SO_4, dilute to 400 mls)

F. .05 N sodium thiosulfate (12.5g $Na_2S_2O_3 \cdot 5H_2O$, .lg Na_2CO_3, dilute to 1000 ml)
G. Potassium bromide standard solution (1.489g KBr, dilute to 1000 ml) = (1 mg Br/ml)
H. .5% starch indicator solution (1 g soluble starch, mix with 5 ml water to form a paste, add to 200 ml boiling water, boil for one minute more)
I. Calcium carbonate, reagent grade
J. Methyl red indicator .01% (.lg Methyl red, dilute to 1000 ml)

3, Apparatus

A. Buret, erlenmeyer flasks, pipettes
B. Miscellaneous labware

4. Procedure

A. Standardize the sodium thiosulfate solution

1. Prepare two standards and a blank

a. 10 ml sodium thiosulfate solution, dilute to 50 ml in 250 ml erlenmeyer
b. 20 ml sodium thiosulfate solution, dilute to 50 ml in 250 ml erlenmeyer
c. 50 ml water in a 250 ml erlenmeyer

2. Add one drop .01% methyl red to each flask
3. Acidify slightly with 50% HCl
4. Add 15 ml .8 N $LiOCl$
5. Add 10 drops 50% HCl and .1 to .2 g excess solid calcium carbonate
6. Add glass beads and boil eight minutes on a hot plate
7. Remove from hot plate and add 15 ml 2M $NaCHO_2$ and boil for eight minutes more
8. Rinse inside of flask with water while boiling
9. Allow solutions to cool to room temperature
10. Add three drops of 1% sodium molybdate, lg potassium iodibe, and 10 ml of 25% H_2S_4
11. Titrate with sodium thiosulfate, adding 3 ml starch solution near the endpoint and record.

B. Repeat the entire procedure with the unknown sample and record

5. Calculations

A. Calculate the standard factor for the sodium thiosulfate solution

$$\text{mg Br}^- / \text{ml } Na_2S_2O_3 = \frac{\text{mg Br in sample}}{\text{ml } Na_2S_2O_3 \text{ - Blank}}$$

B. Average the two values for the 10 and 20 ml samples
C. Calculate the ppm bromide in the unknown

$$\frac{(\text{ml } Na_2S_2O_3 - \text{blank}) \text{ x } (\text{mg Br / ml } Na_2S_2O_3)}{\text{grams of sample x } 10{,}000} = \text{ppm Br}^-$$

Note: Development work is currently being conducted on the use of a bromide specific ion probe method for Great Salt Lake brine analysis.

SULFIDE ($S^=$)

DETERMINATION OF SULFIDE WITH SPECIFIC ION PROBE

1. Summary of procedure

An aliquot of Great Salt Lake brine (one to 10 ml) is added to a standard antioxidant buffer (SAOB) solution and the mg/liter of sulfide is read directly from the sulfide ion probe meter.

2. Reagents

A. SAOB solution, 25% (40.0g NaOH + 42.5g Disodium EDTA + 18.0g Ascorbic acid + 300 ml water, dissolve and dilute to 2000 mls)

B. Sulfide standards
   1. 500 mg/liter $S^=$ (.94g $Na_2S \cdot 9H_2O$, dilute to 250 mls with SAOB sol)
   2. 100 mg/liter $S^=$ (25 mls 500 mg/liter $S^=$ in 100 mls SAOB sol)
   3. 10 mg/liter $S^=$ (10 mls 100 mg/liter $S^=$in 90 mls SAOB sol)
   4. 1 mg/liter $S^=$ (10 mls 10 mg/liter $S^=$ in 90 mls SAOB sol)

3. Apparatus

A. Specific ion meter with sulfide ion probe and appropriate reference electrode
B. Magnetic stirrer with stir bars
C. Miscellaneous labware

4. Procedure

A. Calibrate the specific ion probe and meter
   1. 1 ml 10 mg $S^=$/ liter in 100 ml SAOB, calibrate to 10 position on meter
   2. 1 ml 100 mg $S^=$/ liter in 100 ml SAOB, calibrate to 100 position on meter
B. Determine the sulfide concentration of the unknown
   1. 1 ml unknown brine in 100 ml SAOB, take the reading
   2. If the reading is not between 10 and 100 mg/liter, add additional 1 ml increments, up to 10, and divide the reading by the number of mls added.
   3. If readings are less than 10 mg $S^=$/ liter, the meter is then recalibrated for a 1 to 10 mg/ liter range and the samples are rerun.

5. Calculation

A. Readings ($mgS^=/\ell$) are taken directly or divided by the number of mls used.
B. Calculate $ppmS^=$ as follows: $mgS^=/\ell \div \text{specific gravity} = ppmS^=$

Note: SAOB is unstable and should be made daily. Also, brine in excess of 10 mls results in clouding of the SAOB.

pH

DETERMINATION OF pH IN A 5% SOLUTION

1. Summary of procedure

A five gram aliquot of Great Salt Lake brine is diluted with 100 mls of carbon dioxide-, ammonia-free deionized water. The relative pH is then determined with a pH meter and glass calomel electrodes at 25°C.

2. Reagents

   A. Carbon dioxide-, ammonia-free deionized water
   B. Standard pH solutions - 4. 0, 7.0 and 10.0 buffers

3. Apparatus

   A. Constant temperature bath
   B. pH meter with glass calomel electrode pair
   C. Magnetic stirrer with stir bars
   D. Miscellaneous labware

4. Procedure

   A. Weigh five grams of Great Salt Lake brine into a 150 ml beaker and add 100 mls of the carbon dioxide-, ammonia-free deionized water
   B. Stir the solution until dissolved and place the sample and buffers into the constant temperature bath and equilibrate at 25°C.
   C. Calibrate the pH meter at 4. 0, 7. 0 and10. 0 with the buffer solutions
   D. Measure and record the pH of the sample to the nearest .1 pH unit

5. Calculations

   None

Note: The indirect method for measurement of pH is necessary because of the interferences and instability experienced when using non-diluted Great Salt Lake brine, because of its highly ionic species.

HEAVY METALS IN THE GREAT SALT LAKE, UTAH

by Paul L. Tayler, Lynn A. Hutchinson, and Melvin K. Muir

INTRODUCTION

The Great Salt Lake, located in the Great Salt Lake Basin, is known as a dead sea because its high salinity limits the flora and fauna around the lake. The Great Salt Lake Basin, a closed basin that drains a large part of northern Utah and parts of Wyoming and Idaho, is the final repository of all organic and inorganic materials both suspended and dissolved in the waters draining into it. It therefore acts as a natural disposal system. How well this system accomplishes the disposal of suspended and dissolved materials is very important to the health and welfare of the inhabitants of the region.

Organic material brought into the lake is decomposed and consumed by bacteria and algae which are in turn consumed by brine shrimp and the larva of brine flies. Much of the waste from the arthropods serves as nuclei for the precipitation of calcium and magnesium carbonate particles that form the extensive deposits of oolitic sands found in the lake. The simple biosystem of the lake is so effective in dealing with the organic waste that it has been investigated for use by industry as a bioclarification process of salty waste waters.

The Great Salt Lake has also acted as a concentrator of inorganic soluble salts carried by inflowing streams. Salt concentration in the lake is a function of the variations in yearly stream inflow and the net evaporation rate. Salt concentrations reached a recent maximum level of 27.5% in December of 1963, which is approximately nine time saltier than sea water. The concentration and behavior of metals in the lake is less well understood than that of the more common salts and has not been extensively studied. It is possible that heavy metals in high concentrations could be amenable to extraction by industry. It is also known that high concentrations of certain heavy metals could possibly be toxic to life forms.

Many areas within the drainage basin of the Great Salt Lake are heavily mineralized. Much mineral wealth in the form of lead, zinc, silver, gold, and copper ores has been taken from the Wasatch and Oquirrh Mountains in the area, and the weathering of these areas has undoubtedly contributed metal salts to the streams flowing into the lake over the thousands of years that the lake has existed. More recently effluents from the mining, milling and refining operations themselves and from other sources related to industrial development have made additional contributions to the heavy metal loads in the inflowing streams to the lake.

It is therefore of interest to study and characterize the concentration and behavior of various metals in the Great Salt Lake and, in particular, to determine whether they are being concentrated along with the more common salts or if they are being eliminated from the lake waters. Metals for which concentration data in Great Salt Lake have recently been made available include copper, zinc, cadmium, mercury, lead, arsenic, molybdenum, selenium, manganese, and silver. To help understand the concentration and behavior of these metals, studies of other parameters such as pH, specific gravity and temperature have been made as well as the role of carbonate, bicarbonate, dissolved oxygen and soluble sulfides in the lake as they affect heavy metals.

A major difficulty was encountered because the high salt concentration of the Great Salt Lake waters interferes with the analytic determination of minor elements. It was therefore necessary to develop accurate and reproducible techniques for analyzing salt water for metal concentration. Techniques for analysis of metals of saline solutions were recently developed by Kennecott's Metal Mining Division research center (Tayler and others, 1977, 1978), and are included in appendix A.

LAKE STATUS

The lake has been effectively divided into two bodies of water, a southern and a northern arm, by the rockfilled Southern Pacific Railroad causeway which runs west of Promontory Point. The northern and southern arms are noticeably different bodies of water, with the northern arm having a higher concentration of salts. Most of the available data deals with the industrially and recreationally developed southern arm of the lake.

Brine Layers

A unique feature in the south arm is the existence of two brine layers. Dissolved salts in the lower layer are more concentrated than in the upper layer. In July of 1976, the lower layer extended from a depth of approximately 25 feet to the bottom of the lake, and was approaching saturation. The interface between the upper and lower brine layers is identified by abrupt changes in pH and density or specific gravity as illustrated in

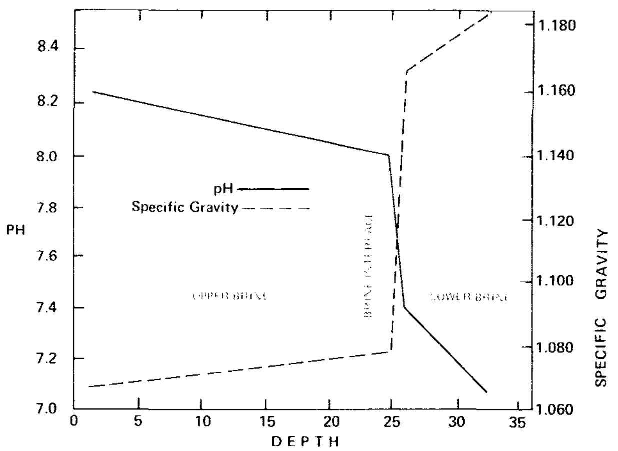

Figure 1. Specific gravity and pH in south arm of Great Salt Lake.

figure 1, and by the distribution of soluble sulfide and dissolved oxygen in the lake as illustrated in figure 2. The pH decreases with depth with a large change occurring across the concentrated brine interface. Specific gravity increases with depth and is directly related to the salt concentration of the brine. High concentrations of soluble sulfide and depletion of oxygen are found in the dense lower brine, while in the upper layer the brine is well oxygenated with little or no soluble sulfide present. The oxygen and sulfide concentrations at the 25 foot depth are indicative of permeation of the sulfide into the upper brine with subsequent oxidation depleting both oxygen and sulfide constituents.

Soluble sulfides have also been detected near the bottom of the lake in areas that do not underlie the deep brine layer. These soluble sulfides originate from underlying anaerobic sediments.

Heavy Metal Concentrations

Heavy metal concentractions for those elements for which data is available are summarized in table 1 in terms of the structure of the lake, namely the south arm upper and lower brines and the north arm brines. While metal concentrations are low in all sections of the lake, they are higher in the lower layer of the south arm brine than in the upper layer. Theoretically, soluble metals should not be detectable in the presence of the soluble sulfides in the lower layer, but the metals could be present either as solid particulates which pass through filters or as soluble metals complexed by the salts in the brine. The analytical techniques used were not sufficient to differentiate between these two possibilities.

In considering the chemical characteristics of the lake, it is of interest to compare the average lake concentration of metals with Environmental Protection Agency's mining and milling interim effluent limitations and guidelines. Table 2 compares the actual metal concentrations of the lake with the permissable effluent limitations. All total concentration and dissolved concentrations of the lake are significantly lower than the effluent limitations, which implies heavy metal toxicity in the lake brines is negligible. In fact the heavy metal concentrations are near drinking water standards.

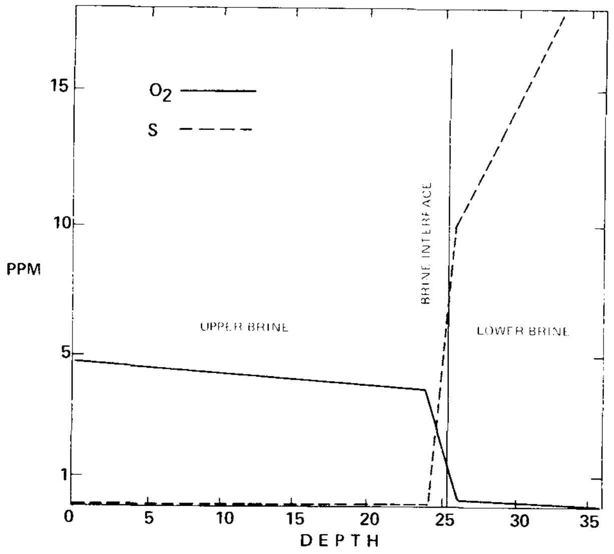

Figure 2. Concentration of oxygen and sulfides in south arm of Great Salt Lake.

Bacteriological Studies

Bacteriological studies show the presence of three types of bacteria that are of interest: 1) bacteria that produce soluble sulfide by reducing sulfates, 2) bacteria that produce soluble sulfides from protein and 3) glucose-fermenting bacteria that are active under anaerobic conditions. The results of the bacterial investigations are summarized in table 3.

Anaerobic bacteria that produce soluble sulfide by reducing sulfates were found in all areas of the lake. Since the Great Salt Lake contains abundant sulfate, the ubiquity of the sulfate reducing bacteria is significant in terms of the production of soluble sulfides.

Anerobic glucose fermenting bacteria and bacteria producing sulfide from protein have also been identified in many of the parts of the lake. These latter bacteria which utilize organic wastes for growth are particularly noticeable in deep brines.

Table 1. Physical and chemical analyses of Great Salt Lake brine (ppm)

	South Arm		North Arm Brine
	Upper Brine	Lower Brine	
pH	8.1	7.3	7.9
Specific gravity	1.073	1.172	1.207
Bicarbonate	630	860	844
Soluble Sulfide	0.055	16.1	(1)
Oxygen	4.1	0.0	(1)
Copper[2]	0.009	0.018	0.001
Zinc	0.011	0.010	0.006
Cadmium	0.0002	0.0007	<0.001
Mercury	0.00003	0.0002	0.0002
Lead	0.002		0.005
Arsenic	0.100	0.205	0.210
Manganese	<0.005	0.070	(1)
Molybdenum	<0.010	<0.010	(1)
Selenium	0.005	0.009	(1)
Silver	0.003	0.002	0.003

(1) no analyses

(2) heavy metal from soluble fraction

Table 2. Effluent guidelines and metal concentrations in the Great Salt Lake (ppm)

	Interim Limitations		Lake Concentrations
	Maximum	30-Day	
Copper	0.1	0.05	0.006
Zinc	1.0	0.5	0.009
Cadmium	0.02	0.001	0.0002
Mercury	0.002	0.001	0.0001
Lead	0.2	0.1	0.004

INTERPRETATION

Distribution of Metals

With no outflow from the Great Salt Lake, the only water losses from the lake occur through evaporation and through precipitation and settling of hydrated solids. To understand the present metal distribution, it is instructive to consider the concentration and precipitation of solids in the lake. Table 4 relates the present average metal concentration in the inflow into the lake to the present lake concentrations. Major industrial inputs are excluded from the present inflow figures to more nearly approximate preindustrial conditions which existed for the major portion of the lake's existence. The high concentration factor for sodium chloride is indicative of its high solubility. The bicarbonate constituent, on the other hand, shows a very small concentration factor; the bicarbonate enters the lake in nearly saturated concentrations and is a major constituent of all lake sediments due to its precipitation from the lake waters as the brines are concentrated by evaporation. The low metal concentration factors also indicate perferential deposition of those elements in the lake. In fact, the concentration factors for copper, zinc and cadimum are less than one because the dissolved concentrations of both elements are higher in inflowing waters than in the lake itself.

If one were to assume that the lake level is in rough equilibrium with the annual inflow (that is, the water loss through evaporation roughly equals the net inflow) and the net inflow roughly equals one-tenth the total lake volume, then the concentration factors can be interpreted as the number of decades required to bring the lake to its present salt and metal concentrations. This interpretation serves to highlight the fact that contemporaneous precipitation of metals must be occurring.

Sediment analysis

Sediment analyses support the concept of preferential deposition. Table 5 summarizes the concentration of metallics and sulfide found in the sediments. The metal concentrations found in the sediments of the south arm are generally higher than in the north. This would be expected if the metals are precipitated soon

Table 3. Results of bacterial investigations. (Tayler and others, 1977)

Sample No.	Sediment Depth	Sample Description	Sulfide Producing From Sulfate	Sulfide Producing From Protein	Glucose Fermenting Anerobic
1	27.5′	Black mud	Present 1,3	Present 2	Present 2
2	29.0′	Black mud	Present 1	Present 1	Present 1
3	11.0′	Bioherm	Present 1	Present 1	Absent
4	8.0′	Oolitic sand	Present 1,4	Absent	Absent
5	6.0′	Oolitic sand	Present 2	Absent	Present 1
6	9.5′	Oolitic sand	Present 2	Absent	Present 1
7	15.0′	Oolitic sand	Present 2	Absent	Present 2
8	18.0′	Oolitic sand	Present 2	Present 1	Present 2

Key: 1. Developed slowly, 2. Many developed rapidly, 3. Mostly spore formers, 4. Typical Desulforibrio

Table 4. Concentration factors of heavy metals in the Great Salt Lake

	Stream Inflow (ppm)	Lake (ppm)	Concentration Factor
Sodium	300	85,700	285
Chlorine	490	147,000	300
Bicarbonate	350	650	1.9
Copper	0.012	0.006	0.5
Zinc	0.014	0.009	0.6
Cadmium	0.002	0.0002	0.1
Mercury	-	0.0001	-
Lead	0.0008	0.004	5.0
Arsenic	0.013	0.150	11.5
Manganese	0.005	0.009	1.8
Molybdenum	0	<0.010	-
Selenium	0.002	0.005	2.5
Silver	-	0.003	-

Table 5. Chemical analyses of Great Salt Lake sediments (ppm)

	South Arm		North Arm
	Beneath Upper Brine	Beneath Lower Brine	
Copper	153	170	31
Zinc	88	97	61
Cadmium	6.5	7.6	7.0
Mercury	0.1	0.2	0.09
Lead	98	101	32
Arsenic	27	43	16
Manganese	175	175	(1)
Molybdenum	28	54	(1)
Selenium	0.6	0.8	(1)
Silver	0.1	0.1	0.03
Sulfide	13	155	(1)

(1) No Analyses

after entering the lake, since approximately 90 percent of the inflow occurs in the south arm.

The content of total sulfide found in the sediments in the south arm on the lake floor below 25 feet of water is much higher than that found in sediments deposited above the dense brine layer (table 5). The sulfide concentration could account for the metal deposition in the sediments below the lower brine but does not account completely for the metal deposition in sediments found above the deep brine layer. It is therefore likely that other chemical reactions such as ion exchange with the clays, absorption by organics, or chemical deposition with basic carbonates or chlorides is occurring in the upper lake brine. These forms would eventually be converted to sulfides through contact with the soluble sulfides produced by anaerobic bacterial activity in the sediments, particularly by the sulfate reducing bacteria that were found in all sediment samples. Investigations of core samples will be necessary to determine the rate and the extent to which the conversion to sulfide is occurring in the upper brine sediments.

CONCLUSION

The Great Salt Lake has been concentrating inorganic salts in its waters for thousands of years. However, the total soluble concentrations of heavy metals in the water are extremely low. The heavy metals in the lake, along with clays, organic materials and carbonates, are precipitating to the sediments and deep brines where anaerobic conditions and sulfides formed by sulfate reducing bacteria immobilize the metals. The lake thus avoids accumulation of heavy metals in the lake waters and is nontoxic and self-cleansing. This also means that concentrations of the heavy metals in the lake waters are not sufficient for commercial exploitation. Even heavy metal concentration in the sediments, to which the metals are constantly precipitating, are not sufficient for exploitation with present technology. The unique saline condition of Great Salt Lake determines the precipitation and immobilitation of heavy metals in the lake.

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APPENDIX A

CHEMICAL ANALYSES FOR HEAVY METALS AND OTHER COMPONENTS IN GREAT SALT LAKE BRINE AND SEDIMENTS

Chemical analyses can be performed for both total and dissolved concentrations. For total concentrations the samples are analyzed without filtering. For dissolved concentrations, the samples are filtered to eliminate suspended solids. Two filters are used to allow filtering of the samples without blinding. A final paper filter is used and is efficient to 0.45 microns. The term "soluble metals" in these comments is defined as the metals that pass through the 0.45 micron paper. Soluble metals are, therefore, either physically dissolved or are contained in submicron particulates that pass through the filter.

The high salt content of the Great Salt Lake waters and sediments invalidates normal procedures for trace element analyses. It is therefore necessary to modify procedures for sample preparation to avoid interference from the high salt content during the elemental determinations. As these procedures are unique, they are described in detail.

Samples should be analyzed on site for carbonate, bicarbonate, specific gravity, temperature, and pH. Preservatives are added as necessary to the samples, which are transported to the laboratory for further analysis.

Carbonate-Bicarbonate

A 50 milliliter sample is titrated with 0.02 N standardized acid to phenolphthalein end point for carbonate (American Public Health Association, 1971, p. 52-55).

Dissolved Oxygen

Standard Biochemical Oxygen Demand bottles are filled with samples with care to prevent introduction of air. These are preserved with 2 milliliters of manganous sulfate and 2 milliliters of basic sodium iodide. At the laboratory 2 milliliters of sulfuric acid are added to each sample and the dissolved oxygen is determined by thiosulfate titration (National Environmental Research Center, 1974, p. 51-55).

Sulfide

A soluble and a total sulfide can be determined on each water sample. Total sulfides are collected and preserved with 1N zinc acetate. Soluble sulfides are collected in 1-liter bottles with care to prevent contact with air. For soluble sulfide, samples are treated with 2 milliliters of 6N aluminum chloride and 2 milliliters 6N sodium hydroxide; the samples are rotated vigorously for 1 minute and then allowed to settle for 15 minutes. The clear supernatant liquid from this treatment is then preserved with 1N zinc acetate, and the flocculant discarded.

At the laboratory, suitable aliquots are treated with acid purged with nitrogen; the resultant hydrogen sulfide is absorbed in 50 milliliters of zinc acetate solution. The zinc acetate solution is then analyzed by the methylene blue colorimetric method, which employs aminesulfuric acid and ferric chloride reagent to develop the color (American Public health Association, 1971, p. 551-559).

Heavy Metal Determination

Arsenic, cadmium, copper, lead, manganese, mercury, molybdenum, selenium, silver, and zinc can be analyzed on soluble and total water fractions. Total metal samples are preserved with nitric acid at the time of sampling. The soluble samples are untreated and unfiltered because of problems associated with on-site filtering (very slow filtering rate). The preparation of the soluble portion requires the development of a special filtering system. The first filter used in this two-part system, to remove the large coarse material, is a Whatman 540. The second filter, a Teflon FHLP from Millipore Corporation, is positioned about one centimeter below the first filter. This combination allowes for rapid filtration without contamination.

After filtering the soluble sample, an extraction step is required on all samples (total and soluble) that are to be analyzed for arsenic, cadmium, copper, lead, manganese, molybdenum, selenium, silver, and zinc.

manganese, molybdenum, selenium, silver, and zinc.

A 100 milliliter sample is initially adjusted to pH 3.0. Five milliliters of a chelating solution, 1 percent APDC (Ammonium Pyrrolidine Dithiocarbamate) and 1 percent DDDC (Sodium Diethyl Dithiocarbamate), are added and the pH readjusted to 3.0. The sample is then transferred to a separatory funnel and 20 ml Methyl Iso-butyl Ketone (MIBK) added. The separatory funnels are agitated for 2 minutes and left to stand for 15 minutes. The aqueous layer is discarded, and the MIBK layer is washed with 50 milliliters of distilled water and agitated again for 30 seconds. The wash water is discarded, and the MIBK layer is analyzed for cadmium, copper, lead, manganese, molybdenum, and zinc by flame atomic absorption (AA) spectroscopy (Jenne and Ball, 1972, p. 90-91; Kinrade and Van Loon, 1974, p. 1894-1898; American Public Health Association, 1971, p. 156-165).

Mercury is analyzed by the flameless, atomic absorption, cold vapor technique on the total and soluble fractions (National Environmental Research Center, 1974, p. 118-123.

Arsenic and selenium are measured on both portions by the sodium borohydride generation method (American Public Health Association, 1971, p. 95-96). This method is modified by the addition of 1 percent potassium iodide (KI) solution as outlined by Wanchope (1976, p. 33-37) to enhance the hydrogen selenide evolution.

For silver analysis the MIBK is evaporated to dryness and the residue digested in nitric acid. Concentrations are then determined by the standard additions method on the flameless graphite-furnace of the Maussman design.

Sediment Samples

Sediment can be collected and transported in sealed bottles to the laboratory where the moisture content is measured. A dried weight of each sample is digested in nitric acid and analyzed for cadmium, copper, lead, manganese, molybdenum, zinc, arsenic, selenium, and mercury. The first six elements are analyzed by flame atomic absorption (American Public Health Association, 1971, p. 156-165). These elements are high enough in concentration to allow for dilution, which eliminates the effect of the salt content.

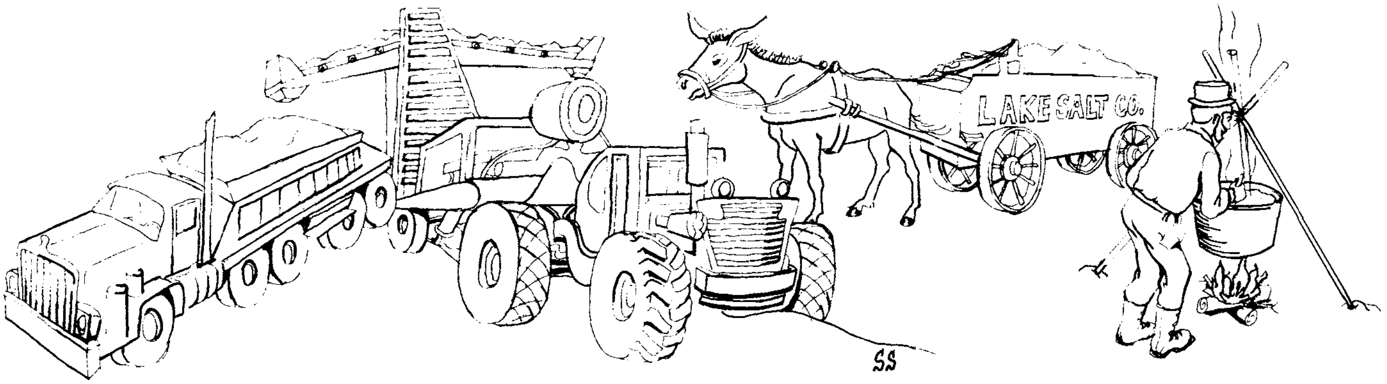
Arsenic and selenium are measured on the digested sample by the use of a graphite furnace AA (Fernandez and Manning, 1971, p. 65-71). Mercury is analyzed by the flameless cold vapor AA technique on digested samples (National Environmental Research Center, 1974, p. 134-138).

Silver is measured after extracting the digestate into MIBK then proceeding with silver analysis as outlined previously.

Sulfide in Sediment

Sulfides can be run as total sulfide using the same procedure and apparatus as that in the water sulfide analysis (American Public Health Association, 1971, p. 551-559).

LAKE INDUSTRIES



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IV. LAKE INDUSTRIES

HISTORY AND TECHNOLOGY OF SALT PRODUCTION FROM GREAT SALT LAKE

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ABSTRACT

This study traces the development of methods used to recover and refine salt from Great Salt Lake by the industry, in general, and by specific companies. It provides brief historical sketches of the major corporations and the economic and environmental factors affecting their growth. A summary is given of present day salt production methods and markets.

HISTORY OF SALT PRODUCTION FROM GREAT SALT LAKE

Before the Mormons

Use of salt from Great Salt Lake in the pre-Mormon period was so limited that the mere mention of trappers, immigrants, or explorers using it becomes historically significant. It can be reasonably assumed that native Americans used the lake as a salt source, but no evidence remains of any extensive developments by them.

The first white men known to use salt from the lake were mountain men from Ashley's Rocky Mountain Fur Company. During the late fall of 1825 a rendezvous site was established near the present site of Ogden City. While camped in the area they boiled away some of the lake brine in a kettle to obtain salt (1).

Early pioneers passing through Utah on their way to California usually brought salt with them and, like the trappers who preceded them, refer to salt only incidently. The explorers in the inter-mountain region were more directly interested in Great Salt Lake and its nature and leave more complete descriptions of it than did their mountain man and pioneer predecessors.

In John C. Fremont's memoirs of his second expedition west he reported floating in a specially prepared rubber raft from a point near the outlet of Weber River to what is now called Fremont Island (2). While returning to the mainland the next morning Fremont filled a five-gallon bucket with brine from which he intended to make salt. Fremont described the process by saying:

> Today we remained at this camp, in order to obtain some further observations and to boil down the water which had been brought from the lake for a supply of salt. Roughly evaporated over the fire, the five gallons of water yielded fourteen pints of very fine-grained and very white salt, of which the whole lake may be regarded as a saturated solution (3).

Fourteen (14) pints of salt were produced from 40 pints of brine, indicating a 35 percent solution. This ratio of salt to water, and the subsequent chemical analysis Fremont had run of the salt sample do not correspond to modern chemical data in similar experiments (4).

Although Fremont's reports were published prior to the settlement of Salt Lake Valley, and they were studied by the Mormons in their preparations to move west, it does not appear the availability of salt as a resource to meet local needs or as a future commercial enterprize had any significant effect on the decision to settle the area.

Mormon Pioneers

The Mormons left Winter Quarters, Nebraska in their exodus to the valley of the Great Salt Lake in April of 1847. A pioneer group was selected to go west in advance of the main body in order to find a suitable route for the upcoming migration. This advance group entered the valley between July 22-24 and immediately began to explore the region and evaluate its resources.

Great Salt Lake, the most dominant feature of the valley, was high on the list of prospective sites to explore. On July 28, Brigham Young and some of his associates made a special trip to the lake to satisfy their curiosity as to the nature of this well-known landmark, and to bathe in its bouyant water. William Clayton, a Mormon chronicler, reports the brethren "suppose the water will yield 35 percent pure salt. They gathered some off the rocks, which is as pure, white and fine as the best that can be bought on the market" (5).

Salt found deposited on the shore of the lake proved to be as important to the pioneers as that found in the water. A committee which had been assigned to extract salt from the lake and shore left August 9 and returned August 13, "having prepared 125 bushels of coarse white salt, and boiled down four barrels of salt water to one barrel of fine white table salt" (6). William Clayton recorded in his journal that the committee found a large bed of beautiful salt, six inches deep, lying between two sand bars. There appeared to be enough pure salt in this bed to provide at least ten wagon loads without further refining (7). There were no restrictions on the use of this salt by the pioneers. Those who required it would simply drive to the lake and take what they needed. More enterprising individuals could bring back an ample supply and sell a heaping bushel for fifty cents.

These shore deposits yielded a poor quality, bitter tasting salt due to the other minerals found in suspension in lake water. Only 84 percent of the percipitate is sodium chloride. The other 16 percent is made up of chlorides and sulphates of magnesium, calcium and potassium (8). These latter minerals give salt a bitter taste. To improve the quality and develop a profitable commercial enterprise, attempts were made to set up a salt boiling apparatus near the south end of the lake.

When the first salt boiling operation was set up is not known, but it marks the genesis of salt production as a serious commercial venture. There is some indication that some type of permanent structure that would identify a "salt works" had been constructed near the lake in 1847. A reference was made to it in a report by several men exploring the lake the following year (9). The Council of the Twelve made a decision in May of 1849 to "ascertain . . . the most suitable point to establish a manufactory of salt" (10). The indication from this decision would be that whatever salt works had been there was either no longer suitable or did not exist in 1849.

A permanent salt-boiling operation was apparently established in the spring of 1850 by Charley White. Neither Gunnison nor Stansbury, who were conducting government surveys on the Lake's south shore, mention salt boilers until the latter part of June 1850 (11). In Gunnison's account of the operation he reported that White could boil 300 pounds of salt per day in his six 60-gallon kettles (12). Charley White operated his salt works, which became the first established salt company of record to operate on the shores of the Great Salt Lake, until 1861.

In 1870, the Ninth Census reports only one establishment producing salt in Utah (13). This operation could have been one owned by the Joseph Griffith and William F. Moss families of "E. T. City" (Lake Point). The Moss and Griffith salt works was a small, home industry, most likely run as a sideline to a farm or ranch (14).

By 1873, the Great Salt Lake had risen to its highest point in recent geologic history, which diluted the brine by about one-third. As a result, the salt boilers had to burn about one-third more wood to obtain the same amount of salt that was produced in the previous two decades. The recently completed railroads were able to import higher quality but cheaper salt.

GENERAL, TECHNICAL, AND ECONOMIC DEVELOPMENTS 1860 - 1895

The salt industry received its first real impetus from the discovery of silver in Montana. Beginning in the mid-1860's, mining camps around Butte experienced a boom. The chlorination process for the reduction of silver ore was developed about the same time, placing a heavy demand on producers to supply the mills with enough salt to reduce the ores. Utah had the raw material and railroads provided a transportation system capable of handling high-tonnage loads cheaply. As tracks were laid to new markets, the demand for salt increased, which in turn stimulated the search for improved methods of production and refining.

By 1873, the level of the lake had risen to such an extent that many of the natural salt beds were covered with water. Dikes were then constructed across the entrance of coves and along the shore of the lake so that the periodic rise and fall of the lake could fill the pond areas. The early salt makers depended on the northwest wind which had the capability of raising the water on the southern shore of the lake from one to one and one-half feet for filling the ponds with fresh brine, but the storms were not always dependable, and some of the stronger winds caused the waves to wash away the dikes and dissolve the salt that had been deposited (15).

With experience, salt makers learned that earth alone was unsuitable for constructing dikes, and planks would not bear the weight of the heavy brine waves. Jeremy and Company, organized in 1870, successfully constructed its ponds by driving a row of cottonwood stakes into the ground every two feet. A parallel row of stakes was driven seven feet away from the first. A lattice work of willows was woven on the stakes and backed by several inches of tule (bullrushes). The area between the two rows of stakes was filled with earth, making a substantial dike that proved effective for constructing ponds from five to one hundred acres in extent. Cost of construction of this type was estimated at one dollar per foot (16).

But the natural fluctuations of the lake were too unreliable for filling the ponds. By the 1880's, some salt companies were using steam or horse powered pumps to fill their ponds with brine. In 1888, Inland Salt Company had established a central power source to run a ten-inch centrifugal pump and the machinery in their mill (17).

To remove the undesirable minerals from the brine, Inland Salt Company, one of the most innovative companies in the growing salt industry, specifically built its pond system in 1888 to use a principle called fractional crystallization (18). As the brine solution becomes more concentrated, calcium and magnesium carbonate are the first to precipitate, followed by anhydrite. Sodium chloride, or common salt, is deposited in the next phase and is followed by the chlorides and sulphates of magnesium, potassium, and perhaps sodium which are deposited as complex mineral compounds upon complete evaporation. By discarding this bittern at the proper time, salt was produced that was reported to have contained over 99 percent sodium chloride (19).

It was not until the Inland Salt Company invested sufficient capital to develop a pond system that could adequately use the fractional crystallization principle, and to improve harvesting techniques utilizing the "split", a method of separating the new salt crop from the bottom of the ponds, that the salt industry in Utah really came of age.

Between the mid-1880's and the turn of the century, five factors coincided to change a highly competitive business into one dominated by a monopoly. Those factors were: First, a decrease in the silver-mill market; second, an increase in the market for refined grades of salt; third, available capital sufficient to construct large plants geared to produce refined grades of salt; fourth, over-production of salt during 1890, 1891, and 1892; finally, the depression of 1893.

By the early 1890's, salt companies in Utah could be placed in two general categories. One was the speculative-type producer who had entered the business to take advantage of the silver-mill market, with emphasis on tonnage rather than on quality. The other category consisted of larger companies with huge production capacities which enabled them to produce for the silver mills and at the same time fill the needs of the new market for refined salt. The Inland Salt Company and its successor, Inland Crystal Salt Company, were such organizations.

By 1890, Inland Salt Company's first harvest came on the market, doubling the average annual production for the preceding five years. Its successor, Inland Crystal Salt Company, doubled and then tripled Inland's production during the next two years, respectively. Increased production in a depressed market dropped prices from the 1885-1890 average of $2.88 per ton to $1.88 in 1892 (20).

Production statistics of individual companies were not published after 1892, making it impossible to be precise in evaluating the effect of the depression. Available statistics, however, indicate that Inland Crystal Salt Company produced over half of the annual output during 1892 (21). Refined grades made up a much higher percentage of salt marketed in 1893 than in preceding years.

The smaller companies, unable to increase their gross profits appreciably through expanded production during the lean years of 1890-1892, were still attempting to sell crude salt in a depressed market. The depression prevented them from building or expanding refineries; consequently, most of them went out of business or sold out to the larger producers.

EARLY SALT COMPANIES ON THE SOUTHERN SHORE OF GREAT SALT LAKE

There were over twenty different companies producing salt on the shores of Great Salt Lake between 1880 to 1915. The men who organized the companies were attracted to the salt busines by the ready market for crude salt provided by the silver mills. A good share of them invested no more capital than was necessary to scrape up crude salt deposited around the lake and haul it to a shipping point. Records from the period reveal very little about these companies other than that they existed (22). The companies on the south shore of the lake that developed salt production into a major enterprise are described below.

Jeremy and Company

Jeremy and Company was one of the first to make a major investment in the production of salt. The company was organized in 1870. It produced refined grades of salt in a plant in Salt Lake City. This company was one of the first to construct artificial evaporation ponds which were located at North Point, three miles north and east of the site of the old Saltair resort (23).

Jeremy and Company and its successor, Jeremy Salt Company, had a refining plant that was unable to meet the growing demand for refined grades of salt. The company failed to compensate for lower prices by expanding its pond facility to increase production, and it faced overwhelming competition from the Inland Salt Company. In addition, the depression of 1893 caused many of the silver mills to discontinue operations, thus eliminating Jeremy's largest market for crude salt. In 1896 the company was sold to Inland Crystal Salt Company (24).

Inland Salt Company

Inland Salt Company, organized November 21, 1887 by a group of Mormon entrepreneurs, was the predecessor of the Inter-Mountain Salt Company, Inland Crystal Salt Company, Royal Crystal Salt Company and Morton Salt Company's Utah branch.

Construction of the ponds began in 1888. These ponds were the first specifically designed to utilize the fractional crystallization process of salt making, although pond systems of other companies built prior to 1888 imply some knowledge of the process (25).

By 1890, Inland was producing two-thirds of the sixty thousand tons marketed by Utah companies (26), but by 1891 the salt company was sold to buyers from Kansas City for $200,000 (27).

Inland Crystal Salt Company

On July 1, 1891, Inland Salt Company was reincorporated and its name was changed to Inland Crystal Salt Company. The valuation of the property was increased to one million dollars (28).

The new officials installed one of the world's largest rotary kiln driers in the mill as a part of a $50,000 renovation program. The drier was forty-two feet long, nine feet high, and five feet in diameter (29). The new company introduced the brand name "Royal Crystal" which appeared on the table and dairy grades of salt. This change was significant because of its historical duration. "Royal Crystal" salt has been sold by Inland Crystal Salt Company and its successors, including Morton Salt Company, until the present time (30).

The new company also developed a process for making salt blocks for livestock consumption. Salt was molded into fifty-pound blocks using a patented adhesive substance (31).

It can be assumed from existing records that Inland Crystal Salt Company produced at least half of the state's salt until its merger with Inter-Mountain Salt Company in 1898 (32).

Inter-Mountain Salt Company

In the fall of 1892, money from the sale of the Inland Salt Company was used to develop Saltair Resort, Saltair Railway, and Inter-Mountain Salt Company on the shore of Great Salt Lake (33).

Inter-Mountain Salt Company operated successfully until March 2, 1898, when the plant burned to the ground. Plans to immediately rebuild on a larger scale were dropped and the company merged with the Inland Crystal Salt Company (34). The consolidated companies were known by the name of Inland Crystal Salt Company.

Diamond Salt Company

Diamond Salt Company, located west of the Inland Crystal Salt works, was incorporated February 2, 1901, with plans for establishing a sanitarium, bathing facility, amusement park, and salt manufacturing business. It appears the company intended to compete with Saltair in the resort business and break the monopolistic hold Inland Crystal Salt Company had on the salt market. Within a year after the company was incorporated, ponds were built. If construction was started on the resort, there is no physical evidence remaining to indicate to what degree it had progressed. Most likely it went no further than the planning stage. The company sold its holdings to E. L. Sheets Company, which in turn was purchased by Inland Crystal Salt Company in 1915 (35).

Weir Salt Company

Weir Salt Company began its operation at about the same time Diamond Salt Company entered the industry. Its works were located on the south shore of the lake near Lake Point, Utah. The Weir Company had problems from its inception. During construction of the long ditch from the water's edge to the pumping station, it encountered the rockhard strata of sodium sulphate that underlies the shore land around the lake. In addition ground water seeped into the canal and diluted the brine. After Weir completed one hundred acres of ponds and pumped water into them, it was discovered the floor of the ponds was composed of a porous material, and much of the brine would seep out before the salt concentrated to the point of deposition (36).

Weir also began construction of a plant, but before it was completed it was discovered the foundation extended onto railroad property, and construction of the facility was never finished (37). Deseret Livestock Company later purchased the property and began construction of its salt works on the same site in 1949.

The Salt Monopoly

The merger of Inter-Mountain Salt Company and Inland Crystal Salt Company in 1898 established a salt monopoly that lasted twenty years.

The role of the Church of Jesus Christ of Latter-day Saints (Mormon) in Utah's salt industry grew steadily through the decade prior to 1898 until it became the dominant influence in the emerging monopoly. At this time, the Church owned a significant amount of stock, and Joseph F. Smith, a member of the First Presidency, was President of the company (38).

Shortly after the merger, efforts were made by the Church-controlled company to maintain and strengthen its monopolistic position. Possible sites for competing salt works around the lake were bought up to prevent competing companies from becoming established (39). Not completely successful in their efforts to ward off competition by buying lake shore land, the company purchased competing firms, or eliminated competition through its ability to control the price of salt (40). The monopoly was not significantly threatened until Morton Salt Company moved into the area in 1918.

SALT COMPANIES ON THE EAST AND NORTH SHORES OF GREAT SALT LAKE

Three sites around the east and north portion of the lake have been used for salt production: Spring Bay, on the extreme north end of the lake: Promontory Point; and the mud flats west of Syracuse, Utah. The companies using these sites supplied the peripheral needs of the salt market, rather than competing with the larger companies on the south shore.

The same salt producing site near Syracuse was used by the following companies in succession: George Payne from 1880 to the middle of the decade. William W. Galbraith purchased the salt works from Payne and sold it to Adams and Kiesel Salt Company in 1888. In 1899 Adams and Keisel sold their operation to William B. Clarke, who did not continue production (41).

Other companies which produced from the east shore of the lake were Deseret Salt Company, Gwilliam Brothers Salt Company, which later re-incorporated as the Solar Crystal Salt Company, owned by Payne, Chesney, and Bills; and the Sears Utah Salt Company. With the exception of the two companies named last, none survived the turn of the century (42). Those two were unable to compete with the Inland Crystal Salt Company and terminated production within a few years.

From the turn of the century until 1939, there was no significant activity on the eastern shore of the lake. Inland Crystal Salt Company and its successors were firmly-established producers, providing the market with all the diversified products it required, and jealously guarding their position in the industry. From 1910 until 1930, the lake was high, leaving no relection land below the occupied uplands available for use.

By 1939, the lake had become stabilized at the bottom of a fifteen-year declining cycle, exposing large areas of relection land. Available shore land encouraged C. J. Call to organize the Ritz Salt Company. Promise of a ready market supplying salt to O. P. Skaggs Company prompted Call to petition Davis County for access across Morton Salt Company land to the lake. A road and ponds were constructed and plans were made for the construction of a salt refinery, but it was never completed (43). Morton Salt Company, believing in the riparian right of the upland owners, threatened to bring suit against the Ritz Salt Company for trespass. Call sold his holdings to Morton Salt Company in 1941 (44).

Unwilling to give up his interest in the salt business, Call moved to the eastern tip of Promontory Point and built a few ponds between the lake's edge and the tracks of the Southern Pacific Railroad (45). There is no record available on how much salt was produced from this site, or how long he was able to operate. It can be concluded, however, that since the lake started into its rising cycle in 1945, his ponds would have been washed out by 1950.

A. T. Smith, owner of Smith Canning Company in Clearfield, Utah, became interested in producing salt for his cannery and for sale on the regular market. With a modest investment he constructed fifty acres of ponds and a small mill at Syracuse. During its operation, the company built up a small market among canneries, stock raisers, and uranium mines; however its success was hampered by a limited labor force during the Second World War. In 1945 rising waters washed away the dikes and 20,000 tons of salt were dissolved. The Syracuse site subsequently has remained inactive as a salt-producing area. In 1949, the small mill was dismantled and used in constructing the Deseret Livestock Company salt plant at Lake Point, Utah (46).

The north shore has never been considered a prime area for a salt operation due to its remote location. However, the north end of the lake offered some promise shortly after the transcontinental railroad came through Utah in 1869. At that time, Corinne was expected to develop into an important railroad junction and city of commerce.

Housel and Hopkins Salt Company, encouraged by hopes of Corinne's future, constructed ponds east of Locomotive Springs on the shore of Spring Bay. A newspaper report indicated it was operating during 1871, although no further disclosure was found to determine the duration of the company. No information has been found of any other salt works using this site until the late 1930's (47).

In 1939 the Quaker Crystal Salt Company was organized as a result of a severe earthquake at the base of Monument Point on the northern shore of the lake. Three warm springs of undetermined depth began to flow. These contained from 11 to 15 percent salt. Analysis of the spring water revealed grades of salt suitable for cheese making and other uses for which salt was at that time being imported into Utah. The combination of a pure source of salt from the springs, and the lake close at hand for conventional salt production provided the stimulus necessary to organize the company (48). However, the rising lake washed out large sections of dike, and vandals stole equipment and in 1965 set fire to the mill. These problems had depleted the company's resources to the point that continued operation could not be justified on the basis of anticipated profits (49).

During the late 1930's and early 1940's, Great Salt Lake had become stabilized at a historically low level. Concentration of the brine had reached saturation point, and salt was deposited on the bottom of the lake. The concentrated nature of the brine encouraged Howard and Harold Pence and Bulo Suttlemyre to organize Lake Crystal Salt Company in 1947. The production and refining operations were located at Promontory Point; the sales and storage facilities were in Ogden (50).

Lake Crystal Salt Company's location was such that its feed brine was higher in salt concentration than that of competing companies. Therefore, they required only some 300 acres of crystallizer ponds with no investment for concentrating ponds (51).

Nevertheless, Lake Crystal's production has never been a significant factor in the salt market and has never exceeded 30,000 tons per year. Recently, the Lake Crystal operation has been purchased by the Carey Salt Company, which in turn is owned by Canadian interests.

Morton Salt Company

Inland Crystal Salt Company did not share its dominant position in Utah's salt industry with any serious competitor until Morton Salt Company leased a potash plant at Burmester, Utah, in 1918, and established a competitive foothold. In 1923, Morton Salt Company purchased controlling interest in the Inland Company from the Mormon Church. By 1927, the remaining stock was acquired, and Inland Crystal Salt Company was reincorporated as a wholly-owned subsidiary under the name of Royal Crystal Salt Company. Morton Salt Company produced salt from its plant at Burmester and also from its subsidiary plant at Saltair until 1933, at which time production and refining facilities were combined at the Saltair location. Although both companies operated from the same plant, the separate identity of Royal Crystal Salt was maintained until that company was dissolved in 1958 (52).

Technological innovations were introduced shortly after Morton Salt Company came to Utah; however, new developments were not due so much to paternalism of the large out-of-state company as they were to the initiative of local employees. In 1923 tractors were introduced in the harvesting process by Ed Cassidy who brought his farm tractor to the Burmester ponds to replace the horses used in pulling the plows. Machinery had not been used in the past because of the fear of the weight breaking through the thin salt floor. Following Cassidy's successful venture the company purchased some Fordson tractors with which to plow the salt, but handwork was still being used to stockpile the salt (53).

The company consolidated its production facilities at Saltair in 1933. Salt was harvested by hand at first because of the need to revamp the pond system. In order to withstand the extra weight of machines, the salt floor had to be increased to a depth of eighteen inches and the dikes heightened. Local inventors modified small farm tractors that scraped salt into a bin which was pulled across the ponds and dumped onto the stockpile. This machine was replaced in 1938 by a local invention called a "Hootin' Nanny". In 1949 another machine also designed by local men, called a "Jackrabbit", was used until it was replaced by a commercially-manufactured machine called the "scoop-mobile". The "scoop-mobile" was replaced in 1964 by a revolutionary new machine called the "Palmer-Richards Salt Harvesting Combine". It was developed locally by James Palmer and A. Z. Richards, Jr., of the Solar Salt Company (54).

Other significant changes at the Saltair complex came about as a result of two fires. After the Inland Crystal Salt Company mill burned in 1926, the site was changed from the west side of the ponds to the east side. Again on January 25, 1949, the plant was destroyed by fire and rebuilt. The new plant capacity nearly doubled the 50,000-tons-per-season figure of the 1926 refinery (55).

Growth of the Saltair facility enabled the Morton Company to retain a dominant position in the intermountain salt market. Its monopoly faced a temporary threat from several new developments around the lake during the late 1930's and early 1940's; however, none of the new companies endured more than three or four years. In the 1950's and 1960's Lake Crystal Salt Company from the north shore, Deseret Livestock Salt Company, and Stansbury Salt Company from the south and southwest shore gained a foothold in the salt business and retained it. Fortunately, these new companies organized at a time when the market was expanding. In the decade following 1950, the market increased 50 percent. It doubled again in the next ten years. Morton Salt Company increased its production in spite of the competitive pressure (56).

American Salt Company

Crystal White Salt Company, the first in a series of predecessors of American Salt Company, was organized in 1938 by Ray B. Elderkin, with the intention of producing salt for the California market (57). The new company selected a site six miles from Grantsville on the mud flats south of Stansbury Island. The west side of the lake was selected because of the purity and concentration of the lake brine, accessibility to the railroad, and the level, impervious nature of the mud flats (58).

The company had been unable to construct a refinery or organize a sales force because of the limited resources with which to operate (59), and when the owner died, the company went out of business because of lack of capital.

The properties of the defunct Crystal White Salt Company were sold at a sheriff's auction in 1938 and the new owners incorporated the Stansbury Salt Company (60). A refinery was built in 1950 on the north side of the intersection of U. S. Highways 40-50 and the Stansbury Island Road (61).

Stansbury Salt Company made limited progress until it was contacted in 1954 by representatives of chemical companies from the northwest. Hooker Electro Chemical Company and Penn Salt Chemical Company, both large users of salt in the Portland and Tacoma area, investigated the possibility of acquiring salt from Utah. They organized Chemical Salt Production Company and engaged Stansbury Salt Company as an agent to build a large, salt-evaporating complex adjacent to the Stansbury property. In 1955, the chemical companies invited the stockholders of the Stansbury Company to merge. The offer was accepted in December, 1956. The new combine was incorporated under the name Solar Salt Company (62).

Enlarged capital resources, made available through the 1956 merger, enabled the local employees to express their initiative in the development of novel ideas for salt production. The old ponds built by Crystal White Salt Company were abandoned in favor of the new pond complex constructed for the Chemical Salt Production Company. The pond arrangement, dike construction, harvesting equipment, and central stockpile comprised an integrated operation to minimize handling of salt, thus lessening production costs (63).

One of the newest and most radical developments in the salt industry, local or nation-wide, was a salt harvesting machine developed by Solar Salt Company. James Palmer, primarily responsible for the design of the revolutionary machine, had started out in the salt business as an employee of Crystal White Salt Company. After being hired by the Stansbury Salt Company, he tried new methods in an effort to make the harvest more efficient. Lack of capital meant cannibalizing parts from old machinery to fabricate the experimental components. With the mechanical assistance of Joe Peterson, a fellow employee, a machine was developed that loosened the salt, excavated it, and conveyed it directly into trucks driven alongside. Mr. A. Z. Richards, Jr., one of the owners of Stansbury Salt Company and co-owner of Caldwell, Richards & Sorensen, Inc., helped redesign and improve the machine. The Palmer-Richards machine has proven its efficiency and is being marketed internationally (64).

In 1965 the company built a new $320,000 plant which tripled the capacity of the project. In 1967 it was sold to Mr. Ludwig, of National Bulk Carriers, over the objections of the Utah stockholders who did not want to sell their shares in the Solar Salt Company they had helped to build (65).

The American Salt Company entered the Utah Salt market in 1972, when it negotiated the purchase of the Solar Salt Company. American Salt has its headquarters in Kansas City and is part of the Cudahy Company which is owned in turn by General Host.

This salt complex on the southern end of Stansbury Island has become one of the largest producers in Utah. Through the initiative of its local employees and with the capital provided by its new owners, it has developed one of the most effective salt harvesters in the industry. Like other salt complexes on the lake, it started out as a locally-owned company and became affiliated with large, national firms.

Lakepoint Salt Company
(Weir, Deseret, Leslie, Hardy Salt Companies)

Salt has been produced from the waters of Great Salt Lake near Lake Point, Utah, since the pioneer period. Salt boilers were set up as a small home industry to supplement the meager income of local farmers. Subsequently, half a dozen companies have used the location in an attempt to make a profitable enterprise out of salt extraction.

Salt production using the solar-evaporation process at the Lake Point site was first introduced by Weir Salt Company in 1901. Nearly fifty years of dormancy followed Weir's abortive attempt to enter the industry before Deseret Livestock Company reactivated the site in the spring of 1949 (66).

The porous soil underlying the floor of the ponds has presented problems to the salt producers at the Lake Point site since 1901, when Weir Salt Company encountered this condition, and the resulting seepage of brine from the ponds was a contributing factor in the demise of that company. This condition was corrected by digging trenches to an impervious clay under-strata and creating a bond between the dike material and the clay; a seal was achieved that prevented seepage (67).

As with other salt makers, men at Lake Point experimented with different methods of production. One of the first salt-harvesting machines used at Lake Point was designed by this salt company. Deseret Livestock Salt Company began using a central stockpile, and each of its successors has followed suit (68).

In late 1952 or early 1953, ownership of Deseret Livestock Company, including the salt works, was sold to David Freed and David Robinson. Knowing little about salt production, they offered that part of their holdings for sale. Council McDaniel purchased the company and reincorporated it under the name of Deseret Salt Company. McDaniel operated the salt works until the latter part of 1958, when he sold to Leslie Salt Company (69).

In 1961, Leslie Salt Company, largest salt producer on the west coast, was charged by the Federal Trade Commission with creating a monopoly. The complaint alleged that Leslie's acquision of Deseret Salt Company tended to creat a monopoly in the production and sale of salt in the west. The proceeding was settled through a divestiture order requiring Leslie to sell its Utah holdings. On November 2, 1965, Hardy Salt Company, of St. Louis, Missouri, purchased Leslie's Lake Point plant (70).

In 1977 the Lakepoint Salt Company was formed by purchasing the Hardy Salt operation at Lakepoint. A group of local investors teamed up with the former local management of the American Salt Company plant to start this operation. The existing Hardy plant was closed down for several months while extensive revisions were accomplished to return this plant to a profitable operation.

Great Salt Lake Minerals Company

Great Salt Lake Minerals and Chemicals Corporation, a division of Gulf Resources Corporation, entered the sodium chloride market in 1970, and is now the largest shipper of bulk crude salt in the area. They have extensive reserves of salt as a byproduct from their potash operation. Prior to this time, they had produced only sulfate of potash, salt cake and magnesium chloride brine. In 1979, Great Salt Lake Minerals constructed a new salt processing plant which will produce a full line of salt products.

SALT PRODUCTION METHODS

The original method of producing solar salt by flooding an area and allowing the brine to evaporate produced very bitter flavored salt. Salt producers learned that by controlling the brine flow they could produce a high quality salt and discard the "bittern".

This process is essentially fractional crystallization. The water from the Great Salt Lake is pumped into a series of concentrating ponds or "settling" ponds where the most of the insoluble materials settle out. In some areas they are known as reservoirs or evaporators. In these ponds the brine is concentrated by evaporation of the water until the " salt point" or saturation with respect to sodium chloride is reached.

The brine then goes into the crystallizer ponds where the salt is precipitated. These ponds were sometimes known as "garden" ponds or pans. The crystallizer ponds are operated either in series or in parallel depending upon the convenience of the operations. In a parallel system each crystallizer independently receives brine and discharges bittern. In the series systems, brine enters one pan, flows through a number of pans, and bittern is discharged from the last pan in the series.

In all the operations on the Great Salt Lake, the ponds have a salt floor on which the salt is crystallized. This is a great advantage as the salt provides a solid base for harvesting equipment and avoids contamination of salt with the natural dirt base. The Great Salt Lake area is also blessed with ideal salt growing conditions, i. e., low rainfall, high net evaporation, large areas of flat land, proper soil conditions and a brine that is three times as strong as sea water.

The important control point is the density at which the bittern is discarded. If the bittern is discarded below the optimum level good salt is lost, or if it is retained too long, the purity of the salt will suffer.

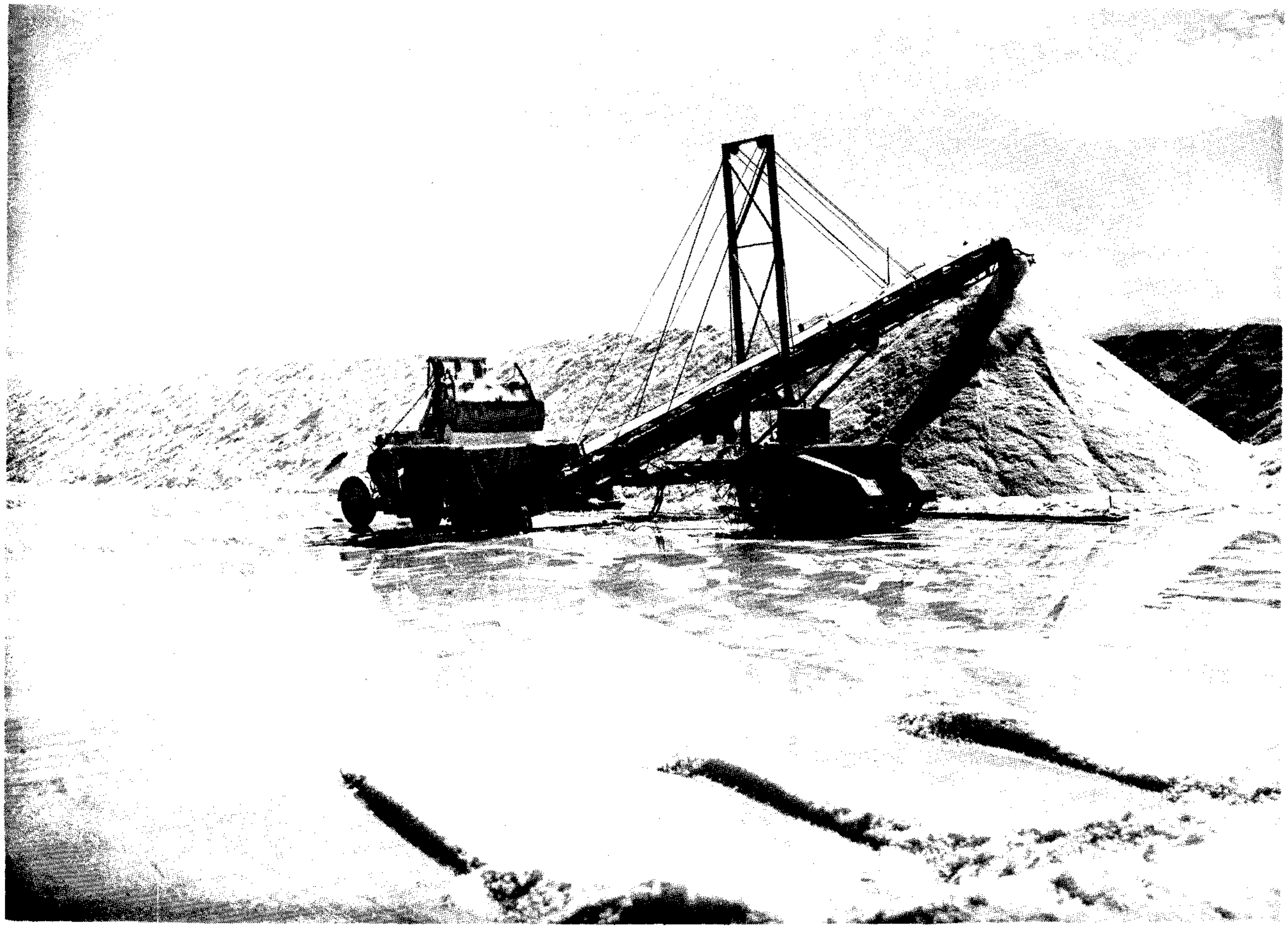
A technique developed by Utah salt makers to increase the rate and ease of salt harvesting was termed the "split". Salt was allowed to build up a permanent layer on the bottom of the ponds to a depth of several inches. At the beginning of each season a thin layer of very fine crystals was deposited, forming a split between the floor and the large crystals of the annual crop. The objective of this procedure was to form a cleavage plane along which the upper layer of salt could be loosened. If a split were not made, the crystals from the new crop would interlock into the salt floor, making a hard, continuous formation with no way of breaking it loose without intermixing soil from under the pond (71).

Two methods were used to make the split. The early pond men formed what they called a "sun split" by draining the pond until a small amount of highly concentrated brine covered the floor. The split was created by precipitating a layer of very fine crystals to the depth of one-eighth inch over the large, jagged crystals below. After the fine crystals were deposited, fresh, highly-concentrated brine was brought into the ponds. The larger crystals of the annual crop built up on the fine salt layer. A mechanical split was made by dragging a rail across the floor of the pond. This process knocked the edges off the crystals and formed a fine layer of salt to separate the floor from the ensuing crop (72).

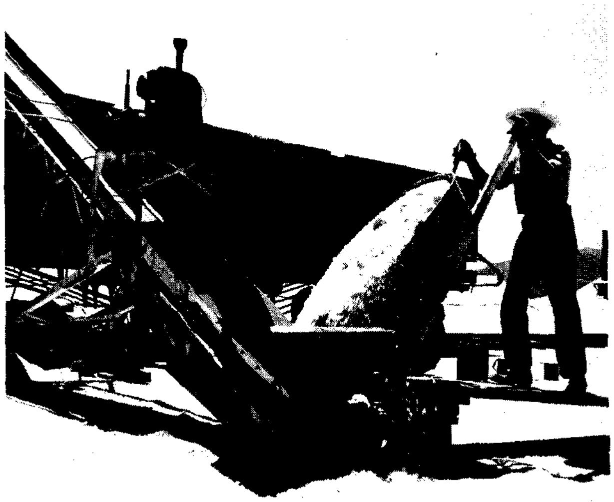
The salt crop grows on both the floor and the surface of the brine. The salt crystallizes on the surface, where the super saturation is the greatest, and forms "hopper" type crystals that fall to the floor and continue to grow.

In the Great Salt Lake area, the production season normally starts in March when the pumps are started and the ponds are filled. The salt making period is from May to October, and the harvest takes place between Labor Day and Thanksgiving. There may be a spring harvest prior to filling the ponds.

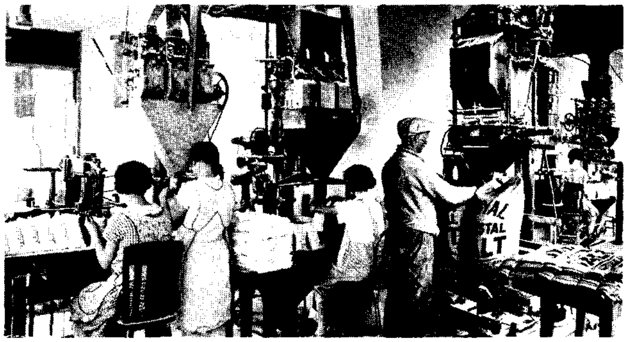
The early harvests were accomplished by plowing up the salt with a disc plow, and then shovelling the salt by hand into wheel barrows and dumping it in small



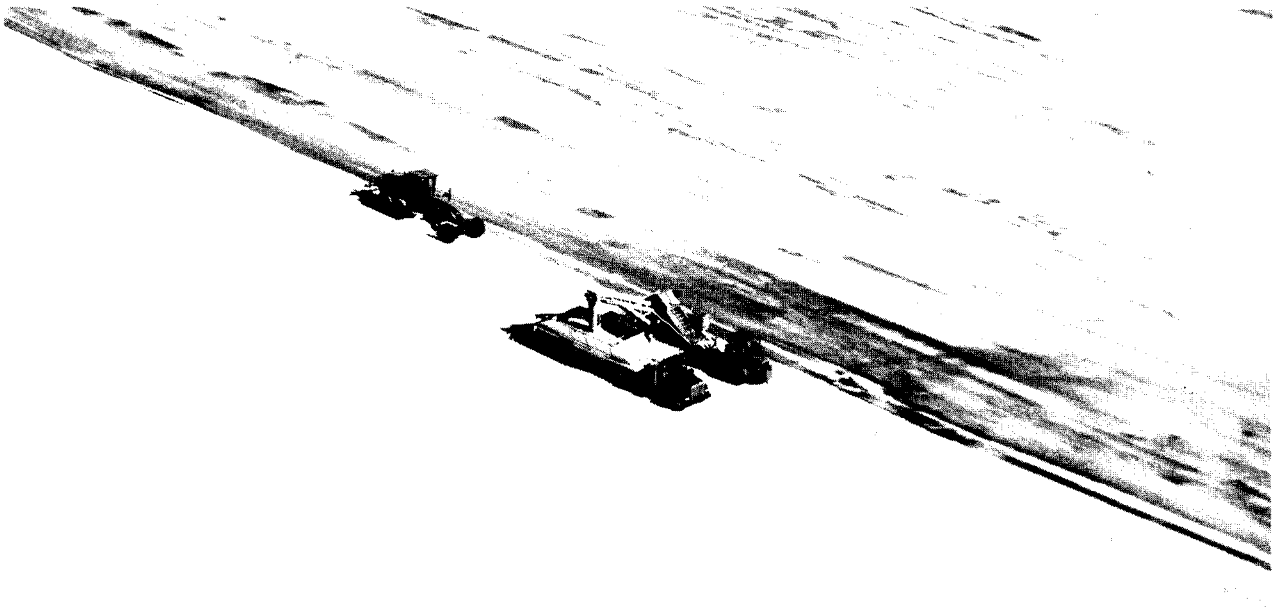
Harvesting Royal Crystal Salt.



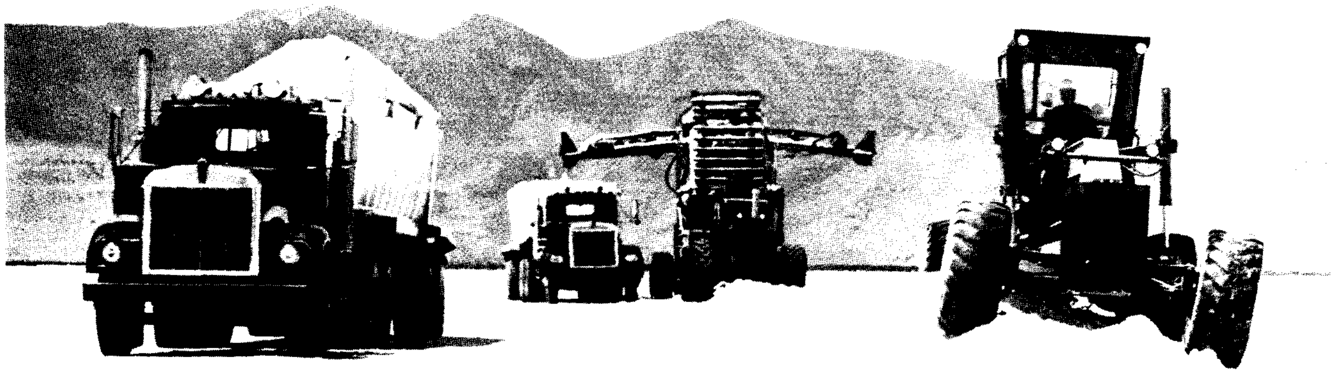
Harvesting salt by wheelbarrow.



Bagging Royal Crystal Salt, early 1900s.



Harvesting sodium chloride (common salt) from solar ponds using Palmer-Richards harvester.



Windrowing, harvesting, with a modified Palmer-Richards harvester, and hauling salt to the plantsite.

Photos courtesy of Great Salt Lake Minerals and Chemicals Corp.

piles along the edge of the ponds. Today specialized harvesting machines pick up the 4 to 6 inches of crop and load it directly on to large dump or bottom dump trucks which unload at a stockpile area.

The salt can either be washed at the time of harvest or washed as it is processed. The salt is washed with slightly under-saturated brine by using screw clarifiers, drag conveyors or wire mesh belt. Washing removes the "bittern" from the salt and also any insoluble material, leaving a salt with a purity of 99.7+% NaCl. Salt is then dewatered by letting it drain in a stock pile, or by using a centrifuge, mesh belts or screens.

Some salt is sold as bulk air dried from the stock pile, but a large percentage is dried, screened and packaged to meet the various customer needs. It is dried in a rotary type kiln. Finely granulated salt requires a grinding or milling operation prior to screening.

Although solar salt uses little purchased energy, it has a rather low yield based on the amount of salt in the brine that is actually recovered and shipped. This yield may be only 25%, and is the result of several factors which include:

1. Seepage loss from ponds.
2. Unharvested salt - including salt on floors and around edges of ponds.
3. Salt in discarded bitterns.
4. Salt losses in washing.
5. Salt losses in stock shrinkage (rainfall, etc).
6. Salt losses in drying (dust mainly)
7. Salt losses in processing (cull, spills, etc).

Every solar salt operation in the world has to adapt its operations to varying conditions of weather, soil conditions, initial brine strength and customer requirements. The brine from the Great Salt Lake changes year to year, and season to season, even from place to place. The brine at the south end of the lake contains less than half the salt found in the north arm above the railroad causeway. Pond acreage required to produce an equivalent amount of salt is twice as great for southend producers as for those on the north portion. The cyclic lake level also causes considerable changes in brine content and in pumping requirements. Pump locations have to be changed to accomodate the fluctuating yearly lake levels. Nevertheless, salt companies have operated successfully on the Great Salt Lake for nearly a hundred years and there are still several billion tons of salt left. There is some evidence that the present operations are not even depleting the annual inflow of salt to the lake.

MARKETS

The Utah salt market, except for large industrial bulk users, is essentially serving the Intermountain West. The bulk of the market is from the borders of Canada and Mexico to California and Nebraska. Movement of solar salt is increasing to the east due to the competitive advantage of reduced energy cost of solar salt compared to solution or underground mined salt. The major markets for solar salt are for water softeners, agricultural uses, and industrial uses including ice control. Only a small fraction is used in the food or table (retail) market.

Actually the Utah salt production, at present, is just a small portion of the U.S. total production. Total U.S. production is about 45 million short tons per year, with Utah's present production at 850,000 tons/year. Total world production of salt is around 145 million tons.

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Aerial view of Morton Salt plant today, looking northeast.

Aerial view of N. L. Industries magnesium plant located on the west shore of the Great Salt Lake. The large oval feature (center right) is a 210,000,000 gallon, segmented plant feed brine holding pond.

PRODUCTION OF MAGNESIUM FROM THE GREAT SALT LAKE

by Dr. Robert Toomey

NL Industries

INTRODUCTION

In 1940, NL Industries began to develop its technology for the production of magnesium by operating a government magnesium plant using the ferro silicon process at Lucky, Ohio, during World War II. The company continued development of its expertise with the formation in 1951 of a jointly-owned company, the Titanium Metals Corporation of America at Henderson, Nevada. Magnesium metal is used in the reduction of titanium and the magnesium values are then recovered as $MgCl_2$, which is electrolyzed to recover both magnesium and chlorine. In the 1960's, NL Industries began an active investigation into the possibilities of producing and selling commercial quantities of magnesium metal. In searching for additional sources of magnesium, NL Industries became aware of the potential of the Great Salt Lake. A review of the various sources of magnesium led to the selection of the Great Salt Lake as the preferred place to locate a plant.

During 1965 and 1966, NL Industries conducted pilot operations to select the best process for use with Great Salt Lake brines. Solar ponds were constructed at Burmester, Utah, and a pilot plant for producing cell feed was built at Lakepoint, Utah. Product from this pilot plant fed a proto-type cell at TIMET in Henderson, Nevada. From this program a decision was made in 1969 to build a magnesium plant at Rowley, Utah, to utilize brine from the Great Salt Lake.

ROWLEY MAGNESIUM PROCESS

Costs and reliability were both critical factors in determining the process to be selected for the Rowley plant. Even at this early stage considerable effort was spent in reducing the energy consumption to as low a value as possible per pound of magnesium produced. From the early pilot plant work and through the initial plant operation, process steps were selected and modified in order to reach these objectives. The present Rowley process is described below.

Solar Evaporation

The first step in the process is the use of solar energy to perform the major part of the concentration of the magnesium values. A 25,000 acre pond system was built in the Stansbury Basin which is west of Stansbury Island and south of Badger Island. This basin is divided into three ponds where the desired brine concentration of 7.5% magnesium by weight is achieved. The progressive concentration of magnesium is illustrated in Table I, which shows the relative concentrations of the Great Salt Lake and the effluent from the three ponds in sequence. The magnitude of this evaporation step is illustrated by the fact that less than three percent of the volume of the original Great Salt Lake brine reaches the plant holding pond. In concentrating the brine over 3,000,000 tons of salts are deposited in the ponds each year.

Table 1. Percent of each constituent.

	Great Salt Lake Brine	Effluent Pond No.1	Effluent Pond No.2	Effluent Pond No. 3 to Holding Pond
Mg	0.4	2.0	4.8	7.5
K	0.3	1.5	3.6	0.8
Na	4.0	7.0	2.6	0.5
Li	0.002	0.01	0.024	0.06
B	0.0018	0.009	0.021	0.054
Cl	7.0	14.0	16.0	20.3
SO_4	1.0	5.0	5.3	4.4

Because of the seasonal variations in weather and temperature in Utah, evaporation of this quantity of brine must take place within the three or four hottest and driest months starting sometime in May. When the proper concentration is achieved, the concentrated brine is pumped to a holding pond, which can store up to two years' supply of brine. This storage is required to insure an adequate supply of brine during a year when the weather conditions would not permit adequate evaporation. Additional separation of solids and concentration is usually achieved in the holding ponds. Thus, the concentration of magnesium is usually brought to an excess of 7.5% Mg or 30% $MgCl_2$ with very little energy input besides solar evaporation.

Feed Preparation

The feed preparation for the electrolytic cells consists of further concentrating the brine, removing unwanted impurities, adjusting for the correct proportions of other salts with the $MgCl_2$, and the melting and final purification of the molten $MgCl_2$. The process steps are outlined in Figure 1. The brine is pumped in from the holding pond and is first heated and concen-

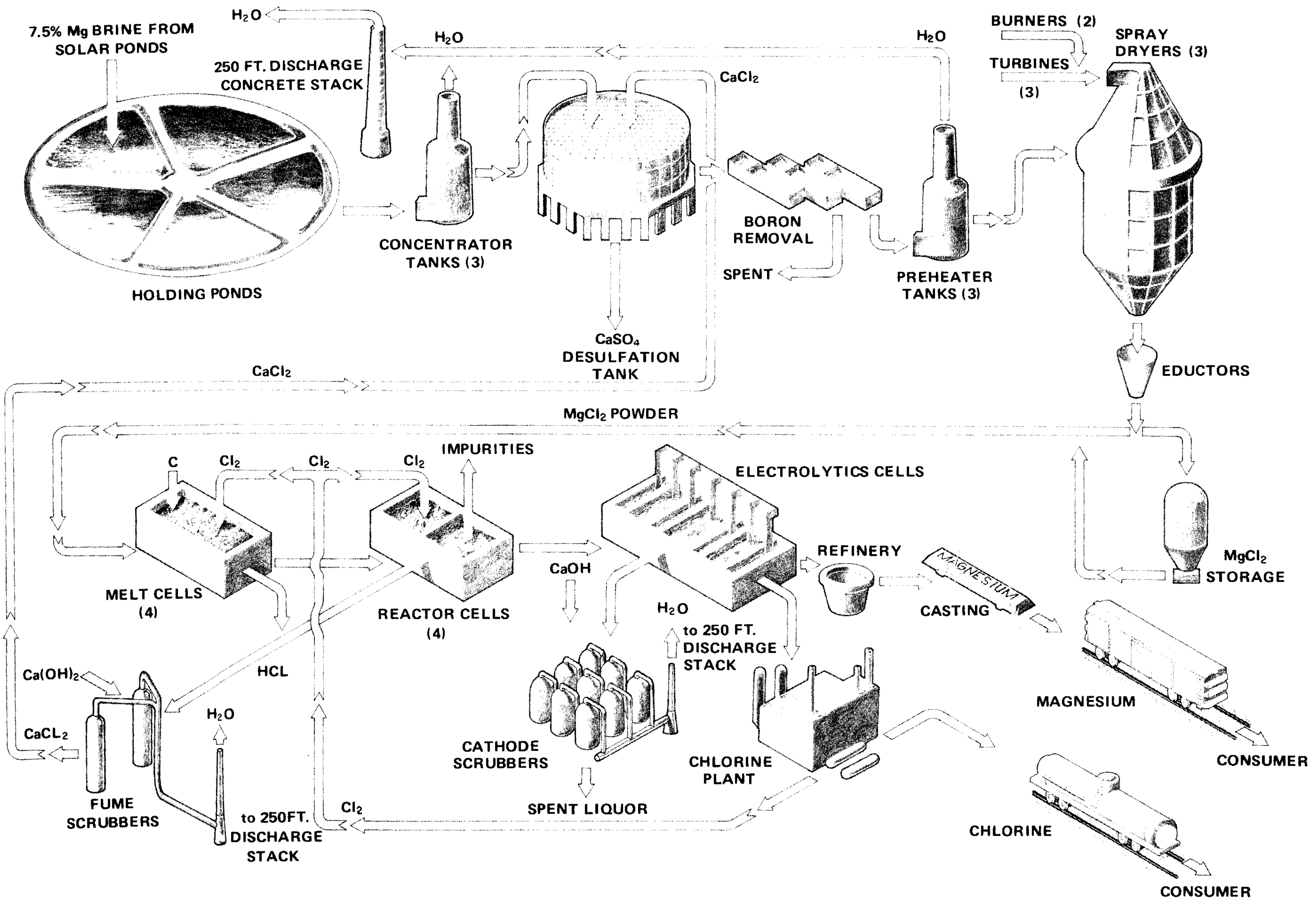

Figure 1. Schematic diagram showing the production of magnesium metal and chlorine gas from the brines of the Great Salt Lake, Utah.

trated. After concentrating, it is reacted with $CaCl_2$ and the resulting gypsum is precipitated and collected in a thickener. This reaction is as follows:

Equation 1.

$$MgSO_4 + CaCl_2 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O + MgCl_2$$

This step removes most of the sulfate, which is not acceptable in electrolytic cell feed. Due to the concentrating and subsequent cooling a majority of the remaining potassium and sodium values are also precipitated as solids in the thickener. The potassium is precipitated primarily as carnallite, $KCl \cdot MgCl_2 \cdot 6H_2O$, and the sodium as NaCl. The brine next passes through a liquid-liquid extraction step whereby the boron values are removed, as this impurity is also very detrimental to electrolytic cell operation. Next, the brine passes through a preheater in which it is heated and further concentrated prior to being fed to spray dryers. The spray dryers convert the concentrated brine to a dry $MgCl_2$ powder. This product contains about 4% MgO and 4% combined water. The MgO is formed by hydrolysis of $MgCl_2$ as shown:

Equation 2.

$$MgCl_2 + H_2O \rightarrow MgO + 2HCl$$

Utilization of energy in the feed preparation step of the plant is extremely efficient. In order to ensure the availability of some on-site power, part of our power is generated in gas turbines. After producing power the exhaust gases pass from the generator to the spray dryer at approximately 930°F where the heat is used to form the magnesium chloride powder. These gases leave the spray dryer at about 550°F and are then used as the heat source in the concentrating and preheating of the brine prior to feeding it to the spray dryer. This gives an overall energy utilization of over 90%. Gas burners are available to operate the spray dryer when the turbines are not in use.

The spray-dryed powder is stored until fed to a melt cell. In this vessel the powder is melted and further purified with chlorine and other reactants to remove MgO, water, bromine, and other impurities including most heavy metals. This is a continuous process and as powder is fed to the melt cell, molten salt overflows from the melt cell through a launder and into a reactor cell where the purification is completed. The reactor cell vessels are brick lined and approximately 13′ x 17′ x 8′ deep. The melt temperature is kept at 1500°F by providing sufficient alternating current to maintain this temperature.

Removal of impurities is complex but can be summarized by the following simplified equations:

Equation 3.

$$MgO + \tfrac{1}{2}C + Cl_2 \rightarrow MgCl_2 + \tfrac{1}{2}CO_2$$

Equation 4.

$$H_2O + \tfrac{1}{2}C + Cl_2 \rightarrow 2HCl\uparrow + \tfrac{1}{2}CO_2$$

Equation 5.

$$MgBr_2 + Cl_2 \rightarrow MgCl_2 + Br_2\uparrow$$

The product continuously overflows from the reactor cells and is fed directly to the electrolytic cells. The specifications for this material are as follows:

Bromine	Less than 0.01%
Boron	Less than 0.001%
Magnesium Oxide	Less than 0.2%
Water	Less than 0.2%
Sulfate	Less than 0.01%

HCl produced from the chlorination of water as shown in Equation 4 is recovered as concentrated hydrochloric acid which is subsequently reacted with lime to produce the $CaCl_2$ needed for desulfation:

Equation 6.

$$2HCl + Ca(OH)_2 \rightarrow CaCl_2 + 2H_2O$$

Production and Handling of Magnesium Metal

Molten salt containing about 94% $MgCl_2$ is transferred to the electrolytic cells on a rigid schedule. The cells at Rowley are essentially a modification of the I.G. Farben cell developed in Germany in the 1930's. These are normally referred to as I.G. cells and figure 2 shows a sketch of a typical cell. This cell consists usually of three to five graphite anodes with steel cathodes on either side. Semiwalls extending from the top of the cell down into the bath isolates two gas compartments. The gas compartments around the anode collect the chlorine gas, which is generated on the anode surface. The chlorine is then pumped to the chlorine recovery plant. The cathode compartment collects the magnesium metal which floats on the salt. The magnesium metal is removed from the cells each day and sent to the foundry. (Sufficient air is passed over the cathode compartment to remove any fumes and then through a scrubber in order to keep the environment around the cells in satisfactory condition). The metal transferred to the foundry is conditioned, purified as needed, alloyed as required, and poured into molds for shipment. These molds may vary from 16 pounds to 500 pounds or more and may be in the form of special shapes in order to serve specified end uses.

USE OF PRODUCTS

In 1977 the total free world consumption of magnesium approached 220,000 short tons of which about 120,000 tons were consumed in the United States. The plant at Rowley is the third largest in the free world and represents about 10% of the world production and 20% of the domestic production.

The largest single use of magnesium is for alloying aluminum to provide strength, malleability, and corrosion resistance. The aluminum beverage can is the largest single user, but significant quantities of aircraft and automotive sheet also require magnesium additions.

When magnesium is added to iron, brittle gray iron is transformed into higher strength ductile iron. Automotive crankcases, which used to be forgings, are now ductile iron. Recently, magnesium has been injected into steel to remove embrittling sulphur compounds.

Magnesium is used as a reducing agent in the production of titanium, zirconium, hafnium, and beryllium. Other chemical uses are as a grignard reagent, motor oil additive, pyrotechnic material, and as consumable anodes for cathodic protection.

As a structural material, magnesium is most viable as a die casting for chain saws, lawn mower housings, and the famous Volkswagen Beetle engine. Volkswagen is still the largest structural user of magnesium for engine and transmission components. NL supplies magnesium to Volkswagen's Brazilian plant for this purpose. Extrusions, tool plate, sheet, and plate also find a variety of uses.

While most of the magnesium produced is for domestic consumption, NL has shipped material overseas primarily to Europe, South America, and Japan.

A co-product to magnesium is chlorine, most of which is recycled in the process; however, excess chlorine (approximately 18,000 ton/year) is being sold in the Salt Lake area and the western United States. Chlorine has a variety of chemical uses and is also used in water purification. The plant at Rowley provides a Utah source of chlorine to replace that previously shipped in from the Pacific Northwest.

Other by-products presently being considered from the production of magnesium at Rowley, Utah are $CaCl_2$, HCl, lithium compounds, and bromine compounds. In addition, millions of tons of salt are being deposited in the ponds. These salts are largely sodium chloride and various sulfates. Sales of these salts, direct or after modification, will add potential income in the future.

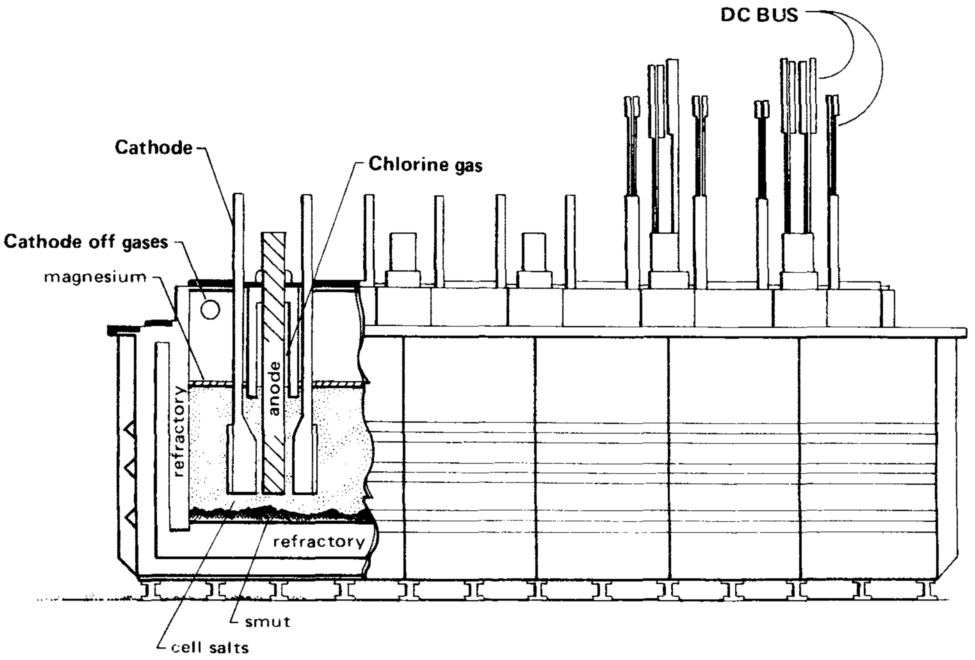

Figure 2. Typical I. G. electrolytic cell used for the production of magnesium metal and chlorine gas.

INDUSTRIAL PROCESSING OF GREAT SALT LAKE BRINES BY GREAT SALT LAKE MINERALS & CHEMICALS CORPORATION

by Peter Behrens, President

ABSTRACT

The Great Salt Lake Minerals & Chemicals Corporation (GSL) extracts mineral products from the brine from the Great Salt Lake. Each product requires a different separation and refinement technique in accordance with its physical and chemical properties. A brief outline of the history of GSL and of its industrial process techniques is given.

INTRODUCTION

Natural saline brines or natural deposits of evaporite minerals are the chief sources of potassium which can be converted to forms usable by the fertilizer industry. The usable forms of potassium are the muriate of potash (potassium chloride or KCl), and the sulfate of potash (potassium sulfate or K_2SO_4). The most commonly used fertilizer is the muriate form because of its abundance and relative ease of production. However, because some soils cannot tolerate additional chloride or have become poisoned from over use of the muriate fertilizer, demand has been shifting to the use of potassium sulfate. Sulfate of potash (SOP) has the added advantage of providing two nutrients to the soil, i.e. both potassium and sulfur in the form of sulfate.

The valuable quantities of potassium contained in the Great Salt Lake has long been known; however, the lake also contains an appreciable amount of sulfate, which complicates the chemistry for production of a relatively pure potassium chloride fertilizer.

This, coupled with the early demand for the muriate (KCl), encouraged early producers to go west to the Utah-Nevada border, where subsurface brines are relatively low in sulfate. During World War I, when essential potash supplies from Germany were cut off, the U.S. Government built a potash plant at Salduro, near Wendover, Utah. When the German supplies again became available, the Salduro plant could not compete economically and was abandoned. Subsequent development of the salt flotation process for physical separation of potassium chloride from sodium chloride permitted Bonneville Ltd. to compete successfully with the Germans when it began producing muriate of potash from its plant near Wendover, Utah in 1938.

Over the years, several small-scale attempts had been made to exploit the resources of the Great Salt Lake itself. However, common salt production was the only type of operation to persist until the present GSL operation began in the 1960's.

GREAT SALT LAKE MINERALS & CHEMICALS CORPORATION

The present GSL operation at Little Mountain, Utah, began as an exploration project of the Lithium Corporation of America. Laboratory studies conducted in 1963 and 1964 to examine the feasibility of commercially extracting minerals other than common salt (sodium chloride) from the Great Salt Lake led to three years of pilot pond and pilot plant testing. These pilot operations proved the economic feasibility of the project. Construction of the commercial-scale ponds and plants was started in May of 1967.

To finance such a large and complex venture, partners were sought. A prominent, experienced German company, Salzdetfurth, bought into the venture and contributed significantly to its development. Later, Gulf Sulphur Company merged with Lithium Corporation of America and founded Gulf Resources and Chemicals Corporation of Houston, Texas, a diversified resource-based company. Gulf Resources later acquired and today has full ownership of Great Salt Lake Minerals & Chemicals Corporation.

Mineral extraction by GSL

All of the salts that GSL produces are originally found in the Great Salt Lake in a dissolved form; consequently, the removal of water is the first step in each of the refinement processes. Economy dictates that evaporation, or the process of water removal, be accomplished using solar energy. To this end, GSL uses a complex solar pond system consisting of some 80 solar ponds, comprising 17,000 acres of evaporation area, shown in figure 1.

The solubilities of the minerals contained in the brine vary with composition and temperature. As the brine becomes more concentrated, salts precipitate; the composition of these salts depends chiefly on temperature and brine composition. Solar evaporation to predetermined concentrations, or winter chilling of concentrated brine, allows specific salt minerals or mixtures to precipitate in solid form. These salts all require additional refinement before they become salable products; they must be harvested, stockpiled, and subjected to in-plant processing to remove contam-

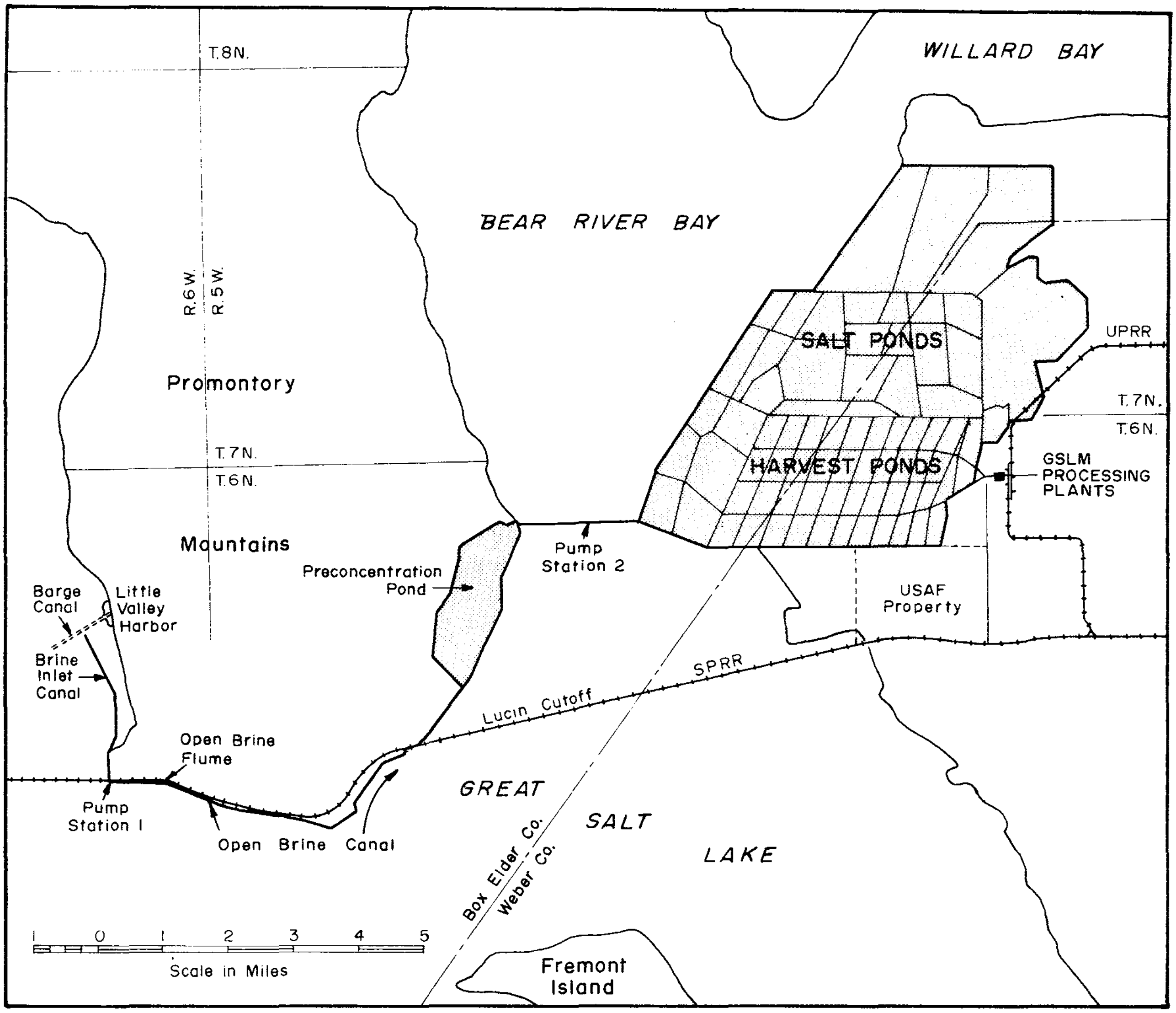

Figure 1. Great Salt Lake solar pond complex.

inants or possibly change the chemical structure. These products are then distributed to market throughout the world.

The products currently produced at GSL, and the uses for these products, are:

1. Common salt (sodium chloride, $NaCl$) is used as an industrial chemical, for highway de-icing, water softening, as a cattle and poultry food supplement, and in the processing of foods.

2. Salt cake (sodium sulfate, Na_2SO_4), is used as a detergent filler and in making paper and ceramics.

3. Sulfate of potash (SOP) (potassium sulfate, K_2SO_4), is used as a fertilizer.

4. Magnesium chloride brine, a highly concentrated solution of magnesium chloride ($MgCl_2$), is now being used in well drilling and in the sugar industry and has a high future potential in the production of magnesium metal, in refractories, and in magnesium chemicals.

The following sections will describe briefly the processing steps that are required to produce common salt, salt cake, sulfate of potash and magnesium chloride salt and brine.

Salt (sodium chloride, NaCl)

As the waters of the Great Salt Lake are evaporated, they soon become saturated with common salt, $NaCl$, and pure salt begins to precipitate. Further evaporation continues to produce pure salt until the concentrated brine becomes saturated with more complex chemical salts. Under normal summer conditions, nearly 90% of the contained NaCl can be precipitated from the lake water before contaminating materials begin to precipitate. However, the pure solid sodium chloride, which now forms the floor of the solar evaporating ponds, contains contaminants such as entrained brine. This brine is partly removed by draining away from salt windrows which are set up as a step on the harvest operation, by draining away from the stockpile; and more is removed by stockpile weathering. For most applications, further in-plant treatment is required to remove the vestiges of contaminants by washing the product. The NaCl is then dried, sized for specific needs, and conveyed to a distribution facility, from which it leaves the plant site in bags or in bulk, by truck or train. Figure 2 shows a schematic of the NaCl process.

Salt cake (sodium sulfate, Na_2SO_4)

In winter, large quantities of mirabilite, a salt mineral having the composition of $Na_2SO_4 \cdot 10H_2O$ (glaubers salt), precipitates as a solid in the Great Salt Lake and in the solar evaporating ponds which contain concentrated brine. The waters of crystallization in the mirabilite account for over 55% of its weight, and, as with NaCl, contaminants exist in the form of entrained brine. So, in-plant operations are required to remove the contaminants and to transform the heavy hydrous salt into a lighter anhydrous form.

The contaminating brines are drained away in the ponds by windrowing, and at the plant site by stockpiling. In-plant purification consists of re-dissolving the glaubers salt and filtering off the solid impurities. Anhydrous sodium sulfate or salt cake is precipitated from this saturated solution by "salting out" with sodium chloride. The sodium sulfate is then filtered, dried, sized and bagged or bulk stored for shipment by truck or by rail. Figure 3 shows a schematic of the salt cake process.

Sulfate of potash (SOP) (potassium sulfate, K_2SO_4)

Potassium sulfate does not precipitate from the

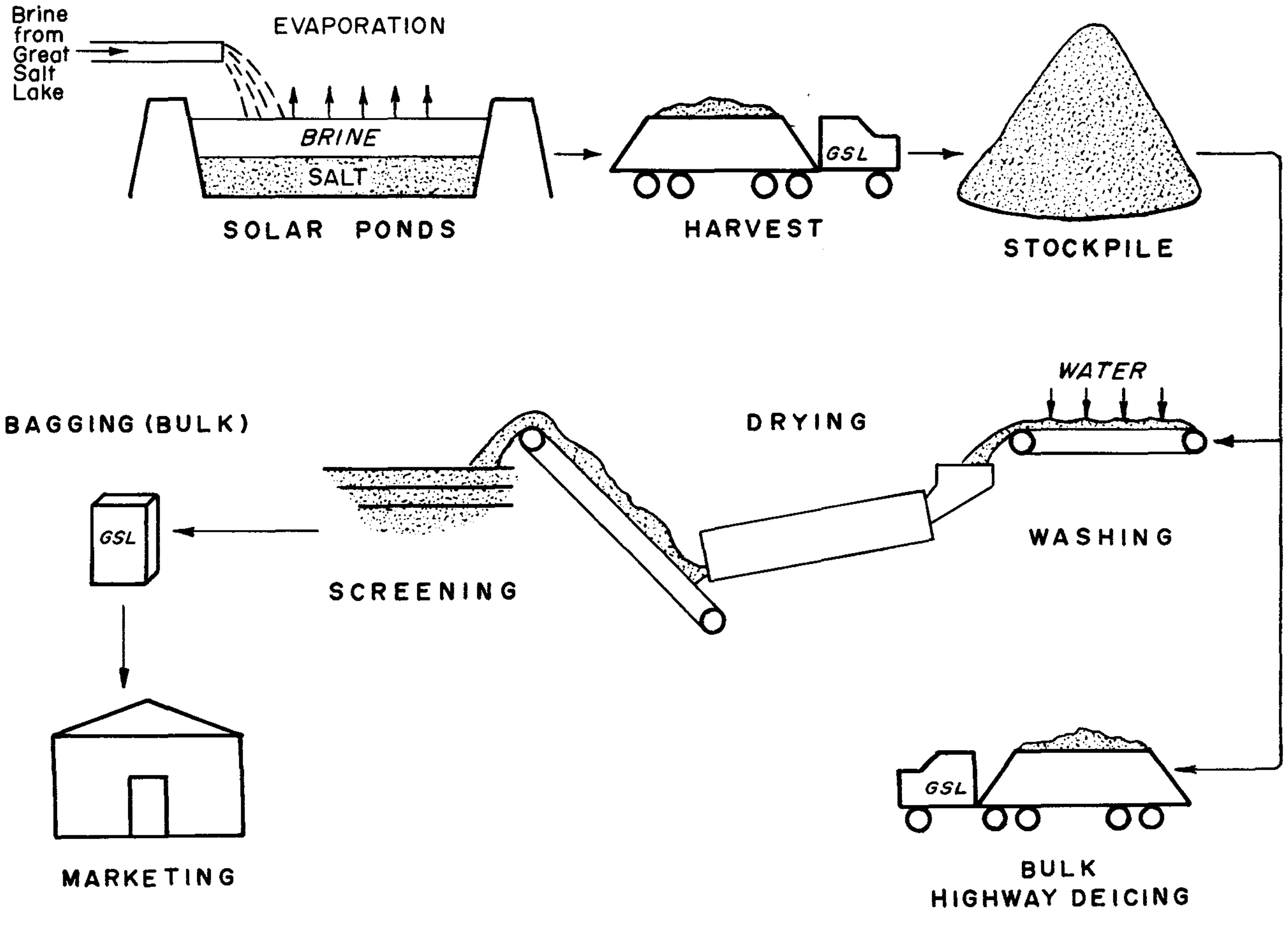

Figure 2. Sodium Chloride Process

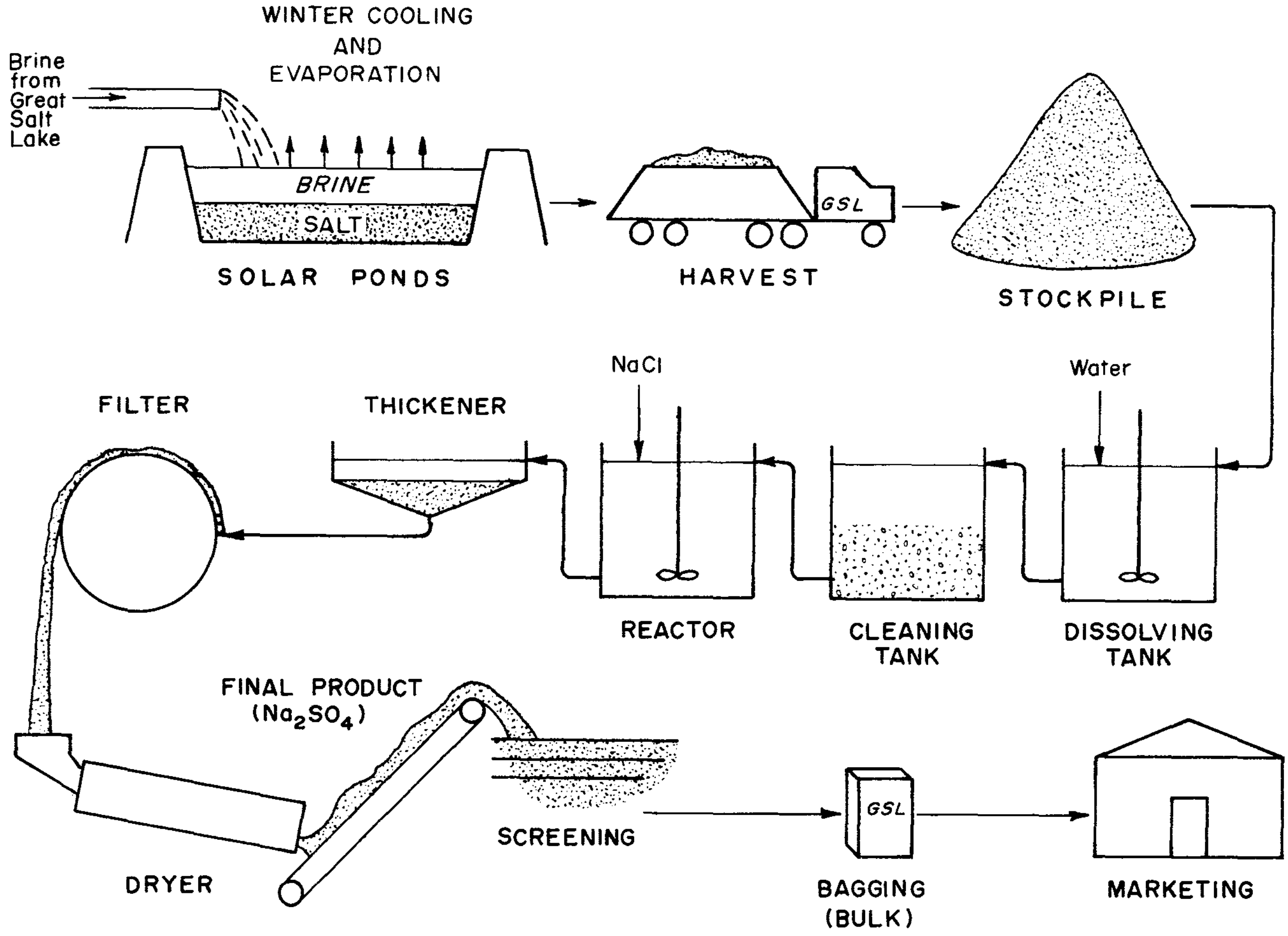

Figure 3. Sodium Sulfate Process

waters of the Great Salt Lake by simple solar evaporation. As the lake water is evaporated, first common salt, NaCl, is precipitated in a pure form. By the time evaporative concentration has proceeded to the point that saturation in another salt is encountered, most of the NaCl has precipitated. It does, however, continue to precipitate and becomes the major contaminant to the potassium-bearing salts as they are precipitated. The brine phase chemistry from the point of potassium saturation becomes complicated, and a variety of potassium double salts are possible, depending on brine concentration, temperature and other factors. Chief among the minerals precipitated that contain atoms of both potassium and magnesium in the same molecule are kainite, a double salt of sulfate and chloride ($KCl \cdot MgSO_4 \cdot 3H_2O$); schoenite, a double salt of sulfate ($K_2SO_4 \cdot MgSO_4 \cdot 6H_2O$); and carnallite, a double salt of chloride ($KCl \cdot MgCl_2 \cdot 6H_2O$). Note that all the above are highly hydrated; that is, they contain waters of crystallization that must be removed. Purification also involves removal of the considerable quantities of sodium chloride that are precipitated simultaneously after which the salts must be chemically converted into potassium sulfate.

The exact mineralogy of the precipitated salts and their composition mixtures varies beyond reasonably precise control. Many of the complex salts are stable only under fixed conditions, so that transitions of composition may take place in the ponds and even in the stockpile and early processing plant steps.

While weathering, draining, temperature and other factors can be controlled to a degree, it is essential that the plant be able to handle and effectively accommodate a widely variable feed mix. To do this, GSL has developed a basic process comprising a counter-current leach procedure for converting the potassium-bearing minerals through mineral transition stages to a final potassium sulfate product. This process is sensitive to sodium chloride content, so a supplemental flotation circuit has been provided to handle those harvest salts which are high in common salt content and to upgrade them to the point where they can be handled by the basic process. The potassium sulfate resulting from the basic process is filtered, dried, sized and stored. Final products may be compacted, graded and provided with additives as desired. The products are distributed in bulk or bagged, by rail or truck. Figure 4 is a schematic of the potassium sulfate process.

Magnesium chloride ($MgCl_2$)

In its natural state, magnesium chloride precipitates in a highly hydrated form, bischoffite ($MgCl_2 \cdot 6H_2O$) and is over half (53 weight percent) water. Actually, solar evaporation alone can proceed to the point where the residual brine is nearly of this composition, with only vestiges of potassium and sodium remaining, but with appreciable sulfate. As a practical matter, since the concentrated magnesium chloride brine is itself hygroscopic, an evaporative equilibrium is reached in the solar ponds at about 35% $MgCl_2$. At this concentration, the heavy brine has value to the sugar industry and to the drilling industry without further treatment. The $MgCl_2$ brine is stored in deep ponds to prevent excessive dilution from rains, thus maintaining a high quality product.

For other uses, such as for the production of magnesium metal or magnesium chemicals, purification is necessary to remove the remaining potassium, sodium, sulfate and trace elements. GSL has a plant to do this purification and to produce a pure bischoffite ($MgCl_2$

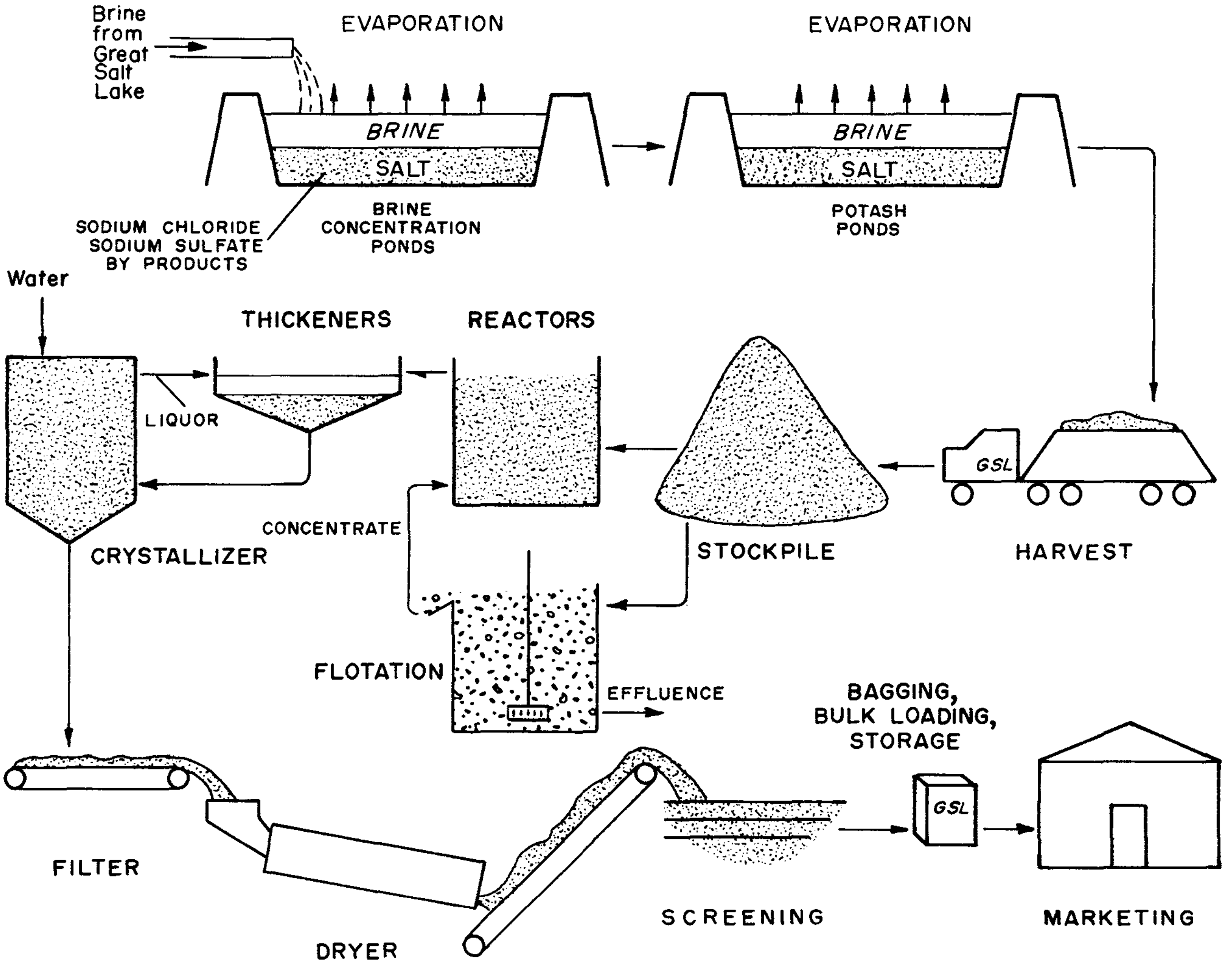

Figure 4. Potassium Sulfate Production (K_2SO_4, Sulfate of Potash).

$\cdot 6H_2O$) product, but does not operate it at the present time. Future development of a market for purified magnesium chloride may lead to startup of the plant. This in-plant process is simply one of controlled vacuum evaporation to crystallize first magnesium sulfate, which is rejected, then pure $MgCl_2 \cdot 6H_2O$, which is centrifuged, dried and marketed. Figure 5 shows a schematic of the magnesium chloride process.

REFERENCE

Brock, T. D., 1976, Halophilic blue-green algae: Archives of Microbioloby v. 107; p. 109-111.

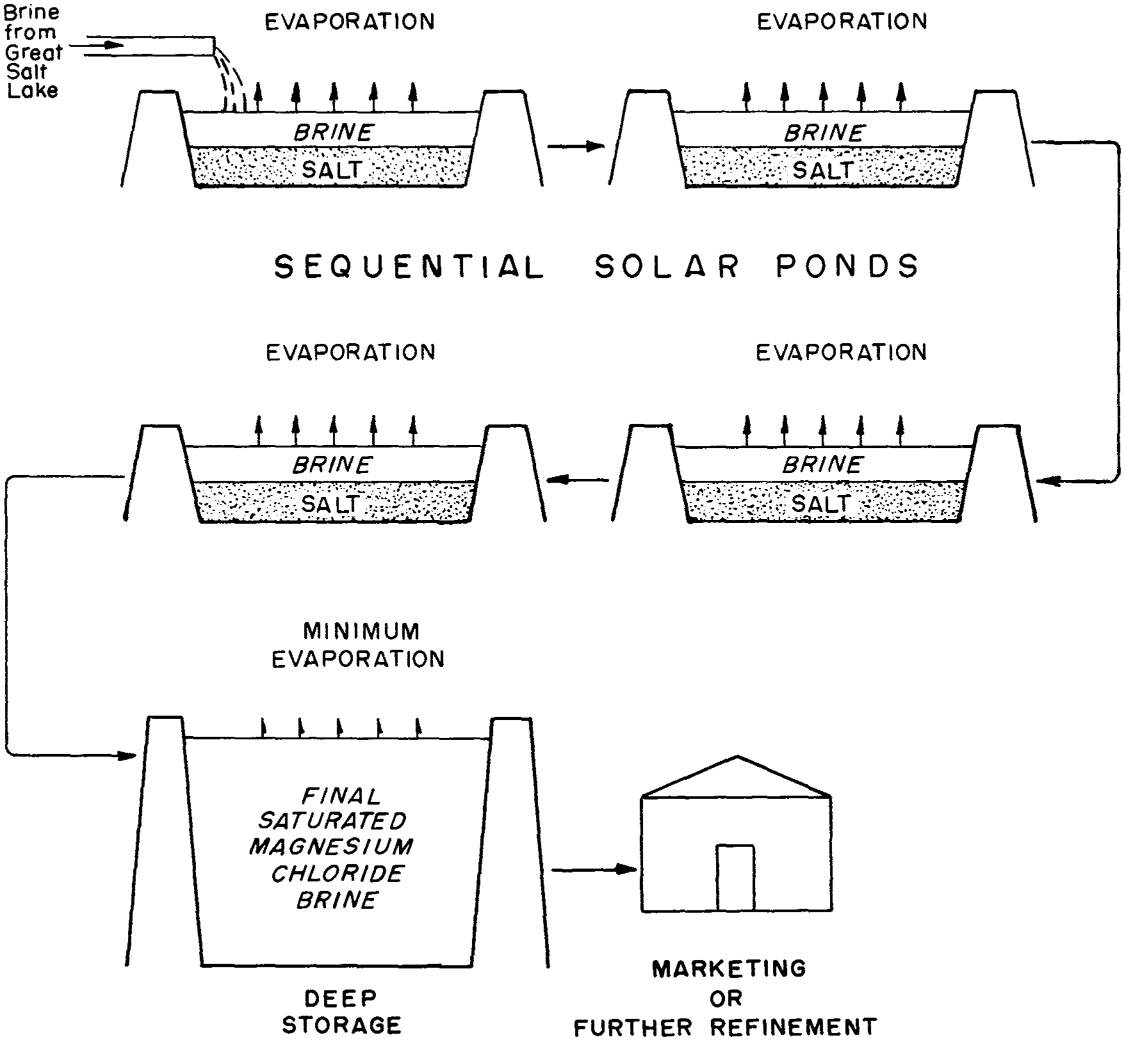

Figure 5. Saturated Magnesium Chloride Brine.

SOLAR PRODUCTION OF POTASH FROM THE BRINES OF THE BONNEVILLE SALT FLATS

C. P. Bingham
Senior Geologist
Kaiser Aluminum & Chemical Corporation

ABSTRACT

Potash–bearing brine occurs in the salt crust and the underlying calcarerous sediments of the Bonneville Salt Flats. Although the principal dissolved salt is sodium chloride, the brine also contains a nominal 1% equivalent potassium chloride.

The Industrial Chemicals Division of Kaiser Aluminum and Chemical Corporation operates a plant which produces commercial muriate of potash from the brine by a combination of solar evaporation and froth flotation. In the process the desert brine is collected in open ditches by gravity drainage; thence it is pumped to a primary pond where concentration from 1% KCl to 7.5% KCl is accomplished by solar evaporation. The concentrated brine is then transferred to a harvest pond where solar evaporation continues until sylvinite, a physical mixture of halite ($NaCl$),and sylvite (KCl), is precipitated. The harvest pond is then drained and the sylvinite is loaded into elevating scrapers and hauled to a flotation mill. Here it is ground in ball mills and treated by froth flotation to separate the sylvite from the halite. The potash concentrate is partially dewatered by filtration and gravity drainage and then dried in a rotary kiln. A portion of the dried product is diverted to a compacter plant where it is compacted and crushed. Commercial products are standard muriate of potash, coarse muriate of potash, and manure salts.

INTRODUCTION

Kaiser Aluminum and Chemical Corporation (KACC) through its Industrial Chemicals Division (Kaiser Chemicals) produces a nominal 77,000 mt (85,000 short tons) per year of potash products by solar evaporation of brines extracted from the Bonneville Salt Flats. In this paper the physiography and geology of the Great Salt Lake Desert are summarized, the historical background of the present operation is reviewed and the current plant operations are described.

Location and Access

Kaiser Chemicals' potash production facilities are located in western Tooele County, Utah a few miles east of the Nevada State Line (figure 1). The nearest town is Wendover, Utah, approximately 4.8 km (3 miles) to the west. The office, shop and flotation plant are located adjacent to old U. S. Highway 40 and the main line of the Western Pacific Railroad. Interstate 80 passes about 0.8 km (0.5 miles) to the north. The evaporation ponds and most of the brine collection facilities are located south of Interstate 80. Access to the plant from the east is by an interchange off Interstate 80 and a portion of old U. S. Highway 40. Access from the west is by a county-maintained part of old Highway 40.

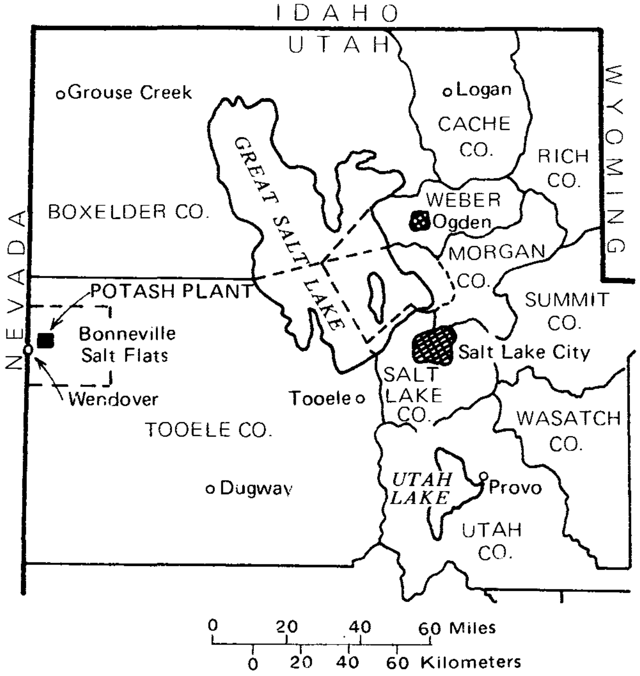

Figure 1. Location of the Bonneville Salt Flats and Kaiser Chemicals' potash.

Physiography

The salt pan known as the Bonneville Salt Flats is located near the western edge of the Great Salt Lake Desert, one of the many desert valleys included in the Great Basin portion of the Basin and Range physiographic province. The Great Salt Lake Desert is essentially a single drainage unit which is separated from the drainage basin of the Great Salt Lake by a low divide. The desert is almost completely surrounded by mountain ranges whose maximum relief is about 2,410 m (7,900 feet) from the highest point in the Deep Creek Mountains range at an elevation of 3,689 m (12,100 feet) above sea level to the lowest part of the desert at an elevation of 1,279 m (4,195 feet) above sea level. Many of the mountain ranges were islands during the high stages of Lake Bonneville.

Erosional and constructional features from four long-term and numerous short-term levels of Lake Bonneville are etched with varying degrees of clarity on the flanks of the mountain ranges bordering the desert.

The Salt Flats (figure 2) is bordered on the northwest and north by the Silver Island Mountains and on the other sides by the barren, level mudflat surface of the desert. A few miles to the northeast a small hill called Floating Island protrudes from the desert floor.

The surface of the Bonneville Salt Flats is a salt pan at an elevation of 1,285 m (4,215 feet) above sea level. It represents the drainage sump for much of the Great Salt Lake Desert basin. The area of the salt pan varies from year to year and even seasonally within the same year in response to changes in the amount of precipitation. The maximum area of which we have a record was 409 square km (158 square miles) in 1925 (Nolan, 1927); the minimum area of which we have a record was 282 square km (109 square miles) in 1976 (Turk, 1977). Changes in area as great as 91 square km (35 square miles) have occurred within a single year (Turk, 1977). Thus the maximum annual variation in the area of the salt pan represents 70% of the maximum long-term variation.

Climate

The climate of western Utah is classified as arid continental. It is characterized by low precipitation, low relative humidity and moderately large seasonal fluctuations in the temperature. For the period from 1931 through 1975 inclusive the annual mean temperature at Wendover, Utah was between 11°C and 12°C (52°F and 53°F) and the average annual precipitation was about 12.3 cm (4.9 inches). The highest temperature recorded during this period was 44°C (112°F) in July, 1959 and the lowest temperature recorded was minus 28°C (-19°F) in February, 1933. The greatest annual precipitation for the period 1912-1975 was 26 cm (10.13 inches) in 1941 and the lowest annual precipitation was 5.4 cm (1.77 inches) in 1926. Winds usually are light to moderate, though variable; but occasionally the winds become very strong and gusty, particularly during the spring months when they sometimes reach destructive velocity and create dense clouds of dust.

History

All of the early groups which crossed the Great Salt Lake Desert en route to California, from Jedediah Smith in 1826 to the ill-fated Donner-Reed party in 1846, encountered serious physical difficulties. Most of their problems were caused by the soft, mushy ground which is present over much of the desert. From 1850 until the railroad was completed across the salt flats in 1909, the area was largely avoided in favor of the longer, but easier, routes to the north and south.

Although the Great Salt Lake Desert was reconnoitered by a scientific expedition under the leadership of Howard Stansbury in 1849 (Stansbury, 1863) and the Bonneville Salt Flats was mentioned by G. K. Gilbert in his U. S. Geological Survey Monograph of 1890, apparently it was Gale (1914) who first recognized the economic potential of the potash-bearing brines. In 1925 and 1926 T. B. Nolan conducted a field study of the potash brines and published the results of his study in a U. S. Geological Survey Bulletin (Nolan, 1927). This report included the analyses of the brines from 405 shallow test wells and a map showing the outline of the salt pan. More recently, reports dealing with the salt flats, either directly or indirectly, were written by Eardley (1962), Nackowski and Mehrhoff (1960, 1961), Nackowski (1962), Cook and others (1964), Davis (1966, 1967), Kaliser (1967), Turk (1969, 1970, 1973), Turk and others (1973), Lallman and Wadsworth (1976) and Lines (1977).

The first production of potash from the brines of the Bonneville Salt Flats was by the Utah Salduro Company, a subsidiary of the Solvay Process Company, in 1917. The Utah Salduro plant was located about 11 km (7 miles) east of Wendover. It operated from 1917 until 1921, at which time imports of potash from Germany made it uneconomic.

Between 1920 and 1930 a company known as the Bonneville Corporation made several unsuccessful attempts to establish an economic potash operation based on 100 square km (40 square miles) of salt flats land acquired in fee by a special act of the U. S. Congress and 127 square km (49 square miles) of fee land acquired from the Utah Salduro Company. The company became completely inactive after 1930.

The present operation had its beginning in 1936 when Bonneville Limited was formed to take over the land holdings of the defunct Bonneville Corporation. Commercial potash production began in 1939 and has continued up to the present time.

In February, 1963 Bonneville Limited was acquired by Standard Magnesium Corporation of Tulsa, Oklahoma which in turn was acquired by Kaiser Aluminum and Chemical Corporation (KACC) in March, 1964. The plant is now operated as a unit of the Industrial Chemicals Division.

GEOLOGY

Regional

As shown by the very generalized geologic map of figure 2, rock strata cropping out in the mountain ranges bordering the Great Salt Lake Desert range in age from Paleozoic to Pleistocene. Paleozoic strata, although not differentiated on the map, are mainly of sedimentary origin and include every system from Cambrian to Permian. Rocks of Mesozoic age are absent and those of Tertiary age are principally of igneous origin.

Strata of Quaternary and Recent ages are, for the most part, unconsolidated to poorly consolidated sediments of lacustrine, fluvial and alluvial origins. Deposits from Pleistocene Lake Bonneville are represented by terrace and deltaic deposits along the flanks of the mountains facing the desert.

The Great Salt Lake Desert is underlain by poorly consolidated, fine grained, calcareous sediments of mainly lacustrine origin. Dunes of windblown gypsum sand are common features in the eastern part of the desert. The western flanks of three small inlying hills have been almost completely covered by the dunes.

Strata exposed in the Silver Island Mountains, which is the closest range to the Bonneville Salt Flats, include 7,100 m (23,000 feet) of miogeosynclinal sedimentary rocks representing every system of the Paleozoic, 850 m (2,800 feet) of Tertiary lacustrine rocks, 410 m (1,350 feet) of Tertiary volcanic rocks and minor thicknesses of Quaternary lacustrine and fluvial sediments (Schaeffer and Anderson, 1960, p. 15). Paleozoic strata are intruded by 5 small igneous stocks and numerous igneous dikes.

Structure

The older rock units of the desert ranges have undergone deformation by both folding and faulting with varying degrees of intensity. Major faults are recognized on at least one flank of most of the ranges. The Silver Island Mountains are bordered on their southeast side by a major fault with a downthrow to the east and displacement reported to be at least 335 m (1,100 feet), and possibly as much as 1,525 m (5,000 feet) (Schaeffer and Anderson, 1960, p. 148-149). The existence of this fault has been verified by the data from gravity surveys (Cook and others, 1964). These data have also indicated the presence of other essentially parallel faults to the east, and that part of the salt flats is underlain by a graben.

The surface of the Bonneville Salt Flats is a salt pan representing the final precipitate from the complete dessication of the western arm of Pleistocene Lake Bonneville. At its maximum size, Lake Bonneville covered an area of about 51,700 square km (20,000 square miles) and reached a maximum depth of about 305 m (1,000 feet). Gilbert (1890) first suggested that isostatic compensation resulting from the dewatering of the western arm could best explain the apparent upwarping of the central and eastern parts of the surface of the Great Salt Lake Desert. Eardley (1962) also proposed the principle of isostatic compensation to explain the present location of the salt pan. He speculated that the salt pan originally may have deposited near the center of the desert, but that the upwarping of the central and eastern parts followed by cycles of re-solution and evaporation gradually shifted the salt pan westward until it finally came to rest in its present position at the foot of the Silver Island Mountains.

Stratigraphy of the Salt Flats

Data from 14 deep brine wells and one oil test well provide the stratigraphy of the salt flats to a depth of 899 m (2,948 feet). From top to bottom they show lacustrine sediments, fluvial sediments, volcanic rocks and intrusive rocks. The sediments range from 268 to 434 m (880-1,425 feet) in thickness and are described in the drillers' well logs mainly as clay and gypsum with minor sections of sand and conglomerate. The deep brine wells were bottomed in what is described in the drillers' logs as conglomerate at depths ranging from 326 to 625 m (1,070-2,051 feet). Turk (Turk and others, 1972) suggests that the conglomerate is probably volcanic breccia corresponding in age to the post-early Pliocene and pre-late Pleistocene volcanic rocks de-

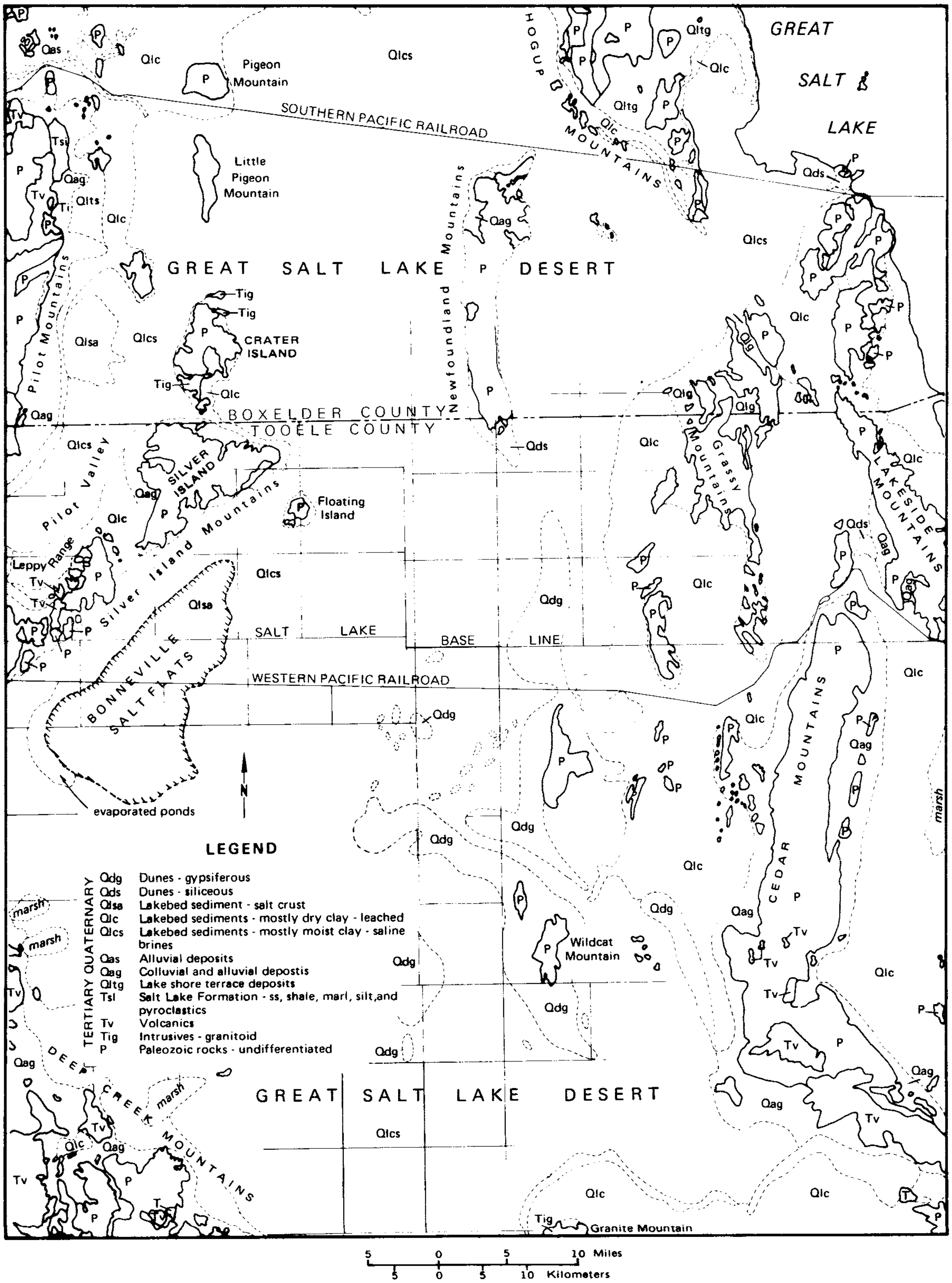

Figure 2. Generalized geologic map of the Great Salt Lake Desert and adjacent mountain ranges.

scribed by Schaeffer and Anderson (1960, P. 143) in the Silver Island Mountains. Shell Oil Company's Salduro Number 1 oil test well is reported to have penetrated 427 m (1,400 feet) of volcanic rocks from a depth of 419 m (1,375 feet) before drilling into basic intrusive rock at a depth of 836 m (2,742 feet) (Heylmun, 1965, p. 28).

The most important part of the stratigraphic section from an economic standpoint is the top 6 m (20 feet) which includes the salt pan, a sulphate (gypsum) transition zone and the fractured clay zone. The typical lithologies are as follows:

Salt pan

In cross section the salt crust is an asymmetrical, lens-shaped deposit with thicknesses up to about 1.2 m (4 feet). The composition of the crust is predominately sodium chloride with variable lesser amounts of calcium sulphate and very small amounts of potassium chloride, magnesium chloride, and silt.

Sulphate zone

A gray to dark gray layer of calcium sulphate occurs immediately below the salt bed in most parts of the salt flats. Presumably it is mostly gypsum, but the hemihydrate $CaSO_4 \cdot \frac{1}{2}H_2O$ has been identified in some samples (Turk and others, 1973, p. 68). The maximum observed thickness of the layer is 61 cm (2 feet).

South of Interstate 80 much of the salt crust is overlain by a layer of loose gypsum sand up to 40 cm (16 inches) in thickness and the sulphate layer which usually underlies the salt is either very thin or absent.

Calcareous clay zone

The sulphate layer is underlain by beds of soft, silty, plastic clay, oolitic sand, and coarse, nodular to platy gravel. The clay beds are separated by sand or gravel beds. Individual clay beds have thicknesses ranging from 0.3 m (12 inches) to 1.2 m (4 feet). The sand and gravel beds usually are less than 0.3 m (12 inches) in thickness.

The clay beds are, for the most part, carbonate muds. In each of 40 samples for which the mineralogy was determined the predominant mineral is aragonite. Dolomite, quartz, montmorillonite and gypsum are present also, but in lesser, and often minor, percentages. In the upper 3 m (10 feet) of the clay zone, the beds are light gray, greenish gray, yellow or tan, probably due to partial oxidation. In the lower 3 m (10 feet) the clay beds change in color to blue gray, dark gray, or, sometimes, black due to the presence of carbonaceous material. Crystals of platy selenite gypsum up to 10 cm (4 inches) in length are abundant in some of the clay beds.

Oolitic sand beds are composed principally of cylindrical shaped fecal pellets from brine shrimp. Gravel beds contain both flat algal plates and irregular shaped nodules. Aragonite is the principal mineral in both the sand and the gravel beds. Individual sand and gravel beds can be traced continuously for several miles in the collection ditches, but they do not remain of uniform thickness throughout this distance.

The clay beds contain numerous vertical to subvertical fractures, many of which extend from top to bottom and provide connecting channels between sand layers. Exposures in the walls of the collection ditches show that some fractures are very tight and others are open gashes up to 2.5 cm (1 inch) wide. Brine seeps very slowly from the tight fractures and, sometimes, actually gushes from the open fractures.

Hydrogeology

The Bonneville Salt Flats contain two brine-bearing aquifers and one brackish water aquifer which are important to KACC's operation. They are (1) the shallow aquifer comprising the upper 6 m (20 feet) of lacustrine sediments, (2) the deep aquifer comprising the "conglomerate" or volcanic breccia zone and (3) the alluvial aquifer located at the western edge of the desert. The shallow lacustrine aquifer is the principal source of the potash brines used by KACC's Bonneville plant. The deep "conglomerate" aquifer also contains large quantities of brine, which is much more dilute than the brine of the upper zone. Because it contains less than half the quantity of total dissolved salts and potash, although otherwise similar in chemical composition to the brine of the shallow aquifer, brine from the deep horizon is used mainly for filling and maintaining the fluid level in the seal ditches. The alluvial aquifer is the source of the brackish water used for dissolving the mill tailings and leaching the carnallite pond precipitates.

The shallow aquifer has characteristics of both a confined and an unconfined aquifer. The sand beds seem to be largely confined, but some leakage occurs from and into them through the fissures in the clay beds. Brines occur in both the salt pan and the underlying calcareous sediments. Tests have shown that the salt pan usually has a much higher transmissivity than the underlying calcareous clays, but that even the clays have higher transmissivities than normally would be expected for such fine grained sediments (Turk and others, 1973, p. 72). This is attributed to the combination of the fecal pellet sand beds and the vertical fissures in the clay beds. Transmissivities in the shallow acquifer determined from pumping tests range from less than 500 gpd/foot to more than 100,000 gpd/foot. The higher transmissivities are attributed to the presence of the highly permeable halite of the salt crust.

The shallow aquifer is recharged seasonally by infiltration of the precipitation which falls directly on the surface of the salt flats and also by infiltration of the runoff water from the Silver Island Mountains which periodically floods the salt flats. The surface water enters the subsurface both through vertical infiltration and through horizontal infiltration from flooded collection ditches. It is believed that the brine grade is maintained by the reaction of the infiltrating fresh water and concentrated residual or "pore" brine. The infiltrating water also redissolves salts which precipitated as the upper beds were drained and partially dried. The natural recharge procedure serves to renew the supply of brine for the annual production cycle. However, since it is dependent on natural precipitation, the amount of recharge is variable. In very wet years there is an abundant supply of relatively dilute brine and in very dry years there is a very limited supply of relatively concentrated brine. Lateral movement of brines from outside the area of the salt pan is believed to be a relatively insignificant source of recharge (Davis, 1967, p. 4).

Fourteen wells have been drilled into the deep aquifer and four are presently in service. Aquifer tests in 1970 and 1977 indicated that the transmissivity ranges from 50,000 to 145,000 gpd/foot. This aquifer has typical characteristics of a confined aquifer with a piezometric surface approximately 18 m (60 feet) below the ground surface and a storage coefficient of approximately .0004.

The third aquifer of importance to the Bonneville plant is located northwest of the plant along the western edge of the salt flats where a large alluvial fan from the Silver Island Mountains is partially overlain by lacustrine clays. This aquifer yields brackish water containing 6,000 to 8,000 ppm dissolved solids, mostly sodium chloride, from depths between 24 m (80 feet) and 67 m (220 feet). Some of these wells originally flowed but the static water level is now 2-3 m (6-10 feet) below the collar. Transmissivities determined from pumping tests ranged from 160,000 gpd/foot to 475,000 gpd/foot and storage coefficients ranged from .00023 to .00046. These indicate that the aquifer is confined (Turk, 1973, p. 3).

PLANT OPERATION

General

The production of commercial potash from the desert brines is accomplished in a four-stage operation consisting of (1) brine collection, (2) concentration and precipitation by solar evaporation, (3) sylvinite salt harvest and (4) concentration by froth flotation.

Figure 3 is an old aerial photograph showing the plant and evaporation ponds as they looked in the period 1964-1968. A diagramatic map of the plant layout as it now exists is shown in figure 4, and a general flow diagram of the production process is shown in Figure 5.

Brine Collection

Raw brine is collected in an extensive system of open ditches dug into the desert floor. The aggregate length of collection ditches currently is about 152.4 km (95 miles or 500,000 feet). Ditches are dug with draglines to a nominal depth of 6 m (20 feet) and to the nominal width of the dragline bucket, or between 1.5 and 1.8 m (5-6 feet). However, the ditches are gradually widened by the continual dredging required to keep the ditches cleaned of windblown sand and slump clay from the walls. In current practice the adverse effects of the windblown sand are reduced by constructing baffle walls along the ditches. The baffle walls, which consist of two levees about 9 m (30 feet) from, and parallel to, the ditches on either side, act much the same as a snow fence in that they intercept and stack the windblown sand on the windward side of the levee.

The spacing of the collection ditches is designed to balance the annual extraction rate with the annual recharge from precipitation and thus maintain a perennial supply of brine (See figure 4). However, the relatively short duration of the brine production season at Bonneville (approximately 180 days) makes it necessary to space the ditches closer together than would be necessary if brine collection were a year-round opera-

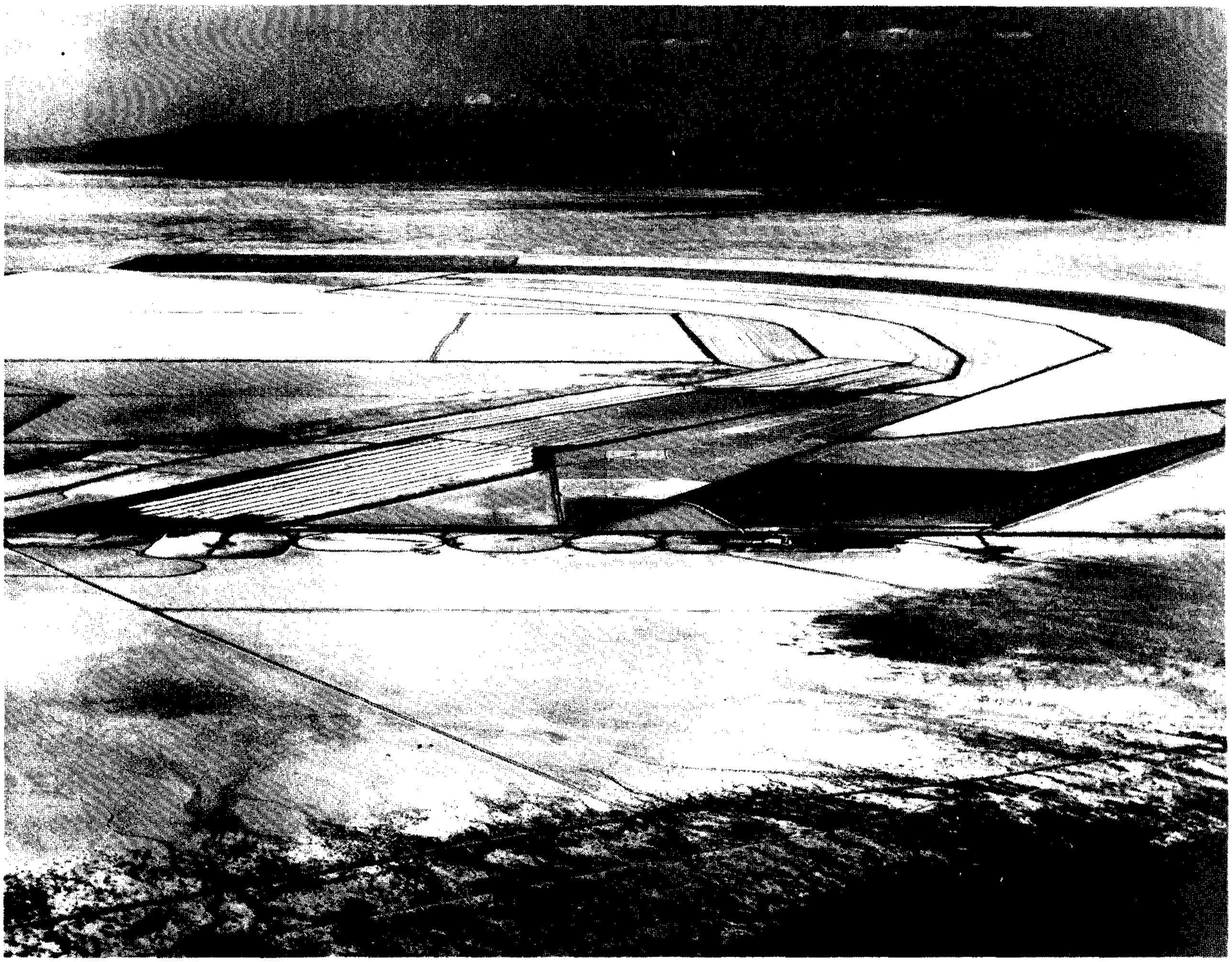

Figure 3. Oblique aerial photograph looking southerly to Kaiser Chemicals' plant and solar evaporation ponds as of the 1965-1967 period.

tion.

The collection system operates by the flow of brine into the ditches under a gravity head created when the brine level is lowered by pumping. The usual induced head during the production season is from 1.5 to 4.6 m (5 to 15 feet).

As collected, the raw brine contains a nominal 1% KCl, although the grade may range from about 0.5% KCl for rain diluted brine to nearly 2.0% KCl for some of the late summer brine.

Brine Transfer

The brine is moved through the collection ditches to six pumping stations strategically located around the primary evaporation pond (See figure 4). At the six pumping stations the brine is elevated to a seal ditch which extends around the perimeter of the primary evaporation pond. The seal ditch serves as both a transfer ditch for the raw brine and as a seal to inhibit the leakage of brine from the evaporation pond.

The six primary pumps are electrically driven, single stage, mixed flow pumps having capacities ranging from 5,000 to 10,000 gpm, depending on the pumping head.

Seal Ditches

At the present time all of the evaporation ponds are surrounded by seal ditches consisting of an elevated, brine-filled ditch confined by two levees constructed of mounded clay dug from the desert floor. To inhibit the leakage of brine under the levees, seal walls are constructed below the planned levees. The seal wall consists of a narrow trench dug into the desert floor to the bottom of the fissured clay and sand beds and then

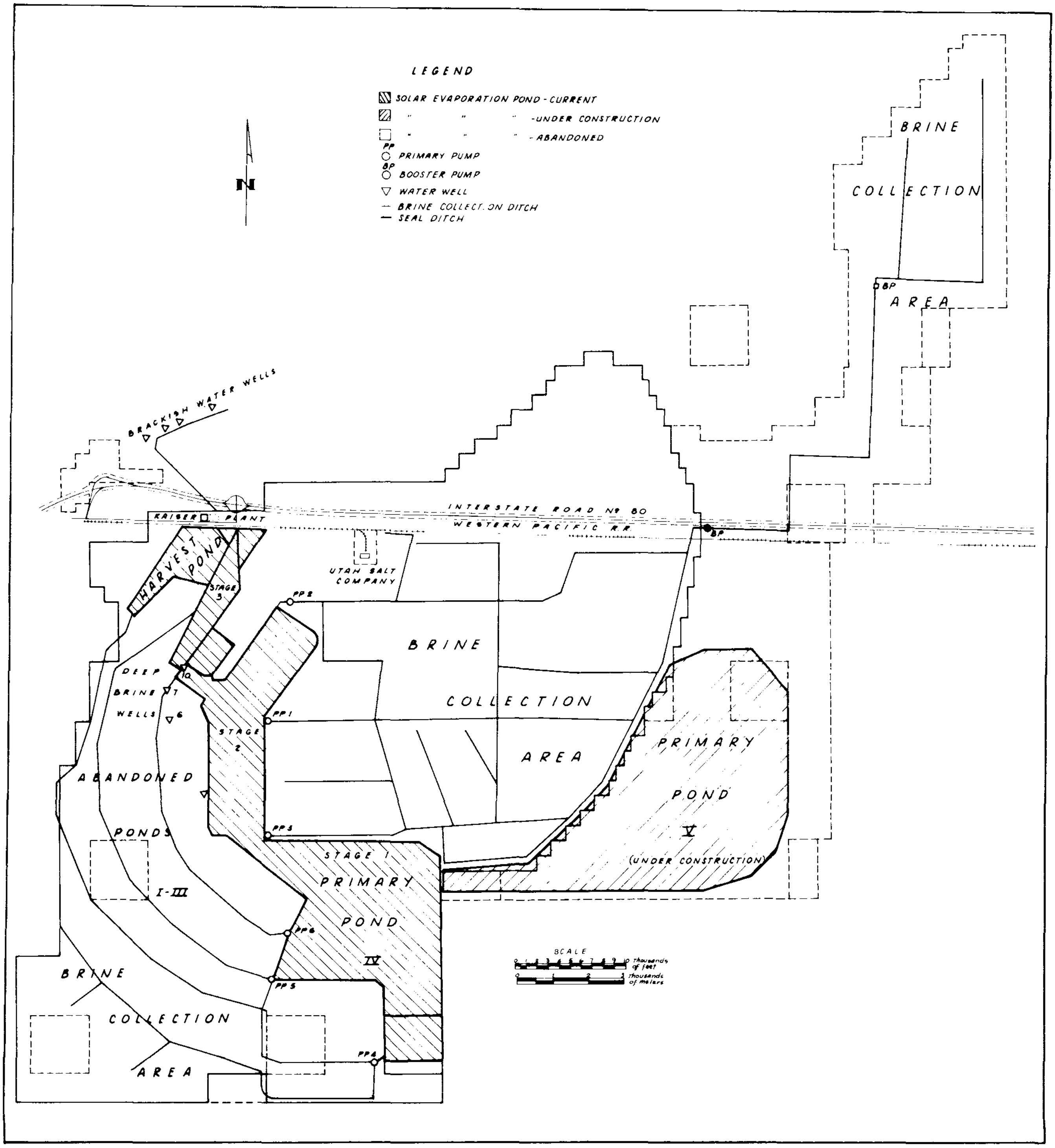

fig. 4

GENERAL LAYOUT OF KAISER CHEMICALS POTASH OPERATIONS
Wendover Plant, Tooele County, Utah

back-filled with clay. The back filling tends to break the continuity of the natural channels in the aquifer and greatly reduces the permeability of the ground. The seal ditch is filled with brine to a level slightly higher than the level of the brine in the evaporation pond to balance the hydrostatic head of the heavier brines in the pond. At the present time brine pumped from the deeper aquifer is the principal source of brine used for the seal ditches around the harvest, carnallite and magnesium chloride storage ponds. However, the primary evaporation pond uses mainly desert brine supplemented only as necessary by brine from the deep wells.

Evaporation Ponds

The first stage of the brine concentration takes place in the primary evaporation pond. Here the raw desert brine containing a nominal 1% KCl is concentrated by solar evaporation until the concentration reaches 7.5%.

The brines entering the primary pond, although variable in composition, typically have compositions in the following range:

Table 1

Salt	Weight %		
	Dilute	Typical	Good
NaCl	16.0	21.0	23.0
KCl	0.7	0.9	1.0+
$MgCl_2$	1.0	1.3	1.4
Other Salts	0.3	0.4	0.5
H_2O	82.0	76.4	75.1
	100.0	100.0	100.0

The raw brine is introduced into the primary pond at the south end; thence, it is moved northward as solar evaporation occurs with the resultant precipitation of sodium chloride and concentration of potassium and magnesium chlorides. The current primary pond occupies about 3,040 ha (7,600 acres) and is divided into three sections or stages of 1,000 ha (5,000 acres), 960 ha (2,400 acres) and 80 ha (200 acres) corresponding to the increasing degrees of brine concentration and the resultant decrease in volume (See figure 5). The staging of the brine concentration permits better pond control and insures against a total loss of brine in case of major washout.

The brine is moved from one stage to another in the primary pond and from one pond to another by means of brine elevators. A brine elevator is an electrically driven drag conveyor mechanism which moves the brine up an inclined trough through a vertical height of about 1.2 m (4 feet) maximum (figure 6). A dilute brine is used to spray the elevator paddles and elevator mechanism to inhibit salt buildup. Nevertheless the elevators still must be desalted after every 8 to 10 days of continuous operation. In the current operation five constant speed elevators are used to transfer the brine from primary stage 1 to primary stage 2 and one constant speed and one variable speed elevator are used to transfer the greatly reduced volume of brine from primary stage 2 to primary stage 3.

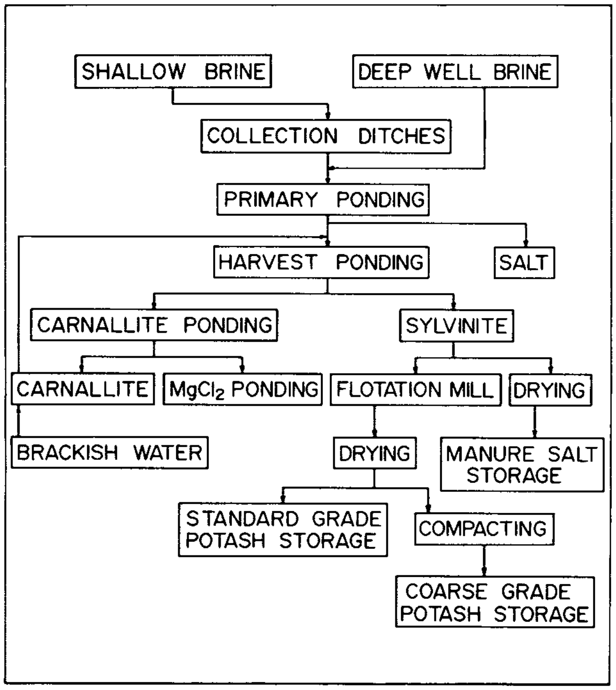

fig.5

FLOW DIAGRAM - KAISER CHEMICALS
WENDOVER POTASH OPERATION

Although the actual rate of evaporation is quite variable from year to year, a typical rate of evaporation in the primary pond is about 2,720 mt (3,000 st) of water per acre per year. At this rate about 15 cm (6 inches) of salt (predominately NaCl with minor $CaSO_4$) is deposited on the pond floor each year. As the floor of the primary pond is raised by each annual increment of precipitated halite, the hydrostatic head is increased and erosion of the levee becomes more of a problem. As a result, operating economics dictate that an old pond be replaced by a new one every 8 to 10 years. The fourth primary pond currently is in use. It became operational in 1969 and is scheduled for retirement in 1980 when the fifth primary pond, which is now

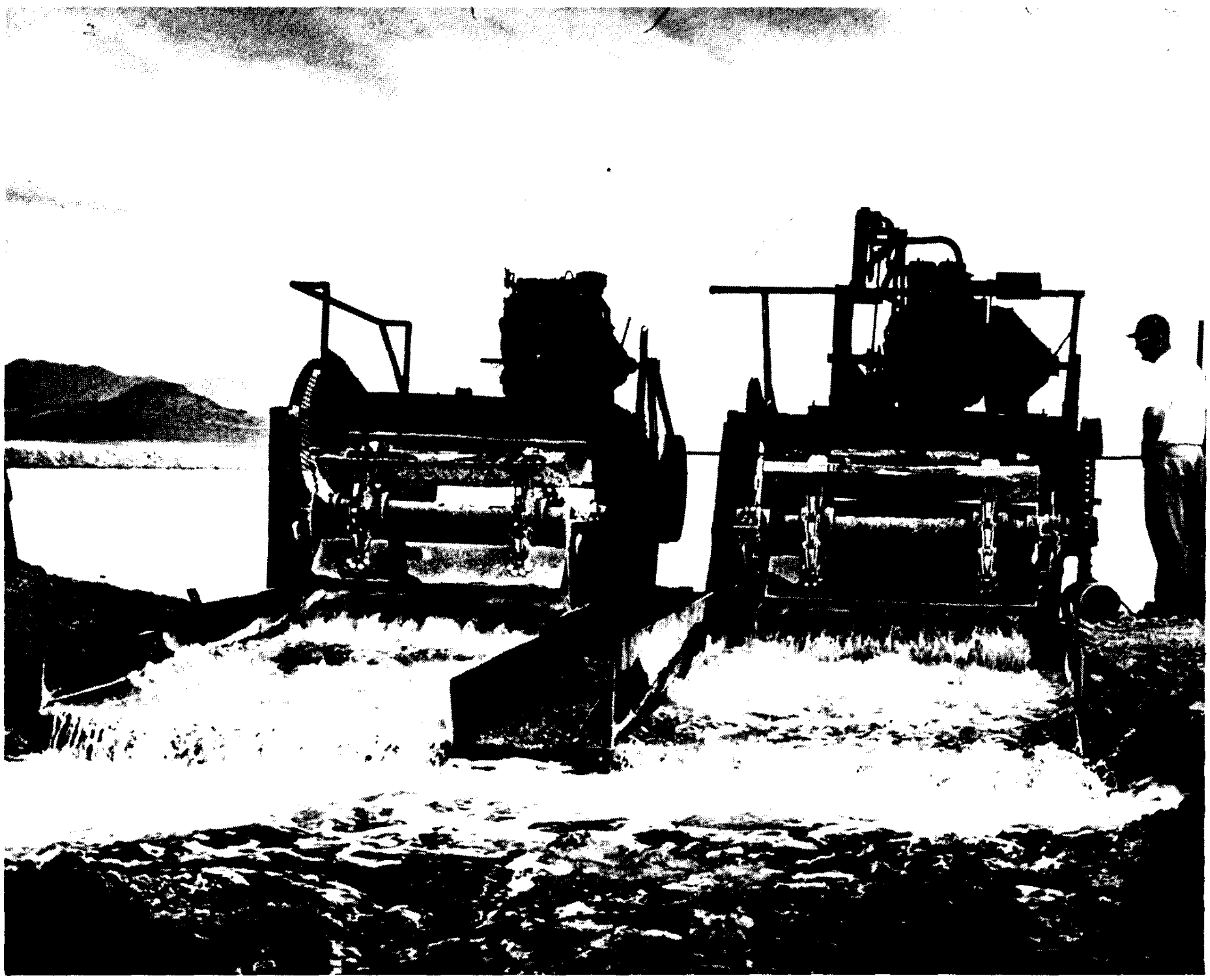

Figure 6. Brine elevators in operation viewed from the discharge end.

under construction, is scheduled to become operational (figure 4). Pond IV will then join retired ponds I, II and III as part of the brine collection area.

Concentrated brine is transferred from primary pond stage 3 to the harvest pond when its specific gravity reaches 1.245, the concentration at which sylvite (KCl) begins to precipitate. The typical concentration of the brine at this stage is as follows:

Table 2

Salt	Weight %
NaCl	12.5
KCl	7.5
$MgCl_2$	9.8
Other Salts	1.7
H_2O	68.5
	100.0

In the harvest pond sylvinite, a physical mixture of halite (NaCl) and sylvite (KCl), is precipitated. Although in theory sylvinite should contain about two-thirds halite and one-third sylvite, the typical composition of the sylvinite laid down in our harvest ponds is 70% halite and 30% sylvite. Typical evaporation in the harvest ponds is about 2,000 tons of water per acre per year.

To support the heavy equipment used to harvest the sylvinite it is necessary to lay a hard floor of halite in the harvest pond prior to putting it into service. This floor is usually slightly more than 30 cm (12 inches) in thickness. The harvest pond occupies an area of 220 ha (550 acres) and is divided into 23 sub-sections of about equal area (figure 4). This permits harvesting sylvinite from some of the sections while precipitation continues in the others.

When a section of the pond is ready for harvesting, the remaining brine is pumped from it so that the sylvinite is left as a slushy precipitate on the bottom. The sylvinite slush is then pushed into windrows by a motor grader (figure 7) and subsequently picked up by elevating tractor scrapers. The scrapers which have a capacity of about 17.5 cu m (22-23 yards) each, (figures 8 and 9), load and haul the sylvinite to the raw stockpiles at the flotation mill. Haul distances presently range from 488 m (1,600 feet) to 3,200 m (10,496 feet) and average about 1,463 m (4,800 feet).

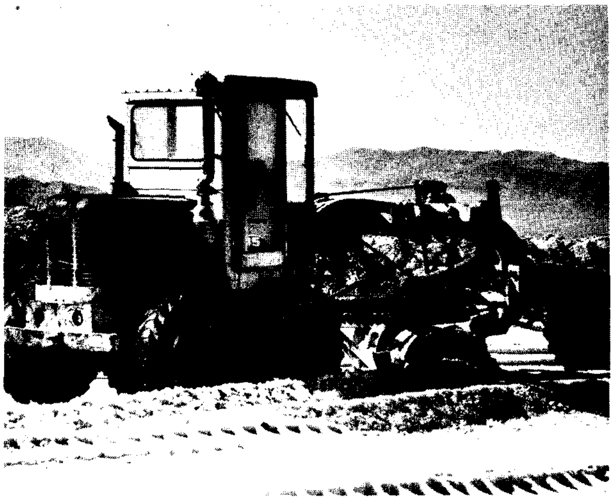

Figure 7. Motor grader pushing sylvinite into windrows as first step in the harvesting process.

Sylvinite continues to precipitate in the harvest pond until the brine reaches a specific gravity of 1.257, the concentration at which carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$) begins to precipitate. Before this can occur, the brine is transferred to the carnallite pond where evaporation continues. The typical composition of the brine entering the carnallite pond is as follows:

Table 3

Salt	Weight %
NaCl	4.0
KCl	5.0
$MgCl_2$	18.0
Other Salts	1.0
H_2O	72.0
	100.0

Flotation Mill

At the mill the sylvinite is prepared for flotation by wet grinding in ball mills to liberate the sylvite from the halite. The ground ore is screened and the undersize then goes through a two-stage froth flotation treatment which floats off the sylvite and leaves the halite as the tailing. The oversize is recycled through the mill. Fatty amines are used as collectors in the flotation cells. The flotation concentrate is washed, filtered to remove excess water and then transferred by a belt conveyor to a stockpile where further dewatering takes place by gravity drainage and exposure to the air. The halite tailing from the flotation cells is redissolved and transferred to a brine collection ditch for recirculation through the pond system. Figure 10 is an aerial photograph of the flotation plant with a large stockpile of potash concentrate.

The drained concentrate is reclaimed from the flotation stockpile and dried in an 18 x 24 m (60 x 80 feet) oil fired rotary kiln. A portion of the dried product is diverted to a compactor where it is compacted and then crushed to make a coarse granular product.

A relatively small quantity of sylvinite is sent directly to the drier. It is dried and then stockpiled separately for sale as a manure salt.

The dry products are conveyed to covered storage sheds for separate stockpiling. Reclaiming is done by belt conveyors fed through draw points in the floors of the storage sheds. Practically all of the products are bulk-shipped by rail in either hopper or boxcars.

Products and Markets

Currently the Wendover plant produces a standard grade muriate of potash, a coarse grade muriate of potash, and a manure salt. In addition, a small volume of concentrated magnesium chloride bittern is sold for use as a flame retardant and in sugar beet refining.

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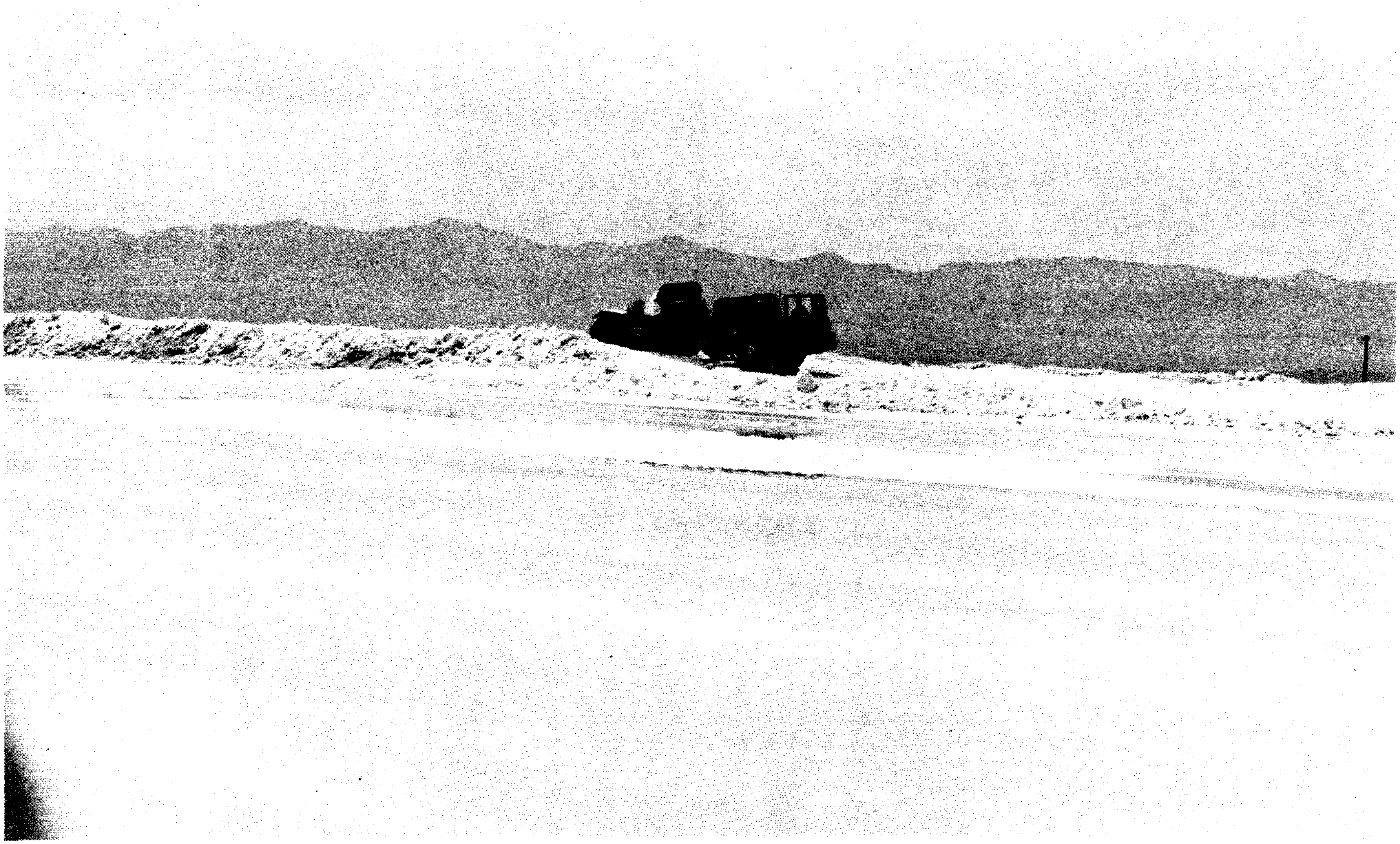

Figure 8. Self loading scraper loading sylvinite salts as second step in the harvesting process.

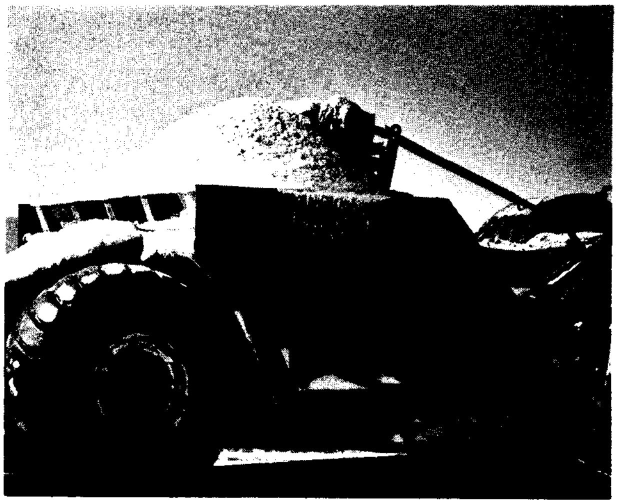

Figure 9. Close up view of a scraper loaded with sylvinite.

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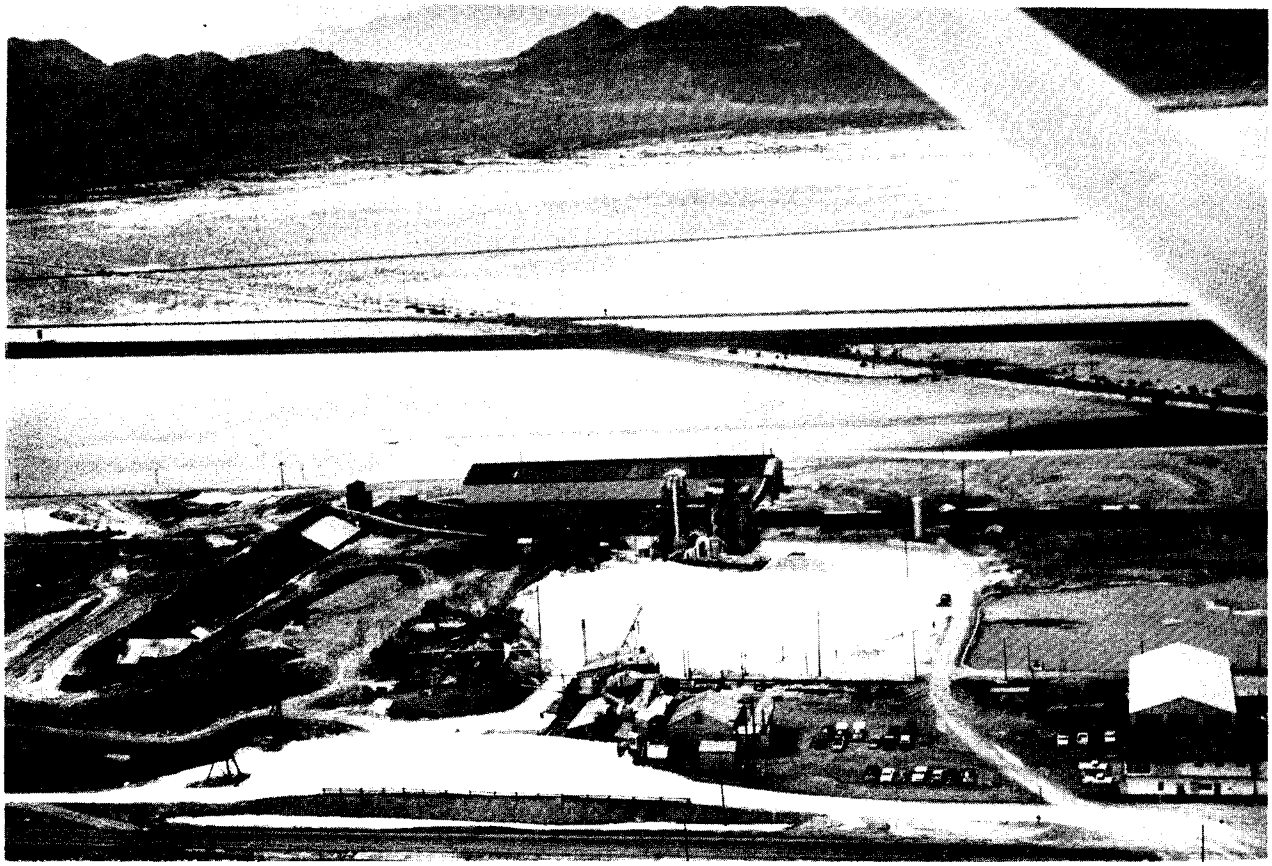

Figure 10. Aerial photograph looking northerly toward the plant buildings. Note the large stockpile of flotation concentrates.

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THE BRINE SHRIMP INDUSTRY ON THE GREAT SALT LAKE

by Paul A. Sturm, UGMS Research Geologist
in Cooperation With
Gail C. Sanders and Kenneth A. Allen
Sanders Brine Shrimp Company

HISTORY

Mr. C. C. Sanders, founder of Sanders Brine Shrimp Company, was an enthusiastic tropical fish hobbyist who managed his own tropical fish hatchery during the late 1940's. In 1949 Mr. Sanders heard of the brine shrimp contained in the Great Salt Lake and investigated their use as a better and less expensive food for his fish. He found that the Great Salt Lake brine shrimp (*Artemia salina*) was an excellent and nutritious food for tropical fish.

In 1950 C. C. Sanders sent an article to "*The Aquarium*" magazine describing this new source of fish food. Shortly after his article appeared, requests for frozen adult brine shrimp arrived from various parts of the country. The Sanders Brine Shrimp Company was formed to harvest, clean, package, and market the shrimp.

HARVESTING AND PROCESSING

Adult Brine Shrimp

Brine shrimp can be found throughout the lake during the summertime. The quantity of shrimp in the lake is primarily determined by the concentration of the brines and by the summer temperatures, which regulate the amount of algae on which the brine shrimp feed. The brine shrimp eggs begin to appear on the shorelines approximately the first part of August and continue through November.

The commercial harvesting of brine shrimp or brine shrimp eggs from the Great Salt Lake is under the jurisdiction of the Utah Division of Wildlife Resources, which is responsible for the licensing of commercial firms, for the enforcement of aquatic wildlife proclamations, and for the collection of royalty payments from commercial firms. This royalty is in the amount of four cents per pound (.45 kg) of dried shrimp and/or eggs. Individuals are permitted to collect a maximum total of ten pounds (4.5 kg) of unwashed brine shrimp and or brine shrimp eggs per week for non-commercial purposes.

In the early 1950's the level of the Great Salt Lake was at a high point and the adult shrimp were harvested along the Syracuse road, which has now been extended to Antelope Island. As the lake receded, access to the lake from this road was no longer available. Airboats were then used in the harvesting operation and were launched from the Farmington Bay Bird Refuge.

Brine shrimp were harvested from the shallow areas near the shore by using a hand net and scooping the clusters of brine shrimp into small rubber or plastic wading pools. The wading pools were taken to the main harvest boat where the shrimp were separated from sand and other debris. The shrimp were then placed on ice to preserve them until processing could begin. The processing of the adult brine shrimp entailed further cleaning to remove debris, washing to remove excess salt, packaging in plastic bags, and freezing.

The frozen brine shrimp were distributed worldwide, but in 1965 the collection of adult brine shrimp was discontinued because it became unprofitable, due in part to the many difficulties encountered in handling a frozen product and the inherent production costs and shipping limitations.

Brine shrimp eggs

In 1952 the Sanders Brine Shrimp Company started collecting brine shrimp eggs as well as the adult shrimp. The eggs were sold to tropical fish fanciers to be hatched and fed as a live food to their fish. Some eggs were hatched by the company and the brine shrimp nauplii frozen for commercial distribution, but this product was soon discontinued because of low profitability.

At that time the brine shrimp eggs were found to be more concentrated at the north end of the lake as the result of winds which blew the floating eggs in from the lake and stacked them in windrows on the shoreline, sometimes 1.5 - 2 inches (3.81 - 5.08 cm) deep. But at times rain and wind washed away the eggs, making harvesting difficult if not impossible.

In 1962, when numbers of brine shrimp and eggs at the north end of the lake declined due to increasing salinity of the north arm, the brine shrimp/egg harvesting operation was moved to the western shore of the south arm of the Great Salt Lake to the areas shown in figure 1.

Brine shrimp eggs are harvested by raking them into piles on the shore for draining and bagging, and then hauling them to the warehouse for storing and aging. Initially, rakes, shovels, and wheelbarrows were used in the harvesting operation. Improvements in harvesting techniques have been made, and at present, the Sanders Brine Shrimp Company uses two four-wheel drive vehicles towing wagons for their harvesting operation.

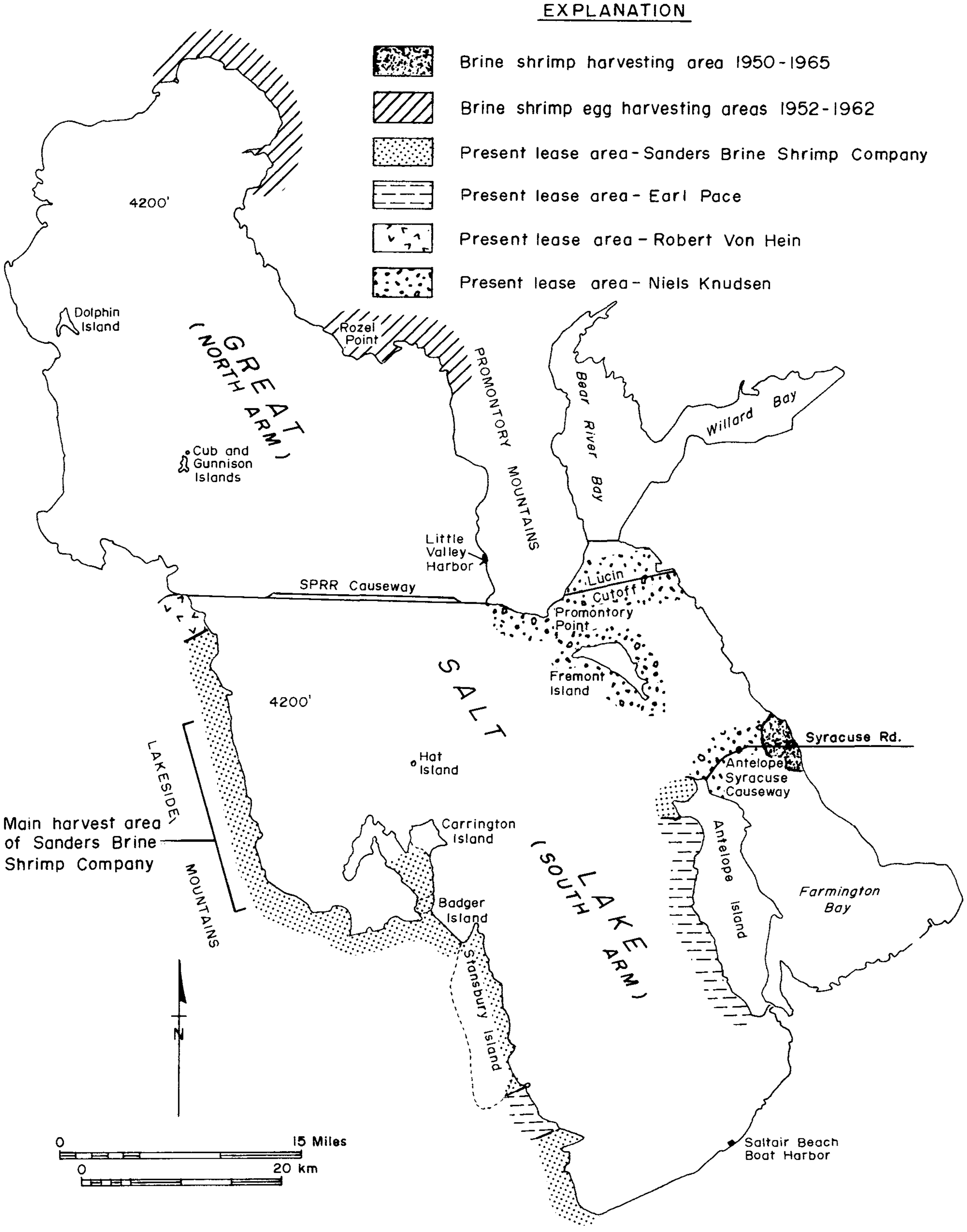

Figure 1. Brine shrimp/egg harvesting areas - past and present

To preserve the viability or hatch rate of brine shrimp eggs, the harvested eggs are aged on special racks, without washing. Water will cause the eggs to swell and crack prematurely. After proper aging, the viable brine shrimp eggs are separated from the bad eggs and debris by selective screening and flotation. The eggs are then washed several times to remove excess salts, immediately dried to less than three percent moisture, screened, and vacuum packed in metal cans. Processed eggs tend to deteriorate after a year if not vacuum packed. Brine shrimp eggs can also be preserved by freezing or by placing them in a concentrated brine solution, although neither of these processes is commercially feasible due to cost and weight factors, respectively.

Table 1 shows the harvest figures for the years 1963-1978. At the present time there are four seiners who have commercial licenses to harvest brine shrimp and their eggs. These are: Robert Von Hein, Pioneer Enterprises, California; Niels Knudsen, Brigham City, Utah; W. Earl Pace, Salt Lake City, Utah; and Gail C. Sanders, Sanders Brine Shrimp Company, Ogden, Utah. The areas in which these companies harvest eggs is shown on figure 1.

MARKETING

Brine shrimp eggs are used in the tropical fish, mariculture, and aquiculture industries. The newly hatched shrimp are fed to young fish to promote fast development and are an excellent food source for tropical fish. At the present time, the Sanders Brine Shrimp Company distributes their brine shrimp egg product nationwide and is investigating the potential for foreign export.

HATCHING

Brine shrimp eggs are hatched in a solution of approximately six tablespoons (125 g) of salt (NaCl) to a gallon (4 liters) of water. The solution temperature is maintained at about 80° F (24.3°C), at which temperature the eggs will hatch in approximately thirty-six hours. The solution should be aerated to keep the eggs in suspension.

THE BRINE SHRIMP INDUSTRY IN UTAH

Utah's brine shrimp industry has been confronted with the changes that man and nature have created in the lake. Since the construction of the Southern Pacific causeway, the increased concentration of the brines at the north end of the lake has produced a poor environment for the brine shrimp. At the same time the brine in the south end of the lake has remained more dilute, resulting in premature cracking of the brine shrimp eggs. In 1966, when the density of the brine in the south arm was 1.175 g/cc, the viability rate of eggs harvested was 90%, in 1975, when the south arm density; was 1.087 g/cc, the viability rate was only 5% and the eggs were not marketable. The above normal precipitation of that year and resulting rise of the lake level nearly spelled disaster for the brine shrimp industry. Only a small quantity of marketable eggs was harvested in 1977. Microscopic examination indicates that the eggs harvested in 1978 appear to be of slightly better quality than those of the 1977 harvest, but their actual quality cannot be determined until after proper aging.

The future of Utah's brine shrimp industry will be determined by the concentration of brine in the Great Salt Lake. If the lake level lowers, thus raising the brine concentration, the brine shrimp industry will improve and expand. If the level rises, thus lowering the brine concentration, the industry could falter and die.

Table 1. Great Salt Lake reported shrimp and shrimp eggs harvest and royalty payments 1963 - 1978

Year	Pounds of Shrimp/Eggs	Royalty
1963	4,148	$ 165.92
1964	93,136	3,725.00
1965	170,150	6,806.00
1966	167,075	6,683.00
1967	90,660	3,626.00
1968	265	11.00
1969	49,600	1,980.00
1970	148,543	5,942.00
1971	135,165	5,407.00
1972	144,200	5,553.00
1973	880	35.00
1974 - 1976	144,261	5,556.00
1976 - 1978	30,529	1,237.00

Source: Utah Division of Wildlife Resources

Photo 1. Brine shrimp eggs are carefully raked from the shoreline to prevent contamination with debris.

Photo 2. The eggs are piled away from the shore to facilitate their bagging prior to transport.

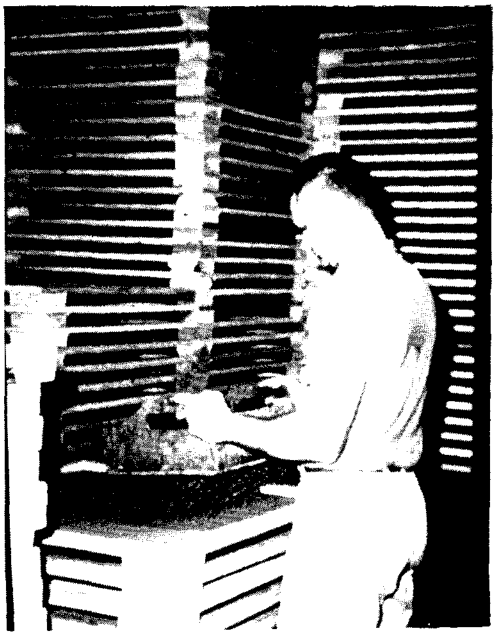

Photo 5. After proper aging, the eggs are cleaned by screening followed by flotation to separate good and bad eggs.

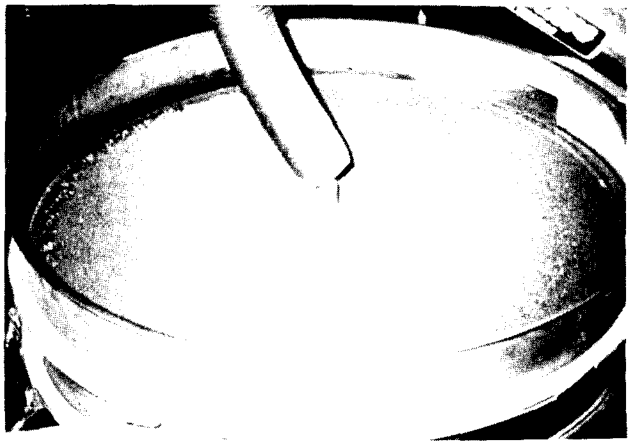

Photo 6. The cleaned eggs are dried to less than 3% moisture and given a final screening.

• • • • • • Harvesting Through Processing

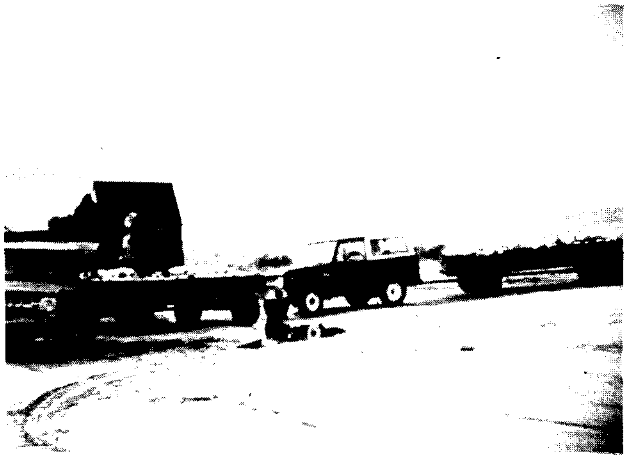

Photo 3. Eggs are hauled by wagon to a central location for trucking to the processing plant.

Photo 4. Bagged eggs are aged in a warehouse for a year prior to processing.

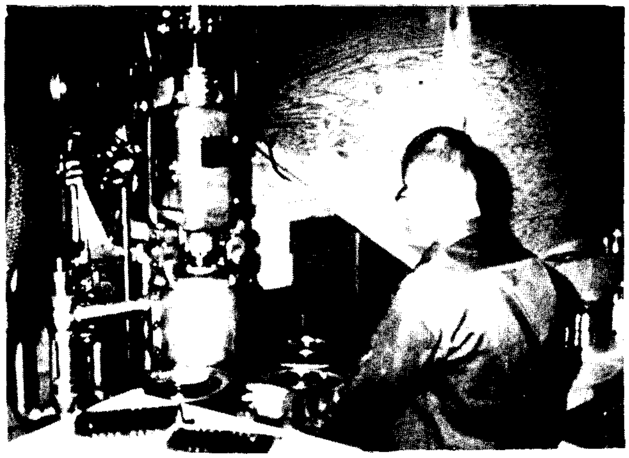

Photo 7. The dried eggs are vacuum packed to preserve their viability.

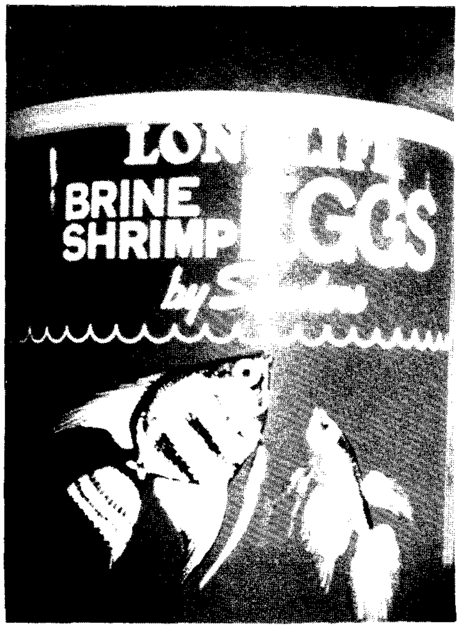

Photo 8. The final product is packaged, labeled, and made ready for shipment.

The Life Cycle Of The Great Salt Lake Brine Shrimp

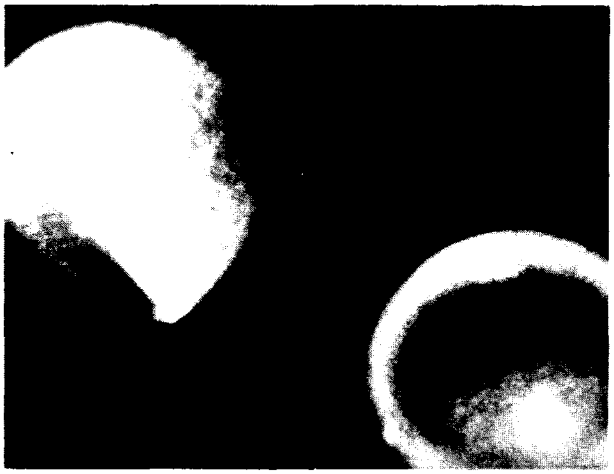

Photo 1. Microscopic closeup of dried brine shrimp eggs – note the bowl shape.

Photo 2. Eggs in hatching solution swell to a spheroid shape, and begin hatching within 36 hours - see bottom of photo.

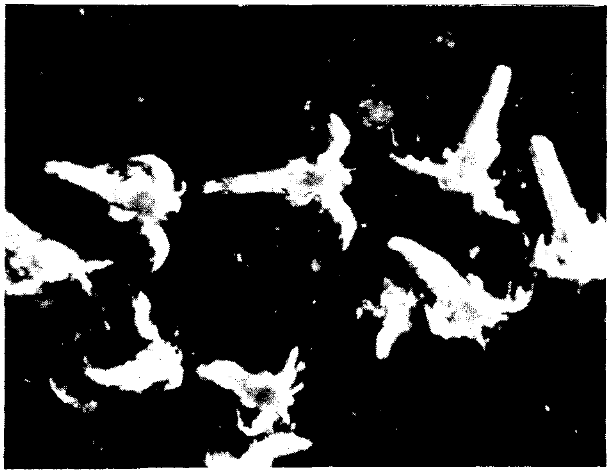

Photo 3. Newly hatched brine shrimp (nauplii), grow one set of flippers after each succeeding skin shedding.

Photo 4. Adult brine shrimp: Female (L) and male (R) – note the egg sac on the female brine shrimp.

THE HILL/WENDOVER/DUGWAY RANGE COMPLEX

by J. Wallace Gwynn
in cooperation with the
HAFB Range Management Office

West of the Great Salt Lake in Box Elder, Tooele, and Juab Counties lies the expansive Great Salt Lake Desert (figure 1). This area is a remnant of the floor of the ancient, fresh-water Lake Bonneville, an inland sea that covered much of western Utah, eastern Nevada, and a portion of southern Idaho perhaps some 10,000 years ago. Bench terraces formed by this lake at various levels can be seen on the mountains around the present Great Salt Lake and on the islands within it. In describing the Great Salt Lake Desert, Stokes (1977, p. 17) has given the following description of the area, as a subdivision of the Basin and Range physiographic province:

> "The Great Salt Lake Desert...can be outlined along fairly distinct topographic boundaries. Practically all of the Great Salt Lake Desert section is an extensive flat area floored by crystalline salt, wet mud, and silt. A number of desert ranges that are more or less surrounded by the flats are in this section. These include Pilot Range, of which only the foothills are in Utah, the Newfoundland Range, the Desert Range with a semidetached outlier called Crater Mountain, the Wildcat Hills, and the Granite Range (see Stokes, this volume). A few unnamed bedrock ridges that rise above the general level are obviously the summits of buried ridges. Beneath the barren featureless flats, the structure and stratigraphy must be complex."

One's first impression of the desert as one drives along the long, straight freeway from Knolls to Wendover is that of quiet and lifeless surroundings, interrupted occasionally by a passing vehicle or train. Towards the western edge of the desert, approximately eight miles east of Wendover, is a rest stop that overlooks the famed Bonneville Salt Flats. It was here that the world land speed record of 622.507 mph was set in October of 1970 by Gary Gabelich, in his jet-powered racer, the Blue Flame. About two miles east of Wendover are the Utah Salt Plant, which produces sodium chloride, and Kaiser Chemicals' potash plant and solar ponding complex where potassium chloride salts are produced from subsurface brines.

However, the greater part of activity on the desert takes place at a distance both to the north and south of the freeway on the combined Hill/Wendover/Dugway range complex. This complex is composed of two separate Air Force ranges and the Army-owned and managed Dugway Proving Ground, used by the Air Force on a share-use basis by mutual agreement (figure 2). These three areas are shown on figure 1. The combined test ranges cover about 2,650 square miles of unproductive land which are nontraversable and "off limits" to the general public. It is one of the largest land-mass areas held by the Department of Defense (DOD) in the United States. In addition to the land included under the jurisdiction of the range, there are approximately 5,600 square miles of special use air space operated under a joint-use agreement with the Federal Aviation Administration to allow for multiple usage. Most of the land area surrounding the complex is owned by the Bureau of Land Management and is very sparsely populated.

The range complex supports a variety of testing programs; and it is also used by various tactical Air Force groups for combat mission training. All areas within the complex have been designed for a specific use or uses.

Hill Air Force Range: This range was initially established in support of Air Force Logistics Command (AFLC) and has been used extensively in Department of Defense (DOD) munition testing programs. The range area was withdrawn from the public domain in 1941 for these purposes. Munitions testing within the range is conducted in three general areas. Area (1) (figure 1) is used for low and high altitude bombing, air-to-surface gunnery and rocketry, radar bomb scoring, ground testing of high explosives, explosive ordnance disposal and service engineering testing. Area (2) is used for static testing of rocket motors, high explosives testing, systems propulsion evaluation and air-to-surface testing of inert munitions. Area (3) is used for air-to-surface tactical training and specialized testing. Tactical targets including armored vehicles are located throughout the area in fields, canyons and on roads adjacent to the west shoreline of the Great Salt Lake.

Also, service engineering test flights are performed to test aircraft and ordnance modifications. Such modifi-

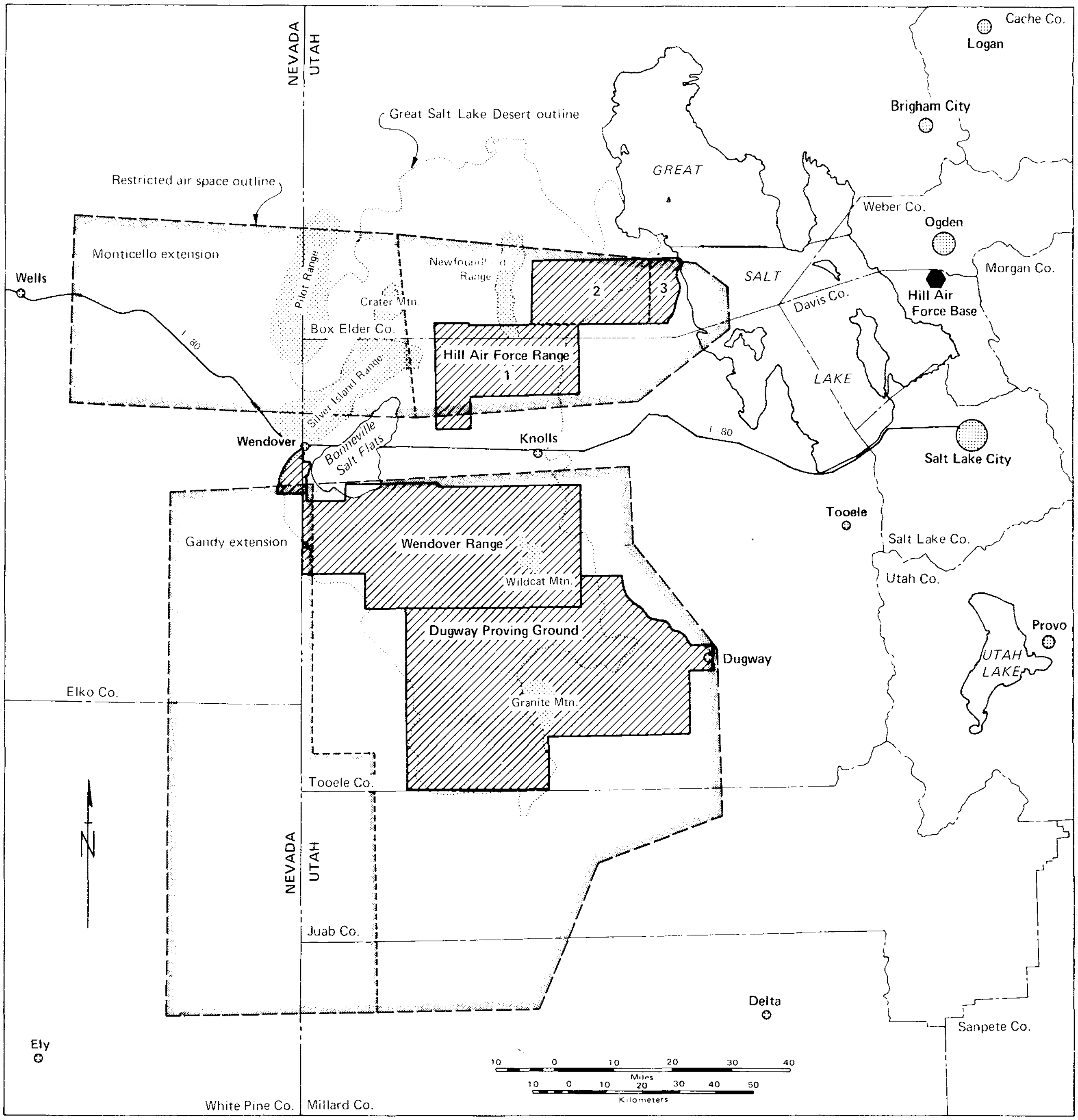

Figure 1. Location map for the Hill/Wendover/Dugway Range complex.

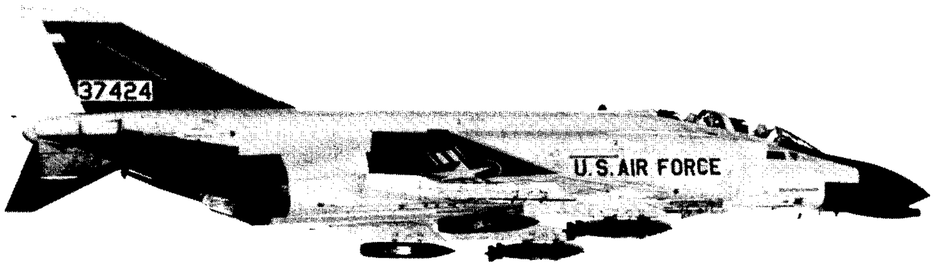

Figure 2. Fighter aircraft over Hill Air Force Range. USAF photo.

cations generally result in weapon system improvements. In 1963 the Hill Air Force Range was configured to support a Minuteman solid rocket motor test, evaluation and storage program.

Wendover Air Force Range: Soon after World War II began, Wendover Army Air Base was constructed and activated for research and development on guided missiles and similar weapons. The Wendover area became one of the first Army/Air Force rocket test and evaluation facilities. Heavy bombardment groups trained here for combat duty in the European and Pacific theaters. In December 1944, Col. Paul Tibbets and the crew of the B-24 aircraft called the "Enola Gay", began their training as the first organization equipped for atomic warfare. This group dropped the first atomic bombs on Hiroshima and Nagasaki, Japan, in August 1945.

Today, this area is used primarily for air-to-air rocketry and air-to-surface gunnery, rocketry, missile firing and bombing (figures 3 and 4). A tactical range for air-to-surface inert bombing and strafing missions is located in the vicinity of Wildcat Mountain.

Dugway Proving Grounds: This area was originally selected for testing and evaluation of chemical weapon systems primarily because of its seclusion and sparsity of wildlife. A need for such a facility was recognized by the Chemcial Warfare Service after Pearl Harbor. On February 6, 1942 Dugway Proving Ground was established. Testing of military weapons commenced shortly thereafter. Limited biological testing began in 1945. From 1947 to 1951 the area was inactive, but in 1951 the area again became active in an intensive testing and evaluation program. The mission of the Dugway Proving Ground includes three aspects: (1) testing and evaluation programs to assess the military value of, among other things, chemical warfare and biological defense systems, (2) research and development programs and, (3) installation management and operations. Dugway suspended open air biological testing about 1968.

Since that time the Army's requirement for controlled air and ground space has been significantly reduced. The Air Force requirement for a flight test range, however, is increasing and, accordingly, it is now the principal user of the Dugway area.

The Hill/Wendover/Dugway range is used regularly by a number of other organizations located at Hill Air Force Base. Among these are (1) 6514th Test Squadron (Remotely Piloted Vehicle (RPV) Testing); (2) Detachment 508, 301st Tactical Fighter Wing, (F-105 Fighter/Bomber Training and Tactical Operations); and (3) 388th Tactical Fighter Wing, (F-4 and F-16 Fighter Training and Tactical Operations). Off-base users include: (1) Tactical Air Command (TAC) aircraft from surrounding Air Force bases conducting proficiency training; (2) Strategic Air Command (SAC) bomber aircraft combining training and testing requirements during conventional munition deliveries; (3) Pacific Missile Test Center (PMTC), U.S. Navy, DT&E of Tomahawk Cruise

Figure 3. Munitions disposal on the north range. USAF photo.

Figure 4. Target 13, used for live munitions with impact-type fuzing only. Hill A. F. Range. USAF photo.

Missile; (4) U.S. Army ordnance testing to include containerization and stowage test program; (5) 396th Aviation Company (Attack Helicopter), Utah Army National Guard, aerial gunnery training; and (6) Idaho Air National Guard, air-to-surface and air-to-air gunnery training.

Besides air and ground space, the Hill/Wendover/Dugway range complex provides to users of the range instrumentation and equipment, communication networks (microwave, telephone, radio and television), static test facilities, data acquisition and processing, personnel support structures, and the combined resources of Hill Air Force Base.

The test range represents a significant investment by the Air Force within the Beehive State. Over $62 million in range instrumentation and facilities have been installed to date. Several organizations of Hill Air Force Base which include Range Management, Operations and Maintenance, Civil Engineering and Security Police, provide support to the range. Hill Air Force Base is Utah's largest single employer.

The term "remotely nearby" has been used to describe the geographical setting of the range complex. It is sufficiently close or "nearby" to sources of manpower, materials, transportation and other resources to be supported in its activities, yet it is located a sufficient distance or is sufficiently "remote" from population centers (being separated from them by the Great Salt Lake and the desert itself) to permit daily use of the area for hazardous activities.

The Hill/Wendover/Dugway range complex is an all important link in the military strength of the United States and has been identified as a "Major Range and Test Facility Base" by the DOD. As such, the DOD soon will name the Air Force Systems Command as the executive agent to manage it.

As weapon systems of the future become more complex and sophisticated, they will in turn require larger footprints (ground and air space) for their subsequent testing, training and evaluation requirements. The unique capabilities of this range complex are expected to play an increasingly vital role in the future.

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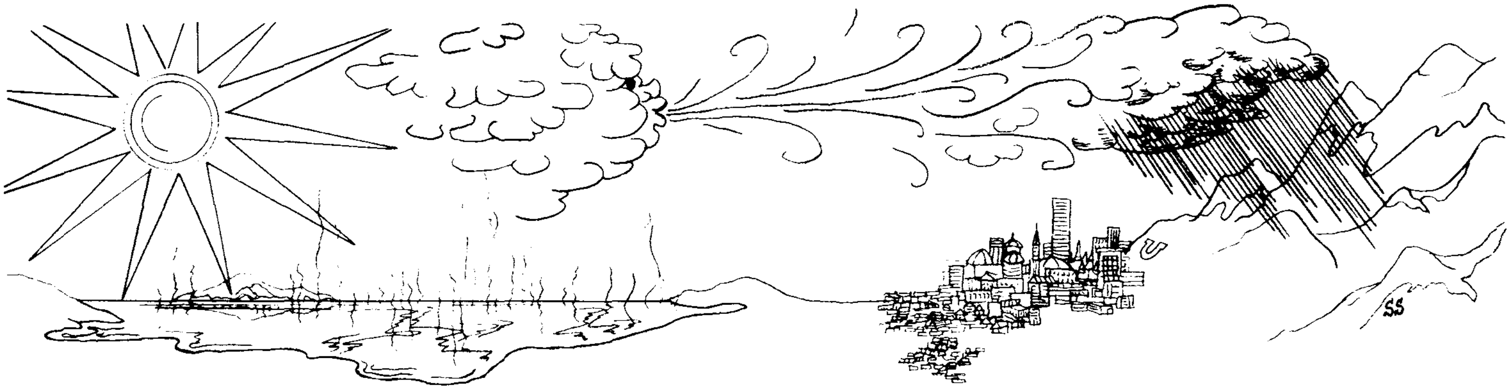
Stokes, W. L., Subdivisions of the major physiographic provinces in Utah, *in* Utah Geology, Utah Geological and Mineral Survey, v. 4, no. 1, 1977, p. 1 to 17.

HYDROLOGY
AND CLIMATOLOGY



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V. HYDROLOGY AND CLIMATOLOGY

WATER BUDGET AND WATER-SURFACE FLUCTUATIONS OF GREAT SALT LAKE

by Ted Arnow

U.S. Geological Survey, Salt Lake City, Utah

ABSTRACT

The water-budget equation for Great Salt Lake is:

Inflow (surface water, ground water, precipitation)=
Outflow (evaporation) ± Storage change.

The average annual inflow for the period 1931-76 was about 2.9 million acre-feet: 1.9 million acre-feet from surface sources, about 900,000 acre-feet from direct precipitation, and about 75,000 acre-feet from ground water. The average annual outflow for the same period, all by evaporation, also was about 2.9 million acre-feet.

Storage changes are computed on the basis of changes in the surface level of the lake. During the period of historic record, 1847-1978, the lake surface has fluctuated within a range of about 20 feet but has shown little overall change. The lake surface would have been about 5 feet higher in 1978 than it was in 1847 had there been no consumptive use of water caused by man's activities in the lake basin.

Since 1959 the lake has been divided into two parts by a railroad causeway which has restricted the natural circulation. This has resulted in a difference of salinity and of surface level across the causeway. The difference in surface level between the two parts of the lake varies both seasonally and annually and has been as much as 2.35 feet.

INTRODUCTION

The surface level of Great Salt Lake fluctuates continuously, primarily in response to climatic factors. The level reflects an equilibrium between the inflow to the lake from surface and ground water and precipitation directly on the lake, and the outflow from the lake by evaporation. Man's activities have had a lesser effect on the lake level.

During dry years the surface level drops, causing a decrease in surface area, and consequently the volume of evaporation decreases. But less inflow is required to raise the lake level a given increment. In contrast, during wet years the surface level rises, causing an increase of surface area, and consequently the volume of evaporation increases. More inflow is required to raise the lake level a given increment. For example, at the historic low level of 4,191.35 ft, a net increase in inflow of about 600,000 acre-feet was necessary to raise the lake 1 ft; whereas at the historic high level of 4,211.5 ft, a net increase in inflow of about 1.5 million acre-feet would have been necessary to raise the lake level 1 ft. (See figure 1).

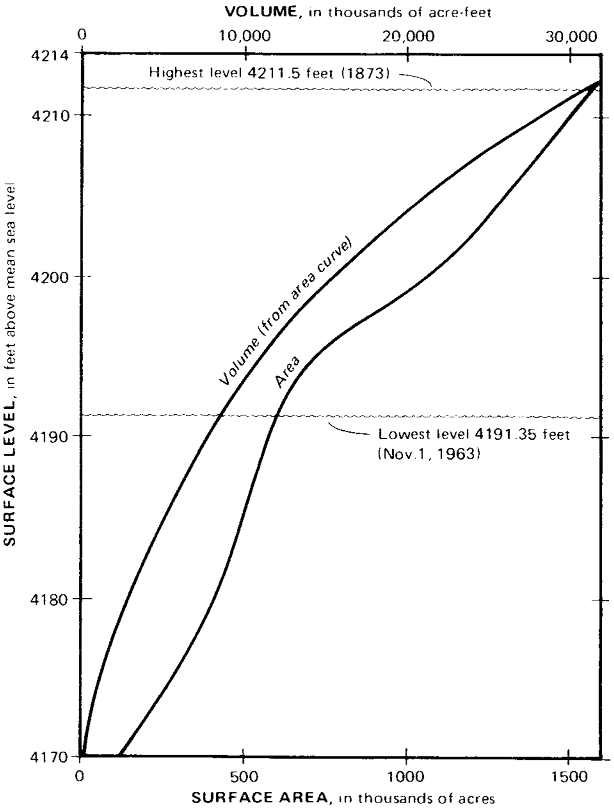


Figure 1. Relations between the level, area, and volume of Great Salt Lake prior to 1957. (Adapted from Hahl and Handy, 1969, p. 10).

WATER BUDGET

The water-budget equation for a selected time increment for Great Salt Lake can be written as follows:

Inflow = Outflow ± Storage change

The inflow comes from surface water that flows into the lake, from precipitation that falls directly on the lake surface, and from ground water that moves upward through the bottom of the lake. The outflow is entirely by evaporation. The storage change is the change in the volume of the lake during the selected time increment.

Values for the elements of the water-budget equation are discussed in the following pages for the 46-year period from 1931-76. Most of the discussion is based on the results of computer-model studies of Great Salt Lake made by Waddell and Fields (1977) and Waddell and Barton (1978).

Inflow

Surface water constitutes about 66 percent of the average annual inflow to Great Salt Lake, precipitation about 31 percent, and ground water about 3 percent. Figure 2 shows the distribution of inflow by source. The total annual inflow during 1931-76 ranged from about 1.3 (1961) to 5.0 (1971) million acre-feet and averaged about 2.9 million acre-feet.

Surface water

Approximately 92 percent of the average annual surface inflow to Great Salt Lake is from the Bear (59 percent), Weber (20 percent), and Jordan (13 percent) River drainage systems. The U.S. Geological Survey has operated gaging stations on the main stems of these streams upstream from the lake for many years. During 1971-76 records were obtained at numerous gaging stations near the lakeshore in the three drainage basins. Surface inflow to the lake during 1931-76 was estimated by correlation of the short-term records obtained near the lakeshore with the long-term records obtained farther upstream. The locations of all gaging stations are shown in figure 3, and the period of record at each site is shown in table 1.

An additional 5 percent of the surface inflow to the lake is from ten tributaries on the east and south shores. Measurements made in these tributaries during varying periods from 1950-76 were used as a basis for estimating the inflow during 1931-76. These sites are also shown in figure 3 and are listed in table 1. Surface inflow from the remainder of the lakeshore is negligible.

Approximately 3 percent of the surface inflow to Great Salt Lake is from five sewage plants. These all discharge their effluent directly into Farmington Bay, east of Antelope Island.

The total annual surface inflow during 1931-76 ranged from about 700,000 (1934) to 3.8 million (1971) acre-feet and averaged about 1.9 million acre-feet.

Precipitation

Inflow to Great Salt Lake from precipitation directly on the lake surface was calculated by using the average annual precipitation during 1931-76 for 68 sites in a large area surrounding the lake. A multiple-regression equation was derived to describe the average annual precipitation as a function of altitude, latitude, and longitude. The equation was used as a means of drawing lines of equal average annual precipitation for the lake area. Then the annual precipitation directly on the lake was computed for the period 1931-76 on the basis of monthly lake-surface altitudes and areas during that period.

The estimated annual precipitation on the lake during 1931-76 ranged from about 500,000 (1966) to 1.5 million (1941) acre-feet and averaged about 900,000 acre-feet.

Precipitation that falls on the lakeshore runs into the lake and must be considered as part of the inflow. The amount is relatively small, however, and in figure 2 it is included in "inflow calibration", which is the factor used by Waddell and Barton (1978) to balance their water budget for the lake.

Ground water

The ground-water inflow to Great Salt Lake was estimated by adding inflow values for 13 segments of the lakeshore.

The values in acre-feet per year are: 0 for Curlew, Sink, and Skull Valleys, the lower Bear River basin, and the northern Great Salt Lake Desert (west of Great Salt Lake); 1,000 for Hansel Valley; 3,000 for Antelope Island and Park Valley (northwest of Great Salt Lake); 4,000 for Jordan Valley (Salt Lake County); 7,000 for Tooele Valley; 9,000 for the Promontory Mountains; and 48,000 for the area east of Great Salt Lake (see Arnow and Stephens, 1974).

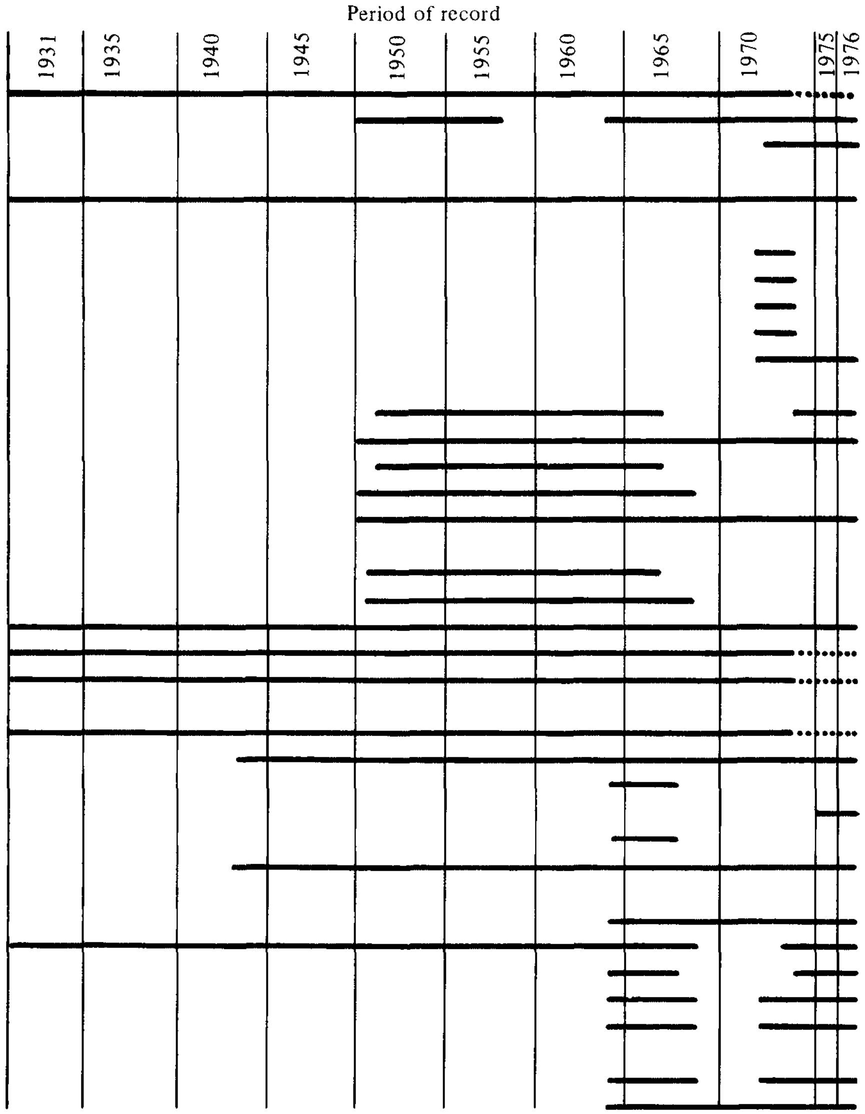
The total ground-water inflow to the lake thus is estimated to be about 75,000 acre-feet per year. This is assumed to be an average annual inflow value for the period 1931-76.

Outflow

Outflow from Great Salt Lake by evaporation from the lake surface was calculated primarily on the basis of pan-evaporation data from 49 sites in Utah and

Table 1. Bar chart of gaging-station records, 1931-76 (From Waddell and Barton, 1978, table 2).

Station No	Name
10118000	Bear River near Collinston
10126000	Bear River near Corinne
10127110	Bear River basin outflow across State Highway 83 near Corinne
10141000	Weber River near Plain City
10141050	South Fork Weber Canal near Hooper
10141100	South Fork Weber River near Hooper
10141150	Middle Fork Weber River near Hooper
10141200	North Fork Weber River near Hooper
10141400	Howard Slough at Hooper
10141500	Holmes Creek near Kaysville
10142000	Farmington Creek above diversions, near Farmington
10142500	Ricks Creek above diversions, near Centerville
10143000	Parrish Creek above diversions, near Centerville
10143500	Centerville Creek above diversions, near Centerville
10144000	Stone Creek above diversions, near Bountiful
10145000	Mill Creek at Mueller Park, near Bountiful
10167000	Jordan River at narrows, near Lehi
10167500	Little Cottonwood Creek near Salt Lake City
10168500	Big Cottonwood Creek near Salt Lake City
10170000	Mill Creek near Salt Lake City
10170500	Surplus Canal at Salt Lake City
10170700	North Point Consolidated Canal below Goss flume, at Salt Lake City
10170750	Surplus Canal at North Temple Street, near Salt Lake City
10170800	Surplus Canal at Cohen flume, near Salt Lake City
10171000	Jordan River at Salt Lake City
10171600	Parley Creek at Suicide Rock, near Salt Lake City
10172500	City Creek near Salt Lake City
10172600	Jordan River below Cudahy Lane, near Salt Lake City
10172630	Goggin Drain near Magna
10172640	Lee Creek near Magna
10172650	Kennecott Drain near Magna
	Salt Lake City sewage canal



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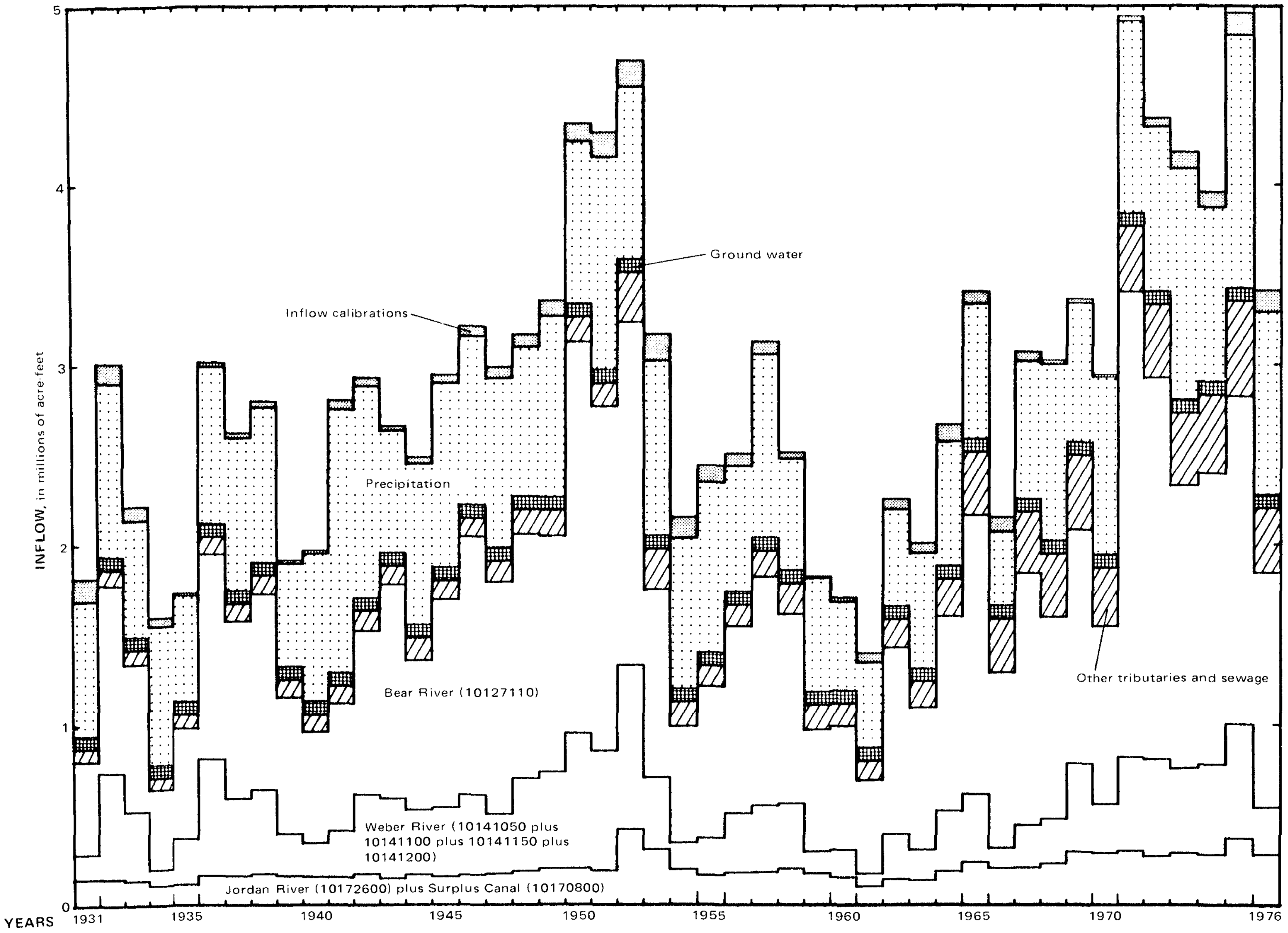


Figure 2. Annual inflow to Great Salt Lake from all sources, 1931-76. (From Waddell and Barton, 1978, figure 7). Numbers in parentheses are gaging-station numbers listed in table 1.

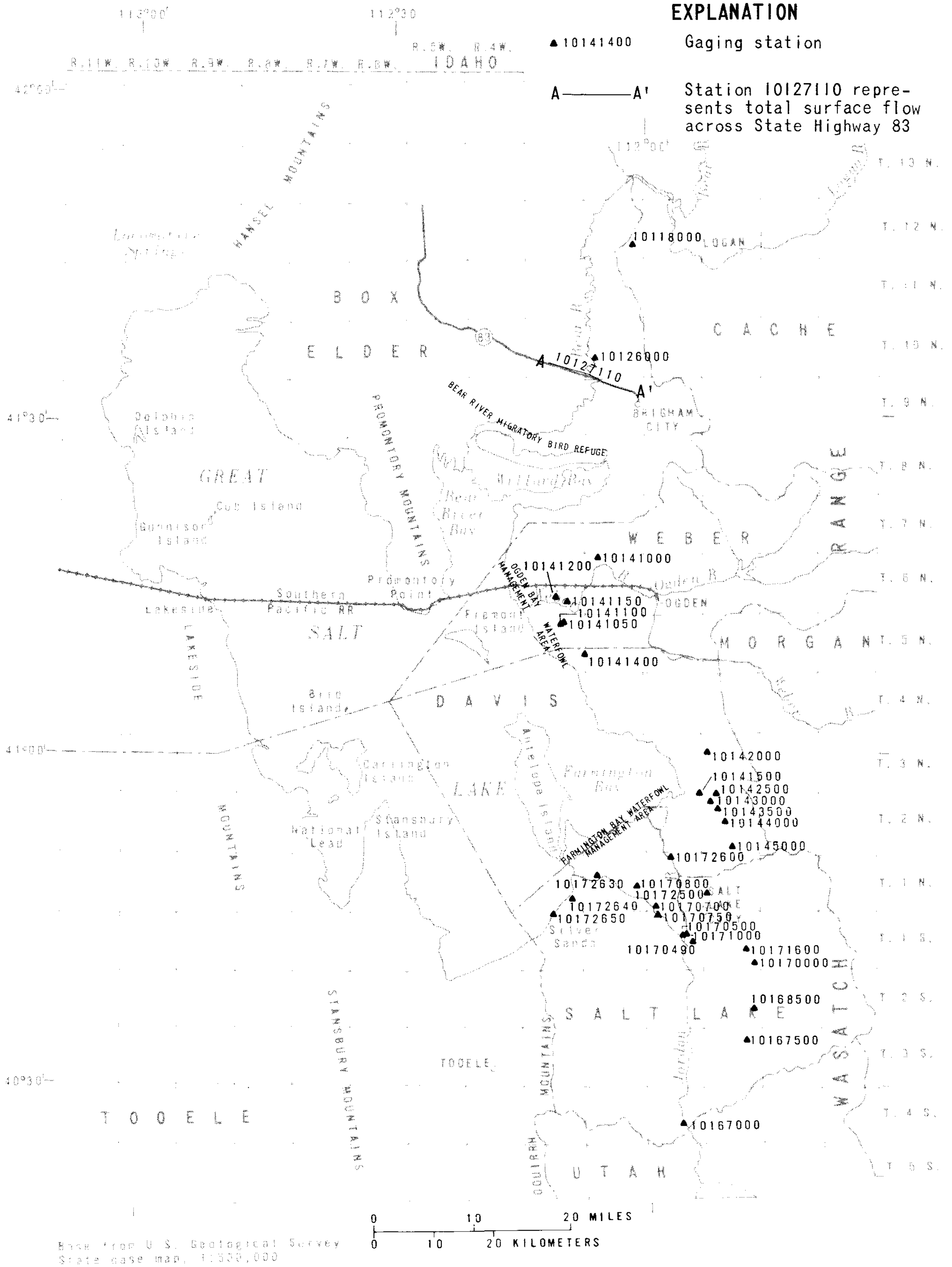


Figure 3. Map showing location of gaging stations used for estimating surface inflow to Great Salt Lake. (Modified from Waddell and Barton, 1978, figure 3).

bordering states. Short-term records were extended to the full period 1931-76 by correlation with a site near Lehi (about 30 miles southeast of Great Salt Lake), and seasonal records were extended to the entire year by use of ratios developed for a few sites where complete annual records were available. Pan coefficients were applied, and a multiple-regression equation based on latitude, longitude, and altitude was used to draw lines of annual freshwater evaporation for the lake. The fresh water evaporation was then corrected for the effect of salinity by applying the appropriate factors for each part of the lake.

The estimated annual evaporation from the lake for the period 1931-76 ranged from about 2.1 to 3.9 million acre-feet and averaged 2.9 million acre-feet. The latter is equivalent to about 45 inch per year for the average lake level during 1931-76.

A small amount of water has been withdrawn from Great Salt Lake during the entire period 1931-76 and evaporated for salt production, but in recent years the amount has increased because of withdrawals for production of other minerals. The total withdrawal for mineral production in 1976 was about 71,000 acre-feet.

Storage changes

The final element in the water budget (storage change) is the change in the volume of the lake. Changes in volume are computed on the basis of changes in the surface level of the lake, and figure 1 illustrates the relation between volume and surface level.

A discussion of the record of water-surface fluctuations and the effects of man's activities on the level of the lake is given in the following sections, which are taken largely from a report by Arnow and Jensen (1977).

WATER-SURFACE FLUCTUATIONS

Source of record

The historic record of lake-level fluctuations begins in 1847. The level was determined indirectly by Gilbert (1890, p. 240-241) for the period of 1847-75 on the basis of reported observations of the depth of water over the sandbars between the mainland and Antelope and Stansbury Islands. This information was relayed to Gilbert by stockmen who rode horses across the bars to reach the islands. Gilbert related these oral reports to later measurements by determining the altitudes of the Antelope and Stansbury Island bars, making soundings on the Antelope Island bar, and relating the water level there to gage readings near Black Rock and Farmington.

From 1875 to 1938 the lake level was measured periodically by staff gages at six different sites. The level has been measured continuously at the Salt Lake County boat harbor since 1939 (figure 4), at Saline since 1966, and at Promontory Point since 1968. The gaging sites and the chronology of the record are shown in figure 5.

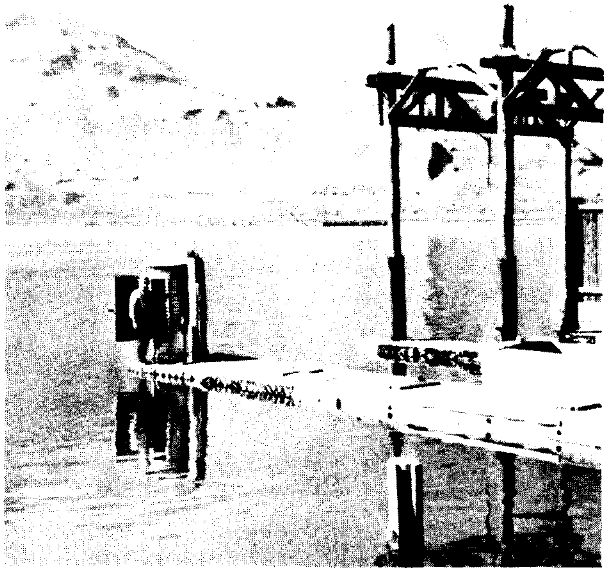
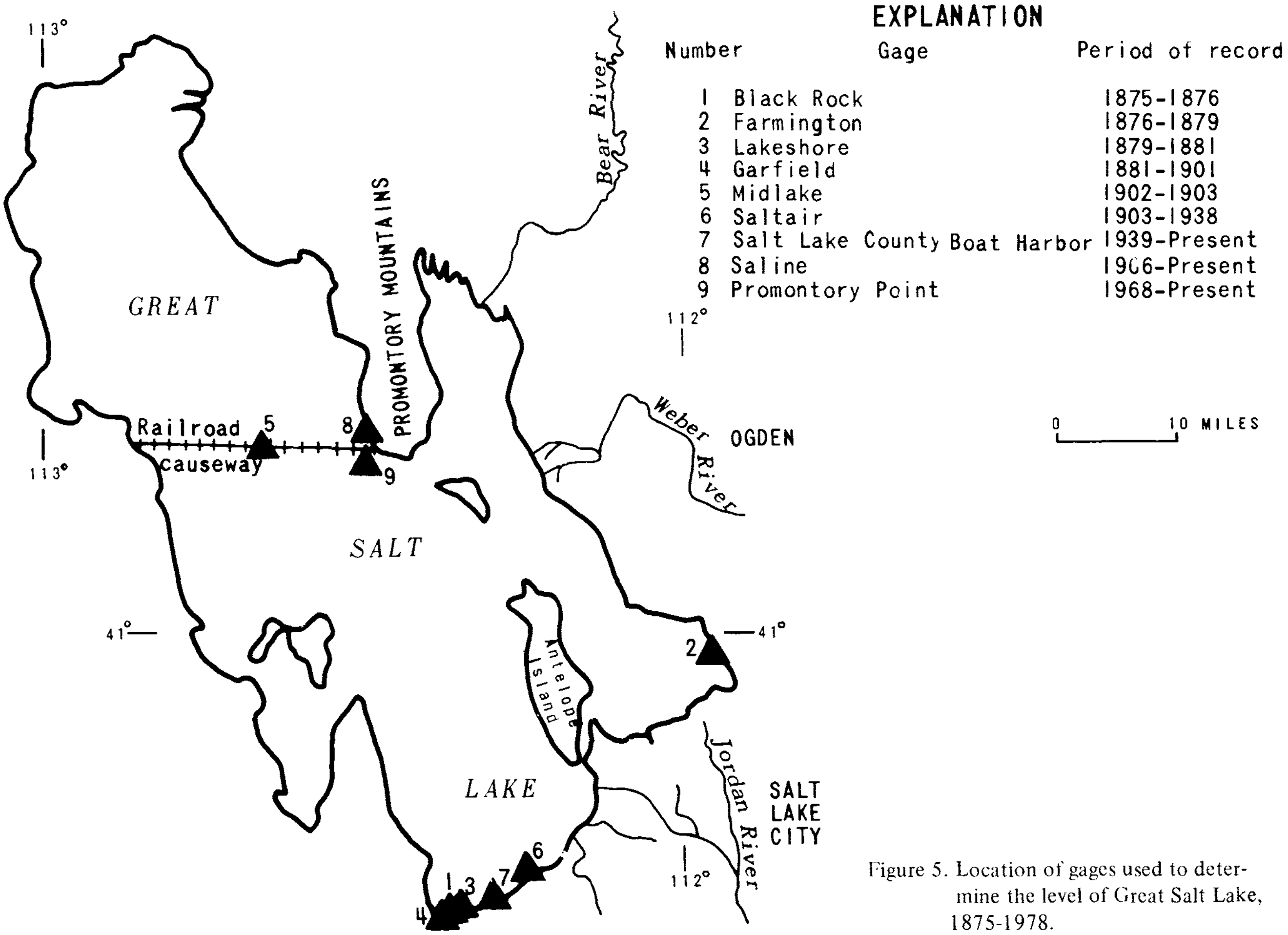


Figure 4. Photograph of continuous lake-level recording gage at Salt Lake County Boat Harbor, 1972. (Photograph by Verda Jensen).

Historic record

When the Mormon pioneers arrived in Utah in 1847, the surface of Great Salt Lake was at about 4,200 feet above mean sea level (figure 6). It rose almost 5 feet by 1855 but then declined again to 4,200 feet by 1860. From 1862 until 1873 the lake level rose almost 12 feet to reach a historic high of about 4,211.5 feet. The rapid rise of the lake from 1862-73 was of considerable concern to the Mormon settlers. If the lake continued to rise, they feared that Salt Lake City and adjacent farmlands would be flooded. In the hope of being able to avert such a calamity, they sent out an exploration party to determine if the water could be spilled from the lake into the vast desert area to the west. But the lake peaked in 1873, ending the problem for the time being.



EXPLANATION

Number	Gage	Period of record
1	Black Rock	1875-1876
2	Farmington	1876-1879
3	Lakeshore	1879-1881
4	Garfield	1881-1901
5	Midlake	1902-1903
6	Saltair	1903-1938
7	Salt Lake County Boat Harbor	1939-Present
8	Saline	1966-Present
9	Promontory Point	1968-Present

Figure 5. Location of gages used to determine the level of Great Salt Lake, 1875-1978.

During the next 31 years the lake level declined almost 16 feet and by 1905 it was at a then historic low of slightly less than 4,196 feet. A series of fluctuations followed, each time the lake declining to a lower level, and by 1963 it had dropped to an alltime historic low of 4,191.35 feet. The fluctuations of the lake surface generally reflected fluctuations of precipitation as represented by the record for Salt Lake City (figure 7) where systematic recordkeeping of precipitation was started during 1874.

Many people thought that the lake was going dry. Roads, railroads, wildfowl-management areas, and industrial installations encroached on the relicted shores. But then the lake began to rise again in response to above-average precipitation, and by 1976 it had risen almost 11 feet to slightly above 4,202 feet. Again fears of a calamity arose, and studies were made of the feasibility of pumping water out of the lake into the desert to the west. But the lake began to decline in 1977 in response to unusually low snowfall during the preceding winter, again ending the problem for the time being.

In the summer of 1978, the lake surface was at about 4,200 feet, the same level that it was 131 years prior when the pioneers arrived. Thus, the lake surface has fluctuated within a range of about 20 feet but has shown little overall change.

Effect of man's activities

Consumptive use

The lake surface would have been about 5 feet higher in 1978 than it was in 1847 had there been no consumptive use of water caused by man's activities in the lake basin. Figure 8 shows the effect of such consumptive use on the level of the lake for the period 1850-1965. The difference between the observed level and the level adjusted for consumptive use reached a maximum of about 5 feet around 1925 and has remained relatively constant since then. Thus, the lake surface is about 5 feet lower than it would have been if man had not caused evapotranspiration of water by impounding it in reservoirs and marshes upstream from the lake and diverting it for irrigation and other uses.

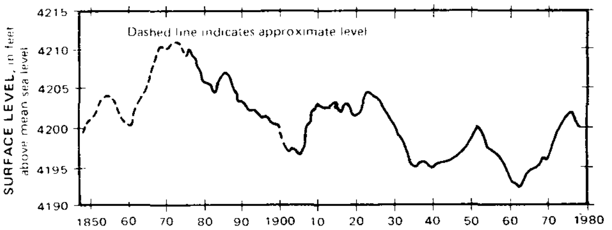


Figure 6. Fluctuations of the surface level of Great Salt Lake, 1847-1978.

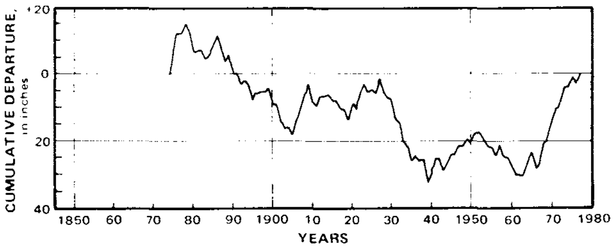


Figure 7. Cumulative departure from average annual precipitation at Salt Lake City, 1875-1977. (Data from E. A. Richardson, Utah State Climatologist).

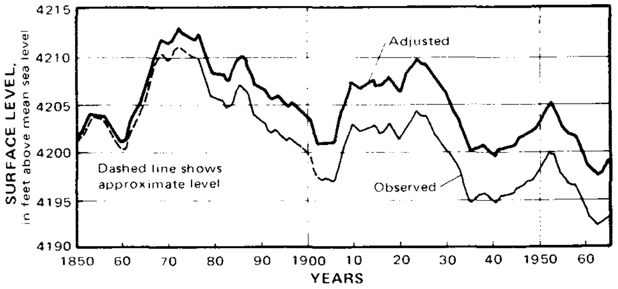


Figure 8. Effects of consumptive use of water resulting from man's activities on recorded levels of Great Salt Lake, 1850-1965. (From Whitaker, 1971, figure 3).

Railroad causeway

The Southern Pacific Transportation Company built a railroad causeway during 1957-59 between Promontory Point and Lakeside (figure 3). The causeway, which replaces an open trestle, was constructed mostly of gravel and sand fill capped with boulder-sized riprap. It is breached by two box culverts, each 15 feet wide. The causeway separates the lake into two parts; about two-thirds of the lake is south of the causeway and about one-third is north of it. Because the causeway fill is permeable, however, brine can move both northward and southward through the causeway.

The southern part of the lake receives most of the freshwater inflow, whereas the northern part receives most of its water in the form of brine that moves through the causeway from the southern part. These factors, in conjunction with restriction of flow by the causeway, have caused differences of salinity and of surface level between the two parts of the lake. The differences increased steadily throughout the 1960's. Since 1966, when measurements of the surface level were started in the northern part, the southern surface has been consistently higher and the difference reached a maximum of 2.35 feet in June 1975 (figure 9). The difference of surface level also varies seasonally, with the minimum generally occurring during the fall and the maximum generally occurring during the late spring.

CONCLUSIONS

The surface level of Great Salt Lake fluctuates in dynamic equilibrium between inflow and outflow. Although man's use of water has affected the level somewhat, the greatest effect is caused by natural variations of climate. Unless climatic conditions or man's use change significantly from that experienced since 1847, the lake will not dry up or rise above the historically recorded high level.

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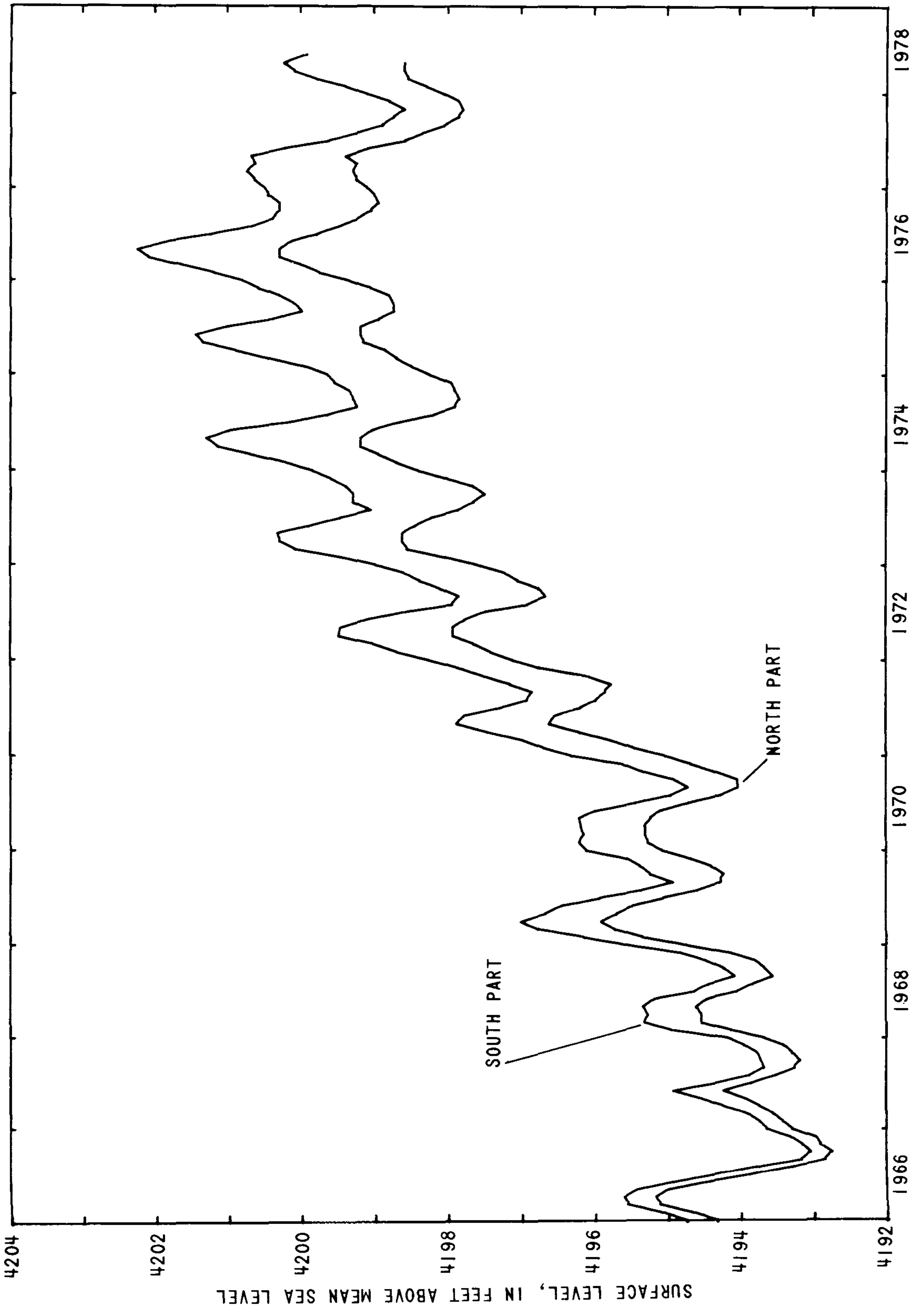

Figure 9. Surface levels of the north and south parts of Great Salt Lake, 1966-78.

COMPUTER MODELING OF THE GREAT SALT LAKE

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ABSTRACT

During the 1970-1978 period, a number of computer models were developed to simulate the hydrologic and salinity systems of the Great Salt lake. Most of the models were developed in response to problems of the industries around the lake concerning salinity differences between the North and South portions of the lake caused by the Southern Pacific Railroad causeway, and to flooding problems associated with the rapid rise of the lake during this period. A review of a number of these models was made to present an overview of the modeling that has been done on the Great Salt Lake. An attempt is made to summarize the objectives, abilities, and limitations of these models and to present some of the results from the computer simulations.

INTRODUCTION

A number of mathematical models have been developed for computer simulation of the hydrologic and salinity systems of the Great Salt Lake. The first hydrologic models developed were primarily for water budget analysis accounting for inflows, precipitation, evaporation, and storage change to determine lake level fluctuations. These basic hydrologic models have been expanded to predict future lake levels by modifying the inflows to simulate future conditions in the Great Salt Lake drainage basin due to water development projects and changes in water use patterns. Hydrologic models have also been expanded to include stage-damage analysis for estimating the flood damage reduction that could be achieved by various management alternatives. Hydrologic simulations have also been developed using stochastic methods to provide the surface inflow and precipitation estimates.

The first salinity models that were developed for the lake centered on modeling the dissolved and precipitated salt loads in the North and South portions of the lake and the flows through the culverts and causeway fill of the Southern Pacific Railroad causeway. These models have been developed with the capability of simulating the effects of providing additional culverts in the causeway on lake salinities and relative lake stage.

Some models have been expanded to include both the salinity and hydrologic systems of the lake into one simulation.

HYDROLOGIC MODELS

State and Federal Water Resources planning agencies have for several years prepared mean annual water budgets of the Great Salt Lake for water planing purposes. However, the first published results of using a computer model for a water budget analysis of the Great Salt Lake was made by Steed and Glenne (1972). This model was based on mean monthly historic flows for the 1944-1970 time period. Precipitation and evaporation estimates were obtained from climatological stations near the lake. The result of this model was a refinement of a water budget for the Great Salt Lake based on mean monthly values for a 26 year period.

To facilitate the analysis of the hydrologic system of the Great Salt Lake, the Utah Division of Water Resources (1974) developed a hydrologic simulation model of the Great Salt Lake. The model uses annual data and is able to predict June 1st and October 1st lake elevations for present conditions and with additional upstream depletions to the system for the 1901-1973 hydrologic period. The model was modified by the Division (1976) to simulate removal of water by pumping from the Lake during high lake stages and the data base was expanded to include the 1851 through 1975 hydrologic period. The basic data required by the program includes the inflow of the Bear, Weber, and Jordan Rivers, precipitation at the Salt Lake Airport, and elevation-area-volume data for the lake. Ungaged inflow and groundwater inflow are computed as a function of gaged inflow with the latter including lag-times up to three years. The Salt Lake Airport precipitation is adjusted to mean lake precipitation. Evaporation is computed assuming an evaporation rate of 4.33 feet per year and adjusted as a function of salinity. A mean annual water budget from the model for the Great Salt Lake for the 1851-1975 time period based on 1975 levels of water use is shown in Table 1. Lake stage probabilities from the model for the 1975 water use levels and for projected additional water depletions of 250,000 acre-feet and 500,000 acre-feet are shown on Figure 1.

Table 1 Great Salt Lake Water Budget in Acre-Feet for the 1851-1975 Time Period Based on 1975 Levels of Water Use

Inflow		
Gaged or correlated		1,950,000
Bear (60%)	1,160,000	
Weber (25%)	490,000	
Jordan (15%)	300,000	
Ungaged		400,000
Estimated Surface Water	150,000	
Estimated Groundwater	250,000	
Total Inflow		2,350,000
Precipitation		900,000
Total Supply		3,250,000
Evaporation		3,250,000
		0

In 1971, the U. S. Geological Survey, in cooperation with the Utah Division of Water Resources, began a 7-year study to monitor the parameters controlling the water and salt budget of Great Salt Lake. These parameters included ground and surface water inflow, precipitation on the water surface, outflow from evaporation, and chemical quality of the surface water inflow. In 1974, a digital computer model was developed on the basis of preliminary inflow data by Waddell and Fields (1977). The simulation has since been updated by Waddell and Barton (1978) using additional data collected for calibration of the model.

The model simulates both the hydrologic and salinity systems of the lake using a simple budget approach that combines the inflow and outflow parameters and computes the resulting lake level hydrograph and lake salinities for the 1931-1976 base period. It can also be used to evaluate the water and salt balance for various combinations of diked bay areas of Great Salt Lake such as the Farmington Bay area created by the recently constructed Antelope Island Causeway.

Results from this model indicate that the total annual inflow to the Great Salt Lake during the 1931-1976 period of 46 years ranged from approximately 1.3 to 5.0 million acre-feet and averaged 2.9 million acre-feet. The average inflow consisted of 1,926,000 acre-feet from surface inflow, 870,000 acre-feet from precipitation on the lake surface, and 75,000 acre-feet from groundwater inflow. The total annual outflow from the lake by evaporation during the 1931-1976 period ranged from 2.1 to 3.9 million acre-feet and averaged 2.9 million acre-feet. Results of this model pertaining to salinity and the Southern Pacific Railroad causeway are described under the salinity models below.

Hydrologic models of the Great Salt Lake have been developed using stochastic approaches. Glenne *et al.* (1977) developed a Markov model using hydrological variables and a random rainfall generator. Good agreement was found between the historic levels of the Great Salt Lake and the model output for the 1875 to 1975 period using the historic annual precipitation values as the random input. Development of the model showed that lagging run-off with respect to drainage area precipitation significantly improves the model's ability to reproduce historic lake levels. Specifically annual lake inflow is best correlated with precipitation in the previous years. The model lends itself to sensitivity analysis of the equilibrium water level of the Great Salt Lake. The model predicts that a sustained 10 percent change in mean annual precipitation over the drainage area would result in a five foot change in the mean annual lake surface elevation of the Great Salt Lake.

The Utah Water Research Laboratory is developing a stochastic hydrologic simulation model for the Great Salt Lake. The basic water balance equation for the simulation is taken from the Utah Division of Water Resources' hydrologic model described above. The annual surface and precipitation inflows for this simulation are independent synthetic time series generated by stochastic models. Efforts are currently underway at the Utah Water Research Laboratory to use multivariate time series analysis techniques to reproduce the cross-correlation between the surface inflows and precipitation. This model has been used for stage-damage

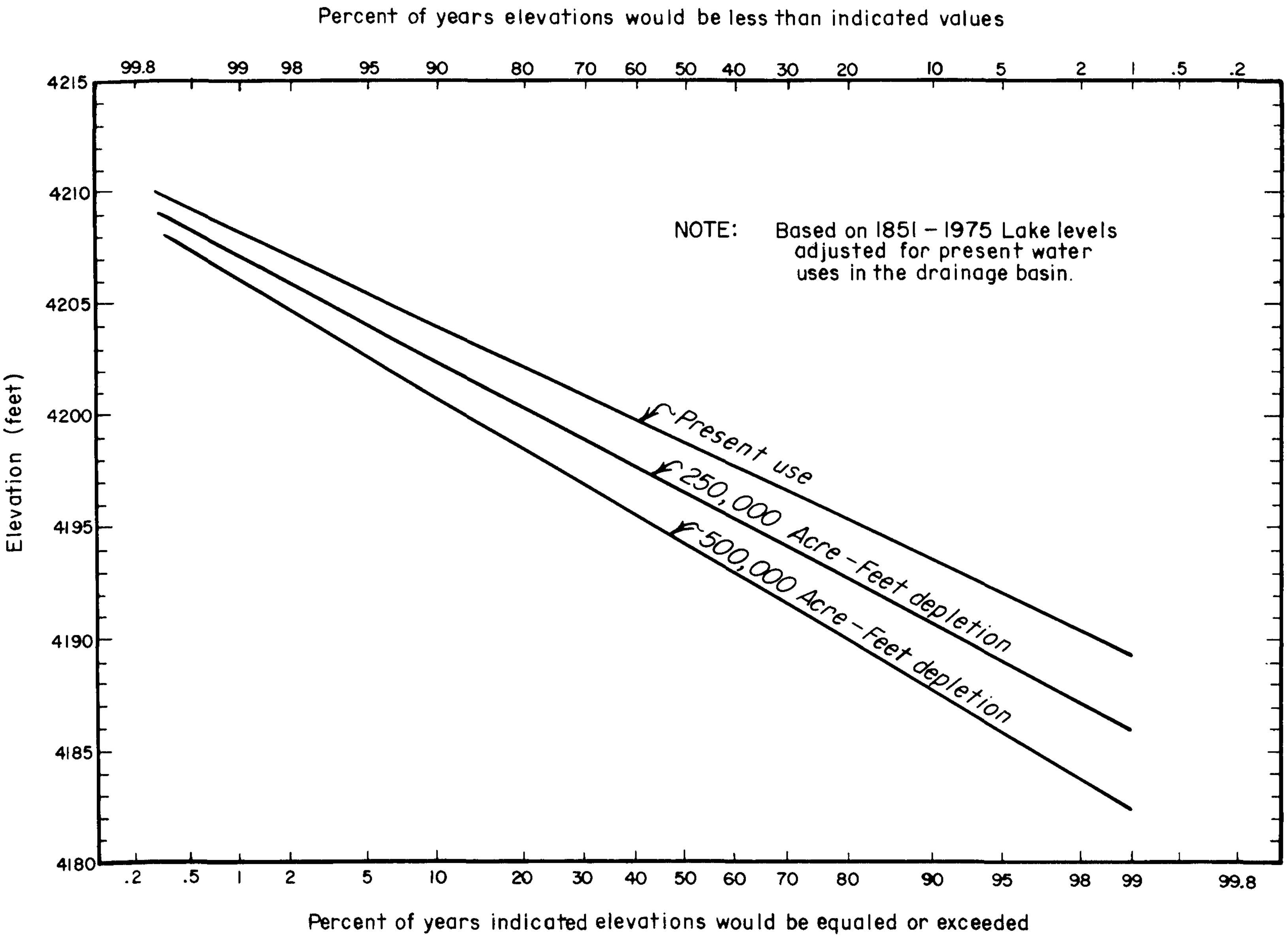

Figure 1. PROBABILITY CURVE for GREAT SALT LAKE ELEVATIONS

analysis of the Great Salt Lake which will be described below.

SALINITY AND CAUSEWAY MODELS

Construction of the Southern Pacific Railroad causeway across the Great Salt Lake has caused migration of salt to the North Arm. This has caused a significant dilution of the South Arm brine by the inflowing fresh water. The density gradient across the causeway has resulted in a reverse southward flow of dense North Arm brine through the culverts and fill. The reverse flow has maintained a stable dense layer of brine at the bottom of the South Arm.

For development of computer models for simulating salinity, the Great Salt Lake is divided into three district bodies of water including the Upper South Arm, Lower South Arm and the North Arm. A definition sketch for the causeway model simulations is shown in Figure 2.

The first published analysis of the flow through the culverts in the Southern Pacific Railroad causeway and salt balance of the north and south portions of the Great Salt Lake were made by Hansen (1970). Equations were developed for estimating culvert flows and the necessary additional culverts required to equalize the salinity and water surface elevations between the North and South Arms of the Lake.

The efforts to simulate the exchange of salts between the North and South Arms of the Great Salt Lake with a computer model started with the work of Waddell and Bolke (1973) of the U. S. Geological Survey. They developed a model that would predict the effects of the causeway on the salt balance of the lake for simulated inflow and evaporation rates. The model computes both culvert and causeway fill flows. The equations for the causeway flows are based on emperical relationships. The model has been used extensively for predicting future lake conditions for different lake stages and causeway modifications. This model was incorporated into the U. S. Geological Survey model described above of Waddell and Fields (1977) combining both a hydrologic and salinity model into one simulation.

A model has been developed by Glassett and Smith (1976) based on theoretical hydrodynamics for predicting salinities in the various portions of the lake for different lake stages and for additional culverts placed in the causeway fill. The basic parameters which were modeled include: (1) the overall salt and water balances, (2) the diffusion and mixing of salts from the dense lower layer of the South Arm of the lake into the more dilute upper layer, (3) the two directional flow of brine through the culverts which breach the causeway, and (4) the two directional flow through the permeable causeway fill. This model has also been used extensively for predicting future conditions in the Great Salt Lake.

Another salinity model was developed by Jones et. al. (1976). This model is very similar to the one developed by the U. S. Geological Survey and used the equations of Waddell and Bolke (1976) for culvert and causeway fill flows. The principle difference is in the treatment of the salinity layers in the South Arm. This model simulates several layers in the South Arm instead

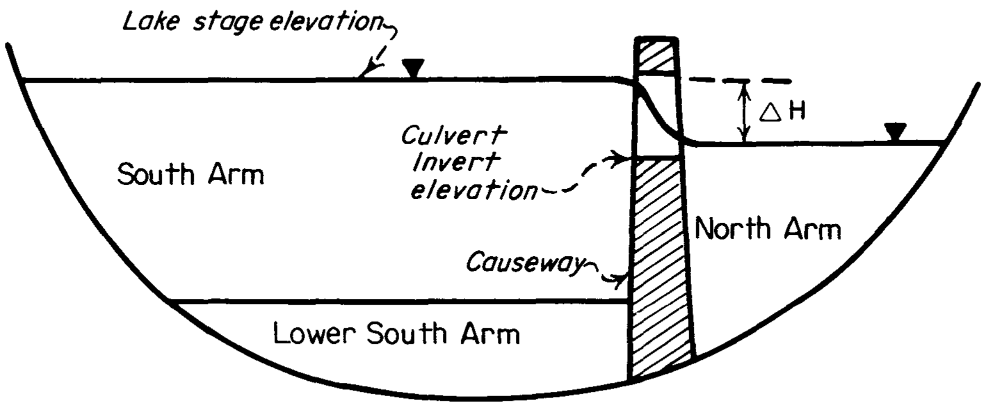

Figure 2. CAUSEWAY MODEL DEFINITION SKETCH of the GREAT SALT LAKE

of two. The hydrologic portion of the model was based on the work of Steed (1972).

Results from the above salinity and causeway computer simulation models were used in the Great Salt Lake Resource Management Study prepared for the Utah Department of Development Services (1977). The results from the models were not identical, and were not expected to be. However, the models show the same trends for different causeway openings and the results were generally in good agreement. The results from the models summarizing the effect of causeway openings on salinity and elevation difference between the North and South Arms as a function of lake stage are shown on Figure 3, and indicate that with the present openings in the causeway the salinity in the South Arm will remain relatively low and will change very little as the lake rises or falls. The results can also be plotted as a function of new causeway opening length for a given lake stage. Figure 4 shows the predicted salinity and elevation difference as a function of new causeway opening length for a lake stage of 4,200 feet.

FLOOD DAMAGE MODELS

Stage-damage models for the Great Salt Lake have been developed and incorporated into the Utah Division of Water Resources' hydrologic simulation model and the Utah Water Research Laboratory's stochastic hydrologic simulation model. These models have the capability of predicting peak and low lake elevations for (1) increased depletions due to upstream developments; (2) removing "excess" water from the lake by pumping during high lake stages; (3) additional openings constructed in the Southern Pacific Railroad causeway; and (4) any combination of the above three management alternatives. With this capability, the effect of selected management alternatives at the lake or on the tributaries can be simulated to determine the reduction in flood stages of the Great Salt Lake and flood damage reduction around the lake. There are considerable differences in the results of these two models. A description of these models and their results is found in the Great Salt Lake Resource Management Study prepared for the Utah Department of Development Services (1977).

CONCLUSIONS

Several computer models have been developed to simulate the hydrologic and salinity systems of the Great Salt Lake. The results from the various models are generally in good agreement. With the hydrologic data available and the hydrologic simulation models that have been developed, the hydrologic system and water budget analysis of the lake are very well defined. The salinity and causeway models are believed to be fairly reliable in predicting salinities in the future for the present causeway conditions and with proposed modification to the causeway. One assumption made by the salinity models is that the elevation of the interface between the upper and lower brines in the South Arm remains relatively unchanged. Monitoring and modeling of the interface should be considered a priority item on future research pertaining to the Great Salt Lake.

Other models have been developed for the Great Salt Lake. Undoubtedly models have been developed of which the author is not aware. However, the computer models described in this paper are those which government and industry have primarily been using the past few years in resource management studies of the Great Salt Lake.

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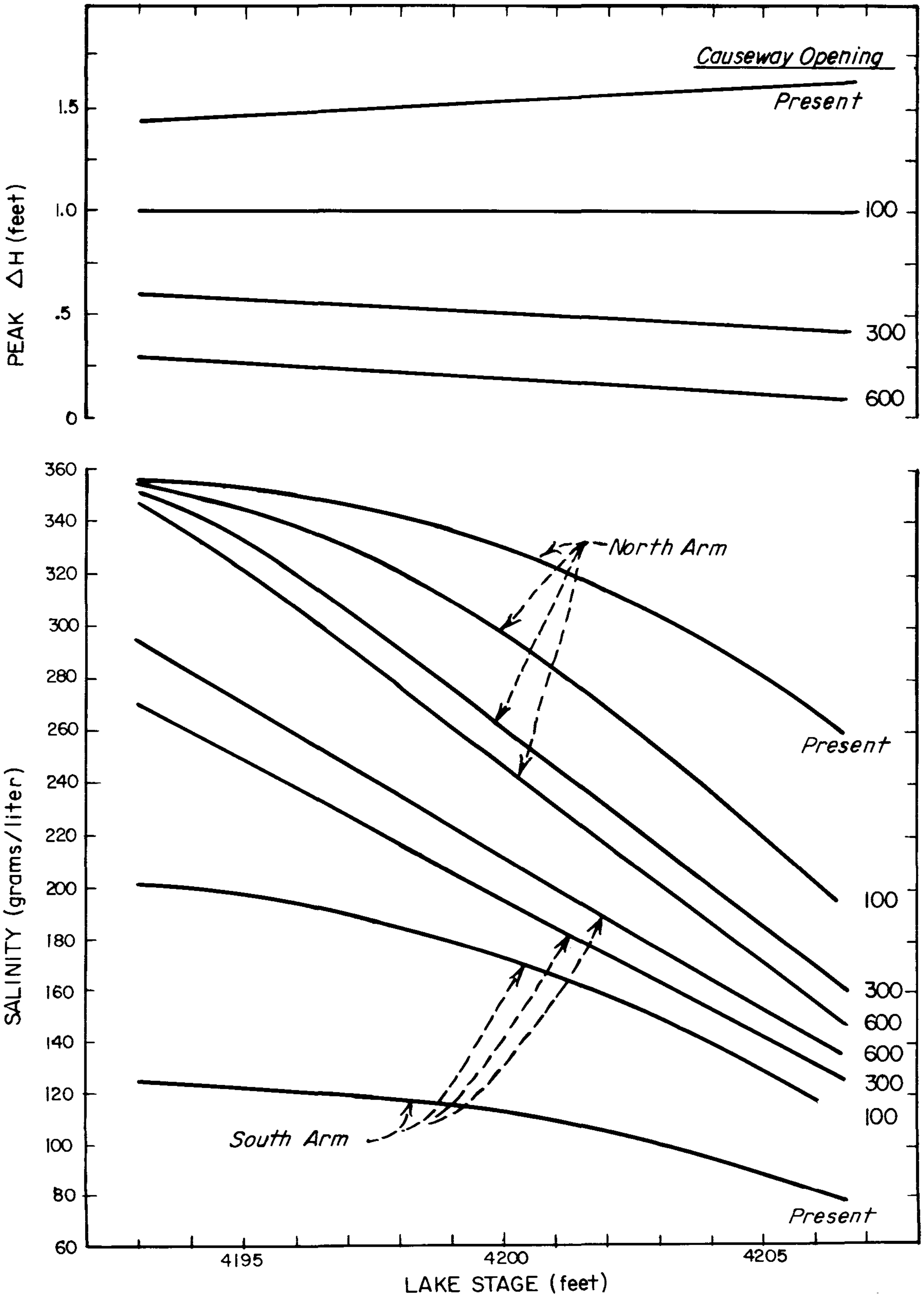

Figure 3. SUMMARY of NEW CAUSEWAY OPENING EFFECTS on SALINITY and ELEVATION as a FUNCTION of LAKE STAGE for GREAT SALT LAKE.

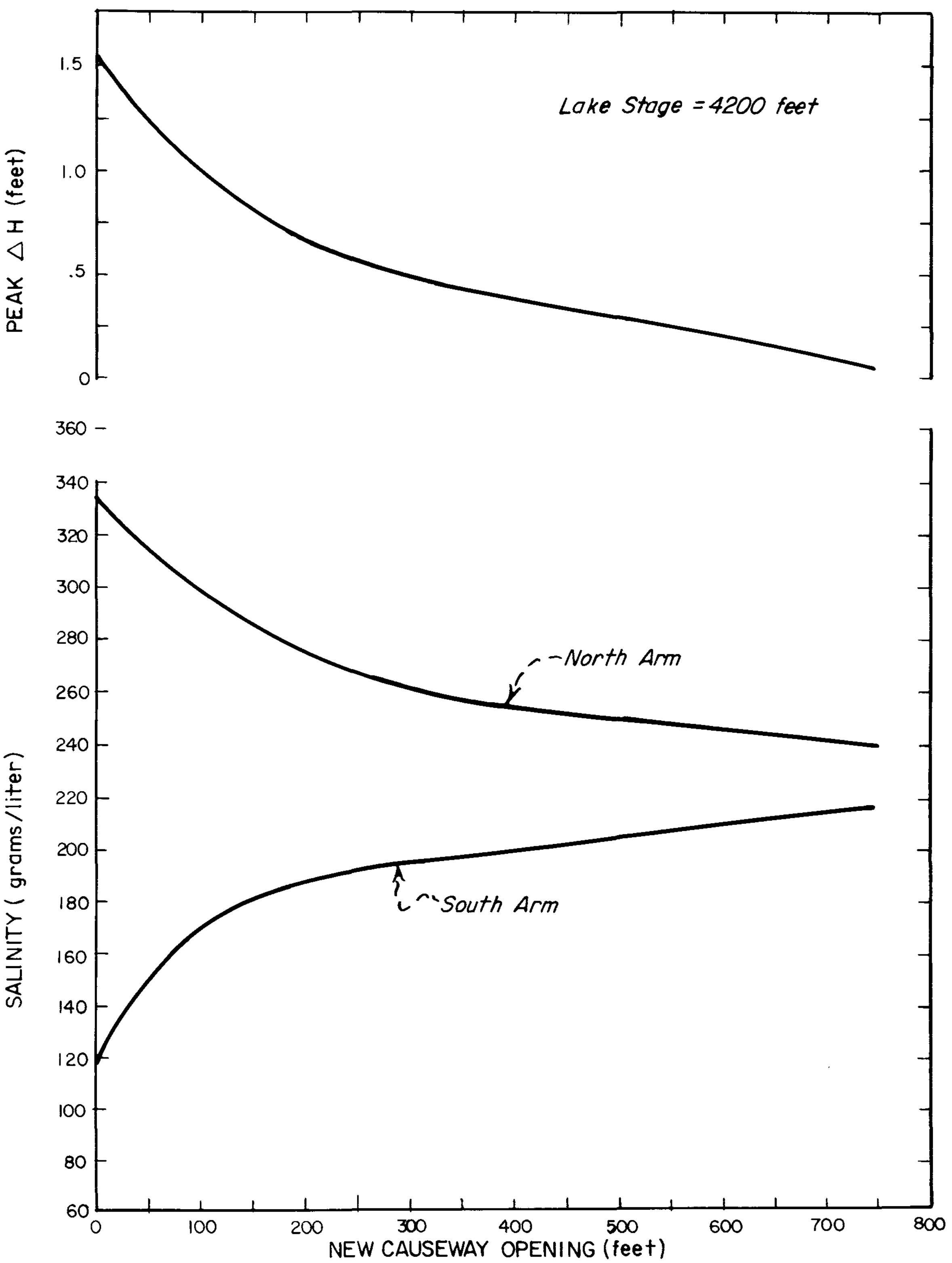

Figure 4. PREDICTED SALINITY and ELEVATION CHANGES in GREAT SALT LAKE as a FUNCTION of NEW CAUSEWAY OPENING.

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LAKE LEVEL PREDICTIONS
OF THE GREAT SALT LAKE

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ABSTRACT

The Great Salt Lake lies at the bottom of a closed basin. Due to the wide range of inflow to the lake, the surface level, surface area and volume of the lake has experienced wide fluctuations in the recent past. Efforts have been made to predict future levels of the fluctuations to avoid problems of development around the lake that would be damaged by high lake levels. Recent studies have predicted levels to elevation 4,212 feet in the near future. The general consensus of researchers and climatologists is that such predictions can not yet be made with any degree of assurance. The data should, however, serve as a warning that the lake could rise to levels that would cause considerable damage to new and existing development around the lake.

INTRODUCTION

The Great Salt Lake lies at the bottom of a closed basin in northern Utah. The lake has a surface area of approximately 1,500 square miles, a mean elevation of 4,200 feet, an average depth of 13 feet and is the 33rd largest lake in the world.

Since the Great Salt Lake is a closed basin and its only outflow is evaporation from the surface, the change in the lake's surface area, volume and stage reflects the integrated effect of all processes of the hydrologic cycle within the drainage basin. Historically these effects have been displayed by wide fluctuation in the inflow to the lake which have caused wide fluctuation in the surface area, volume and stage of the lake. Since 1851, the total annual inflow to the lake has ranged from 1.1 to 7.5 million acre-feet. The stage reached a high of 4,211.5 feet in 1873 and a low of 4,191.6 feet in 1963. During this period, the respective volumes were approximately 30 million and 9 million acre-feet.

In 1973 when the State of Utah began the process of formulating a comprehensive plan for the Great Salt Lake, an Interagency Technical Team was set up to assist in that process. A water resources subcommittee was assigned to report on the water resources which included the problems associated with the then rising lake level which had been increasing approximately one foot a year since 1961. The central concerns voiced in the planning process were, what will happen to the stage of the lake? Will it reach the previous high level or go even higher? Or, will it dry up as many had been predicting just a few years earlier?

Work was started under the water resources subcommittee and since carried on by the Great Salt Lake Division to analyze the hydrologic data of the Great Salt Lake and to review technical papers or research on the state of the art of predicting future levels of the Great Salt Lake. This paper will present an overview of this information.

PROBABILITY ANALYSIS

Since the settlement of the Great Salt Lake Basin, man's activities have increased depletion of water which has reduced the natural flow into the lake and, consequently, has reduced the average level of the lake. Because of these depletions to the inflow, the probabilities of various lake levels are not the same as in the past. To get around this problem in hydrologic studies, historical data are adjusted to show the present man-caused depletions as if they had existed over the entire period being studied. The adjusted flows are then called present modified flows. The hydrologic probabilities presented in this paper are based on the present-modified flows data from 1851 to 1975 available in Appendix B of the "Great Salt Lake Hydrologic System Management Alternatives Report" (Austin, 1977). The present modified data were analyzed using the lognormal method to determine the probability of future lake levels based on past hydrology. The probability curve for that data is shown in Figure 1.

The data show the lake stage would be equal to or exceed elevation 4,204 feet 10 percent of the time. On the low stages, the level would be equal to or less than elevation 4,193.5 feet 10 percent of the time. The probability for the lake level to equal or exceed elevation 4,210 feet is approximately once every 200 years. The reader should be reminded that the probability values are given for present-modified data. The same analysis of historical data shows that for the same recurrence interval of 1 to 200 years the lake elevation would equal or exceed 4,213.5 feet.

The probability analysis information is presented in this paper to show what can be expected for future lake levels from the analysis of 125 years of data, and for use as a comparison with predictions of future lake levels using other methods.

PREDICTING LAKE LEVELS

An excellent article summarizing the state of the art of predicting future climatic changes was published in National Geographic (Mathews, 1976). The importance of gathering information and what is presently being done is well documented in the article. This author concluded his findings by stating: "It may seem that there are as many theories on climate as there are climatologists, but experts agree on one point. They cannot yet predict climate changes with any assurance." This should not say that it is not possible that one or more of the theories may yet prove reliable and provide for predicting future changes in climate.

This section will briefly present some of the predictions made for the level of the Great Salt Lake. It will not be the objective of this paper to attempt to justify any of the material presented.

The Great Salt Lake and Cyclic Changes

The objectives of the work of Weather Bank, Inc. (Eubank, 1976) was to assemble data relating the lake elevation changes to sunspot cycles, mean temperatures, tree rings indices, and other natural cycles to determine if any objective forecast of the lake elevations could be made.

The contract with Weather Bank, Inc., was limited and did not allow them to pursue any of the objectives in great detail. A review of the predictions made for each objective does show highly variable results with wide confidence intervals in all cases. The work does substantiate the cyclic nature of the lake and suggests a complicated series of cycles of different periods superimposed on each other.

Their report concluded that without further analysis they could only speculate from the complex cyclic nature of the lake that it would continue to experience a pattern of shorter cycles superimposed on 180 year cycles as shown in Figure 2.

The Prediction of Future Water Levels of the Great Salt Lake

The purpose of the work by Dr. Willett (Willett, 1976) was to apply available information from past cycles of sunspots and climate, and data from other non-outlet salt lakes in the middle latitudes to predict levels likely to be attained by the Great Salt Lake in the years ahead.

Although the contract with Dr. Willett was also limited, he had done considerable work in this area and was asked to extend his previous work to the Great Salt Lake.

Based on longer-term solar-climatic and lake level cycles, the Willett report presented the following long-term predictions of the Great Salt Lake levels:

1. A primary high peak to be reached most probably some 15 to 25 years hence, substantially higher than the 4,212 foot peak of the mid 1870's but well below the peak 4,222 foot level of overflow into the western desert basin apparently reached near the year 1700 at the end of the Maunder sunspot minimum of 1670-1700.

2. A secondary minimum level, probably not below 4,200 feet to be reached during the second decade of the next century.

3. A secondary maximum peak, probably around 4,212 feet, well below the predicted 4,216-18 feet peak, to occur probably about 2050-60 A.D.

4. A primary minimum level, possibly even lower than the 4,192 foot minimum of the 1930-60 period, to occur probably during the period of 2110-2140 A.D.

5. Extremely high peak levels to be reached probably early in the 23rd and again near the beginning of the 25th centuries. These peaks, particularly the second one, may exceed even the 4,222 foot level of the Maunder sunspot minimum, perhaps with a water volume of the lake several times as great. However, if the subglacial cycle reaches its peak at this time as seems probable, this level will not be reached again for thousands of years.

The work of Dr. Willett was based on historical data rather than present modified data. If the lake level

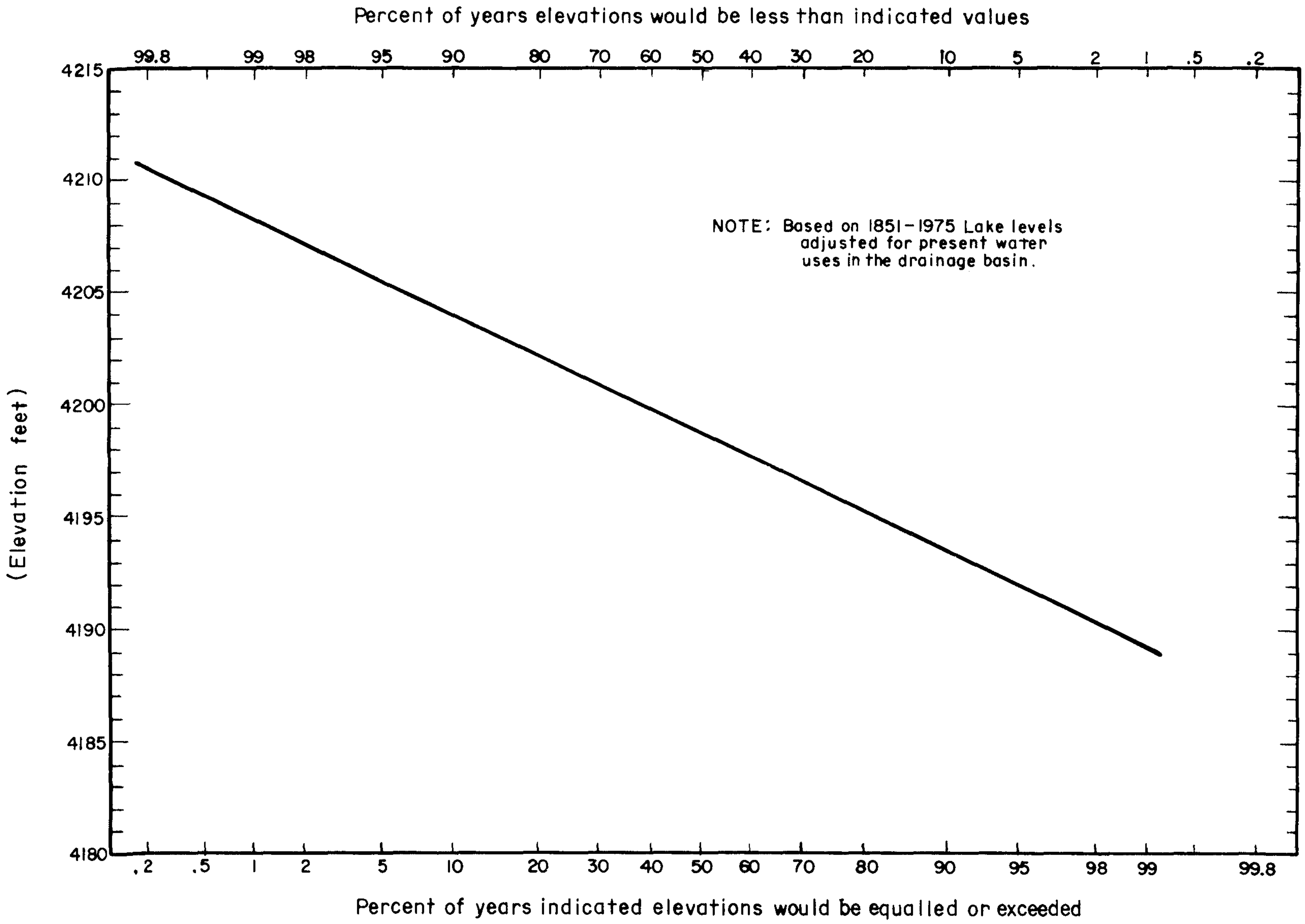
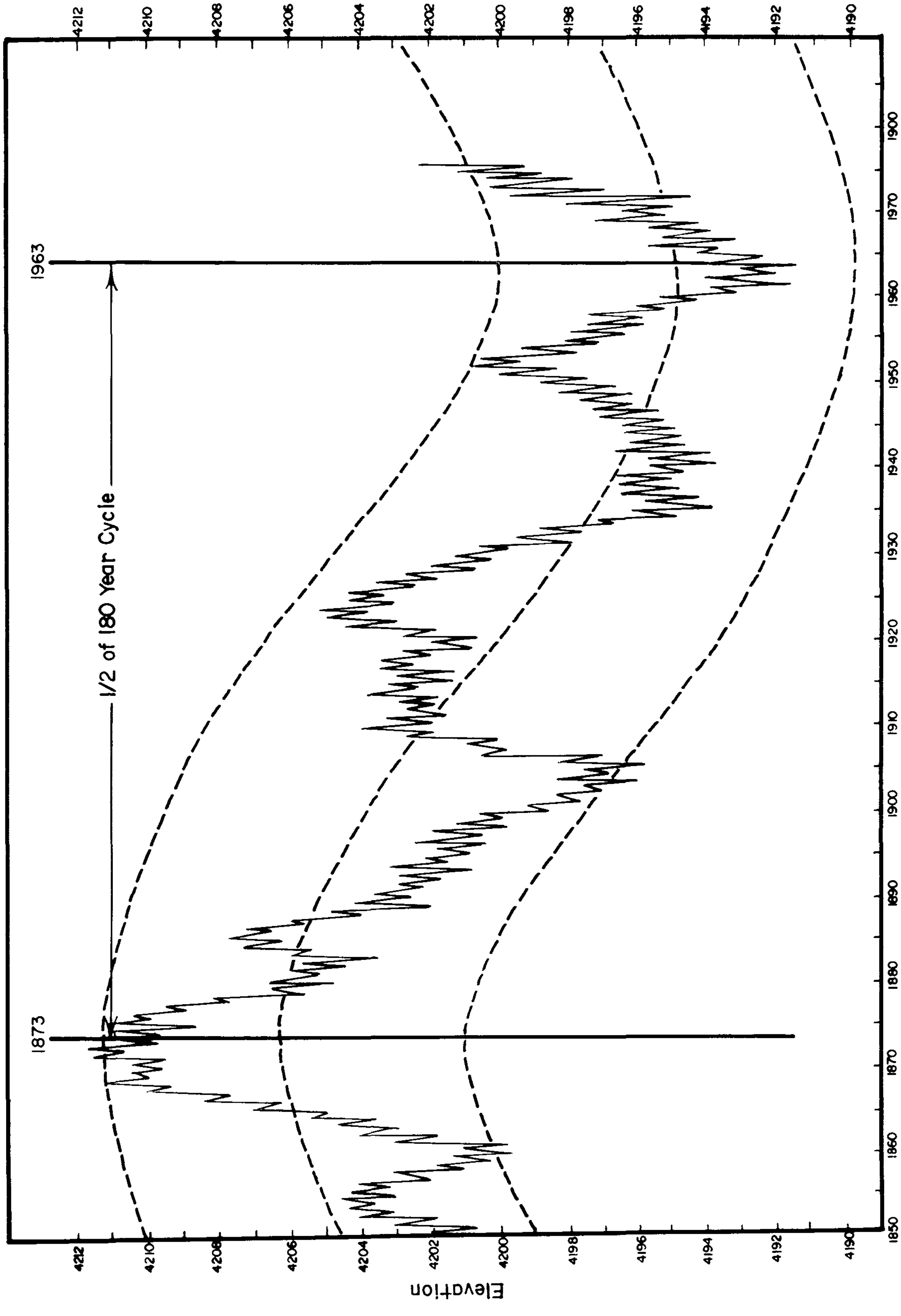


Figure 1. PROBABILITY CURVE for GREAT SALT LAKE ELEVATIONS



HISTORICAL LEVELS of GREAT SALT LAKE

Figure 2.

were to even approach levels near those being predicted, a great amount of damage would occur to development around the lake. Dr. Willett, as well as others, has continued to research correlations with natural cycles which would add to our understanding of the Great Salt Lake and predict future levels of the lake. Some of this work is reported in the 1977 International Conference on Desertic Terminal Lakes held at Weber State College (Greer, 1977) and in Utah Geology, volume 4, number 2, 1977.

SUMMARY

The work of hydrologists and climatologists have established much information about the probability and nature of future levels on the Great Salt Lake. From a hydrologic point of view the inflow/outflow components of the hydrologic cycle that influence the rise and fall of the lake are well defined. The problem, however, lies in being able to forecast climatic conditions that influence the inflow/outflow components.

Although it is generally agreed that these future climatic conditions can not be predicted with any degree of assurance, the probability and predictive studies do leave one clear warning. That is, the stage of the lake could rise to levels where extensive damage would occur to development around the lake.

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THE GREAT SALT LAKE AND ITS INFLUENCE ON THE WEATHER

Mark E. Eubank and R. Clayton Brough

WEATHERBANK, INC.

ABSTRACT

Although no in-depth study has yet been undertaken to determine the specific amount of influence the Great Salt Lake exhibits upon local weather phenomena, nevertheless it appears that the lake does alter local temperatures, precipitation, and wind patterns. Examples: 1) The warming this 3,000-plus square mile lake gives to the air above it is considerable. This may be why extensive fruit crops around the lake are able to be raised at elevations up to 5,000 feet above sea level. 2) When the temperature difference of the lake and the air 6,000 feet above it is 35°F (19°C) or more, significant precipitation ($\geqslant$.40 inches) occurs 60 per cent of the time. 3) Numerous salt particles over and around the lake allow for the formation of very large water droplets, which when combined with lake induced thermal instability and long overlake fetches of wind, result in heavy "lake effect" storms. This is especially true when this moisture laden air is forced into a cove and up the mountain slopes south and east of the lake. 4) The lake may double the amount of fog around its shores.

THE GREAT SALT LAKE AND ITS INFLUENCE ON THE WEATHER

In a recent poll of residents living near the shores of the Great Salt Lake, over 90 per cent felt that the lake did influence local weather. Scientists and laymen seem to agree that this large salt water lake does have "some" effect on the local temperature, precipitation, and wind patterns. It seems amazing that there has never been a serious scientific study to specifically answer this question. Therefore, most of what can be and is presented in this article is based on current meteorological models and climatological theories, as well as the findings of researchers who have investigated other similar situations elsewhere in the United States.

INFLUENCE ON TEMPERATURES

On a clear day, the air absorbs a certain amount of solar energy. At night that solar energy is lost to the upper atmosphere and the air cools rather quickly. Around the shores of the lake, the air temperature will commonly change more than 30°F (17°C) from the high to the low, but the temperature of the surface water (the top six inches) of the lake may change only 10 to 15 per cent of this value. Like the oceans, the Great Salt Lake is a more efficient retainer of the sun's energy than the air. For longer periods, the lake temperatures do seem to follow the trend of the mean air temperatures. Chart number 1 shows this relationship. On the average, the lake temperature is 4°F (2°C) higher than the mean air temperature at Salt Lake City for the previous five days.

During an 11 year period from 1966 through 1977, the surface temperature of the lake varied from a low of 22°F (-6°C) (February 11, 1976, North Arm) to a high of 89°F (32°C) (July 29, 1970 South Arm). The major reason for this wide variation is the fact that the lake is quite shallow, with little mixing of the water layers. There are few, if any, lakes in the world that experience this much temperature variation.

During most nights, the lake is warmer than the surrounding air, and sometimes by as much as 30°F (17°C) degrees. Although it has never been specifically investigated, the warming the lake gives to the air is probably considerable when the 3,000 square mile lake is 89°F (32°C) and the air above it is 60°F (16°C)! This may be one reason why extensive fruit crops can be raised around the lake at elevations up to 5,000 feet above sea level.

INFLUENCE ON PRECIPITATION

The greatest temperature differences between the water and the air above the lake occur in the fall and spring, when the major weather patterns are undergoing large transitions. It is during these times that the "lake-effect" appears to be strongest. It would appear that there are three major lake-related phenomena which could be possible candidates for causing the enhancement of storms passing over the lake. They are: 1) added moisture to the air from lake evaporation; 2) natural seeding from salt crystals; 3) thermal instability from the air-lake temperature contrasts. While all three of these candidates may play a weather modification role independently or in combination with each other, many meteorologists believe that the thermal instability produces the major effect.

Meteorologists have studied the role of storm enhancement around the Great Lakes and have found

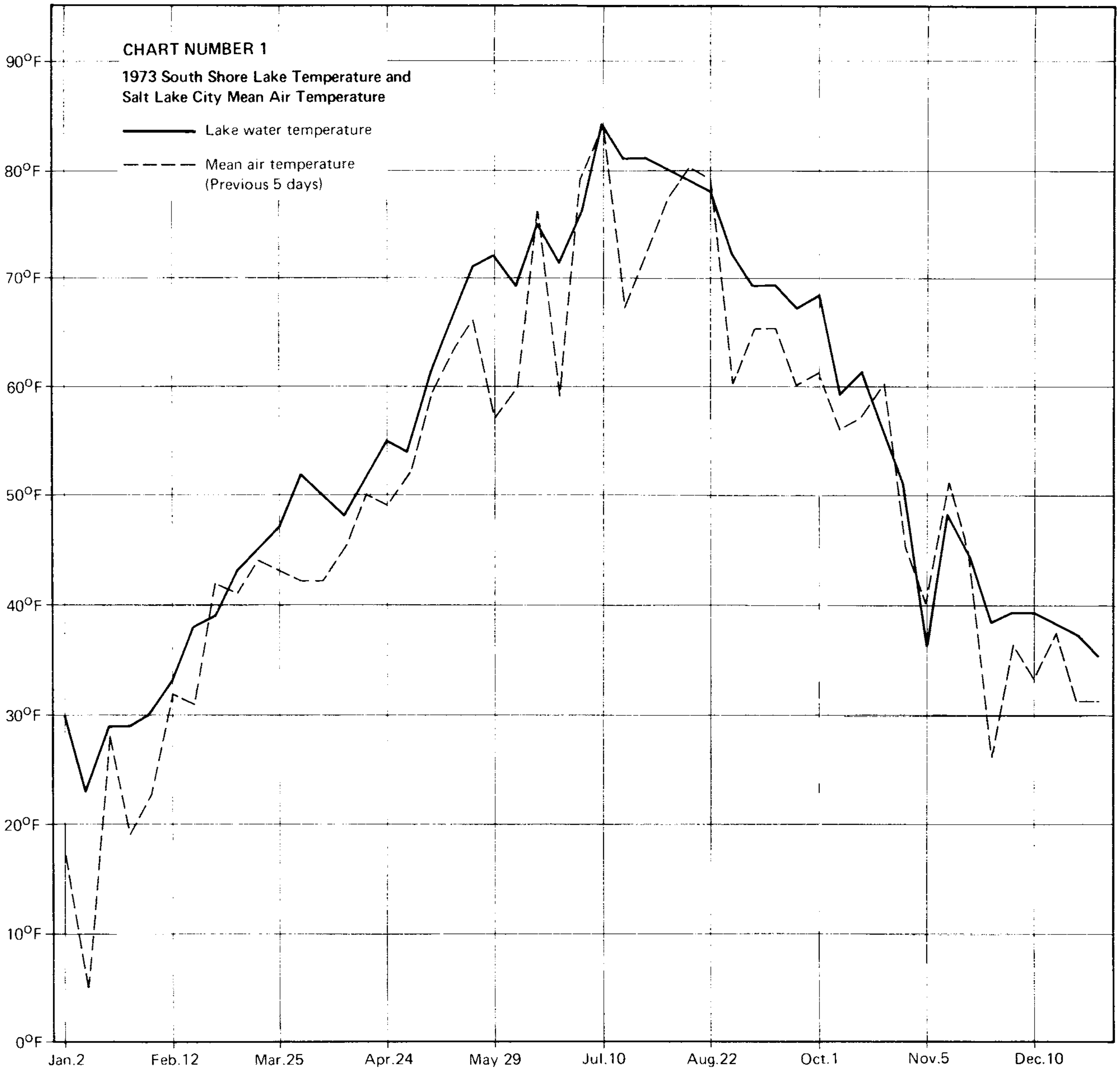
CHART NUMBER 1
1973 South Shore Lake Temperature and Salt Lake City Mean Air Temperature
Lake water temperature
Mean air temperature (Previous 5 days)
90°F
80°F
70°F
60°F
50°F
40°F
30°F
20°F
10°F
0°F
Jan.2
Feb.12
Mar.25
Apr.24
May 29
Jul.10
Aug.22
Oct.1
Nov.5
Dec.10

that the temperature difference between the lake surface and the region approximately 5,000 feet above the lake plays a key role. A scientific summary of the "Effect of Lake Ontario on Precipitation" indicates the following:

> "During the cold season, localized precipitation bands occur when cold air passes over the relatively warm lake waters. These storms are referred to as lake-effect storms and generally occur with a long overlake fetch of wind combined with an unstable lapse rate,...the lake frequently stimulates precipitation over and downwind of the lake when the surface winds are westerly and the 850mb temperature is more than 13°F (7°C) colder than the lake."

In the Great Lakes area, the *greatest* storm enhancement comes when the 850mb temperature is more than 23°F (13°C) colder than the lake surface temperature.

Weather records taken around the eastern shore of the Great Salt Lake indicate that some of the heaviest snowfalls occur during spring and fall when the lake water-air temperature contrast is at a maximum. During the three and one-half year period (February, 1971 - August, 1974) there were 26 times when the lake was 10°F warmer than the preceding 5-day mean air temperature. During these conditions, significant precipitation ($\geqslant$.40 inches) fell 27 per cent of the time at the Salt Lake City weather station. However, when the temperature difference was 15°F (9°C) or more, significant precipitation occurred 60 per cent of the time. Using a standard temperature lapse rate to the 700mb (10,000 foot) level, this would indicate that a temperature difference of 35°F (20°C) between the lake and the 700mb level results in significant precipitation over half of the time. In addition, the probability of significant storminess probably increases sharply if the jet stream is near or just south of the lake and the winds aloft are from a southwest through northwest direction. This agrees well with the thermal instability rules developed around the Great Lakes and indicates that to some degree the Great Salt Lake does alter the normal precipitation patterns of surrounding vicinities.

Other effects in addition to instability add to storm enhancement. Most heavy snows along the shores of the Great Salt Lake occur in narrow strips, often only 25 to 50 miles wide, and appear to be under or near the jet-stream core and downwind from the lake. Another important element seems to be the long overlake fetch of wind that suddenly becomes perturbed at the shore line. A further enhancement occurs when this moist, unstable air is then forced up a mountain slope immediately downwind of the lake.

There is also another lake-related effect that tends to increase precipitation. As the moist, unstable, lifting air is squeezed or converged into a cove or a canyon, it causes additional intensification of vertical motions which further heightens precipitation. Bountiful, which is in a position to benefit from all of these effects, experiences snowfall of over 100 inches nearly every winter. Heavy lake-effect snows are known to occur in Tooele, the Salt Lake Valley, Bountiful, Ogden, Brigham City, and Tremonton. During the warm season, from about May to September, the lake is often cooler than the surrounding land areas, so storm enhancement by thermal instability is non-existent. However, several meteorologists have visually observed thunderstorms to suddenly intensify as they pass over the lake at night. Therefore during a *summer night*, when the air temperature may be in the 60's°F (15-20°C) and the water temperature may be in the 80's°F (25-30°C), there probably is some enhancement of air-mass and frontal thunderstorms due to thermal instability.

During windy conditions that often accompany storminess, the surface of the lake develops white caps with a salt spray. As the water mist evaporates, minute salt particles become airborne and float away with the prevailing winds. These salt crystals become hygroscopic nuclei, that is they tend to absorb water and form water droplets. Of probably greater importance are the larger salt crystals that become airborne off of the salt flats around the lake. These large crystals tend to produce much larger drops and therefore heavier precipitation. The heavy snowpack found at the ski resorts in the mountains near the lake has a higher than normal salt content. To our knowledge, nobody has ever checked the salt content of the snow immediately after a "lake-effect" snow storm.

INFLUENCE ON WIND

The lake's relatively constant day-to-day temperature and the large day-to-day temperature change of the air set wind currents in motion. During most afternoons of the year, the air and land around the lake are warmer than the lake water, while at night the air and land are cooler than the lake. Each of these conditions produces a different wind pattern. When the land is warm, during the middle of the day, the air rises leaving a small low pressure area. The cooler air near the surface of the lake is slightly denser and has a slightly higher pressure. The air then moves from the lake toward the land creating a lake breeze. This lake breeze is like a small sea breeze but it is not usually very strong and is easily overcome by larger scale pressure systems moving through the area. During summer, when pressure patterns are fairly stable, the lake breeze is quite noticeable.

Usually, just before noon, the lake breeze will begin moving toward the land, and then around 1:00 or 2:00 p. m., the breeze will begin moving up the canyons. When the leading edge of the breeze passes by, it is like a miniature cold front, sometimes with brief strong and gusty winds. Near sunset, the wind direction reverses and begins blowing toward the lake. The heavy cool air flows from the mouth of each of the mountain canyons toward the warmer lake surface. This gives a prevailing southeast wind at night along the benches. This condition continues until the sun heats the land the next day and the land temperature exceeds the lake temperature.

On occasion, the advancing lake breeze will meet an opposing larger scale wind. During this time, whirlwinds are sometimes seen to form. In most cases these whirlwinds (sometimes called "dust devils") are small and of no consequence, but on rare occasions, minor wind damage does occur. These small scale whirls always seem to move in a northeast through southeast direction along the wind shear line.

At night the wind blowing toward the lake stirs the air and prevents or retards radiational cooling on the land. This is especially true near the mouths of the canyons. During the springtime of the year, this may determine whether the tender fruit blossoms will survive the chill nights. This night-time wind does exactly the same thing as the wind machines that are used in the orange groves of Southern California.

INFLUENCE ON FOG

The swampy areas near the shoreline of the Great Salt Lake are often foggy when radiational cooling is taking place around the lake. The lake offers enough moisture to become a breeding ground for the fog. During the day, the fog may "burn off" over the land and retreat to the Great Salt Lake where it will remain until after sunset.

It is paradoxical that the Salt Lake International Airport is located in one of the worst possible areas for heavy fog. On the average, Salt Lake City receives eleven days a year of heavy fog (visibility ¼ mile or less) while Wendover, at a similar elevation but over 50 miles west of the lake, has only five days of heavy fog.

This would suggest that the lake may cause double the amount of fog that would otherwise occur.

ODDITIES OF THE LAKE

Devil Winds

Winds on the lake can be very strong especially over the long open stretches of water. Sailboaters tell of frequent 70 and 80 mph winds buffeting the lake, especially just before a cold front moves through. Because these prefrontal winds blow from a southerly direction, at times it becomes difficult, if not impossible for sailboats to navigate toward the south shore against them. Occasionally, great damage is done to buildings and boats along the south shore from these "Devil Winds" of the Great Salt Lake. Boaters on the lake call this wind a "Tooele (too-will'-a) Twister", since south winds from the Tooele side of the Oquirrh Mountains are especially strong. The Oquirrh Mountains seem to have some strong topographical influence on these winds. At least once or twice each year, these winds will reach speeds of 75 to 100 mph in gusts, and about every five to ten years, the winds will gust over 100 mph doing considerable damage along the south shore.

Balls of Fire

John Silver, who used to operate a beach and marina on the south shore of the Great Salt Lake, for many years had the opportunity to observe the lake and all of its varied weather conditions. One of the oddest events he ever observed was the appearance one summer of several "balls of fire" on the surface of the lake. A night watchman became so spooked over this that he quit on the spot. The color of the "fire" was red, the shape was spherical; the fireballs appeared to be quite large and would dance all around on the surface of the water. Several sightings were reported. On one or two occasions, dinner patrons of the Islander Cruise Boat were witnesses to the phenomena. It is possible that some electrical-optical event was taking place similar to ball lightning or possibly some chemical reaction between the air and the lake-brine solutions.

Salt Storms

Another lake related effect is precipitation of salt upon man-made structures--particularly "power poles" around the lake. When wind storms blow up clouds of salt-dust prior to a storm, the salt-dust settles on trees, buildings, power poles, etc. When a light, drizzly precipitation begins to fall the salt crystals and water combine to make brine (a salt water solution). Since brine conducts electricity, the power lines begin arcing across the insulators and result in pole fires! Utah Power and Light Company indicates that more than several dozen poles a year are burned in the Great Salt Lake desert. In 1977, 80 pole fires occurred in the month of March alone.

Icebergs

Another lake weather effect is that, during extremely cold conditions, icebergs are found on the concentrated brines of Great Salt Lake.

On January 23, 1972, helicopter pilots from Hill Air Force Base spotted icebergs floating in the Great Salt Lake. "Warm temperatures broke up the ice which had formed in the shallow, nearly salt-free waters of Farmington Bay and areas east of Antelope Island, and then high winds blew the ice out into the lake, which is normally ice free." (Daily Herald Newspaper, Provo, Utah)

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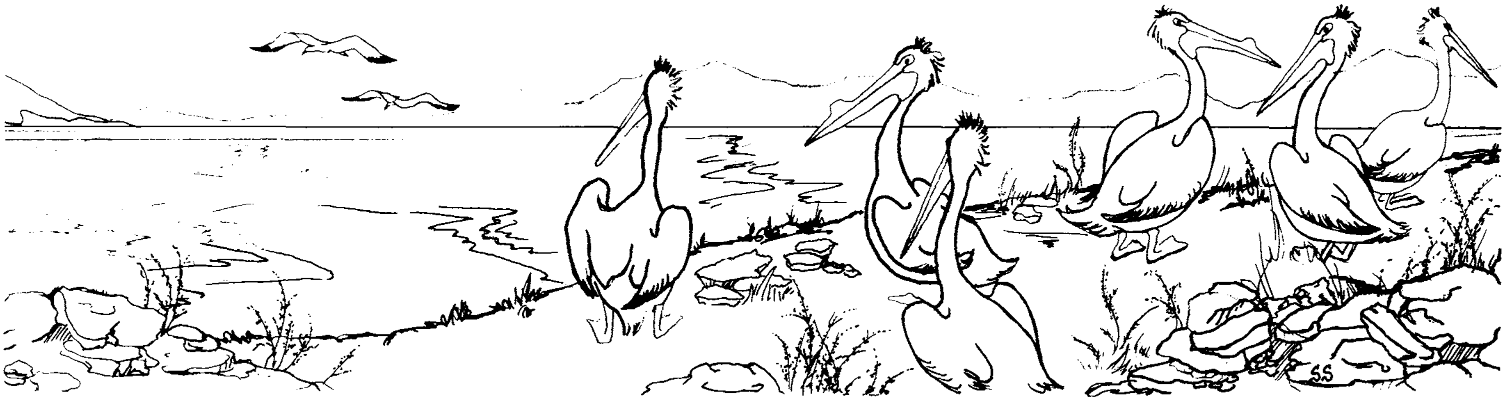
BIOLOGY



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WILDLIFE OF THE GREAT SALT LAKE

by Edwin V. Rawley

State of Utah Department of Natural Resources
Division of Wildlife Resources

INTRODUCTION

The information included in this review of the wildlife system of the Great Salt Lake was obtained from field investigations, examination of published and unpublished reports, consultation with knowledgeable persons, and personal knowledge.

The boundaries of the area considered in this report encompass the entire lake proper, its islands, the entire shoreline, plus the northern Lakeside Mountains, the eastern portion of the Hogup Mountains, Kelton, Locomotive Springs, lower Hansel Valley, the entire southern Promontory Mountains, the entire Bear River delta from Penrose to Honeyville to Perry, western Weber and Davis counties, northwest Salt Lake County, and the south shore including the northern tip of the Oquirrh Mountains and Stansbury Island.

With the exception of the brine shrimp (Artemia salina) and protozoa found in the lake proper and noxious insects found in the lake and its immediate environs, emphasis is placed on vertebrate fauna.

Of the vertebrates, investigations have revealed that within the Great Salt Lake area there are 23 species or subspecies of fish, 8 species or subspecies of amphibians, 2 species or subspecies of snakes, 257 species of birds, and 64 species or subspecies of mammals.

Three Merriam life-zones are included in the Great Salt Lake area. They are the Upper Sonoran Salt Desert area which encompasses that portion of the study area from the lake shoreline to an elevation of 5,500 feet; the Upper Sonoran Pinyon-Juniper belt from 5,500 feet to 6,500 feet; and the Transition Zone from 6,500 feet to 7,372 feet, the highest point in the study area, which is located in the Promontory Mountains west of the Bear River Migratory Bird Refuge.

Because wildlife organisms cannot be adequately discussed without involving a discussion of the environment within which they exist, this report includes a review of both wildlife and wildlife habitat (fauna and flora).

The habitat for wildlife provided by the Great Salt Lake and its environs is very marginal for most species. This fragile situation creates a delicate balance for the wildlife system of the Great Salt Lake area which must be given serious consideration when contemplating any plan that would tend to upset this balance.

There is an urgent need to preserve the identity of plant and animal communities in which these animals evolved and are but a small part. The factor contributing the most heavily to the demise of many of these life forms is the loss or alteration of habitat by urbanization, industrialization, agriculture, flood control, and water development.

Some relationships between species and their environment may not now be apparent or fully understood, but each species is of value in its natural community. The Division of Wildlife Resources of the Utah Department of Natural Resources conducts its programs of wildlife management in principal consideration of these inherent and ecologic values.

Since people attribute certain economic, aesthetic, and recreational values to individual species of wildlife, programs of management for these species are designed to allow people to enjoy these values but without wasting, exploiting, or devastating the wildlife involved.

COVER TYPES OF THE GREAT SALT LAKE AREA

The eastern portion of the Great Salt Lake area is dominated by the strip of marsh that extends from the Jordan River Marshes to Bear River Bay. Except for the Bear River Marshes, which are quite extensive, the marshes are generally confined to a narrow strip of ground between the upland agricultural area and the salt and mud flats of the lake itself. This small strip of vegetation along with the shallow water areas nearby serve as a major rest area for millions of migratory waterfowl and shorebirds.

Northward around the lake are the only extensive stands of sagebrush to be found in the area. These sagebrush areas on the Promontory and Hansel mountains are generally related rather closely to livestock interests which winter large numbers of sheep on these areas. The sagebrush areas also serve as winter range for a limited number of mule deer.

The Promontory Mountains are the only location in the Great Salt Lake area where the browse type of vegetation cover is found. The browse type is generally made up of mountain mahogany, serviceberry, and bitterbrush and is valuable to wildlife as food and cover.

Juniper types are located on the Promontory, Hogup and Stansbury mountains at higher elevations. The junipers are generally well spaced and growing on steep, rocky hillsides in most areas which makes them unavailable for use by wildlife.

The annual type is predominated by cheat grass. Depending upon the location, sagebrush, rabbitbrush or shadscale may also be present or even cover extensive areas such as on the northern end of Antelope Island where sagebrush covers large areas or on Fremont Island where rabbitbrush covers the southern end.

The shadscale-greasewood type covers almost all the western portion of the area and has many gradations from almost pure greasewood to pure shadscale. This type is used heavily by wintering sheep herds due to its extensiveness.

The upland type is a catch-all used to designate the remainder of the Great Salt Lake area. Generally it is composed of agricultural, urban, and industrial areas.

Of the 416,942 acres of 1st, 2nd, and 3rd magnitude marsh listed on table 1, 128,019 acres (30%) are on the seven state and one federal waterfowl management areas, and 50,196 acres are controlled by private duck clubs around the lake. Of the area controlled by private clubs, generally only those areas owned by the clubs can be considered to be managed for waterfowl. Numerous other clubs exist, most of which have only leased hunting rights from private individuals. This leaves 238,737 acres (57.3%) of marsh around the lake which are currently not being managed by any group.

Even though unmanaged at present, many of these areas are as productive in terms of waterfowl produced as the waterfowl management areas. This is dependent entirely upon land use practices in the marsh areas and is subject to rapid and irreversible change by such practices as drainage and industrialization.

Vegetation may be damaged on unmanaged marshes by uncontrolled grazing by livestock at unfavorable times of the year. Grazing can be beneficial to marshlands if done at the proper time and in the right amount. Uncontrolled muskrat trapping with the use of tracked vehicles may also be causing significant damage to the vegetation although this has not been documented.

Use of the Great Salt Lake marshes by waterfowl is historic, and developments in this area by the Utah Division of Wildlife Resources for the benefit of waterfowl have been extensive. Substantial values have accrued to the State through its waterfowl management program. In addition to local benefits, these marshes are essential to the preservation of international populations of migratory waterfowl, and in maintaining the distribution of these birds.

The marshes of Great Salt Lake are probably the most important single breeding ground for waterfowl that now remains in the United States.

WATER NEEDS

Fresh water is critical for the survival of the marshlands. Water for these areas comes primarily from excess water not used by upstream municipalities and agriculture. Water needs by county for the Great Salt Lake marshes are shown on table 2.

INVERTEBRATES OF THE GREAT SALT LAKE

Phylum Protozoa

Euglena sp, and an amoeba resembling *Amoeba linax* have been reported from the waters of the Great Salt Lake. In addition, Vorhies states that several protozoa are normally found in the lake water. Little is known concerning these animal micro-organisms. The protozoa may prove upon further investigation to constitute the most abundant and diversified life inhabiting the waters of the Great Salt Lake, at least in the vicinity of fresh water inlets.

Regarding protozoa in the Great Salt Lake, Evans in 1960 reported:

> There have been found in samples of water taken from Great Salt Lake and nearby briny ponds eight species of protozoa heretofore unrecorded including *Cristigera, Cyclidium, Podophrya, Euplotes, Oikomonas,* a small amoeba, and two unidentified ciliates. All except *Podophrya*, which feeds on *Euplotes*, appear to be bacterial feeders.
>
> Evidence suggests that *Cristigera* and the amoeba are specialized halophilic protozoa and that certain of the other species of protozoa may be salt-tolerant, fresh-water forms.

Reddy, in 1972, identified a new species of *Euplotes* from the Great Salt Lake. The new ciliated protozoan, *Euplotes persalinus*, was taken from the southern shore of the lake near Black Rock and at the southern end of Antelope Island. The genus *Euplotes* belongs to the order *Hypotrichida*, subclass *Spirotricha,* and class *Ciliata.*

Phylum Arthropoda

The arthropods constitute the most conspicuous and apparently the most abundant group of animals inhabiting the water of the Great Salt Lake. This phylum is represented by the brine shrimp (*Artemia salina* Syn. *gracilis* Verrill), and the brine flies *Ephydra gracilis* Packard, and *Ephydra hians* Say.

Brine Shrimp

The brine shrimp reproduces by two methods: in the presence of males the same females sometimes produce viviparous nauplii, and at other times they release encysted embryos which are encased in hard chitinous shells. It has been shown by several investigators that the animals reproduce parthenogenetically. Jensen claims that this process, along with the laying of eggs, takes place during the summer months. He also stated there are males and females among both groups, and that it is difficult to distinguish between those hatched from fertilized eggs and those born parthenogenetically.

The eggs are viviparous but only when the shell glands of the uterus are not functional. That shrimp reproduce by laying both summer eggs (soft shelled) and winter eggs (hard shelled) is a well known fact. Investigation shows that under normal conditions, *Artemia* will produce eight generations, part of which are hard shelled. The soft shelled eggs usually hatch out within an hour or two after having been laid. The winter eggs must first be dried before they will hatch. The adult shrimp will reach maturity in 3 to 4 weeks and begin to reproduce. It will pass through 12 to 24 instars (stages between molts) during the 4-week period.

Gladys Relyea, in 1937, stated that when cold weather comes with water temperatures below 6° C., the adults die off, but winter eggs live until the next spring. These have been known to hatch as early as

Table 1. Great Salt Lake Marshes

First magnitude marsh	
(stable water supply, used by waterfowl for nesting, migration and wintering)	
State marsh developments:	
Locomotive Springs Salt Creek Harold Crane Timpie Springs Ogden Bay Howard Slough Farmington Bay	
Total	63,124 acres
Federal marsh developments:	
Bear River	
Total	64,895 acres
Private marsh developments:	
Private duck clubs	
Total	50,196 acres
Total developed first magnitude marsh	178,215 acres
Total undeveloped first magnitude marsh	160,096 acres
Total first magnitude marsh	338,311 acres
Second magnitude marsh	
(lacks continuous water supply but provides wildlife benefits during certain periods of the year)	69, 651 acres
Third magnitude marsh	
(those which have water only in years of high precipitation and provide only marginal wildlife habitat)	8,980 acres
Wetted marsh	
(open, shallow water and flooded vegetation used by waterfowl as resting areas)	204,336 acres
(The Great Salt Lake Minerals and Chemicals Company settling ponds have utilized approximately 24,000 acres of this total.)	

Table 2. Water needs by county for the Great Salt Lake marshes

	Box Elder	Weber	Davis	Salt Lake	Tooele	Great Salt Lake Area
Acre-feet of water needed annually for existing marshes	880,641	88,982	502,470	103,162	48,657	1,543,858
Acre-feet of additional water required for future development	25,000	75,555	22,666	60,444		183,665

March 12, when the water temperature was 9° C. The eggs have great vitality. Siebold in Munich was able to grow several generations of *Artemia* from eggs sent to him from Great Salt Lake in dried mud.

Talmage, in 1900, claimed that the shrimp could be found in the lake at all seasons of the year, but were most numerous during the months from May to October. C. C. Sanders of Ogden, Utah, observed shrimp in large numbers in the lake when the water was below freezing in December. Talmage stated that females greatly outnumber the males at all seasons, and that during the colder months of January and February it was almost impossible to find a male.

Shrimp will school where organic waste is plentiful. Shrimp do, however, eat algae, and appear to grow most rapidly on *Dunaliella viridis.* The shrimp will eat other types of algae, but if forced to eat *Stichococcus* sp. will starve. The cells of the *Stichococcus* found in the fecal material of the shrimp are still viable.

The dry cysts are very resistant to certain conditions. Sanders reports finding shrimp eggs that had been deposited, by lake level indications, in the lake in 1925 or 1926. He was able to obtain a large percentage hatch from those eggs. He also reported that on another occasion he found some *Artemia* eggs which were viable in a sand pit on Promontory Point.

The *Artemia* of Great Salt Lake may have been, according to Gilbert, a fresh-water phyllopod which was able to adapt itself to the gradual changing of the fresh-water Lake Bonneville to the present Great Salt Lake. This theory is supported by Anikin's experiments and by those of other workers. Kellogg, in speaking of *A. franciscanus,* says that "differences in proportional length of the post-abdomen to the rest of the body, in character of the abdominal segmentation, and in length and hairiness of the caudal appendages are apparent in the new *Artemia* and evidently bear a definite relation to the different densities of the pools in which they are living." Kellogg found differences in number, color, size and activity among the *A. franciscanus* living in the different pools. Those in densities above 1.20 were reddish, small, less active and fewer in number.

Jensen's experiments showed that eggs developed better in water of lower density than that of the Great Salt Lake. This may be a possible explanation of the fact that the eggs of *Artemia* of Great Salt Lake hatch best in the early spring, when there is a fresh-water inflow from surrounding streams.

Corixids in the Great Salt Lake

Specimens of the family Corixidae (water boatmen) were collected in salt water on the south shore of the Great Salt Lake at the Silver Sands Marina and were sent by Dr. Don Rees of the University of Utah to the National Museum in Washington, D. C. for identification. They were identified as *Trichocorixa verticalis* Fieber. This is one of the species also found in San Francisco Bay.

Dr. Rees reports that they do not breed in the lake but fly to fresher side pools to breed and lay their eggs. He also reports that they are basically predatory and prey on brine shrimp, *Artemia salina*, and larvae of the two species of brine flies, *Ephydra cinerea* and *Ephydra hians,* in the Great Salt Lake.

In addition to those specimens collected by Rawley at the south shore, Dr. Rees has collected them off the west coast of Antelope Island.

Noxious Insects of the Great Salt Lake Area

The principal noxious insects associated with the Great Salt Lake are brine flies, mosquitoes, deer and horse flies and biting and non-biting gnats. All are dependent upon an aquatic habitat to reproduce. Terrestrial insects that are present and may at times be in sufficient numbers, in certain localities, to be considered noxious are several species of domestic flies, ants, bees, wasps and fleas. Arachnids in the same category are spiders, ticks, mites, and scorpions.

Brine Flies

The only noxious insects that are produced in the saline water of the Great Salt Lake are two species of brine flies, *Ephydra cinerea* Jones *(gracilis* Aldrich), the smallest and most abundant, and *Ephydra hians* Say.

These species do not feed on man or other animals but become objectionable at times to bathers and those using the beaches because of their great numbers. The adults living and dead accumulate in the water and on the beaches in such great numbers that it is impossible to avoid and difficult to endure them. The pupae cases of these flies wash up on the beaches to form windrows of decaying animal matter that emits a repulsive odor and in which other fly larvae develop.

Adult brine flies are widely distributed on the lake but are more concentrated in certain areas. Wind direction and velocity seem to have a direct affect on their distribution. They first appear in April and continue to late September. The population peak is during July and August with a decrease in numbers as daily temperatures drop.

Mosquitoes

Eleven species of adult mosquitoes representing four genera have been reported as collected on the Great Salt Lake or vicinity. The larvae of nine of the eleven species have been reported as present in this area. The adults of the other two species are apparently migrants from other localities.

All species of mosquitoes require water for the development of the larvae and pupae, but mosquito larvae and pupae cannot survive in the brine water of the Great Salt Lake. All mosquito breeding is confined to the freshwater bordering the lake, but adult females of several species can fly miles in search of a blood meal. Only the females are capable of taking a blood meal. The males confine their feeding to plant and other available fluids.

The most widely distributed, abundant and annoying species are *Aedes dorsalis, Culex tarsalis*, which is also a potential vector to man of the Western Equine Encephalitis virus (brain fever), and *Culex erythrothorax.*

Culiseta inornata are widely distributed and very abundant but seldom feed on man.

Aedes dorsalis is the most pestiferous species at Great Salt Lake and vicinity. The females are vicious biters and will attack during the day or night but are particularly active during the evening and on calm, cloudy days. The females are strong fliers and occasionally migrate in large broods. They are commonly found ten miles from their nearest breeding place and a flight of 22 miles has been recorded from the marshes near the lake.

The female lays her eggs singly in moist depressions shortly after mating. Each female lays approximately 130 eggs. The eggs, under favorable conditions, hatch within a few days after they are deposited or they can remain viable for several years before they hatch if conditions are not favorable. The winter is passed in the egg stage and the first larvae appear generally about March from over-wintering eggs.

The larvae are generally found in or near salt grass. During the mosquito season, each time these salt grass areas are flooded a brood of *A. dorsalis* larvae hatch from the eggs. As many as seven different broods of larvae have appeared in the same locality during a season.

In a few days after emergence from the egg, the larvae pass through four instars and pupate from which state the adult mosquito emerges. From the time the egg hatches until the emergence of the adult requires a minimum of about six days. During this period, surface water must be present in order to complete the process.

Culex tarsalis Coq. is the most abundant and widely distributed Culex species at the Great Salt Lake and throughout the state of Utah. These mosquitoes feed from dusk to dawn on man, birds and other animals including reptiles. They attack rather stealthily and their bite is very irritating to most of their victims.

In addition, they are capable of transmitting encephalitis viruses to man and other animals. Their wide distribution around the lake, abundance, feeding habits and potential as vectors of this dreaded disease of man make their control of major importance in the program of developing the lake and its resources.

Like all species of the genus *Culex* in Utah, *tarsalis* survive the winter as fertilized females in semihibernation in places such as rodent burrows, brush and rockpiles, caves and other available shelters. These over-wintering females emerge in April or May, depending on favorable climatic factors, and lay their eggs in rafts that float on the surface of the water. Each raft contains approximately 250 eggs and each mosquito may deposit several rafts.

The larvae emerge from the eggs and develop into pupae within a minimum of about a week, or it may be two or three weeks if weather conditions are unfavorable. The adult can emerge from the pupae stage within 24 hours after the pupa appear.

The adults mate and begin egg laying within a few days after emergence. There may be a dozen generations during the year extending from April to late October or early November. The peak population of this species is generally from late July to early September.

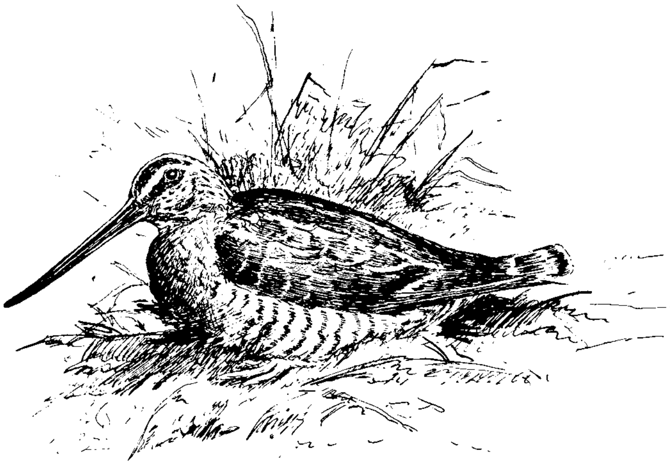
The eggs, larva and pupa of *C. tarsalis* may be found in all stages in a wide variety of water habitats such as lakes, ponds, margins of slow moving streams, and drains. The immature stages are usually associated with emergent and submergent aquatic vegetation and are rarely found in abundance in open water devoid of vegetation.

The flight range of the female adults seems to be in the form of a dispersion but may follow along waterways and extend for eight miles or more. Most flights apparently are confined to shorter distances.

Culex erythothorax and *C. pipiens* are found in habitats similar to that of *C. tarsalis*, and their life history, feeding habits and behavior are similar.

C. erythothorax larvae and pupae seem to be more prevalent and abundant in the late summer and early fall in ponds heavily vegetated with sago pondweed and similar submergent plants.

At dusk near these breeding sites this species may cause extreme annoyance and irritation to man and other animals.



Culiseta inornata (Williston) is the only species of this genus reported in significant numbers near the Great Salt Lake. It is very widely distributed and abundant as adults and in the immature stages. It is not considered a great pest or potential vector of disease because it rarely feeds on man, confining its feeding generally to larger wild and domestic animals. Therefore, the control of this species is not as important as other species present in this area.

Tabanids - Deer and Horse Flies

Eight species of tabanids that have been reported in the area are: *Chrysops discalis* Williston; *Hybomitra sonornensis* Osten Sacken; *Tabanus punctifer* Osten Sacken; *Tabanus productus* Hine; *Tabanus similis* Macquart; *Chrysops aestuan* van der Wulp; *Chrysops fulvaster* Osten Sacken; and *Atylotus incisuralis* (Marq). There may be other species present.

Of these eight species *Chrysops discalis*, the picture winged deer fly, is the most abundant pest and principal vector of the tularemis pathogen. The horse fly, *Hybomitra sonornensis*, is second in numbers and importance.

The adults of tabanids are produced in one generation per year appearing in early May and continuing as late as November. The population of the deer fly, *Chrysops discalis*, attains the peak in June or July and the horse fly, *H. Sonornensis* in, September or October.

These Tabanids mate soon after emerging from the pupa stage and females lay their eggs in masses on the vegetation over water or moist marsh ground. The egg masses contain an average of approximately 400 eggs. A female may lay more than one egg mass.

The eggs hatch within a few days of deposition and the larvae drop into the water or soil and burrow into the mud. They feed on organic material in the soil, pass through four instars and pupate in the following year. Larvae are generally found in the mud in shallow water near emergent vegetation, particularly salt grass.

Where water has been withdrawn from impoundments or waterways exposing the bottom soil, pupation and eventual emergence of the adult occurs at the last larval instar. Where water is maintained during the season at near constant level, the last larval instar is forced to migrate to the moist soil at the margin of the water where it pupates just beneath the surface of the soil. The adults emerge from the pupal case and soil covering.

Gnats

"Gnats" is a common name that refers to several families, genera and species of insects included in the order *Diptera*. Gnats are commonly classified as biting or nonbiting. Both kinds are present in abundance on the marshes and create considerable annoyance to man and to other animals. The biting gnats are present in greatest numbers and are most annoying around the Great Salt Lake from about the middle of April until the end of June. The nonbiting gnats are present from April to early November.

Biting Gnats

Leptoconops kerteszi Kieffer is the most abundant, widely distributed and annoying gnat around the Great Salt Lake. There are other biting gnats of the genus *Culicoides* that have been collected in this area but they seem to be confined to localized areas and are usually not present in sufficient numbers to constitute a problem requiring extensive control measures.

Nonbiting Gnats

Seven related genera of gnats were collected, six represented by one species each. Five species of gnats of the genus *Tendipes* have been collected on the marshes near the Great Salt Lake. These include *Tendipes utahensis* Malloch, *T. plumosus*, Linn.; T. *tentans* Fabr., *T. decorus* Johan., and *T. fumidus* Johan.

Tendipes utahensis is the most abundant and annoying of these species with *T. plumosus* second in importance. Adults of *T. utahensis* appear in February or March and are present until freezing temperatures in November or December. Population peaks are attained in May and June and again in September and October with minor peaks in July and August.

VERTEBRATES

Fish Habitat Classifications

The streams and impoundment of the Great Salt Lake area have been rated numerically for esthetics, availability, and productivity, ranging from 1 to 5. This value was then multiplied by a factor of 1 for esthetics, 2 for availability and 4 for productivity. The subtotals were then added to obtain a composite rating, which was used to assign a water to a class. Classes range from Class I, the best fishing waters, to Class VI, the poorest. Waters of the study area ranged from Class II to Class V (Tables 3 and 4).

Fish Species

A total of 12 species of fish have been identified from the Great Salt Lake area:

Cutthroat Trout, *Salmo clarki* Richardson. The only trout native to Utah. Found in the Davis County portion of the Great Salt Lake area.

Rainbow Trout, *Salmo gairdneri* Richardson: Native to the Pacific coast. Introduced into Utah in 1883. Found in the Davis County and Locomotive Springs portions of the Great Salt Lake area.

Brown Trout, *Salmo trutta* Linnaeus. Native to Europe. Introduced into Utah in about 1899. Found in the east portion of the Great Salt Lake area.

Brook Trout, *Salvelinus fontinalis* (Mitchill). Native to northeastern North America. Introduced into Utah in 1884. Found only in Farmington Creek in the Great Salt Lake area.

Carp, *Cyprinus carpio* Linnaeus. Native to Asia. Introduced into Utah in 1881. Found in most drainages of the Great Salt Lake area.

Utah Chub, *Gila atraria* (Girard). Native to the drainage basin of ancient Bonneville. Found in most of the drainages in the Great Salt Lake area.

Redside Shiner, *Richardsonius balteatus hydrophlox*

Table 3. Impoundments of the Great Salt Lake Area

Box Elder County					
Locomotive Springs	Class	Rating	Maximum Capacity:	Surface acres	53
	III	22		Acre feet	159
			Minimum capacity:	Surface acres	53
				Acre feet	159
			Conservation pool:	none	
			Level required for minimum habitat:	Surface acres	53
				Acre feet	159
Willard Bay Reservoir	Class	Rating	Maximum capacity:	Surface acres	10,000
	II	29		Acre feet	159,000
			Minimum capacity:	Surface acres	5,000
				Acre feet	45,000
			Conservation pool:	none	
			Level required for minimum habitat:	Surface acres	5,000
				Acre feet	45,000
Tooele County					
Timpie Springs	Class	Rating	Maximum capacity:	Surface acres	.5
	III	19	Minimum capacity:	Surface acres	.5
			Conservation pool:		.5
			Level required for minimum habitat:	Surface acres	.5

(Cope). Native to the Bonneville Basin. Found in all suitable waters of the Great Salt Lake area.

Speckled Dace, *Rhinichthys osculus* (Girard). One of the most widespread and variable fishes in western United States. East Great Salt Lake area.

Longnose Dace, *Rhinichthys cataractae* (Valenciennes). Known in Utah only from streams tributary to Utah Lake and Great Salt Lake; East Great Salt Lake area.

Fathead Minnow, *Pimephales promelas* Refinesque. Generally limited to the Colorado River drainage in Utah, but found in Willard Bay Reservoir.

Utah Sucker, *Catostomus ardens* Jordan and Gilbert. Native to the basin of old Lake Bonneville. East side of Great Salt Lake area.

Mountain Sucker, *Pantosteus platyrhynchus* (Cope). Native to the drainage basin of ancient Lake Bonneville.

Channel Catfish, *Ictalurus punctatus* (Rafinesque) Native to the eastern United States. Introduced into Utah in 1911. East side of the Great Salt Lake area.

Black Bullhead, *Ictalurus melas* (Rafinesque). Introduced into Utah in 1871. East side of Great Salt Lake area.

Rainwater Killifish, *Lucania parva* (Baird and Girard). Native to the Atlantic coast of North America. Found only in Timpie Springs in Utah.

Western Mosquitofish, *Gambusia affinis affinis* (Baird and Girard). Native to central United States. Introduced into Utah for mosquito control in 1931.

White Bass, *Roccus chrysops* (Rafinesque). Introduced into Utah Lake in 1955. Native to the Great Lakes and Midwest. Found in the Jordan River.

Largemouth Bass, *Micropterus salmoides* (Lacepede). Introduced into Utah in 1890. Found in suitable habitat in Great Salt Lake area.

Green Sunfish, *Lepomis cyanellus* Rafinesque. Introduced into Utah in 1890 in the Weber River and Utah Lake. East side of Great Salt Lake area.

Bluegill, *Lepomis macrochirus* Rafinesque. Introduced into Utah in 1890 in the Weber River and Utah Lake.

Black Crappie, *Pomoxis nigromaculatus* (LeSueur). Introduced into Utah in 1890. East side of Great Salt Lake area.

Yellow Perch, *Perca flavescens* (Mitchell). Introduced into Utah in 1890 in the Weber River.

Table 4. Streams of the Great Salt Lake Area

Box Elder County				
Bear River	Class III	Rating 18	Minimum flow: Minimum habitat:	16 Cubic feet per second 16 Cubic feet per second
Davis County				
Bear (Haight) Creek	Class III	Rating 19		
Farmington Creek	Class III	Rating 21	Minimum flow: Minimum habitat:	10 Cubic feet per second 10 Cubic feet per second
Farmington Creek (lower section)	Class IV	Rating 11		
Holbrooke and Stone Creeks	Class III	Rating 19	Minimum flow: Minimum habitat:	1 Cubic foot per second 1 Cubic foot per second
Holmes Creek	Class III	Rating 18		
Kay's Creek	Class IV	Rating 11		
Mill Creek	Class III	Rating 18		
Salt Lake County				
Jordan River	Class V	Rating 9	Minimum flow: Minimum habitat:	30 Cubic feet per second 30 Cubic feet per second
Weber County				
Weber River	Class IV	Rating 16	Minimum flow: Minimum habitat:	40 Cubic feet per second 40 Cubic feet per second

Walleye, *Sitzostedion vitreum vitreum* (Mitchill). Introduced into Utah in 1951. Found in Willard Bay Reservoir.

Herpetofauna of the Great Salt Lake Area

Very little serious work has been done on the amphibians and reptiles of Utah, especially in the area included in the current study.

The concern expressed by Woodbury in 1931 still exists regarding the need for further investigations into geographical distribution, faunal relations, and the derivation of Utah's reptilian fauna. He presented some basic ideas concerning reptilian faunal relations for Utah.

> "Our reptilian fauna is derived from various sources. Since reptiles usually spread from the warmer parts of the earth toward cooler regions, it is not surprising that most of our forms belong to species whose range lies mostly to the south of us. In general, it appears that northern Mexico has been the center of dispersal from which most of the U. S. forms have been derived, spreading to the northeast through Texas, to the north through the Rocky Mountains, and to the northwest through the deserts of Arizona.
>
> Some forms which perhaps reached Utah from the south, have continued to spread beyond our limits and may in a sense be considered Great Basin forms. We might include here *Crotaphytus c. baileyi, Crotaphytus wislizenii, Sceloporus g. graciosus, Phrynosoma d. ornatissimum, Masticophis t. taeniatus, Rhinocheilus lecontei*, and *Crotalus confluentus lutosus*.
>
> There is a group that appears to have reached Utah from the west through the deserts of Nevada. In this group, we may place *Sceloporus o. biseriatus, Phrynosoma platyrhinos, Eumeces skiltonianus*, and *Thamnophis o. vagrans*.
>
> One form, *Coluber c. mormon*, appears to have its closest connection with the northwest.
>
> Two forms, at least, appear to have differentiated here in Utah and spread from this dispersal point. These include *Uta stansburiana stansburiana* of the Salt Lake Basin, and *Charina*

> *bottae utahensis* of the mountains of northern Utah. A third form, *Crotalus c. concolor*, appears to have differentiated along the Colorado River Basin in eastern Utah, western Colorado and southern Wyoming."

One form mentioned by Woodbury, *Uta stansburiana stansburiana*, appears to have differentiated in the study area.

Herpetofauna Species

Eight amphibians, two turtles, nine lizards and eight snakes were identified from the Great Salt Lake Area.

Amphibian Species

Tiger Salamander, *Ambystoma tigrinum nebulosum* Hallowell. North, northeast and east Great Salt Lake area.

Great Basin Spadefoot, *Scaphiopus hammondi intermontanus* Cope. Entire Great Salt Lake area.

Woodhouse's Toad, *Bufo woodhousei* Girard. North, northeast, east and southeast portions of Great Salt Lake area.

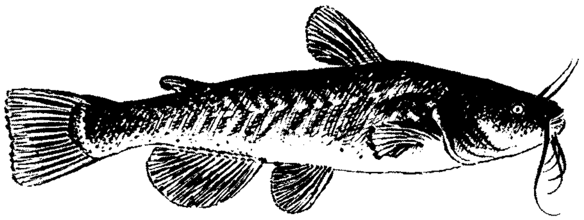
Chorus Frog, *Pseudacris nigrita* Le Conte. North, northeast, east and southeast Great Salt Lake area.

Bullfrog, *Rana catesbeiana* Shaw. East portion of Great Salt Lake area.

Green Frog, *Rana clamitans* Latreille. Lower Weber River. Does not occur naturally in the West.

Leopard Frog, *Rana pipiens* Schreber. Entire Great Salt Lake area in suitable habitat.

Western Spotted Frog, *Rana pretiosa pretiosa* Baird and Girard. East portion of Great Salt Lake area.



Turtle Species

Painted Turtle, *Chrysemys picta*. Not normally found in Utah, but collected at Radial gate, Ogden Bay WMA.

Pond Terrapin, *Pseudemys scripta* Schoepff. Normally found only from east Colorado and east New Mexico and eastward into southeast United States. The young are widely sold as pets. Specimen collected at the causeway on south end of Antelope Island.

Lizard Species

Western Collared Lizard, *Crotaphytus collaris bicinctores* Smith and Tanner. Northwest, north, northeast, east, southeast, and south portions of Great Salt Lake area.

Leopard Lizard, *Crotaphytus wislizeni* Baird and Girard. North and west portions of Great Salt Lake area.

Great Basin Fence Lizard, *Sceloporus occidentalis biseriatus* Hallowell. Southwest, south, and southeast portions of Great Salt Lake area.

Sagebrush Lizard, *Sceloporus graciosus graciosus* Baird and Girard. Entire Great Salt Lake area.

Northern Side-blotched Uta, *Uta stansburiana stansburiana* Baird and Girard. Entire Great Salt Lake area, including Carrington Island, and Fremont Island.

Salt Lake Horned Toad, *Phrynosoma douglassi ornatum* Girard. Northwest, north, northeast, east, and southeast portions of Great Salt Lake area.

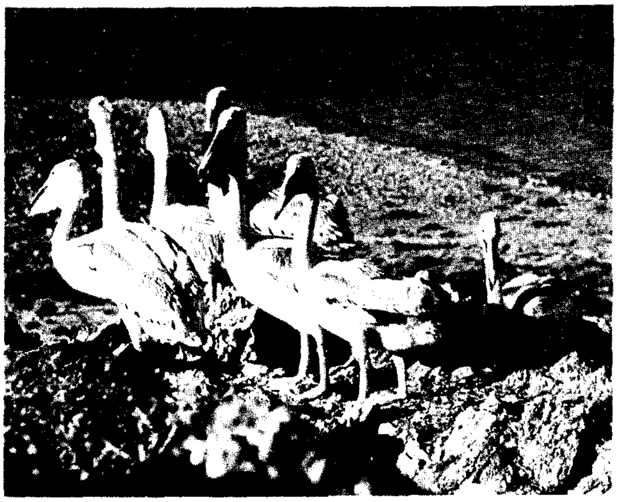
Great Basin Horned Toad, *Phrynosoma platyrhinos platyrhinos* Girard. Northeast, east, southeast, south and southwest portions of Great Salt Lake area.

Western Skink, *Eumeces skiltonianus utahensis* Tanner. Northwest, north, northeast, east, southeast, and south portions of Great Salt Lake area.

Western Whiptail, *Cnemidophorus tigris tigris* Baird and Girard. Entire Great Salt Lake area, including Fremont Island, Stansbury Island and Dolphin Island.

Snake Species

Rubber Boa, *Charina bottae utahensis* Van Denburgh. Normally limited to the Northern Wasatch Mountains, but collected on the East side of Promon-



tory Mountain 11 miles south of Golden Spike NHS.

Wandering Garter Snake, *Thamnophis elegans vagrans* Baird and Girard. Entire Great Salt Lake area.

Red-Sided Garter Snake, *Thamnophis sirtalis parietalis* Say. North, northeast, east, southeast, and south portions of Great Salt Lake area.

Western Yellow-Bellied Racer, *Coluber constrictor mormon* Baird and Girard. Northwest, north, northeast, east, southeast and south portions of Great Salt Lake area.

Desert Striped Whipsnake, *Masticophis taeniatus taeniatus* Hallowell. Entire Great Salt Lake area, including Fremont Island.

Great Basin Gopher Snake, *Pituophis catenifer deserticola* Stejneger. Entire Great Salt Lake area.

Desert Night Snake, *Hypsiglena torquata deserticola* Tanner. Great Salt Lake area in suitable habitat.

Great Basin Rattlesnake, *Crotalus vilridis lutosus* Klauber. Great Salt Lake area in suitable habitat.

Birds of the Great Salt Lake Area

Great Salt Lake Islands and Birds

Records show that in years past, six of the islands in the Great Salt Lake were important rookeries for white pelicans, California gulls, Treganza great blue herons, and double-crested cormorants. The islands are Gunnison, Hat, Egg, Carrington, Dolphin, and White Rock. Only three of these remain as important rookeries; Egg Island and White Rock for California gulls and Gunnison Island for white pelicans.

Waterfowl Production

Utah has always been considered an important waterfowl state, both for breeding of ducks and geese, and for furnishing excellent feeding grounds for migratory waterfowl.

Annually, counts are made on the eight state Waterfowl Management Areas and one Federal Refuge located in the Great Salt Lake area to obtain reliable estimates of the waterfowl species nesting in the area.

In addition to the breeding species composition counts, aerial and dikeline trend counts are made of the number of breeding pairs at the state waterfowl management areas and on selected trend areas.

Figures concerning waterfowl use, production, and peak numbers show waterfowl use of the marshes to be extremely high, with a peak fall population of nearly 3/4 of a million birds; this includes *only* managed public areas. Although production figures are not available for the entire marsh, or even a majority of it, state waterfowl management areas can be considered to equal Bear River's waterfowl production per acre, as can the natural marsh areas around the lake, especially the Kaysville-Layton marsh complex and the Jordan River marshes. These areas together produce approximately 175,000 ducks and 10,000 Canada geese annually.

Management and control of these areas are essential to the perpetuation of huntable populations of Great Basin Canada geese, prized by western waterfowl hunters.

These areas also provide for the needs of at least three fourths of the whistling swan population of the entire Pacific Flyway during both spring and fall migrations.

Approximately 30 percent (3,000,000 of 10,000,000) of the ducks of the Pacific and Central Flyways use the Great Salt Lake marshes.

Hunter Use

Marshlands surrounding Great Salt Lake in northern Utah are, without question, among the best for waterfall hunting in the United States. Here, considerable marsh restoration and development have been undertaken by State and Federal Governments and private clubs. These developments are mostly shallow, diked impoundments which catch and store the waste waters from cities and agriculture. Managed marshlands around the lake total over 150,000 acres. There are also several thousand acres of unmanaged marsh on state and private grounds. As a result, extensive marshes are open to public hunting.

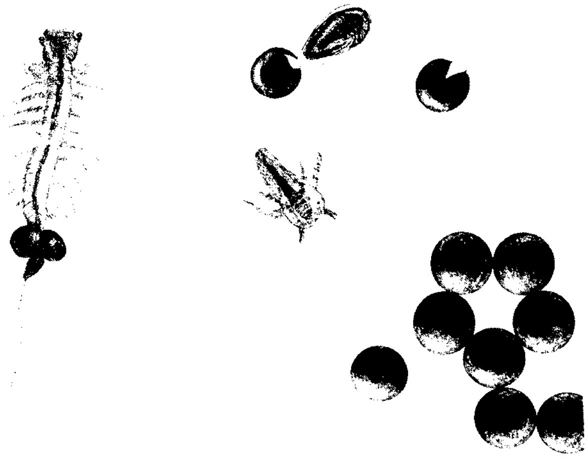
These shallow impoundments have demonstrated that they form valuable waterfowl production areas. The majority of all Canada geese shot in northern Utah are raised locally, and surprisingly the number of ducks produced by these marshes almost equals the annual kill. Most of this kill is from the thousands of ducks that migrate through and feed on the marshes. Many ducks reared locally leave the State early.

Pintail, mallard and green-winged teal are the most common ducks in the hunter's bags around Great Salt Lake. The shoveller, gadwall, and baldpate also are quite common. Canada and snow geese are shot both in the marshes and in the grainfields north of the lake.

Excellent waterfowl habitats are found along the streams which enter Great Salt Lake. The Bear, Weber, and Jordan rivers have oxbows and marsh areas that provide hunting opportunities and offer nesting and feeding areas for waterfowl.

Non-consumptive Use

Aside from the consumptive use of waterfowl, there is a growing trend toward non-consumptive uses by bird watchers, photographers and nature enthusiasts other than waterfowl hunters. Over 25,000 days use are recorded annually on state waterfowl management areas, with at least an additional 15,000 days use on the Bear River refuge. As the figures for Bear River show, there is an increasing number of people visiting this area simply to observe the wildlife rather than consume it.



Brine Shrimp and eggs.

Studies of the avian fauna in the Great Salt Lake Region are numerous; however, most of the available information deals with the colonial-nesting birds of the Great Salt Lake Islands, principally the California Gull *(Larus Californicus)* and White Pelicans *(Pelecanus erythrorhynchos)*. Stansbury in 1852 was the first to document island nesting, but before this in 1848, Carrington directed a party of men to Antelope and Fremont Islands where they found vast nesting areas. More recently, William H. Behle of the University of Utah has written on the bird life of the Great Salt Lake. While dealing primarily with the colonial-nesting birds of the lake, he also provides an extensive history of early explorations and findings on the Great Salt Lake Islands.

Bird Species

Of the 257 species of birds reported in the Great Salt Lake area, 117 reportedly nest in the area. In terms of abundance, 29 species are classified as abundant, 63 common, 77 occasional, 73 rare and 15 accidental or out of their range.

In reference to the habitat preferences of the birds, 112 species are associated almost exclusively with the extensive marshland areas of the lake. The most prominent of these species are the loons, grebes, ducks, geese, herons, ibis, plovers, sandpipers, phalaropes, gulls and terns.

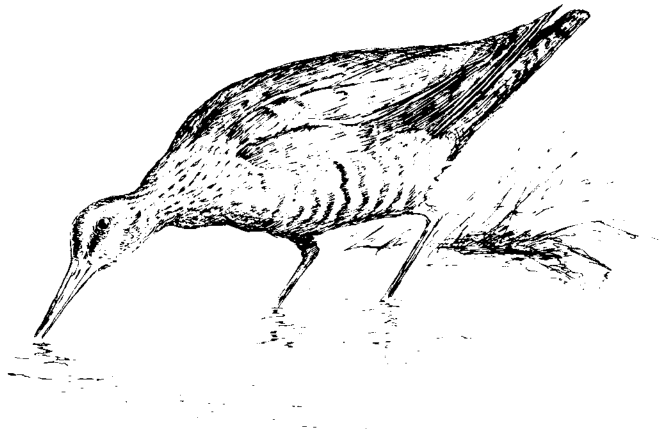
Most of the remaining species prefer the upland areas, which include the open and weedy fields, sagebrush, and thicket areas which surround the entire lake. The exception to this is the raptors, which may frequent all the habitat types in the Great Salt Lake area.

Only the more common of the 112 species of birds associated with marshlands of the Great Salt Lake area are listed in this account. For a complete checklist of the birds of the Great Salt Lake area see Publication No. 74-13 of the Division of Wildlife Resources entitled, "The Great Salt Lake Biotic System" published September, 1974.

The list which follows includes the common name, scientific name, season the species is found in the area, and relative abundance:

Seasons Present	Abundance
PR - Permanent Resident	a - abundant
Sp - Spring	c - common
S - Summer	o - occasional
F - Fall	* - nest in area
W - Winter	
M - Migrant	

Common Loon, *Gavia immer*, SpF - o
Eared Grebe, *Podiceps caspicus*, SpSF - c*
Western Grebe, *Aechmophorus occidentalis*, SpSF - c*
Pied-billed Grebe, *Podilymbus podiceps*, PR - c*
White Pelican, *Pelecanus erythrorhynchos*, SpSF - a*
Double-crested Cormorant, *Phalacrocorax auritus*, SpSF - c*
Great Blue Heron, *Ardea herodias treganzai*, SpSF - c*
Snowy Egret, *Leucophoyx thula brewsteri*, SpSF - c*
Black-crowned Night Heron, *Nycticorax nyticorax hoactli*, SpSF - c*
American Bittern, *Botaurus lentiginosus*, SpSF - o
White-faced Ibis, *Phegadis chihi*, SpSF - a*
Whistling Swan, *Cygnus columbianus*, SpF - a
Lesser Canada Goose, *Branta canadensis parvipes*, SpF - o
Great Basin Canada Goose, *Branta canadensis moffitti*, PR - a*
Snow Goose, *Chen hyperborea hyperborea*, SpF - a
Mallard, *Anas platyrhynchos platyrhynchos*, PR - a*
Gadwall, *Anas strepera*, SpSF - a*
Pintail, *Anas acuta*, SpSF - a*
Green-winged Teal, *Anas carolinensis*, SpSF - a*
Blue-winged Teal, *Anas discors*, SpSF - o*
Cinnamon Teal, *Anas cyanoptera*, SpSF - a*
Widgeon (Baldpate), *Mareca americana*, SpSF - a*
Shoveller, *Spatula clypeata*, SpSF - a*
Wood Duck, *Aix sponsa*, SpF - a
Redhead, *Aythya americana*, SpSF - a*
Ring-necked Duck, *Aythya collaris*, SpF - o
Canvasback, *Aythya valisineria*, SpF - c
Greater Scaup, *Aythya marila*, SpF - o
Lesser Scaup, *Aythya affinis*, SpF - c
Common Goldeneye, *Bucephala clangula*, SpF - o
Bufflehead, *Bucephala albeola*, SpF - o
Oldsquaw, *Clangula hyemalis*, M - o
White-winged Scoter, *Melanitta deglandi*, F - o
Ruddy Duck, *Oxyura jamaicensis*, SpSF - c*
Common Merganser, *Mergus merganser*, SpF - c
Red-breasted Merganser, *Mergus serrator*, SpF - c
Virginia Rail, *Rallus limicola*, SpSF - o*
Sora Rail, *Porzana carolina*, SpSF - o*
American Coot, *Fulica americana*, SpSF - a*
Snowy Plover, *Charadrius alexandrinus nivosus*, SpF-o*
Killdeer, *Charadrius vociferus*, SpSF - a*
American Golden Plover, *Pluvialis dominica dominica*, M - o
Wilson's Snipe, *Capella gallinago delicata*,SpF - c*
Long-billed Curlew, *Numenius americanus*, SpSF - c*
Whimbrel, *Numenius phaeopus*, M - a
Spotted Sandpiper, *Actitis macularia*, SpSF - o*
Solitary Sandpiper, *Tringa solitaria cinnamomea*, M - c
Willet, *Catoptrophorus semipalmatus*. SpSF - c*
Greater Yellowlegs, *Totanus melanoleucus*, SpF - a
Lesser Yellowlegs, *Totanus flavipes*, SpF - a
Pectoral Sandpiper, *Erolia melanotos*, M - c
Baird's Sandpiper, *Erolia bairdii*, M - c
Least Sandpiper, *Erolia minutilla*, SpF - c



Red-backed Sandpiper, *Erolia alpina pacifica*, M-0 o
Long-billed Dowitcher, *Limnodromus scolopaceus* , SpF- a
Western Sandpiper, *Ereunetes mauri*, SpF - c
Marbled Godwit, *Limosa fedoa*, SpF - c*
Sanderling, *Crocethia alba*, SpF - o
Avocet, *Recurvirostra americana*, SpSF - a*
Black-necked Stilt, *Himantopus mexicanus*, SpSF - a*
Wilson's Phalarope, *Steganopus tricolor*, SpSF - c*
Northern Phalarope, *Lobipes lobatus*, SpS - a
California Gull, *Larus californius*, SpSF - a*
Ring-billed Gull, *Larus delawarensis*, W - c
Franklin's Gull, *Larus pipixean*, SpSF - a*
Bonaparte's Gull, *Larus philadelphia*, S - c*
Forster's Tern, *Sterna forsteri*, SpSF - c*
Caspian Tern, *Hydroprogne caspia*, SpSF - o*
Black Tern, *Chlidonias niger*, SpSF - o*
Long-billed Marsh Wren, *Telmatodytes palustris plesius*, SpSF - a
Yellow-headed Blackbird, *Xanthocephalus Xanthocephalus*, SpSF - a*
Red-winged Blackbird, *Agelaius phoeniceus utahensis*, SpSF - a*

Mammals

The large size, changing levels, and receding of Lake Bonneville of the Pleistocene Age have had important influences on the distribution and subspeciation of small mammals of the Great Salt Lake area.

Stephen D. Durrant, in 1952, made the following comments regarding mammals and Pleistocence Lake Bonneville:

> No account of the history of Lake Bonneville and its effect upon mammals would be complete without some comments on its surviving remnant, Great Salt Lake. Studies of this lake, as they pertain to mammals, have a two-fold significance: first, the effects of Great Salt Lake on distribution and speciation and second, the vista

it unfolds in miniature of the effects of the large parent, Lake Bonneville. Seven distinctive subspecies appear to have evolved in this region. Great Salt Lake belongs to the late Postpluvial, and is no older than 2,000 years. Consequently, these subspecies of mammals now recognized as being endemic to the islands in the lake are no older. Those subspecies of mammals that have evolved on the islands in Great Salt Lake, and especially those on islands that have emerged only recently, give us a time scale on how long it takes some kinds of mammals to undergo subspeciation. Moreover, they enable us, in part at least, to interpret some of the effects of Lake Bonneville.

Mammal Species

A total of 64 species or subspecies of mammals have been identified from the Great Salt Lake area.

Sixteen different mammals have their type localities in the Great Salt Lake area. Seven of them are in Box Elder County, one in Weber County, one in Davis County, and seven in Tooele County.

A type specimen is an individual animal or plant from which a description of a species has been prepared. A type locality is the locality in which a type specimen was first collected.

In the following mammal species accounts, seven types are listed as rare, not because of declining numbers but because of limited range. Six are each limited to one or another of the Great Salt Lake islands. The seventh is found on only two of the islands.

In the species and subspecies accounts that follow, the common name is given first followed by the scientific name. The general code of relative abundance is also given with C for common, U for uncommon, and R for rare.

Vagrant Shrew, *Sorex vagrans monticola* Merriam (C). East shore of Great Salt Lake, Box Elder to Salt Lake County.

__________ S. *v. obscurus* Merriam (C). East shore of Great Salt Lake.

Little Brown Bat, *Myotis lucifugus carissima* Thomas (C). Entire Great Salt Lake area.

Big Brown Bat, *Eptesicus fuscus pallidus* Young (C). East shore of Great Salt Lake.

Horay Bat, *Lasiurus cinereus cinereus* (Beauvois) (C). Entire Great Salt Lake area.

Long-eared Bat, *Plecotis townsendii pallescens* Miller (U). East shore of Great Salt Lake.

White-tailed Jackrabbit, *Lepus townsendii townsendii* Backman (C). North half of Promontory mountains.

Black-tailed Jackrabbit, *Lepus californicus deserticola* Mearns (C). Entire Great Salt Lake area, including Fremont Island.

Mountain Cottontail, *Sylvilagus nuttallii grangeri* (Allen) (C). Southeast, east, northeast, north, and northwest Great Salt Lake area.

Pigmy Cottontail, *Sylvilagus idahoensis* (Merriman) (C). North, northwest, west Great Salt Lake area.

Yellow-bellied Marmot, *Marmota flaviventer nosophora* Howell (C). Northeast Great Salt Lake area.

Townsend Ground Squirrel, *Citellus townsendii mollis* (Kennicott) (R). Entire Great Salt Lake area.

Uinta Ground Squirrel, *Citellus armatus* (Kennicott) (C). East side of Great Salt Lake area.

Rock Squirrel, *Citellus variegatus utah* Merriam (C). East side of Great Salt Lake area.

Antelope Ground Squirrel, *Citellus leucurus leucurus* (Merriam) (C). Entire Great Salt Lake area.

Least Chipmunk, *Eutamias minimus pictus* (Allen) (C). Great Salt Lake area except east shore.

Northern Pocket Gopher, *Thomomys talpoides wasatchensis* Durrant. North, northeast, east Great Salt Lake area.

Valley or Botta Pockey Gopher, *Thomomys bottae aureiventris* Hall (C). Northwest Great Salt Lake area.

__________ *T. b. minimus* Durrant (R). Known only from Stansbury Island.

__________ *T. b. nesophilus* Durrant (R). Known only from Antelope Island.

__________ *T. b. albicaudatus* Hall (C). South, southeast, east Great Salt Lake area.

Little Pocket Mouse, *Perognathus longimembris gulosus* Hall (C). Northwest Great Salt Lake area.

Great Basin Pocket Mouse, *Perognathus parvus olivaceus* Merriam (C). Entire Great Salt Lake area, including Stansbury, Carrington and Antelope Islands.

Ord Kangaroo Rat, *Dipodomys ordii utahensis* (Merriam) (C). Northeast, east Great Salt Lake area, including Antelope Island.

__________ *D. o. cineraceus* Goldman (R). Dolphin Island (type locality) known only from type locality.

__________ *D. o. marshalli* Goldman (C). Northwest, west, south Great Salt Lake area, Bird Island (type locality).

Chisel-toothed Kangaroo Rat, *Dipodomys microps bonnevillei* Goldman (C). Northwest, west Great Salt Lake area; Kelton, (4,300 feet) (type locality).

__________ *D. m. russeolus* Goldman (R). Dolphin Island (4,250 feet) (type locality); known only from type locality.

__________ *D. m. alfredi* Goldman (R). Gunnison Island (4,300 feet) (type locality); known only from type locality.

__________ . *D. m. subtenuis* Goldman (C). South Great Salt Lake area; Carrington Island (4,250 feet) (type locality).

Beaver, *Castor canadensis rostralis* Durrant and Crane (U). East side of Great Salt Lake area.

Western Harvest Mouse, *Reithrodontomys megalotis ravus* Goldman (C). South Great Salt Lake area; North end of Stansbury Island (type locality).

__________ *R. m. megalotis* (Baird) (C). Entire Great Salt Lake area.

Canyon Mouse, *Peromyscus crinitus pergracilis* Goldman (C). Entire Great Salt Lake area; south end of Stansbury Island (type locality).

Deer Mouse, *Peromyscus maniculatus sonoriensis* (LeConte) (C). Entire Great Salt Lake area, Gunnison Island (type locality).

__________ *P. m. rufinus* (Merriam) (C). East side of Great Salt Lake.

__________ *P. m. inclarus* Goldman (R). Fremont Island, (type locality); Known only from type locality.

Pinyon Mouse, *Peromyscus truei nevadensis* Hall and Hoffmeister (C). Entire Great Salt Lake area.

Northern Grasshopper Mouse, *Onychomys leucogaster utahensis* Goldman (R). Entire Great Salt Lake area; south end of Stansbury Island (type locality).

Desert Wood Rat, *Neotoma lepida lepida* Thomas (C). Entire Great Salt Lake area.

_________*N. l. marshalli* Goldman (R). Carrington Island (type locality); Known only from Carrington and Stansbury Islands.

Bush-tailed Wood Rat, *Neotoma cinerea acraia* (Elliott) (C). Northwest, north, northeast, east Great Salt Lake area.

Muskrat, *Ondatra zibethicus osoyoosensis* (Lord) (C). North, northeast, east, southeast, south Great Salt Lake area.

Pennsylvania Meadow Mouse, *Microtus pennsylvanicus modestus* (Baird) (C). Northeast, east, southeast Great Salt Lake area.

_________*M. p. pullatus* (Baird) (C). East, southeast, south Great Salt Lake area.

Montane Meadow Mouse, *Microtus montanus nanus* (Merriam) (C). Northwest Great Salt Lake area.

_________*M. m. nexus* Hall and Hayward (C). Northeast, east, southeast, south, southwest Great Salt Lake area.

Norway Rat, *Rattus norvegicus norvegicus* (Berkenhout) (C). North, east, south Great Salt Lake area.

House Mouse, *Mus musculus* Linnaeus (C). Throughout Great Salt Lake area.

Porcupine, *Erethizon dorsatum epixanthum* Brandt (C). Entire Great Salt Lake area.

Coyote, *Canis latrans lestes* Merriam (C). Entire Great Salt Lake area.

Red Fox, *Vulpes fulva macroura* (Baird) (U). Northeast, east and southeast Great Salt Lake area.

Kit Fox, *Vulpes macrotis nevadensis* Goldman (C). North, northwest, west, southwest, south, southeast, Great Salt Lake area.

Gray Fox, *Urocyon cineroargenteus scottii* Mearns (U). Not normally found in study area, but observed at Farmington Bay, WMA and at Dove Creek Pass in Box Elder County.

Ring-tailed Cat, *Bassariscus astutus nevadensis* Miller (U). East Great Salt Lake area.

Long-tailed Weasel, *Mustela frenata nevadensis* Hall (C). Entire Great Salt Lake area.

Mink, *Mustela vison energumenos* (Bangs) (C). East side of Great Salt Lake area.

Badger, *Taxidea taxus taxus* (Schreber) (C). Entire Great Salt Lake area.

Striped Skunk, *Mephitis mephitis major* (Howell) (C). Entire Great Salt Lake area.

Spotted Skunk, *Spilogale gracilis saxatilis* Merriam (C). North Great Salt Lake area.

Mountain Lion, *Felis concolor kaibabensis* Nelson and Goldman (U). Stansbury Island.

Bobcat, Lynx *Felis rufus pallescens* Merriam, (C). Entire Great Salt Lake area.

Mule Deer, *Odocoileus hemionus hemionus* (Rafinesque) (C). Northwest, north, northeast, south Great Salt Lake area.

Bison, *Bison bison bison* (Linnaeus) (U). Antelope Island (Private herd).

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Note: Most of the Noxious Insect section is taken from that portion of "The Great Salt Lake Biotic System" (Division of Wildlife Resources Publication No. 74-13) prepared by Don M. Rees, Ph. D., University of Utah.

BIOLOGY OF THE SOUTH ARM OF THE GREAT SALT LAKE, UTAH

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INTRODUCTION

Throughout most of recorded history, the Great Salt Lake has been a relatively homogenous, saline ecosystem with a total dissolved solids (TDS) level of about 200 gm/l^{-1} (= about 20% salinity). This salinity level creates an extremely rigorous biological ecosystem with only a few plants and animals able to exist within the lake. The algae *Coccochloris elabens, Polycystis packardii, Aphanothece packardii, Microcystis packardii,* and *Aphanothece utahensis* and *Dunaliella viridis* (reported earlier as *Chlamydomonas* species) were the only plants consistently reported as growing within the lake. The lake fauna was reported to consist of three species, the brine shrimp *Artemia salina* (= *Artemia gracilis* Verrill) and the brine flies *Ephedra cinerea* (=*Ephedra gracilis* Packard) and *Ephedra hians.*

In 1957 the construction of a railroad causeway across the northern portion of the lake divided the lake into two ecologically distinct bodies of water, a northern arm and a southern arm. As a result of interference with lake circulation, the northern arm became salt saturated (TDS = ± 300 gm/l^{-1}) and the southern arm decreased in salinity to 113-129 gm/l^{-1}. As a result of these changes in salinity, changes have occurred in the compositon of the biological communities in the north and south arms. Thus, an apparent decrease in the diversity of species has been documented in the north arm (Post, 1977). Conversely, an increase in species diversity has occurred in the southern arm (Felix and Rushforth, in review).

The objective of this paper is to report on the present status of the south arm biota. Emphasis will be placed on organisms that actually live within the lake. The flora and fauna of the various islands in the lake and of the region surrounding the lake have been recently reported in other papers and will not be included here (Flowers and Evans, 1966; Rawley, Johnson and Rees, 1974).

Bacteria

Relatively few bacterial studies have been done on the southern Great Salt Lake (Frederick, 1924; Smith, 1936; Smith and Zobell, 1937), and such studies were done before the alteration of the lake's salinity. At that time 11 species of bacteria were reported as occurring within the lake (table 1). Bacterial studies have been initiated since the alteration in salinity to determine the concentration and survival time of coliform bacteria (Utah State Department of Health Report, 1965; 1968).

Table 1. Bacteria reported to occur within the Great Salt Lake prior to construction of the railroad causeway (Frederick, 1924).

Species	Description
*Micrococcus subflavus**	non-motile sphere
Bacillus cohaerens	motile rod, single or in pairs
Bacillus freudenreichii	motile rod, single or chains
Bacillus mycoides	rods in chains with spores
*Achromobacter solitarium**	slender motile rods
*Achromobacter album**	non-motile rods
*Achromobacter hartlebii**	motile single rods
Flavobacterium arborescens	non-motile rods, pairs or chains
*Bacterioides rigidus**	motile slender rods, single or in pairs
Serratia salinaria	single motile rods, non-motile in Great Salt Lake
*Cellulomas subcreta**	single motile rods, non-motile in Great Salt Lake

*Names not in current use in Bergey's Manual of Determinative Bacteriology (Eighth Edition).

A recent investigation of the northern lake reported that *Halobacterium* and *Halococcus* were the only bacterial genera present in the north arm, reaching concentrations of 1.0 x 10^{8} cells/ml^{-1} (Post, 1977). This apparent decrease in bacterial diversity is probably directly attributable to the rapid increase in salinity of the north arm.

Conversely, bacterial diversity in the southern arm has apparently not decreased. For instance, in a study of protozoa of the south arm, Evans (1960) reported the isolation of 15 distinct bacterial taxa. Likewise, our own observations lead us to conclude that south arm bacterial diversity has probably increased. Expanded research on southern arm bacterial floristics is necessary, and it is likely that interesting changes in the flora have occurred.

Protozoa

The earliest information on protozoa of the lake was included as part of a report on the fauna of the Great Salt Lake (Vorhies, 1917). Vorhies observed a small amoeba, similar to *Amoeba limax*, a ciliate similar to a species of *Urolepus* and a species of *Euglena*. He stated that there were several species of protozoa in the lake, but they were present in low numbers. Shortly after his report, Pack (1919) described two new species of ciliata from the lake. The first, *Urolepis packii* Calkins, was probably the same organism seen by Vorhies in 1917. The second, *Prorodon utahensis* Pack, has since been renamed *Chilophyra utahensis* (Pack, 1919). Both of these species were described as bacterial feeders. Kirkpatrick (1934) observed three species of protozoa in her Great Salt Lake algal cultures. Two of these may have been the same as those described by Pack. The third was a very small ciliate different from any previously described. David Jones, in 1944, described a small amoeba, *Amoeba flowersi*, and *Euglena chamberlini* from the lake. The former fits the description of the amoeba first reported in 1917 by Vorhies. Evans (1960) reported eight species of protozoa including species of *Cristigera, Cyclidium, Podophyra, Euplotes, Oikomonas*, a small amoeba, and two unidentified ciliates previously undescribed. He noted that all of these organisms were bacterial feeders except *Podophyra* which fed on *Euplotes*. Two additional species of protozoa have recently been described from the lake, *Pseudorohnilembus persalinus* (Evans and Thompson, 1964), and *Euplotes persalinus* (Reddy, 1971). Additionally the present authors have collected specimens of *Fabrea salina* from along the south shore of the lake and an undescribed diatom ingesting ciliate from periphyton samples.

Algae

The algal flora of the lake has been of interest to several investigators (Packard, 1897; Daines, 1917; Flowers, 1934, 1942; Flowers and Evans, 1966; Patrick, 1936; Cottam, 1942; Carozzi, 1962; Stephens and Gillespie, 1976; Felix and Rushforth, 1977, in review). Prior to 1966 a total of 16 species of algae had been reported as growing within the lake (table 2). However, several of these species have since been shown to be washed into the lake from surrounding less saline areas; they remain viable for a period, but are not actual residents of the lake.

At the present time the resident south arm flora consists of seven species of Chlorophyta (green algae), four species of Cyanophyta (blue-green algae), one species of Pyrrhophyta (dinoflagellate) and 17 species of diatoms (table 3). The most abundant of these species are the green alga *Dunaliella viridis* and the diatoms *Amphora coffeiformis, Navicula graciloides, Navicula tripunctata*, and *Rhopalodia musculus* (figures 1-6). This is significant since previous reports have indicated that diatoms were not part of the resident lake flora but rather grew in the less saline marshy areas surrounding the lake and in areas of freshwater inflow (Flowers, 1934; Flowers and Evans, 1966; Patrick, 1936). Also *Coccochloris elabens*, a periphytic blue-green alga, previously reported as the single most abundant algal species in the lake (Flowers and Evans, 1966), has been observed only infrequently and in small numbers by the present authors throughout three years of intensive study. An explanation for the reduction in the abundance of *C. elabens* as well as the increase in diatom populations in such a short time can be deduced from the preliminary experiments of Daines (1917) and Kirkpatrick (1934). Both of these investigators used various dilutions of Great Salt Lake water to grow algae in the laboratory. Both reported abundant growth of diatoms in dilutions of lake water between 7-17% salinity (specific gravity 1.050 - 1.1225). Conversely, *Coccochloris elabens* was most abundant at salinities of 22-26% (specific gravity 1.1675 - 1.222). Thus, decreasing salinity in the south arm would be predicted to foster diatom growth and limit the production of *C. elabens*, which is what we have observed.

Stephens and Gillespie (1976) reported the results of their experiments on determining annual algal production in the south arm. By sampling biweekly during the growing season of 1973 at two south arm stations, these investigators found that annual primary production averaged 145 g C/m^2. This rate is rather high, placing the south arm into the eutrophic category, but is not out of line with other hypersaline lakes in the world. The production occurred primarily during the spring bloom period and was composed mostly of a species of *Dunaliella*. We have not reperformed these experiments, but our observations since 1973 have indicated to us that production is below the 1973 level at the present time in the south arm proper. Farmington Bay, on the other hand, supports large yearly blooms of Chlorophyta and/or Cyanophyta. Preliminary observations we have made concerning this apparent decrease in south arm algal productivity cause us to believe that the most important reason is a decrease in the occurrence of *Dunnaliella*. Further experiments to confirm this are planned.

Brine Shrimp

Of all the organisms that inhabit the Great Salt Lake none is better known than the brine shrimp, *Artemia salina* (= *Artemia gracilis* Verrill). The brine shrimp is a small phyllopod invertebrate. The males are

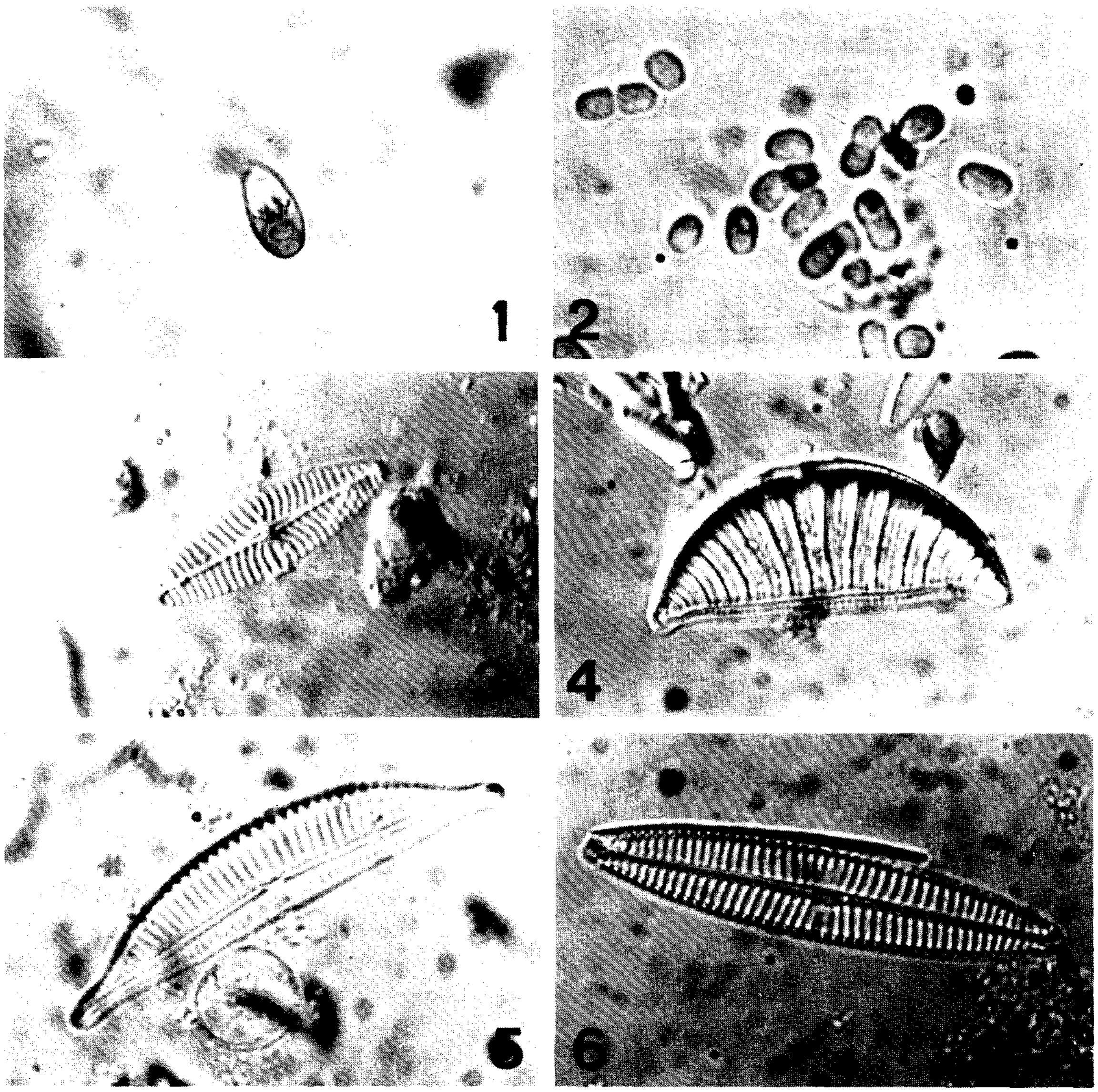
Table 2. Algal species reported to occur in the Great Salt Lake to 1966.

Species	Packard	Tilden	Daines	Kirkpatrick	Flowers	Flowers & Evans
	1879	1898	1917	1934	1934	1966
Aphanotheca utahensis		X	X	X	X	
Chara contraria		X				
Chlamydomonas species			X	X	X	X
Coccochloris elabens						X
Cymbella species			X			
Dichothrix utahensis		X				
Enteromorpha tubulosa		X				
Entophysalis rivularis						X
Microcystis packardii					X	
Navicula species			X	X		
Oscillatoria tenuis var. *natans*					X	
Oscillatoria tenuis var. *tergestina*					X	
Polycystis packardii	X	X				
Rhizoclonium species	X					
Tetraspora lubrica var. *lacunosa*					X	
Ulva marginata	X					

Table 3. Resident algal species presently occurring within the Great Salt Lake including the north arm and Farmington Bay (after Felix and Rushforth, in review).

Species	Farmington Bay	South Arm	North Arm
Coccochloris elebans		X	
Microcoleus lyngbyaceus	X	X	
Nodularia spumigena	X	X	
Spirulina major	X		
Carteria species	X		
Sphaerellopsis gloeocystiformis	X		
Dunaliella salina		X	X
Dunaliella viridis		X	X
Oocystis parva (?)	X	X	
Spermatozoopsis exultans (?)	X		
Treubaria triappendiculata	X		
Glenodinium species	X		
Cyclotella meneghiniana	X		
Chaetoceros muelleri	X		
Biddulphia levis	X	X	
Navicula graciloides	X	X	
Navicula lanceolata	X	X	
Navicula tripunctata	X	X	
Navicula tripunctata var *schizonemoides*	X	X	
Navicula species 1	X	X	
Entomoneis pulchra (?)	X	X	
Amphora coffeiformis	X	X	
Amphora delicatissima	X	X	
Rhopalodia musculus	X	X	
Nitzschia acicularis	X		
Nitzschia epithemoides	X	X	
Nitzschia fonticola	X	X	
Nitzschia palea	X	X	
Surirella striatula	X	X	

8-10 mm long and the females slightly larger, 10-12 mm. Coloration varies from pale green to red. The color of the shrimp does not appear to be correlated to the salinity since all color variations can generally be found at all salinities. Sexual reproduction usually begins in April and continues during the summer. During the summer the primary means of reproduction for the shrimp is by the production of parthenogenic eggs. These eggs are thin walled, hatch internally and produce a larger proportion of females than males (Relyea, 1937). Late in the summer the shrimp produce thick-walled over-wintering eggs which are not parthenogenic. These eggs lie dormant throughout the following winter. They float on the water and are often congregated into windrows which frequently accumulate along the lake shore, sometimes forming large masses. With the coming of winter the adult shrimp die. It has generally been thought that adult shrimp died when the lake temperatures dropped below 6° C. However, adult *Artemia* have been observed by the authors and others during the winter at water temperatures below 6°C. Such occurrences are generally in the Silver sands marina and in sheltered pools along the south shore of the lake (W. Katzenberger, personal communication). In the spring, as the water temperature increases to approximately 9°C, the winter eggs begin to hatch. The eggs also seem to be stimulated into hatching by sudden reductions in salinity. This can be seen in areas where fresh water enters the lake during the spring run-off. When the nauplii emerge from the eggs they immediately begin to



Figures 1-6. Examples of some of the most prevalent algal species currently growing in the south arm of the Great Salt Lake. Figure 1, *Dunaliella viridis* (X2000); Figure 2, *Coccochloris elebans* (X4500); Figure 3, *Navicula graciloides* (X3150); Figure 4, *Rhopalodia musculus* (X3125); Figure 5, *Amphora coffaeformis* (X4500); Figure 6, *Navicula tripunctata* (X3100).

feed on phytoplankton. The main hatch of eggs occurs during the peak growth of *Dunaliella viridis*, and this alga provides the growing nauplii with a nutritious and abundant food supply. Large numbers of feeding shrimp reduce the population of *Dunaliella*, although to what extent is still problematical (Stephens and Gillespie, 1976). Katzenberger (Great Salt Lake State Park aquatic specialist) has noted changes in the turbidity of the lake as a result of the brine shrimp feeding on the algae. He has recorded changes in seechi disc readings of less than 1 meter to greater than 4 meters within a two week period due to the decrease in algal concentration (personal communication).

No natural parasites or pathogens have been reported for *Artemia*. Predation by waterfowl and a small corixid beetle has been observed, but it seems to be of little significance in population dynamics of shrimp in the lake.

Brine Flies

Perhaps the most conspicuous invertebrate that inhabits the Great Salt Lake is the brine fly. Two species of brine fly have been identified. They are *Ephedra cinerea* Jones (= *Ephedra gracilis* Packard) (figure 7) and a larger species *Ephedra hians* Say. *Ephedra cinerea* is by far the most abundant of the two in the south arm, outnumbering *E. hians* by a ratio of 100:1 (B. Rosay, Salt Lake County Mosquito Abatement, personal communication). Garvanian and Havertz (1973) estimated the total number of adult flies along the lake shore to be approximately 3.7 X 10^8 flies per mile of beach during peak concentrations. While the flies do not bite, their sheer numbers can be awesome. The following is an account of Dr. E. A. Schwartz (1891), a Canadian entomologist, on the number of flies observed one summer day in the late 1800's.

"On June 25th the number of flies had already considerably increased, but on July 4th, when the little bathing establishment at Syracuse, on the eastern shore of the lake, was visited the number of flies was really alarming. On this point there are numerous shallow pools close to the lake beach, between the railroad dam and the dykes of the salt works, and the flies completely covered the edges and surface of the pools forming an unbroken coal-black mass . . . fortunately the flies could be driven away to some extent, and the roar of the rising flies is such to drown the noise of the railroad trains passing nearby."

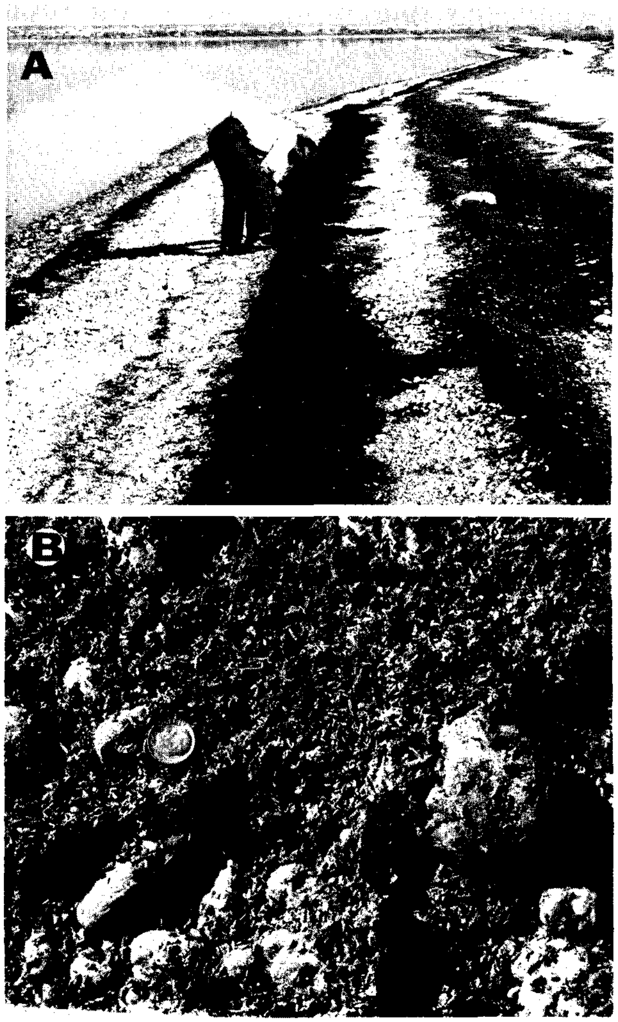


Figure 7. Pupal cases of the brine flies *Ephedra cinerea* and *Ephedra hyans*. A is a view of the Antelope Island causeway with windrows of pupal cases. B is a close-up of a mass of pupal cases.

The brine fly has been noted by numerous investigators (Allen, 1926; Kirkpatrick, 1934; Woodbury, 1936; Rees, 1942; Flowers and Evans, 1966; and others). However, after some unsuccessful attempts to control fly numbers along Sunset and Silver Sands beaches, it was recognized that little was really known about the biology of the fly, especially the aquatic larval stages (Nielsen, 1967). Since then several investigations on brine fly biology have revealed considerable information.

The adult flies are small, 3-6 mm in length and black in color. They have an average life span of 3-5 days and observations indicate they feed on bacteria and algae that grow on the surface of rocks or wood along the shoreline (Garvanian and Havertz, 1973). Egg laying is continuous throughout the summer. Each female lays approximately 75 eggs, either on or beneath the surface of the water. The latter is accomplished by the female actually walking under water while surrounded by a bubble of air (Rees, 1942; B. Rosay, personal communication). The eggs hatch into long cylindrical larvae that consume large quantities of algae and decaying organic detritus in the lake. Larvae are distributed in the lake at depths from a few millimeters to several meters, especially in areas where algal "reefs" have formed (Winget, *et al.*, 1969). The larvae attach themselves to the fissures in the "reefs" and exist completely submerged, obtaining their oxygen by means of tracheal gills. Pupation occurs in the final larval skin. Laboratory observations of the larvae indicate a very high natural mortality and a low rate of pupation by those surviving (Nabrotzky, *et al.*, 1973). Adults emerge from the puparium enclosed in a bubble of air formed within the pupal case. They rise to the surface of the water and are often driven by the wind into massive windrows. These windrows are frequently pushed onto shore where they form great black masses. The life cycle of the fly is estimated to be 3-4 weeks in duration (Jorgensen, 1969), though the length of time for each stage has not yet been determined. Under laboratory conditions, 7-10 days are required for eggs to hatch (Winget, *et al.*, 1969). It has yet to be determined if the flies over-winter in the egg stage or as puparia or whether any of the larvae are active during the winter months.

Aquatic Insects

The earliest report of invertebrates other than brine shrimp or brine flies occurring within the lake was made by Allen (1926) when he reported the occurrence of small corixids in the southern portion of the lake. However, shortly thereafter, Woodbury (1936) stated that no invertebrates other than *Artemia* and *Ephedra* were present within the lake. Recently specimens of adult corixid beetles were collected from the Silver Sands Marina by Edwin Rawley, Utah Division of Wildlife Resources. These were subsequently sent to the National Museum in Washington, D. C. for identification. They were identified as *Trichocorixia verticalis* Fiber. According to Dr. Don Rees, University of Utah, who has also collected specimens of this corixid along the west shore of Antelope Island, these insects do not reproduce within the lake but fly to less saline areas near the margin of the lake to mate and deposit their eggs.

Winget (in review) reported collecting numerous specimens of a corixid, identified as *Trichorixia verticalis* var. *interiores*, from many areas of the south arm. He has collected not only the adults but also numerous immature specimens. Based on the presence of flightless immature specimens he concluded that this corixid is a true inhabitant of the lake since it would not be possible for flightless immature corixids to be present in significant numbers several miles from the nearest freshwater source if the beetle did not reproduce within the lake.

We have also collected specimens of a small corixid, probably *T. verticalis*, from the Silver Sands marina and more especially from Farmington Bay on many occasions. During the summer of 1976 these insects were so numerous in Farmington Bay that in a sampling of 100 liters of water they could not all be contained within a 30 ml plankton vial. These corixids have been observed to prey upon brine shrimp in Farmington Bay (Hayes, 1971). The effect of this predation on the brine shrimp population has yet to be investigated.

Conclusions

Even though the environment of the south arm of the Great Salt Lake is hypersaline and biologically rigorous, this body of water supports a relatively diverse ecosystem. Furthermore, this ecosystem is in a state of flux due to changing salinity patterns. The algal flora has apparently increased dramatically in species number, particularly due to an influx of diatoms. Unfortunately, less is known about other groups of organisms due to a lack of baseline data and/or post-causeway comparative studies. In our opinion, it is imperative to begin and continue biological and water chemistry monitoring studies to be able to document future changes. This is not only of biological interest and import but is necessary in the establishment of sound management procedures for the Great Salt Lake.

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BIOLOGY OF THE NORTH ARM

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ABSTRACT

The extreme stress of high salt, about 360 g/1, and low oxygen solubility in the north arm of the Great Salt Lake has led to a biological community of low diversity and few species. Those organisms with adaptive mechanisms evolved to withstand the rigors of this harsh environment occur in numbers large enough to color the water a wine red. Nutrients seem abundantly available except for an inorganic source of nitrogen. The bacteria supply what little ammonia is available for the algae and the algae in turn excrete organic matter used by the bacteria. Organic nitrogen is plentiful but possibly in a form unavailable to the bacteria since it does not seem to support their growth. Each of the biological members, bacteria, bacteriophage, algae, brine fly and brine shrimp is discussed, as well as the community as a whole.

INTRODUCTION

The part of the Great Salt Lake lying north of the railroad causeway has very little freshwater inflow. What there is, is supplied chiefly by precipitation on the lake surface and a few small springs around the margin. Evaporation during the summer months produces a water level lower than the south end of the lake. Consequently there is a flow of water, containing suspended and dissolved organic matter and salt, from the south into the north arm. Over the years, the salt content of the north arm water has slowly increased until it has reached near saturation for sodium chloride. Table 1 shows the relative ionic composition of the north arm in 1975.

THE CHEMICAL MILIEU

The very high level of salt, especially sodium chloride, and the low level of dissolved oxygen create an extreme environmental stress on life-forms entering the lake. At one time the Great Salt Lake (Scientific American, 1861), and other similar bodies of water, were thought to be sterile; devoid of life. Zobell et al. (1937) and more recently Stephens (1974) have reviewed the history of observations on life in the Great Salt Lake. Smith and Zobel (1937) were the first to show the presence of a bacterial community in the lake.

Table 1. Ions in the north arm of the Great Salt Lake, 1975

	g/l	eq./l
Ca	0.3	.02
K	6.7	.17
Mg	11.1	.91
Na	105.4	4.58
Cl	181.0	5.10
SO_4	27.0	.56
HCO_3	0.5	.01
CO_3	0.3	.01
Br	0.2	.001
Total	332.5	
Cation Equiv.		5.68 +
Anion Equiv.		5.681 -
pH	7.7	

One of the consequences of extreme stress is to reduce the diversity of organisms present and at the same time increase the number of individuals of those species which are able to adjust to the environment (table 2). Only a few species have been able to adapt to the harsh north arm environment and these have flourished. Other organisms may occur in much smaller numbers, but much less is known about them.

NUTRIENTS

Part of the dissolved salts, especially phosphate, nitrate, ammonium, and bicarbonate, is necessary for the growth of the algae and other organisms. Table 3 records observations of biologically important chemicals for the period 1973-77 (Post, 1977a and unpublished). Phosphate is plentifully available both as soluble orthophosphate and as particulate phosphate (total P minus o-PO_4-P). Concentrations of both forms in the water are highest near the sediment surface, as would be expected, and several hundred times higher in the sediments (Stube and others, 1976).

Inorganic nitrogen was encountered only in the form of ammonium ion and in only about 55% of the samples. The remaining samples had no detectable ammonia present. Nitrate and nitrite have not been detected in several years of sampling. Ammonia appears to be the only inorganic nitrogen form available to the algae, and then only sporadically. Also, nitrogen fixation by organisms in the north arm has not been demonstrated (Post, 1977a).

Table 2. Kinds, numbers and biomass of organisms in the north arm of the Great Salt Lake 1973-1977. (Post, 1977a; Stube and others, 1976).

Organism	Number per ml	Number per m^3	Biomass g per m^3
Bacteria-Direct count Av.	$7x10^7$	$7x10^{13}$	300
-Viable count Max.	$5x10^6$	$5x10^{12}$	22
Algae-*Dunaliella salina* Max	$1x10^4$	$1x10^{10}$	24
-*D. viridis* Max	$2x10^3$	$2x10^9$	1.4
Brine shrimp	-	1^a	0.1
Brine fly	obs.^{b}	-	-
Fungus (Cladosporium)	obs.^{c}	-	-
Ciliate	obs.^{c}	-	-
Halophages (virus)	obs.^{b}	-	-

[a] Estimated.
[b] Observed in large numbers but not quantified.
[c] One observation.

Table 3. Chemicals of biological interest in the north arm of the Great Salt Lake 1973-1977.

	Wt. per Liter	Low Value	High Value	Average	s.d.
o-PO_4 as P	μg	40	1600	440	174
Total P	μg	350	4000	1032	489
NH_3	μg	0	1120	--	--
Particulate *N	mg	1.0	4.0	1.4	0.5
Soluble *N	mg	3.0	17.3	6.7	3.0
Total *N	mg	4.0	18.9	8.0	3.1
Oxygen	mg	0	1.8	0.6	0.4

*Organic nitrogen forms.

Bicarbonate (or carbon dioxide), table 1, appears plentifully available in the water, and a reservoir of calcium carbonate is available in the sediments (Eardly, 1966).

The amount of dissolved oxygen is extremely low in the north arm (table 3), with only slightly more in the winter than the summer. Saturation has been calculated to be about 1.7 mg/l at 0°C and about 0.9 mg/l at 30°C. In three years, only 6 samples of lake water exceeded 1.0 mg/l and these occurred during massive algal blooms (Stube and others, 1976). As fast as the algae generate oxygen, the bacteria consume it, especially during the summer and near the bottom where light is minimal. The deeper parts of the lake during the summer are frequently anaerobic as a result, with a detectable odor of hydrogen sulfide.

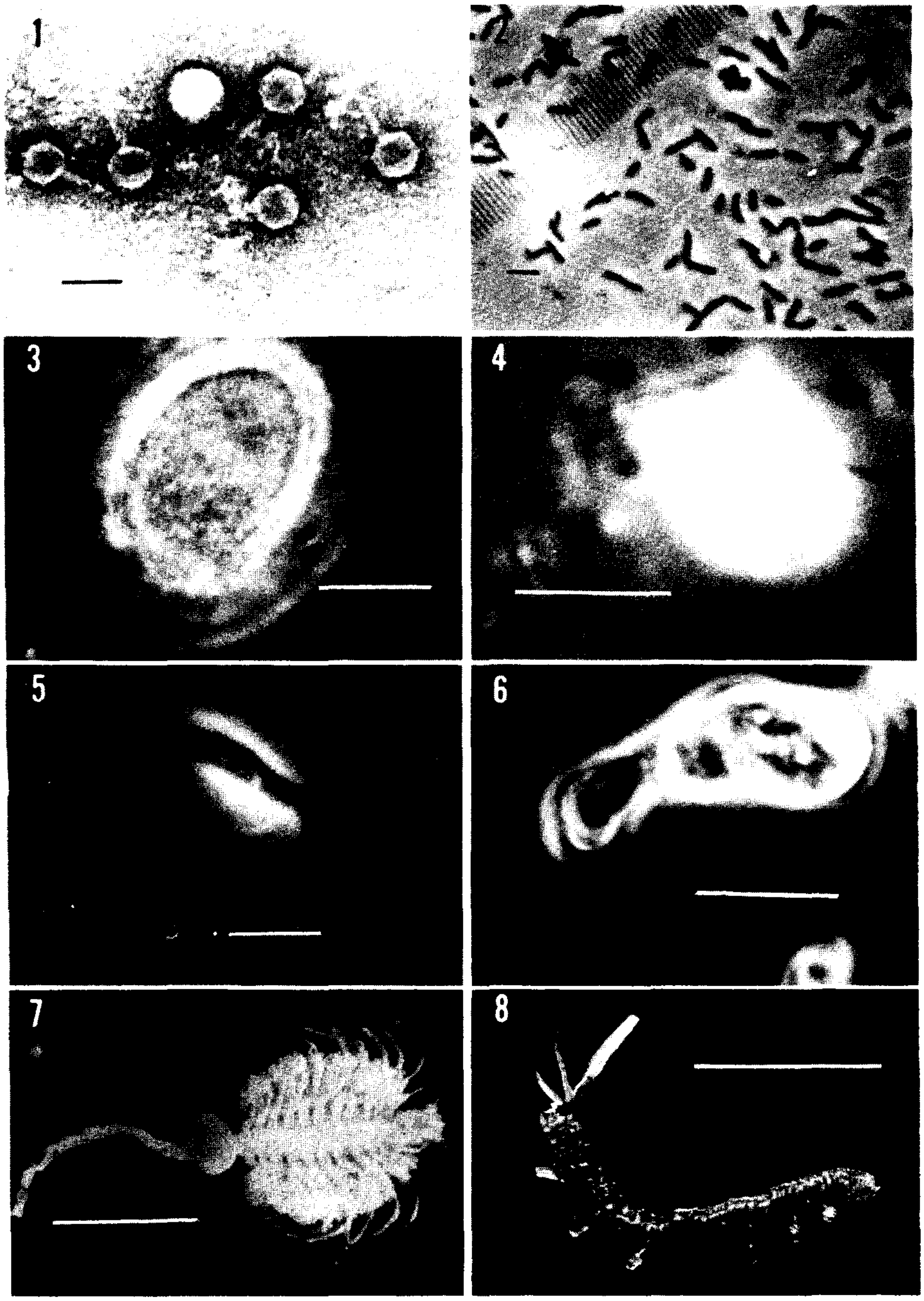
Migration of the dissolved salts from the south to the north is accompanied by migration of organic matter in the form of microbial cells, invertebrates such as brine flies and brine shrimp, wind blown pollen, and detritus of all kinds. This joins a large pool of organic matter generated in the north arm itself by the growth of algae and bacteria. The size of this pool is reflected in the large particulate, soluble, and total nitrogen values listed in table 3. As in most aquatic ecosystems, the greater part of the organic nitrogen is in the soluble pool.

The average nitrogen value and some recent data for organic carbon from the north arm are compared in table 4. The organic carbon is fairly high when compared to that in lakes and streams and is about one quarter that found in settled sewage. The ratio of soluble organic carbon to soluble organic nitrogen is 6.4 to 1, meaning it is very rich in nitrogen, approaching that found in night soil or protein. This is a much lower ratio than found in other aquatic systems (table 4). The specific composition of the nitrogen compounds is unknown, and what part of this organic pool is available to the bacteria or to the other organisms has yet to be determined.

THE BACTERIA

The bacteria, (figures 1, 2) represent the major biological component of the north arm. These very small (1 x 2 μm) organisms are, of all the life forms present, probably the best adapted to the high salinity; they occur in such massive numbers (table 2), that they outweigh all the other organisms combined. The huge numbers, 7 x 10^{13} per m^3 (and even higher near the sediment surface) gives the water of the north arm a wine red color (Post, 1975) most noticeable from the air but easily seen from the shore as well. The reddish coloration is due to carotenoid pigments which protect the organism against sunlight, and a photosynthetic pigment, bacteriorhodopsin. The bacteria feed on the soluble organic matter present in the water. Studies in miniature lake microcosms (Stube and others, 1976) show that the bacteria grow rapidly shortly after blooms of algae excrete organic matter into the surrounding water, or when an organic nutrient is supplied from outside. The amino acid, glutamic acid, a constituent of protein with a C:N ratio of 5:1, actively stimulated bacterial growth in the microcosms. The generation time on glutamic acid, about 60 hours, was considerably longer than on the algal excretion products, about 15 hours.

The bacteria represent an almost complete adaptation to high salinity. Most of the bacteria isolated from the lake and studied (Crane, 1974) are obligate extreme halophiles, meaning that they will not grow unless supplied with 15% sodium chloride or more. Many grow best at 22-27% sodium chloride, about that of the north arm. Several attempts have been made to grow moderate



Figures 1-8. Figure 1. Transmission electron micrograph of halophage (hexagons with tail) parasitic on *Halobacterium*. Bar is 0.1 μm.

Figure 2. *Halobacterium* from the north arm, phase contrast. Bar is 2 μm.

Figure 3. Red pigmented alga, *Dunaliella salina*, phase contrast. Bar is 10 μm.

Figure 4. Green pigmented alga, *Dunaliella viridis*, phase contrast. Bar is 10μm.

Figure 5. Protozoan with two flagella, unidentified, phase contrast. Bar is 10 μm.

Figure 6. Amoeba with one pseudopod (to the left), unidentified, phase contrast. Bar is 10 μm.

Figure 7. *Artemia salina*, the brine shrimp, light microscopy. Original shrimp color was bright red. Bar is 3 mm.

Figure 8. *Ephydra* sp., third or fourth instar larva, the brine fly. Breathing tube extends to upper left. Bar is 3 mm.

Table 4. Organic carbon and nitrogen in the north arm of the Great Salt Lake and other materials, 1976-1977.

	Great Salt Lake		Lakes, Ocean	Sewage			Night	
	Total	Soluble	Total	Settled	Protein	Urea	Soil	Manure
Carbon mg/l	44.1	43.0	1-25	219	-	-	-	-
Nitrogen mg/l	8.0	6.7	0.1-1.2	22	-	-	-	-
C/N ratio	5.5/1	6.4/1	10-30/1	10/1	3.2/1	0.5/1	6/1	19/1

halophiles and non-halophiles from the north arm without success (table 5). Placing non-halophilic bacteria, for example *Escherichia coli,* in north arm water at summertime water temperatures (25°C) causes abrupt death of the cells (P. Burdyl and F. J. Post, 1979).

Table 5. Bacterial counts, Great Salt Lake north arm station LVG-3 at 3 meters on basal medium plus various salt concentrations. Incubation 6 weeks July 1976 (Post, 1977b).

Medium % salt	21°C	37°C
0	0[a]	0
2	0	0
6	0	0
10	160	570
14	5,800	3,800,000
18	110,000	7,600,000
22	150,000	2,200,000

[a]No colonies on the 10^{-1} dilution plates.

The role of halobacteria as decomposers of organic matter with the production of carbon dioxide (CO_2) is essentially the role played by bacteria in most ecosystems. However, under anaerobic conditions where light is present (a common summer occurrence in the lake), many of these bacteria can photosynthesize *without chlorophyll* using the bacteriorhodopsin pigment found in the cell membrane (Stoeckinius, 1976). These are the only organisms in nature known to carry out this type of photosynthesis. Under certain conditions, they might be considered primary producers, a role usually played by the algae. Apparently part of the bacterial adaption to extreme salt involves a high optimum temperature for growth. Many of the strains isolated from the lake (Crane, 1974, and unpublished) have optimum growth temperatures in the range of 40°-50°C. At temperatures below 30°C (most of the lake), growth slows materially and becomes very poor or non-existent at 10°C or below. The colder part of the year prevents growth but does not apparently kill these organisms.

A parasite of the lake bacteria is also found in the water in the form of a virus or bacteriophage (figure 1). So far, nine virus strains have been isolated (Post, 1977b) from the north arm, active on seven strains of *Halobacterium halobium* and two halophiles from the lake. With the extremely large population of bacteria (table 2) these would undoubtedly play an important role in the ecology of the north arm.

Bacteria also occur abundantly in the sediments of the lake but the kinds and their numbers are virtually unknown. Some idea of their physiology comes from indirect evidence. Stube et al. (1976) first demonstrated the production of methane, ethane, propane and ethylene from lake sediment in microcosms. Ward (Montana State University, personal communication) recently has demonstrated the production of methane from the lake itself. Stirring the bottom muds, especially where organic matter is deposited, releases hydrogen sulfide gas. Summer anaerobic areas in the deeper part of the lake also contain hydrogen sulfide, indicating the widespread presence of hydrogen sulfide producing organisms in the lake sediments. Beyond these few observations, little is known.

THE ALGAE

The algae constitute the second largest group in terms of biomass (table 2). Two principal planktonic species are found: the red pigmented *Dunaliella salina,* figure 3, and the closely related green pigmented species *D. viridis,* figure 4. The red species is numerically the most prominent as well as the larger in size. The red pigment of this form is a carotenoid but differs in color from that of the bacteria, being more orange. Pilots flying over the north arm report seeing orange-red patches of a different hue than the purple red bacterial background. Undoubtedly, this is a bloom of the red pigmented alga. These blooms are also occasionally observed from lake samples (Post, 1977a). The green form is less common in the north arm and blooms have not been observed although blooms have been reported south of the causeway. The red pigmented form does not seem to occur in significant numbers south of the causeway. Neither alga has a cell wall yet both organisms appear to be well adapted to the high salinity by formation of intracellular glycerol (Brown, 1976). This keeps the cell free of excessive salt yet prevents its destruction due to the osmotic pressure generated by the external salt concentration. This is in contrast to the bacteria which depend on high intracellular salt, especially potassium ion, to be stabilized (Brown, 1976).

Why the red pigmented form is so much more prevalent than the green form (table 2) is not clear. Studies in the laboratory (May, 1978; Van Auken and McNulty, 1973) indicate both organisms do best at moderate salt levels of 10-15% and at about the same light level requirements. They differ somewhat in optimum temperature, 32°C for the green form and 28°C for the red, and the generation time at optimum conditions, 23.8 hours (Van Auken and McNulty, 1973) for the green form and 40 hours for the red (May 1978). Aquarium observations (Post, 1977a) suggest that the green pigmented alga can reach a much higher population level than observed in the lake but for some reason does not. One possibility is preferential grazing of the green form by brine fly larvae and brine shrimp. In the lake, the green pigmented *D. viridis* is considerably smaller, about 1/20 the volume of *D. salina,* and may be more suitable as a food for these invertebrates.

These same algae grow abundantly on surfaces of rocks, wood, tar balls, and in patches on sandy beaches. It is possible that other types of algae may be found here when more detailed studies are made. The algae are found in a film heavily impregnated with slime and an enormous number of bacteria. Two types of surface habitat are commonly observed: those in direct sunlight, bright red to red-orange, consisting mostly of bacteria and a small component of embedded *D. salina;* and those under rock shelves, out of the direct sun, grass green with light pink areas, consisting most of *D. viridis* with a much smaller component of bacteria. A third habitat has been observed in very shallow water in or under a thick salt crust formed by summer evaporation. In these areas of salt crust, bulges or domes appear in the crust which emit great quantities of gas during the day. Gas analysis shows this to be 82-84% oxygen, the balance nitrogen. A small amount of methane may be present on occasion (Ward, personal communication). The underside of a salt crust from a dome shows a bright red color due to the presence of 10^9 bacteria or more per gram of salt and a large number of *D. salina*. Oxygen is generated by the algae and trapped under the crust, creating the dome, until waves erode the dome top away, releasing the gas as bubbles. As the lake recedes the dome is further eroded until the top completely disappears, leaving a small crater in the crust with reddish brown rings under 1-2 cm of water.

The algae are the principle primary producers of organic matter in the north arm, converting the radiant energy of the sun plus carbon dioxide, ammonia and phosphate into the chemical energy of organic matter. Much of the organic matter probably is excreted into the water in a form useful to the bacteria. The bacteria are always found in great quantity associated with the algae. The relative proportion of bacteria in the two surface habitats, described above, suggests that the red pigmented alga excretes a greater amount of a more effectively used form of organic matter than the green pigmented alga. The nature of these compounds is unknown but the microcosm studies (Stube and others, 1976) show the bacteria to respond to them by reproducing very rapidly. The low carbon to nitrogen ratio of the organic matter in the lake suggests it to be of a nitrogenous nature rathern than glycerol, carbohydrate or fatty acids.

Glycerol appears to act as an internal antifreeze, allowing the algae in the plankton to be motile through the cold winter when the water temperature reaches 0°C and even -5°C, although there appears to be an increase in a round nonmotile dormant form.

ALGAL STRUCTURES

Although the *Dunaliella* species described above are the most numerous algae, other species have been reported from time to time, especially from the algal bioherms. Bioherms (Carozzi, 1962) are structures on the lake margin bottom consisting of precipitations of calcium carbonate brought about by the growth of certain blue-green algae (Brock, 1976; Carozzi, 1962). While these bioherms occur in very shallow water all around the margin of the lake, most studies of them were made when the lake was near its lowest level in history and before the separation of the lake by the causeway had time to affect the salinity of the lake appreciably. The rise of about 3 meters in the lake level makes these now difficult to study, especially in the north end, which is more or less permanently turbid (Secchi reading about 1 meter or less) and the bioherms are almost impossible to locate. Whether the blue-green algae associated with these structures are viable in the north arm bioherms, or have stopped growing due to the rise in salinity and water depth, is an unanswered question. No members of this group have been observed in samples of water, sediments or slime from the north end.

PROTOZOA

Protozoa have been reported once in the north arm (Post, 1977a) and once from the microcosms made with sediment and water from the lake (Stube and others, 1976). The most compelling evidence for the presence of protozoa in the lake comes from the aquarium previously mentioned (Post, 1977a). Here, a number of protozoa have appeared including several types of flagellates (figure 5) and amoeba (figure 6). This evidence suggests that protozoa of several types do occur in the north arm but in numbers too low for our sampling procedures to detect them. Their occurrence in such large numbers in the aquarium poses the rather interesting questions of "why so few in the lake itself?" and "how do these organisms adapt to the high osomotic tension of their environment? Is it the same as the algae, or do other mechanisms exist?"

FUNGI

Several attempts to recover fungi living in the north arm have produced mixed results. Only one recovery has been made. *A Cladosporium* species (Cronin and Post, 1977) was observed growing on wood samples placed in the lake for ten months. Examination of indigenous wood after years of immersion in the lake, and floating pine pollen have proven negative. The role of fungi in the lake, if any, is open to conjecture.

THE BRINE SHRIMP

Little is known about the brine shrimp, figure 7, *Artemia salina,* in the north arm. All attempts by our laboratory to hatch eggs in the highly saline north arm water have been unsuccessful. Yet, each summer, brine shrimp, both nauplii and adults, appear in the north arm in considerable numbers, generally concentrated in the red pigmented *D. salina* bloom areas. None have been found in the winter and a rough estimate of 1 per m^3 for the summer has been made (table 2). It appears that part of the southern spring hatch is carried north along with the flowing water in late June or early July. The high salt and low oxygen tension of the north arm requires considerable and rapid physiological adjustment, presumably with a high death rate. The survivors develop a bright red body color, in contrast to the drab off-white of those in the south arm. This red color is presumed to be caused by an increase in hemoglobin in response to the low oxygen level of the north arm (Post, 1977a), or it could be due to carotenoids deposited in tissue from digested *D. salina* or the bacteria.

Few studies of the feeding habits of the north arm brine shrimp have been made. As observed in our laboratories, they will survive for a period of time on halobacteria from the lake but are smaller than normal with a shorter lifespan. Brine shrimp placed in water from our laboratory aquarium (Post, 1977a) feed extensively on the green pigmented *D. viridis.* Fecal pellets produced during this period are a bright green. Electron micrographs of sections of the epithelial cells lining the midgut of the brine shrimp show the presence of intracellular symbionts of a bacterial nature (Post and Youssef, 1977). What role these may play in the brine shrimp is unknown, although when intracellular symbionts occur in Arthropods, they are often associated with a nutritional function of some kind. The possibility that these organisms may arise from the halophilic bacteria of the lake itself is an intriguing possibility.

THE BRINE FLY

Even less is known of the "brine fly", which actually consists of at least three species of the genus *Ephydra, E. hians, E. gracilis,* and *E. cinerea.* The south end of the lake produces enormous numbers of the fly. Fewer flies are produced on the north arm. The productivity of the north arm seems to be much lower, possibly due to a lower hatching rate, again because of the extreme stresses of salt and low oxygen. Fly larvae (figure 8) seen emerging from eggs in the north arm at Rozel Point are a pale orange. As they grow older and larger, they become a deeper reddish-orange, possibly reflecting, as in the case of the brine shrimp, increased hemoglobin production due to the low oxygen levels or to diet. In contrast, larvae in the south end waters are white to pale gray-white.

BIRDS

Larger animals such as birds, particularly seagulls, white pelicans, and ducks, are frequently observed swimming or resting on the water. While it seems unlikely that they would feed on anything in this concentrated brine (and we have not observed them to do so) they have been reported to do so. Their excretory products provide a small addition to the organic pool. The White Pelican, *Pelecanus erythrorhynchos,* breeds on Gunnison Island on the west side of the north arm, but feeds in the Bear River marshes to the east of the lake. Overflights of these birds result in some droppings added to the organic pool. Aside from an occasional dropped fish or dead bird, wildlife contribution to the north arm of the lake is probably minimal.

COMMUNITY ECOLOGY

The Great Salt Lake is a terminal lake with no outlet and has been, except for one brief period, for several hundred thousand years. Most of the salts entering the lake over that period of time are still present, either dissolved or in the sediments, and more are entering the lake each year. Much organic matter has accumulated along with the salt and is supplemented by new organic matter created by the primary producers, the algae. Organic matter, in contrast to the salt (except for mining), has natural cycles which may allow some escape from the lake in the form of gas (nitrogen, methane, hydrogen sulfide, carbon dioxide) or as organic matter (adult flies). Under normal conditions these losses would be replaced by inflow, redissolving of gases from the atmosphere, bird droppings, etc.

The present organic pool probably reflects an equilibrium between inflowing material refractory to breakdown by bacteria, the organic matter generated by the algae, that used by the halophilic bacteria, and that transformed to other organic forms by bacteria. All of the necessary nutrients for algal growth are in excess of needs *except* an inorganic form of nitrogen (nitrate or ammonia) (May, 1978; Post, 1977a). Considerable nitrogen occurs in the organic matter but is probably not available to the algae in this form, although this remains to be proven. The lack of demonstratable nitrate (or nitrite) production (Post, 1977a; Stube and others, 1976) suggests the absence of halophilic nitrifiers or their inhibition by too low an oxygen concentration. It is possible that nitrate is produced and promptly used by the algae or halobacteria; many strains of halobacteria inhabiting the north arm possess a very active ability (Crane, 1974) to convert nitrate to nitrogen gas. This capability is expressed only when nitrate is present and oxygen is extremely low or absent, the prevalent condition of the north arm. Nitrate and nitrite are produced in the south arm (Post, 1977a) at a much lower salinity than is found in the north arm, indicating the existence of somewhat halotolerant nitrifying bacteria. At what salinity these organisms become inactive needs to be determined.

The algae must depend on ammonia for growth. Ammonia is found in the north arm during periods of low algal and high bacterial activity, and among large populations of brine shrimp which excrete ammonia directly. Bacteria isolated from the lake (Crane, 1974) produce ammonia from organic matter containing nitrogen and are the presumed origin of the ammonia measured in the north arm. The rich nitrogen content of the dissolved organic matter, nature unknown, suggests either that this material is refactory or that some additional energy-rich nutrient is required before the bacteria can act on it. It is apparent from examination of the lake habitats described above and from microcosm data (Stube and others, 1976) that the algae do supply such nutrients and locally stimulate the growth of bacteria to a remarkable degree, but the nature of this stimulating nutrient is unknown. Sources of supply to the pool including materials flowing in from the south arm; fecal pellets of brine shrimp and brine fly larvae containing digested and partially digested food and bacterial cells (either from the water passing through the gut or symbionts of the gut itself); the eggs of the two arthropods and other animals; uric acid excreted by the brine fly larvae; ammonia excreted directly by the brine shrimp; and waste products from the halobacteria of the plankton and those of the sediments. The uric acid excreted by the brine fly larvae can be metabolized by a few of the lake bacteria with the release of ammonia. In the north arm the organic matter and ammonia are the only members of the nitrogen pool. (Post, 1977a).

A model of the interactions between the various components of the north arm of the lake is illustrated in figure 9. Arrows indicate the direction of interaction. Minor components are not included. These interactions are highly seasonal. Figure 10 shows a yearly cycle of the north arm presented as a series of smooth curves. The actual data (Post, 1977a; Stube and others, 1976) consists of recurring peaks and valleys for the organisms and ammonia as they interact with each other. From November to early March the organisms of the lake become dormant with more or less constant counts and chemistry. In March the number of viable bacteria begins to increase rapidly in response to the warming waters, utilizing the dissolved and particulate organic matter left from the previous fall. The ammonium level promptly increases until the algae become abundant enough in May to reduce it again. At this time the brine fly larvae appear, feeding primarily on the algae, which then decline in numbers. As the fly hatch diminishes, the algae again begin to increase and by late July reach a second peak. Sufficient brine shrimp are now present to reduce the algae to a very low level, but the bacteria count remains high, with peaks of population near the peaks of algae and fly growth. As fall approaches the shrimp disappear and a small algal bloom may occur if the weather remains warm.

The picture presented here of the biology of the north arm of the Great Salt Lake is intended as an overview. Some of the interactions are still speculative; most require quantification so that the models presented in figures 9 and 10 can be better delineated. The role of the minor components, the protozoa, sediment bacteria, etc., still need to be worked out.

In summary, the north arm is a nutrient rich ecosystem of extreme stress, high in salt and low in oxygen, with a remarkably well adapted community of organisms very low in diversity and high in population.

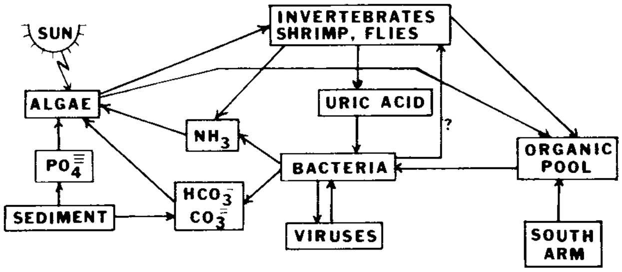


Figure 9. Proposed biological and chemical interactions in the north arm of the Great Salt Lake. (adapted from Post, 1977a).

ACKNOWLEDGMENT

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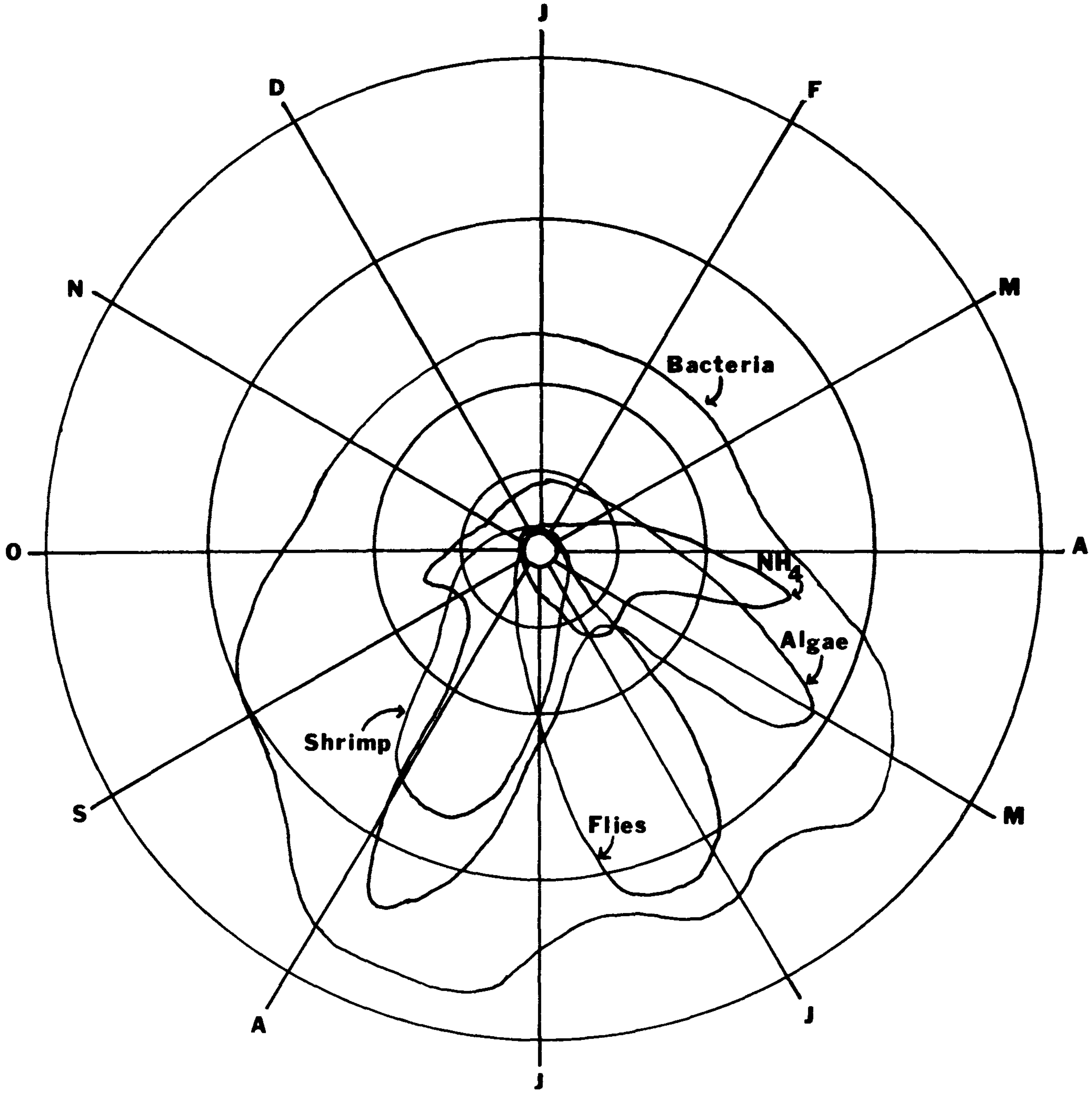

Figure 10. Yearly cycle of organisms and ammonium ion in the north arm of the Great Salt Lake 1975-1977.

COLIFORM BACTERIA CONCENTRATIONS IN GREAT SALT LAKE WATERS

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INTRODUCTION

The Great Salt Lake is a unique saline body of water which is in the terminal drainage basin for most of northern Utah as well as parts of western Wyoming and southeastern Idaho. The major tributaries flowing into the Great Salt Lake are the Bear and Weber Rivers flowing from the north and east, the Jordan River and the Sewage Canal flowing into Farmington Bay from the south, and the C-7 Ditch and Goggin Drain flowing into the south part of the lake.

In the 1950s the Southern Pacific Railroad causeway was constructed through the middle of the lake. Restricted bi-directional flow through the two culverts in the causeway eventually resulted in the lake becoming two distinct bodies of water, the north arm and the south arm. The north arm, with no significant fresh water inflow, received south arm water through the openings in the causeway, acted as a concentration basin due to evaporation and increasing reduction of back flow into the south arm, and thus became more saline than the south arm. Recently, in the 1960s, a second causeway was constructed from Syracuse, Utah to Antelope Island State Park. This causeway defines yet a third body of water, Farmington Bay, which has been historically distinct.

The nutrient, sediment, and bacterial loading which enters a terminal basin under natural conditions is usually high relative to loadings entering upstream impoundments. This natural loading, in addition to the historical pollution resulting from inadequately treated municipal and industrial wastes and poorly managed watershed activities, could result in a cumulative pollution loading that could seriously impair the recreational and other beneficial uses of water in the terminal basin. This cumulative pollution load which enters the south arm has raised questions concerning the potential for health hazards in present or proposed recreational areas, particularly in the proximity of the fresh water inflows. Studies were conducted to determine if hazardous bacteriological conditions exist in the Great Salt Lake.

BACTERIOLOGICAL STUDIES

Many studies of the lake, beginning as early as the 1920s, tested the hypothesis that the dense brine possessed highly bacteriocidal effects. The early conclusion was that the lake was safe as a depository for untreated domestic sewage. In later years improved bacteriological technology found that fecal (coliform) bacteria were not as rapidly destroyed by the brine as was earlier thought. It remains undisputed, however, that bacterial die-off rate is significantly accelerated in the lake brine as compared to fresh water. Burdyl and Post (1979) recently indicated that the bacteriocidal rates of Great Salt Lake water were comparable to that of ocean waters of lower saline levels.

While bacterial standards for health protection have been adopted for fresh water, there have been insufficient scientific data to determine where to base similar standards for the saline waters.

This lack of information has not been a deterrent to use of certain lake areas for recreational bathing, possibly because many people are interested in the unique experience of swimming in water where sinking is impossible due to high specific gravity of the lake brines. From time to time the State's health authorities have been asked about possible health hazards associated with this use, and opinions have been expressed based on best available data.

In 1960, at a hearing in Salt Lake City for the U.S. Senate Interior Committee on Establishment of a Great Salt Lake National Park, a statement presented by the Utah Department of Health included the following paragraph:

> "The heavy salt content of the lake water precludes the use of the usual bacteriologic techniques in assessing possible hazards to health of persons who swim in this water. It has been assumed that discharge to the lake of class "D" water, with proper attention to isolation of concentrated discharges of such water from swimming areas, will reduce health hazards to a suitable degree. Class "D" water can be produced by the type of sewage treatment plant now required by the Utah Water Pollution Control Board in the Great Salt Lake area".

In March of 1965, another statement by the Department of Health at a hearing on recreational and commercial exploitation of the Great Salt Lake included the following:

> ". . . It is assumed that the public health hazards resulting from recreational use of the lake water (including swimming) are not beyond acceptable limits if all wastewater entering the lake is subjected to what is commonly known as "complete" treatment, including chlorination, and if all effluents are dispersed at suitable distances from specific swimming areas.
>
> . . .Some post-war studies of this special question showed that disease organisms will survive in lake brine for at least two or three days, contrary to earlier conclusions that this could not be the case. Also, it is known that fresh water (and also sewage) entering the brine will not readily diffuse, but will float in a thin surface layer for some period of time as it progresses into the body of the lake, eventually mixing with the brine. Since satisfactory measurements of bacteria in this surface layer as well as in the lake water cannot be made under present technology, judgment has been necessary to define the circumstances of sewage effluent discharges to the lake which will be considered acceptable. . ."

In May 1965, however the Great Salt Lake Authority requested the Utah Department of Health to evaluate water conditions adjacent to bathing areas near the north end of Antelope Island. New methodology was developed for sample collection and analyses. A report of this study, published in 1965 by the State Department of Health, concluded that there was positive evidence of sewage pollution in the lake water to such an extent that bathing should not be approved in any of this area for this season. (State Department of Health, 1965).

In 1968 a study by Ford Chemical Laboratory in Salt Lake City for the State Division of Health resulted in further improvements in sampling and analytical technology and added sampling points north of Antelope Island and on the Sewage Canal which received effluent from the Salt Lake City Wastewater Treatment Plant. Conclusions were that there had been a considerable reduction in the pollution load flowing into Farmington Bay, primarily due to construction of the Salt Lake City Wastewater Treatment Plant, and that coliform bacteria levels near beach areas on the north part of Antelope Island, excluding Farmington Bay, did not exceed generally accepted standards for recreation in fresh water. However coliform bacteria were consistently found in both bay and lake waters, justifying additional sampling in succeeding years.

During 1969 and 1970, sixteen additional stations were established for sampling near the south beach of the lake near recreation areas, and sampling was continued at previously established stations north of Antelope Island.

During 1977, a comprehensive monitoring program was initiated on the Great Salt Lake under the direction of the State Division of Health, covering determination of chemical, biological and microbiological constituents. Ford Chemical Laboratories were again contracted to determine the current status of bacterial contamination of waters in Farmington Bay and the South Arm of the lake; those results were compared with the data obtained in the 1965, 1968, 1969 and 1970 studies.

METHODOLOGY

The methodology used in the 1977 study had been developed and refined in the previous studies. At each of the established sample stations, two samples were collected, one from the surface water and another at the one-foot depth. All sampling devices were autoclaved and used only once during a sampling period to avoid contamination of sample water by the sampling devices. The surface sample was taken with a special float skimming device, designed to sample the upper 2 millimeters of surface water. The sample water was drawn through sterilized tubing into a sterilized flask using a suction pump. The sample water was measured into three fractions, two for coliform bacteria determinations and one for total dissolved solids (TDS) determination. The coliform bacteria fractions were immediately filtered through a gridded 0.45 micron filter. Filters were rinsed with sterile water and placed on prepared culture media in petri dishes. One filter was processed for total coliform bacteria incubation and counts and the other for fecal coliform bacteria. The petri dishes were labelled on site and placed in an incubator upon return to the laboratory. Coliform colonies which developed on the cultured filter membrane were counted after an appropriate incubation period and reported as coliform bacteria per 100 milliliters of sample water.

The one-foot depth sample collected at each station was drawn through a sterilized tube attached to a float. This sample was processed as described for total and fecal coliform bacteria determinations and TDS analysis. TDS determinations are described in Standard Methods (1975) and reported as TDS in milligrams per liter. The three-tube MPN coliform bacteria methodology described in Standard Methods (1975) was used to determine the most probable number of total and fecal coliform bacteria in water samples taken on Farmington Bay.

Field measurements were taken of air and water temperatures and water depth at each station. Meteorological observations and recreational activity were also recorded.

Sampling frequency during past studies varied considerably. During 1965, each station in Farmington Bay was sampled once during June and each station north of Antelope Island was sampled once during July. In the 1968 study, each station was sampled 3 times during May in Farmington Bay and 11 times during May north of Antelope Island. During the 1969 study, the south beach areas were sampled 4 times in July and twice in both August and September. There were 12 sampling periods on each station in the south beach area and north of Antelope Island during the 1970 study, 3 periods in June, 4 periods in July and August, and 1 in September. During the 1977 study, 6 new sampling stations were established near beach areas on the northeast shore of Stansbury Island in addition to the 38 stations that had been established during the previous studies (figure 1). Each station was sampled at approximately bi-weekly intervals from late April through September 1977 for a total of 11 sampling periods. Two sampling runs were conducted on Farmington Bay, first on May 26th and again on August 10th.

DISCUSSION OF RESULTS

The data generated during this and previous studies have been tabulated and presented in this report as average and maximum values observed during the study periods. When no coliform bacteria colonies were observed on cultures during the 1968-70 studies, zero counts were reported. For the purposes of this study, zero (0), less than one (<1) and less than three (<3) are to be read as synonomous values. All reported less-than values are shown as zeros in this report.

The tabulated data for total dissolved solids indicates that the thin layer of fresh water which theoretically exists over the denser brine layer was mixed with the underlying brine layer most of the time during the 1977 study. Only in a few instances, such as at stations 101 near the Goggin Drain inflow and 105 near the C-7 Ditch inflow, is there a significant difference between the surface skim sample TDS and the TDS at the one foot level (see table 1). These two layers were apparently mixed by wind action, as suggested by weather conditions reported at the time of sampling. The surface sample data reported for coliform bacteria counts may not represent the maximum values which would be observed under calmer conditions.

The substantial decrease in TDS in the south arm since 1968 confirms a trend now commonly attributed to reduction of circulation in the lake resulting from construction of the Southern Pacific Railroad causeway. This trend is particularly noticeable between 1970 and 1977 (see table I-III).

Conclusions reached several years go that there were no health hazards to swimmers will no longer be valid if the TDS decrease trend in the southern arm continues to the point where the bacteriocidal rate is reduced to that found in fresh water.

South Beach Areas

The south beach sampling points were represented by 16 stations, 101 through 116 (figure 1). In general, there has been a reduction in both total and fecal coliform counts observed along the south beach waters since 1969. However, the tabulated data indicate that the counts are in same order of magnitude for the 1969, 1979 and present study. Highest concentrations of coliform bacteria were found in surface water samples taken adjacent to areas of fresh water inflow such as Goggin Drain, Lee Creek, and C-7 Ditch. The coliform bacteria counts found in samples taken at one-foot depth were considerably lower than in the surface samples, confirming the correlation between bacterial die-off rate and TDS concentration. Samples taken from waters adjacent to beach areas west of station 105, which is near the C-7 inflow, exhibit few or no fecal coliform bacteria and minimal total coliform bacteria.

No fecal coliform bacteria were observed in samples collected during 1977 along the south beach areas where TDS levels were greater than 100,000 mg/1. No total coliform bacteria were observed in samples collected during 1977 in this area where TDS levels exceeded 120,000 mg/1 (see table 1).

Stansbury Island Beach Areas

Stansbury Island beach sampling was represented by 6 stations, 211 through 216 (figure1). Samples taken from the waters near the northeast shore of Stansbury Island exhibited negligible coliform bacteria counts. There is very little pollution input to these waters other than runoff during storm periods. Springs from the east shore of the Island possess relatively good water quality. Occasionally, however, cattle graze on the northeast shore of the Island and frequently enter the lake waters to cool their bodies and escape annoying insects. While in the water, the cattle relieve themselves of metabolic

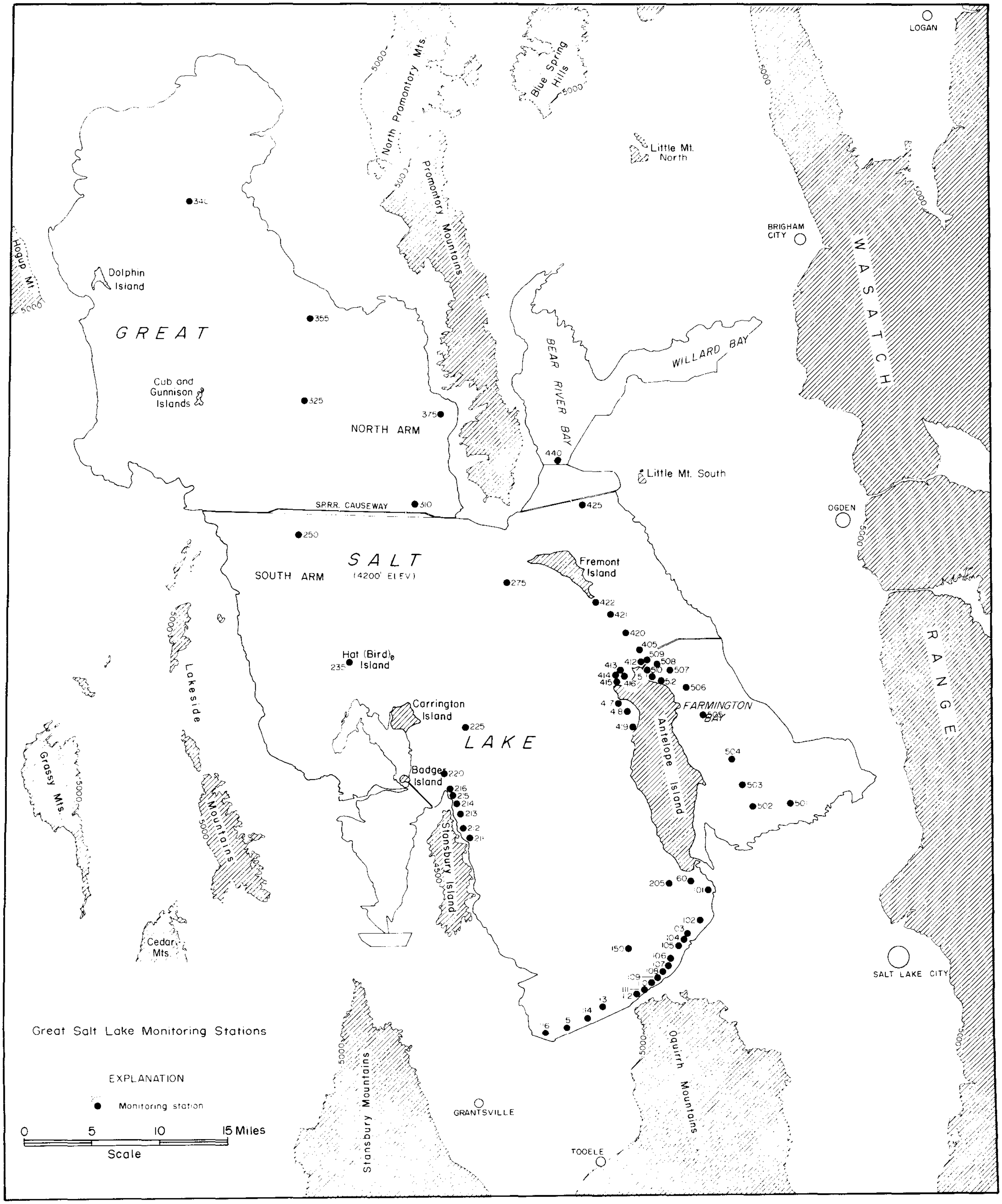

Figure 1. Locations of Great Salt Lake Monitoring Stations.

TABLE I

TOTAL DISSOLVED SOLIDS AND COLIFORM BACTERIA COUNT IN GREAT SALT LAKE, SOUTH BEACH AREA

SUMMARY OF 1969, 1970, AND 1977 DATA

STATION NUMBER	SAMPLE DEPTH YEAR	TDS Mg/L MINIMUM	TDS Mg/L AVERAGE	TDS Mg/L MAXIMUM	COLIFORM BACTERIA/100 ML TOTAL MINIMUM	TOTAL AVERAGE	TOTAL MAXIMUM	FECAL MINIMUM	FECAL AVERAGE	FECAL MAXIMUM
101	Surface									
	1969	3,390	10,993	18,860	120	199	300	30	87	150
	1970	14,500	55,848	188,200	85	263	510	10	62	120
	1977	34,900	58,660	114,325	33	153	280	0	26	90
	1 FOOT									
	1969	105,600	148,273	187,480	0	33	90	0	11	50
	1970	29,600	163,183	196,000	0	23	75	0	3	10
	1977	55,670	99.233	133,363	0	0	0	0	0	0
102	SURFACE									
	1969	168,683	181,900	189,110	5	14	40	0	1	5
	1970	93,100	169,381	209,400	0	6	25	0	1	7
	1977	65,900	104,762	121,266	0	41	310	0	9	80
	1 FOOT									
	1969	174,207	183,841	191,990	0	0	3	0	0	0
	1970	158,500	182,292	210,600	0	0	0	0	0	0
	1977	110,533	119,546	124,700	0	0	0	0	0	0
103	SURFACE									
	1969	169,720	181,258	189,290	0	2	15	0	0	0
	1970	166,800	185,964	200,000	0	2	10	0	0	0
	1977	50,230	115,829	134,836	0	2	10	0	0	0
	1 FOOT									
	1969	169,738	182,449	189,750	0	0	4	0	0	0
	1970	171,120	185,560	201,100	0	0	0	0	0	0
	1977	111,350	123,069	133,950	0	0	0	0	0	0
104	SURFACE									
	1969	170,501	179,825	187,590	0	0	0	0	0	0
	1970	176,000	185,750	193,400	0	0	3	0	0	0
	1977	57,820	102,301	129,450	0	15	62	0	0	0
	1 FOOT									
	1969	170,510	180,970	188,450	0	0	0	0	0	0
	1970	174,100	186,152	193,800	0	0	0	0	0	0
	1977	111,110	122,197	136,200	0	0	0	0	0	0
105	SURFACE									
	1969	8,720	13,469	20,180	60	286	500	15	92	150
	1970	9,400	26,013	116,890	33	182	350	0	28	100
	1977	45,920	67,938	117,333	0	101	210	0	11	40
	1 FOOT									
	1969	125,850	151,434	188,410	0	84	250	0	18	40
	1970	15,800	95,183	187,600	0	5	50	0	1	7
	1977	115,335	122,339	138,160	0	0	0	0	0	0
106	SURFACE									
	1969	109,100	163,061	196,690	0	5	16	0	0	0
	1970	150,230	172,611	198,000	0	3	30	0	0	0
	1977	66,490	114,706	133,200	0	2	15	0	0	0
	1 FOOT									
	1969	149,180	177,470	186,540	0	2	13	0	0	0
	1970	162,800	182,418	198,200	0	0	0	0	0	0
	1977	110,980	119,843	132,650	0	0	0	0	0	0
107	SURFACE									
	1969	128,716	166,612	183,350	0	3	24	0	1	5
	1970	13,840	165,178	194,000	0	14	100	0	1	10
	1977	99,977	119,558	130,385	0	0	0	0	0	0
	1 FOOT									
	1969	150,833	175,974	184,610	0	1	3	0	0	0
	1970	148,700	181,982	197,100	0	0	0	0	0	0
	1977	111,450	120,949	130,450	0	0	0	0	0	0
108	SURFACE									
	1969	67,840	158,075	183,620	0	3	13	0	1	3
	1970	7,175	170,095	191,400	0	17	150	0	3	20
	1977	54,230	96,566	121,224	0	23	120	0	2	15

TABLE I (continued)

STATION NUMBER	SAMPLE DEPTH YEAR	TDS Mg/L			COLIFORM BACTERIA/100 ML					
					TOTAL			FECAL		
		MINIMUM	AVERAGE	MAXIMUM	MINIMUM	AVERAGE	MAXIMUM	MINIMUM	AVERAGE	MAXIMUM
	1 FOOT									
	1969	141,100	173,340	185,760	0	1	4	0	1	1
	1970	170,200	185,338	198,150	0	0	0	0	0	0
	1977	110,430	119,929	129,441	0	0	0	0	0	0
109	SURFACE									
	1969	83,850	166,828	186,524	0	18	55	0	4	16
	1970	156,000	179,383	190,800	0	7	21	0	0	0
	1977	58,220	113,467	123,386	0	0	0	0	0	0
	1 FOOT									
	1969	166,630	181,959	190,270	0	2	5	0	0	0
	1970	160,000	181,363	190,950	0	0	0	0	0	0
	1977	110,474	119,610	124,250	0	0	0	0	0	0
110	SURFACE									
	1969	135,690	162,696	188,480	0	9	40	0	1	5
	1970	164,000	181,800	193,000	0	0	0	0	0	0
	1977	74,650	114,910	123,880	0	2	8	0	0	0
	1 FOOT									
	1969	134,930	175,980	188,950	0	0	0	0	0	0
	1970	174,500	183,396	191,400	0	0	0	0	0	0
	1977	110,880	119,136	124,266	0	0	0	0	0	0
111	SURFACE									
	1969	173,380	180,798	185,622	0	0	0	0	0	0
	1970	181,400	186,892	191,500	0	1	3	0	0	0
	1977	60,885	104,666	128,210	0	2	13	0	0	0
	1 FOOT									
	1969	173,370	181,773	188,750	0	0	0	0	0	0
	1970	181,900	187,988	198,500	0	0	0	0	0	0
	1977	111,926	119,721	129,440	0	0	0	0	0	0
112	SURFACE									
	1970	182,800	186,923	190,800	0	10	35	0	3	18
	1977	112,226	119,807	129,330	0	0	0	0	0	0
	1 FOOT									
	1970	183,600	187,988	191,100	0	0	0	0	0	0
	1977	112,354	120,151	130,110	0	0	0	0	0	0
113	SURFACE									
	1970	185,300	188,196	196,200	0	7	50	0	1	2
	1977	110,893	121,406	127,620	0	0	0	0	0	0
	1 FOOT									
	1970	185,300	188,779	198,150	0	1	1	0	0	0
	1977	110,914	121,680	128,410	0	0	0	0	0	0
114	SURFACE									
	1970	180,600	186,562	192,240	0	6	25	0	1	5
	1977	110,150	120,683	129,620	0	0	0	0	0	0
	1 FOOT									
	1970	181,400	187,442	196,400	0	0	0	0	0	0
	1977	112,230	121,691	129,280	0	0	0	0	0	0
115	SURFACE									
	1970	180,500	188,325	198,900	0	1	10	0	0	0
	1977	114,833	125,121	141,570	0	0	0	0	0	0
	1 FOOT									
	1970	180,700	189,701	198,910	0	0	0	0	0	0
	1977	120,922	125,419	141,690	0	0	0	0	0	0
116	SURFACE									
	1970	180,200	189,125	201,100	0	0	0	0	0	0
	1977	115,020	122,466	121,140	0	0	0	0	0	0
	1 FOOT									
	1970	182,800	190,938	201,100	0	0	0	0	0	0
	1977	115,135	123,917	136,620	0	0	0	0	0	0

wastes without consideration of degradation of water quality.

No fecal or total coliform bacteria were observed in samples collected during 1977 along the Stansbury Island beach areas when TDS levels exceeded 125,000 mg/l (see table II).

Beach Areas and Waters North of Antelope Island

Sampling in waters north and west of Antelope Island, excluding Farmington Bay, was represented by 10 stations between the east end of Bridger Bay and the south tip of Fremont Island (figure 1).

Without one exception, data indicate a substantial reduction in coliform bacteria counts in waters of this region of the lake. This reduction is at least one order of magnitude for most surface waters and two orders of magnitude for stations 420 and 422 (see table III). This reduction is probably a function of decreased pollution entering the lake from Farmington Bay. Coliform bacteria counts observed in one-foot deep samples taken north and west of Antelope Island were negligible, except at station 509 near the causeway opening. During 1977, stations 509, 413, 420, and 421 provided samples with the highest coliform counts. This is indicative of the present flow of water from Farmington Bay into the lake. A reduction in coliform bacteria counts is found at stations 509 through 420, where the waters flow north and mix, resulting in higher TDS values in the surface waters.

No fecal coliform bacteria were observed in samples collected during 1977 in these beach areas and open waters when TDS levels exceeded 105,000 mg/l. No total coliform bacteria was observed in samples from this area during 1977 when TDS levels exceeded 125,000 mg/l.

Farmington Bay

Sampling in Farmington Bay was represented by 12 stations, 501 through 512 (figure 1) through the southeast channel of the bay to the south side of the opening in the Syracuse-Antelope Island causeway. Stations, 510 through 512 were located in Buffalo Bay.

In general, the coliform bacteria counts reported in samples collected in Farmington Bay in 1977 were several orders of magnitude lower than those reported in earlier studies (see table IV). The greatest reduction occurred in the south end of the bay near the Sewage Canal inflow, no doubt resulting from the modern sewage treatment at the Salt Lake City Wastewater Treatment Plant. Similar plants had been constructed earlier to treat sewage entering the bay from Davis County. The surface waters in the bay vary considerably in TDS concentrations. Lowest TDS concentrations were reported at the south end of the bay (Stn. 501, 6690 mg/l in 1977). TDS levels increased to the north through the channel to the causeway (Stn. 508, 87,445 mg/l in 1977). A general decrease in coliform survival appears to occur as the water flows north through the bay, reflecting increased TDS levels and elapsed time.

TABLE II
TOTAL DISSOLVED SOLIDS AND COLIFORM BACTERIA COUNT IN
GREAT SALT LAKE, NORTHEAST STANSBURY ISLAND

SUMMARY OF 1977 DATA

STATION NUMBER	SAMPLE DEPTH	TDS Mg/L			COLIFORM BACTERIA/100 ML					
					TOTAL			FECAL		
		MINIMUM	AVERAGE	MAXIMUM	MINIMUM	AVERAGE	MAXIMUM	MINIMUM	AVERAGE	MAXIMUM
211	SURFACE	96,625	110,077	119,688	0	5	18	0	0	0
	1 FOOT	110,500	116,327	120,750	0	0	0	0	0	0
212	SURFACE	110,736	116,212	124,600	0	0	4	0	0	0
	1 FOOT	112,495	116,741	122,950	0	0	0	0	0	0
213	SURFACE	90,388	115,914	124,565	0	2	14	0	0	0
	1 FOOT	113,495	118,522	126,480	0	0	0	0	0	0
214	SURFACE	89,766	116,834	125,635	0	2	6	0	0	0
	1 FOOT	112,310	119,555	130,330	0	0	0	0	0	0
215	SURFACE	110,550	118,189	123,624	0	2	6	0	0	0
	1 FOOT	110,669	118,947	128,250	0	0	0	0	0	0
216	SURFACE	78,100	113,985	125,466	0	6	36	0	0	5
	1 FOOT	111,226	118,598	125,194	0	0	0	0	0	0

TABLE III

TOTAL DISSOLVED SOLIDS AND COLIFORM BACTERIA COUNT IN GREAT SALT LAKE, NORTH AND WEST OF ANTELOPE ISLAND SUMMARY OF 1968, 1970, AND 1977 DATA

STATION NUMBER	SAMPLE DEPTH YEAR	TDS Mg/L			COLIFORM BACTERIA/100 ML TOTAL			FECAL		
		MINIMUM	AVERAGE	MAXIMUM	MINIMUM	AVERAGE	MAXIMUM	MINIMUM	AVERAGE	MAXIMUM
509	SURFACE									
	1968	185,200	200,340	217,100	1	87	250	--	--	--
	1970	18,400	21,325	24,500	12	24	45	0	14	40
	1977	65,765	76,409	110,400	36	95	180	0	8	30
	1 FOOT									
	1968	188,700	208,500	230,200	1	33	200	--	--	--
	1970	193,600	200,200	206,900	0	1	3	0	0	0
	1977	73,420	88,688	103,400	18	49	130	0	5	13
413	SURFACE									
	1968	185,200	200,340	217,100	1	87	250	--	--	--
	1970	190,200	193,075	196,800	0	11	17	0	0	0
	1977	92,554	108,010	122,177	0	13	36	0	0	0
	1 FOOT									
	1968	188,700	208,500	230,200	1	33	200	--	--	--
	1970	193,600	200,200	206,900	0	1	3	0	0	0
	1977	113,120	121,208	123,300	0	0	0	0	0	0
414	SURFACE									
	1968	180,500	198,900	234,700	1	61	150	--	--	--
	1970	188,200	200,750	208,200	4	8	12	0	0	0
	1977	110,500	117,147	129,850	0	0	5	0	0	0
	1 FOOT									
	1968	189,910	206,670	250,000	1	35	130	--	--	--
	1970	189,500	201,425	208,600	0	1	5	0	0	0
	1977	110,990	120,232	129,610	0	0	0	0	0	0
415	SURFACE									
	1968	184,800	198,150	216,000	1	49	200	--	--	--
	1970	197,300	200,700	206,000	0	0	0	0	0	0
	1977	114,210	118,059	124,375	0	0	0	0	0	0
	1 FOOT									
	1968	189,900	207,800	230,000	1	15	110	--	--	--
	1970	197,320	200,893	206,100	0	0	0	0	0	0
	1977	113,290	118,998	125,585	0	0	0	0	0	0
416	SURFACE									
	1968	188,900	198,200	214,900	1	---	500	--	--	--
	1970	194,800	197,500	204,300	0	0	0	0	0	0
	1977	112,890	120,963	131,620	0	0	0	0	0	0
	1 FOOT									
	1968	196,100	205,630	219,200	1	35	200	--	--	--
	1970	195,800	198,900	204,500	0	0	0	0	0	0
	1977	113,996	123,022	133,425	0	0	0	0	0	0
417	SURFACE									
	1968	185,200	203,700	244,300	1	33	290	--	--	--
	1970	184,600	198,850	220,300	0	7	18	0	1	1
	1977	110,383	119,297	124,880	0	3	10	0	0	0
	1 FOOT									
	1968	197,400	212,300	250,700	1	16	160	--	--	--
	1970	190,100	200,795	220,700	0	0	0	0	0	0
	1977	110,495	210,144	124,920	0	0	0	0	0	0
418	SURFACE									
	1968	181,000	201,100	221,100	0	9	30	--	--	--
	1970	198,600	201,625	207,400	0	1	2	0	0	0
	1977	112,533	122,549	133,200	0	0	0	0	0	0
	1 FOOT									
	1968	193,700	217,300	250,000	0	1	10	--	--	--
	1970	198,800	201,925	207,800	0	0	0	0	0	0
	1977	112,915	123,589	131,900	0	0	0	0	0	0

TABLE III (continued)

STATION NUMBER	SAMPLE DEPTH YEAR	TDS Mg/L			COLIFORM BACTERIA/100 ML					
					TOTAL			FECAL		
		MINIMUM	AVERAGE	MAXIMUM	MINIMUM	AVERAGE	MAXIMUM	MINIMUM	AVERAGE	MAXIMUM
419	SURFACE									
	1968	178,500	202,200	242,200	1	2	10	--	--	--
	1970	181,100	189,425	197,700	0	0	0	0	0	0
	1977	116,500	121,734	141,110	0	0	0	0	0	0
	1 FOOT									
	1968	184,100	212,900	245,600	1	6	50	--	--	--
	1970	188,300	193,150	203,100	0	0	0	0	0	0
	1977	118,225	123,247	141,230	0	0	0	0	0	0
420	SURFACE									
	1968	126,500	155,500	200,700	30	293	1,000	--	--	--
	1970	180,300	121,325	202,200	15	23	30	0	5	10
	1977	81,210	104,575	136,260	0	12	33	0	0	0
	1 FOOT									
	1968	137,900	179,500	203,900	1	90	400	--	--	--
	1970	180,800	192,550	206,100	0	0	0	0	0	0
	1977	117,625	123,363	136,150	0	0	0	0	0	0
421	SURFACE									
	1968	175,000	193,100	212,100	1	102	540	--	--	--
	1970	175,600	189,250	208,400	0	7	18	0	0	0
	1977	73,790	115,965	134,550	0	3	16	0	0	0
	1 FOOT									
	1968	17,520	197,000	223,500	0	15	50	--	--	--
	1970	179,200	191,625	209,100	0	0	0	0	0	0
	1977	115,490	122,433	134,110	0	0	0	0	0	0
422	SURFACE									
	1968	179,400	195,100	210,900	1	103	1,000	--	--	--
	1970	173,300	191,800	214,900	0	0	0	0	0	0
	1977	110,100	121,205	137,334	0	0	0	0	0	0
	1 FOOT									
	1968	180,600	207,450	207,100	0	1	1	--	--	--
	1970	173,600	192,050	215,000	0	0	0	0	0	0
	1977	112,700	122,000	137,040	0	0	0	0	0	0

Most samples from the bay indicated a substantial increase in TDS in surface water from 1965-68 to 1977. Comparsions at the one-foot level were possible in only 3 cases. Two of these showed a substantial decrease and one a substantial increase.

Results of a preliminary study conducted on-site by Utah Division of Health personnel near station 501 in the bay on August 31, 1977 indicated that the decline in numbers of coliform bacteria in water with TDS levels of 60,000-75,000 mg/l was not significant during an eight-hour period.

The bay cannot be considered to have potential for swimming activity at present, primarily because of its confined nature, shallowness, relatively low TDS concentration and the fact that major wastewater effluents are discharged directly to the bay. It might be developed for other types of recreation but this needs more study.

Fresh Water Inflows to the Lake and Farmington Bay

During 1977, State Division of Health personnel collected samples from various inflows to Farmington Bay and the Great Salt Lake to determine pollution and coliform bacteria loadings to the bay and lake waters. Data are shown in tables V and VI.

Pollution loads have been reduced significantly over the years in the drainages entering the bay and lake, yet the waters entering Farmington Bay through the Sewage Canal (250) and the Farmington Bay Water Fowl Management area (FBWFMA) (781 through 784) do not presently meet water quality standards. Based on data collected in 1977, the FBWFMA discharge carries a lower coliform count and pollution load than does the Sewage Canal. This is a function of relatively long detention time in the diked areas of the FBWFMA and of the lower initial pollution load. The Sewage Canal carries a very complex load of pollution discharged to it

TABLE IV
TOTAL DISSOLVED SOLIDS AND COLIFORM BACTERIA COUNT IN FARMINGTON BAY
SUMMARY OF 1965, 1968 AND 1977 DATA

STATION NUMBER	SAMPLE DEPTH YEAR	TDS Mg/L AVERAGE	COLIFORM/100 ML			
			AVERAGE MPN DETERMINATION		AVERAGE MEMBRANE FILTER COUNT	
			TOTAL	FECAL	TOTAL	FECAL
501	SURFACE					
	1965	1,370	-------	-------	10,000	-----
	1968	1,957	201,000	133,830	65,000	-----
	1977	6,690	3,300	625	------	-----
	1 FOOT					
	1977	10,618	1,900	32	------	-----
502						
	SURFACE					
	1965	1,600	-------	-------	10,000	-----
	1968	2,490	48,433	10,930	36,830	-----
	1977	23,860	477	19	------	-----
	1 FOOT					
	1965	1,700	-------	-------	10,000	-----
	1977	24, 685	490	16	------	-----
503	SURFACE					
	1965	1,608	-------	-------	10,000	-----
	1968	4,284	29,000	2,470	13,700	-----
	1977	23,232	290	0	------	-----
	1 FOOT					
	1977	35,822	117	0	------	-----
504	SURFACE					
	1965	1,788	-------	-------	10,000	-----
	1968	4,945	13,166	846	17,390	-----
	1977	31,010	53	0	------	-----
	1 FOOT					
	1977	34,325	22	0	------	-----
505	SURFACE					
	1965	1,608	-------	-------	10,000	-----
	1968	10,045	2,010	440	443	-----
	1977	31,010	9	0	------	-----
	1 FOOT					
	1965	279,200	-------	-------	490	210
	1977	36,288	22	0	------	-----
506	SURFACE					
	1965	25,500	-------	-------	6,000	2,800
	1968	11,583	2,100	37	143	-----
	1977	31,955	157	0	------	-----
	1 FOOT					
	1965	277,040	-------	-------	1,320	810
	1977	37,115	27	0	------	-----
507	SURFACE					
	1965	39,260	-------	-------	6,200	2,470
	1968	13,766	1,107	77	47	-----
	1977	38,310	62	0	------	-----
	1 FOOT					
	1977	39,350	-------	0	------	-----
508	SURFACE					
	1968	14,700	653	71	37	-----
	1977	87,445	535	21	------	-----
	1 FOOT					
	1977	87,580	141	0	------	-----

TABLE IV (continued)

STATION NUMBER	SAMPLE DEPTH YEAR	TDS Mg/L AVERAGE	COLIFORM/100 ML			
			AVERAGE MPN DETERMINATION		AVERAGE MEMBRANE FILTER COUNT	
			TOTAL	FECAL	TOTAL	FECAL
509	SURFACE					
	1968	17,020	3,346	130	283	-----
	1977	84,825	255	14	------	-----
	1 FOOT					
	1977	85,297	33	6	------	-----
510	SURFACE					
	1968	18,860	7,886	509	70	-----
	1977	85,294	67	0	-------	-----
	1 FOOT					
	1977	86,442	66	0	-------	-----
511	SURFACE					
	1968	19,523	400	1	10	-----
	1977	87,820	112	0	-------	-----
	1 FOOT					
	1977	88,013	42	0	-------	-----
512	SURFACE					
	1968	16,580	673	17	333	-----
	1977	87,479	69	0	-------	-----
	1 FOOT					
	1977	87,681	16	0	-------	-----

by the Salt Lake City Wastewater Treatment Plant, industrial effluents, and nonpoint sources, such as runoff and groundwater seepages. While the Salt Lake City Wastewater Treatment Plant has significantly reduced the amount of untreated sewage being discharged to the Canal, biochemical oxygen demand (BOD) and TDS as well as coliform bacteria counts remain relatively high in the discharge to Farmington Bay and warrant concern.

Water entering the south arm of the lake through the C-7 Ditch (815) and Goggin Ditch (820) is generally of better quality than water entering Farmington Bay, but the water does not meet the recreational water quality standards.

The presently planned additional treatment of municipal and industrial wastes and improved control on nonpoint sources on drainages entering the lake will enchance the water quality and hopefully will offset increasing loads of pollution resulting from population growth.

CONCLUSIONS

1. There has been a general reduction in coliform bacteria in lake water since 1965, attributed largely to reduction in pollution load accomplished by modern sewage treatment and improved watershed management.

2. The postive correlation between TDS concentration and bacterial die-off rate previously found was confirmed during the 1977 study. During the 1977 sampling period, no fecal or total coliform bacteria were observed in samples collected from the Great Salt Lake waters when TDS levels exceeded 125,000 mg/1, a salinity level slightly higher than occurred in south arm sampling areas during 1977.

3. There has been a significant reduction in TDS in the upper 12 inches of water in the south arm of the lake. Percent TDS in this portion is now around 10% to 12% as compared with 16% to 18% in 1969. This is probably a function of the restricted flow through the openings in the Lucin Cutoff causeway, and greater precipitation.

4. Data obtained in this study support the earlier Division of Health policy that swimming is acceptable in certain areas (not Farmington Bay) suitably isolated from inflows of wastewater effluents and indicate that most fresh water inflows must be included in the isolation concept.

5. The waters near the northeastern area of Stansbury Island could be included for water contact recreation with the same limitations imposed for Antelope Island and South beach area waters if cattle are restricted from the area.

TABLE V
TOTAL DISSOLVED SOLIDS AND COLIFORM BACTERIA COUNT IN INFLOWS TO FARMINGTON BAY

(STATE DIVISION OF HEALTH DATA)

STATION NUMBER	INFLOW OR SOURCE	DATE	TSS** mg/l	BOD mg/l	TDS mg/l	MPN COLIFORM/100 ML TOTAL	FECAL
411	Salt Lake City WWTP effluent to Sewage Canal in Davis County	May 1968					
		Minimum	----	----	----	75	-----
		Average	----	----	----	882	-----
		Maximum	----	----	----	2,300	-----
		1977					
		Minimum	----	----	----	21	4
		Average	----	----	----	13,489	240
		Maximum	----	----	----	130,000	2,000
473	Sewage Canal at Cudahy Lane	May 1968					
		Minimum	----	----	----	750	-----
		Average	----	----	----	55,218	-----
		Maximum	----	----	----	230,000	-----
		2-2-77	30	16.0	----	40	23
		4-5-77	35	14.0	2,052	2,400	23
		6-28-77	30	17.0	1,654	230	23
		Average	32	17.0	1,853	890	23
250	Sewage Canal at Outfall to Farmington Bay	2-3-77	30	13.0	----	390	23
		4-5-77	25	15.0	2.182	2,400	930
		6-28-77	15	14.0	2,374	24,000	2,300
		Average	23	14.0	2,278	8,930	1,084
781	FBWFMA Outfall to Farmington Bay No.1 from West end of Turpin Dike	4-5-77	90	9.0	1,630	210	23
		4-27-77	170	13.0	----	23	40
		6-28-77	45	3.0	1,146	230	40
782	No. 2 from middle of Turpin Dike	4-5-77	70	13.0	1,780	430	23
		4-27-77	110	14.0	----	23	23
		6-28-77	45	11.0	1,450	23	-----
783	No. 3 from East end of Turpin Dike	4-5-77	50	13.0	2,586	90	23
		4-27-77	55	14.0	----	230	23
		6-28-77	60	7.0	1,194	230	23
784	No. 4 from Unit No. 1	4-5-77	70	15.0	1,690	70	23
		4-27-77	60	13.0	----	40	23
		6-28-77	85	26.0	1,436	150	150
	Average of all FBWFMA outfalls		76	12.6	1,550	146	38
	TABLE VI - INFLOWS TO SOUTH ARM OF GREAT SALT LAKE						
815	C-7 Ditch at I-80 crossing	*2-1-77	146	11.0	1,880	290	23
		4-5-77	315	7.0	4,174	2,400	2,400
		6-29-77	90	2.9	766	2,400	2,300
		Average	184	7.0	2,273	1,697	1,574
820	Goggin Drain at USGS Station	*2-1-77	11	2.8	10,200	876	178
		4-5-77	45	7.0	8,236	90	40
		6-29-77	80	13.0	4,166	930	70
		Average	45	7.6	7,534	632	96

* Values this date represent are an average of 4 values obtained from samples collected at 4-hour intervals.
**Total Suspended Solids.

6. Recreational bathing areas for public use should be isolated from all inflows to the lake until the inflow waters meet water quality standards for contact recreation.

7. The degree of protection from health hazards achieved by the earlier policy covering treatment and isolation of wastewater inflows can be maintained only if degrees of wastewater treatment are adjusted from time to time to compensate for increased volumes of wastes produced by a growing population as well as continual improvement in watershed management.

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PLANT LIFE OF THE GREAT SALT LAKE STUDY AREA

by Edwin V. Rawley

Division of Wildlife Resources

INTRODUCTION

The material for this article was condensed from two previous reports: 1) "The Great Salt Lake Biotic System", 1974, by Edwin V. Rawley, and Bruce C. Johnson, and 2) "Small Islands of the Great Salt Lake", 1976 by Edwin V. Rawley. This article is divided into two major sections, "Plant Life of the Areas Surrounding the Great Salt Lake", and "Plants on the Small Islands of the Great Salt Lake." In addition a small section, "Plants Important to Wildlife", is included from "The Great Salt Lake Biotic System".

PLANT LIFE OF AREAS SURROUNDING THE GREAT SALT LAKE

General Description

A visual reconnaissance of the area around the Great Salt Lake was conducted during July and August, 1974, to observe plant communities. From this field work, and the work of Foster (1968), King (1971) and the use of aerial photographs, a map was prepared which shows the major vegetation patterns in the Great Salt Lake study area (figure 1).

As shown on the map, the eastern portion of the area is dominated by a marsh area that extends from the Jordan River marshes to Bear River Bay. Except for the Bear River marshes, which are quite extensive, these marshes are generally confined to a narrow strip of ground between the upland agricultural areas and the salt flats or lake itself. This small strip of vegetation, along with the shallow water areas nearby, serves as a major rest area for millions of migratory waterfowl and shorebirds.

The only extensive stands of sagebrush to be found around the lake are to the north, on the Promontory and Hansel mountains, and are generally related rather closely to livestock interests which winter large numbers of sheep on these areas. The sagebrush areas also serve as winter range for a limited number of mule deer.

The Promontory Mountains are the only location in the study area where the browse type of vegetation is found. The browse type is generally made up of mountain mahogany, serviceberry, and bitterbrush and is valuable to wildlife as food and cover.

Juniper types are located on the Promontory, Hogup and Stansbury mountains at higher elevations. The junipers in these areas are generally uniformly spaced and grow on steep, rocky hillsides. In most areas they are unavailable for use by wildlife.

The annual type designates those areas that are covered primarily by cheat grass. Depending upon the location, sagebrush, rabbitbrush or shadscale may also be present or even form extensive areas in this type, as on the northern end of Antelope Island where sagebrush covers large areas, or on Fremont Island where rabbitbrush covers the southern end.

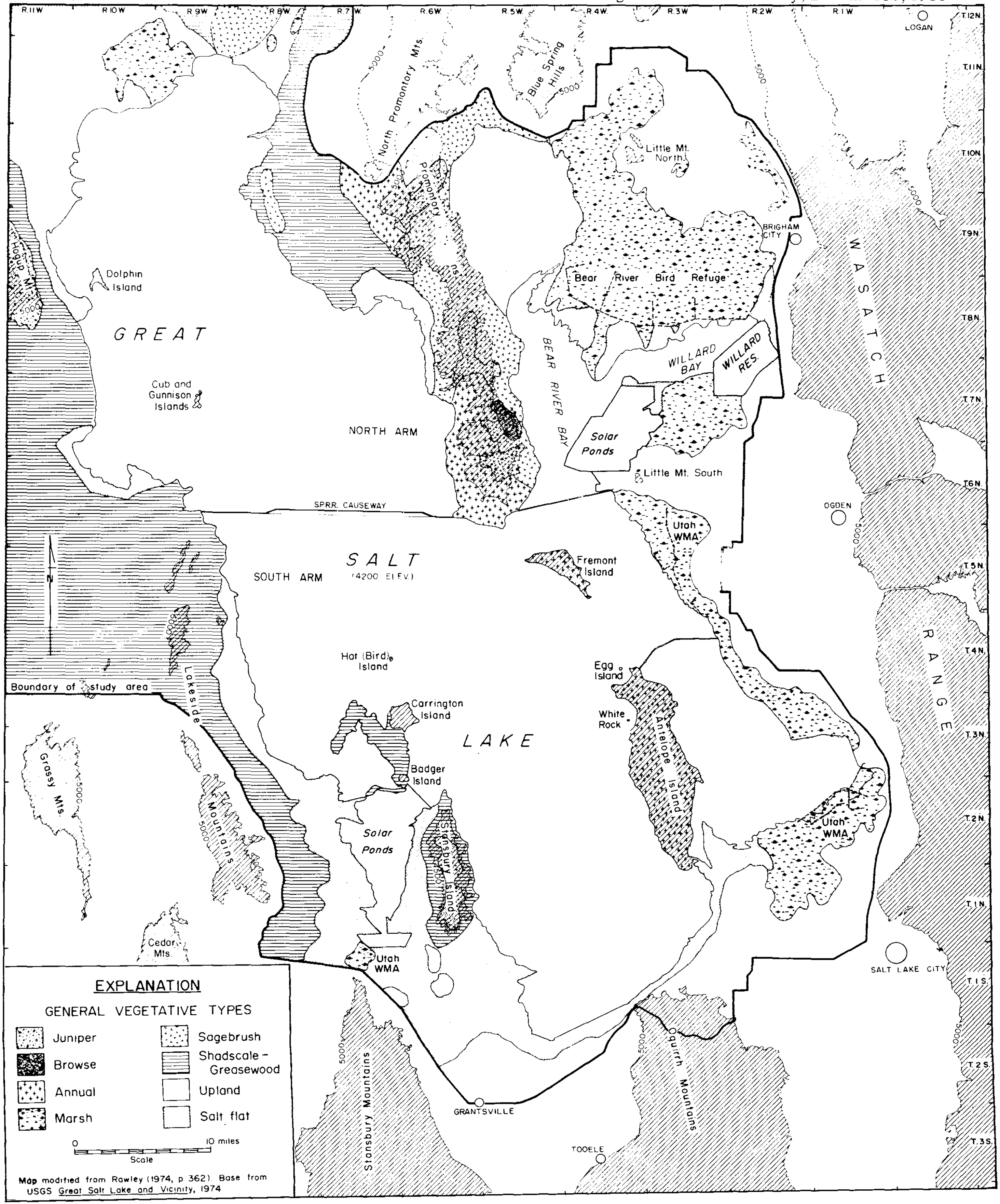
The shadscale-greasewood type covers almost all the western portion of the study area and has many gradations from almost pure greasewood to pure shadscale. Although not a prime area, this vegetative type, due to its extensiveness is used heavily by wintering sheep herds.

The upland type is a catch-all used to designate all areas not before mentioned. Generally this type is composed of agricultural, urban, and industrial areas.

PLANT LIFE

Introduction

Seville Flowers (1934) wrote an extensive account of the plant communities in the Great Salt Lake area. In his paper Flowers listed the plant associations that occur in the strands and beaches, the salt marshes, the playas, the saline plains and the dunes. Additional work concerning the plant life on the shores of the Great Salt Lake was conducted and reported by Seville Flowers and Frederick R. Evans (1966). These works, that of other



Map modified from Rowley (1974, p 362). Base from USGS Great Salt Lake and Vicinity, 1974

Figure 1. Vegetative types around the Great Salt Lake, Utah

authors as noted, and the authors own field work are the basis for the following discussion.

Strands (Beaches)

The term "Strand" includes any ground left exposed between the margin of the water and the highest level attained by the lake since records have been kept.

For the most part the strand is barren. Trees are absent and the pioneer plants invading the strand are mostly restricted to the extreme margins but occasionally widely scattered or in isolated groups on the otherwise barren flats, especially after prolonged periods of low lake level.

Beach Flora

Saltair and Garfield Beaches - Zonation of plants is very distinct at certain places; in other places the zones are diffuse and overlap. A vegetative zone is a subdivision of flora that is dominated by particular species. An ideal situation shows the following zones:

Zone 1

Salicornia rubra A. Nels.	Red samphire
Salicornia utahensis Tidest.	Utah samphire

Zone 2

Suaeda erecta (Wats.) A. Nels.	Annual inkweed

Zone 3

Distichlis stricta (Torr.) Rydb.	Salt grass

Zone 4

Spartina gracilis Trin.	Cord grass or beach grass
Oryzopsis hymenoides (R. & S.) Ricker	Rice grass
Puccinellia nuttalliana (Sch.) Hitch.	Western alkali grass
Bromus tectorum L.	Cheatgrass
Abronia salsa Rydb.	Sand puffs
Sphaerostigma utahensis Small	Utah evening-primrose

Zone 5

Sporobolus airoides Torr.	Alkali sacaton grass
Sporobolus cryptandrus (Torr.) Gray	Closed dropseed grass
Poa nevadensis Vasey	Nevada bluegrass
Sitanion hystrix (Nutt.) J. G. Sm.	Squirreltail
Atriplex hastata L.	Annual atriplex
Atriplex argentea Nutt.	Silver atriplex
Atriplex rosea L.	Rose atriplex
Atriplex confertifolia (Torr.) Wats	Shadscale
Chrysothamnus pulcherrimus Greene	Rabbitbrush
Guiterrezia microcephala Gray	Matchweed
Pachylophus marginatus (Nutt.) Rydb.	Sand lily or evening-primrose

From West Point northward to Hooper the old shore becomes higher and forms a bluff which is fifteen or twenty feet high at some points. The beach pioneers, those species of plants capable of establishing themselves on barren beach areas and initiating an ecological cycle, grow abundantly at the base of the bluff while greasewood grows along the top.

On the east side of the Promontory Point the exposed beaches become narrower from the northern portion southward; in some places the lake water approaches the headlands and abruptly rising borders and there are no beaches. The plants are restricted mainly to the upper border of the shore where the waves do not flood them with lake brine.

Along the western borders of the lake are wide expanses of barren beaches, in some places nearly ten miles in width. The vegetation in this section is somewhat different in aspect in that pickleweed is much more in evidence than along the eastern shores. Red samphire is not nearly so prominent, but the Utah Samphire reaches maximum growth both in size and abundance.

Salt Marshes

Salt marshes are wet areas where fresh water from streams, drainage ditches and springs leach some of the salt from the soil. Some marshes around springs or seepage areas are small; others, in the deltas of the Jordan and Bear River, are quite extensive. Many marsh areas are located where fresh water reaches the borders of the lake and adjacent plains along the eastern side from the southermost tip to Bear River Bay and the eastern side of the Promontory Point.

Plants of Salt Marshes

The dominant swamp plants are much the same throughout the northern hemisphere. Marsh communities show several zones of plant societies which include the following types: Free-floating, microscopic forms, anchored, submerged, emergent, plants of muddy borders, and those of the wet meadow or drier borders further removed from the water.

The dominant marsh plants will be briefly described. The marsh rush and American rush are foremost in the toleration of salt and thrive in its presence. Both plants are rather low, leafy forms with triangular stems and conspicuous clusters of brown, chaffy, grass-like flowers apparent on one side of the stem at the top. Olney's rush, Gray rush, and bulrush are tall and practically leafless. Spike rush has low, very slender, leafless stems with a single, erect, grass-like flower cluster and no subfloral leaf. Wire grass or baltic rush reaches three to four feet in height and has round practically leafless stems with conspicuous clusters of purplish or brownish flowers on long stalks borne on one side. Broad-leaved cat-tails have thick flower clusters and narrow-leaved cat-tails have narrow flower clusters.

The algae constituting the microscopic submerged zone are variable. Blue-green algae, Myxophycene, are primitive forms that occur more abundantly in small sloughs and around warm springs while the higher green algae, Chlorophycene, are most abundant in larger bodies of water and streams. The diatoms, Bacillarieae, are found everywhere, but particularly around springs and in smaller sloughs.

Playas

Playas are low flat depressions in the valley floor that were formed by bottom currents of water in Lake Bonneville in its last stages of recession. Some playas are continuous with the beaches of the lake while others are closed basins. The Great Salt Lake desert west of the lake is a vast playa embracing numerous local depressions and irregular bars.

The pioneer plants invading barren playas from the outer margins are the same species found on the beaches of Great Salt Lake. For the most part there is more distinct zonation due to the increasing gradient of salt concentration toward the center. There are several variations in the order of invasion.

In some playas the gradient of salt in the soil is very gradual and of relatively low concentration so that the invasion of pioneer plants proceeds more rapidly. An intermediate stage is reached when the entire area becomes populated with plants of variable density and composition. Some areas may be mixed and others more or less homogenous.

Plants of Playas

The playas show various stages of reclamation by vegetation ranging from barren salt flats to those completely occupied by plants. Surrounding the bare areas is a succession of plants encroaching from the margins similar to that seen on the beaches of the lake. These frequently show fine zonation.

The zones may vary somewhat as to species, but the following are typical: Zone 1, red samphire; Zone 2, annual inkweed; Zone 3, pickleweed, Zone 4, salt grass; Zone 5, annual and silver atriplex, and western and Moquin's inkweed.

Some playas show the succession to be more advanced, with additional zones of mixed species as follows:

Zone 6

Bromus tectorum L.	Wheat grass
Puccinellia nuttalliana (Sch.) Hitch.	Western alkali grass
Bassia hyssopifolia (Parl.) Kuntze	Bassia
Salsola pestifer A. Nels	Russian thistle
Sessuvium sessile Pers.	Sea puslane
Suaeda intermedia Wats.	Inkweed
Triglochin maritima L.	Arrow grass

Zone 7

Deschampsia danthomioides (Trin.) Monr.	Hairgrass
Allocarya nitens Greene	Allocarya
Arabis spp.	Rock cress
Hutchinsia procumbens (L.) Desv.	Hutchinsia
Lepidium dictyotum Gray	Pepper grass
Lepidium perfoliatum L.	Pepper grass
Myosurus apetalus Gay	Mousetail
Plantago elongata Pursh	Plantain
Plantago purshii R. & S.	Plantain

Saline Plains

Saline plains extend beyond the strand and playas to the bases of the mountains, where the junction with steeper slopes is abrupt. In most of the wider valleys the saline plains gradually rise to long alluvial slopes.

The flora is diverse according to the topography and soil type and is disposed in rather well-defined communities. A plant community is composed of mixed or discontinuous vegetation with no single species or group of species dominating its aspect.

The botanical composition among different communities includes herbs and smaller shrubs, the number of species and their frequency depending largely on the character of the surface soil and the rainfall. In the areas receiving only 15 cm. annual average precipitation, the clay soils harbor a very limited number of species, shrubs, and a few annual herbs.

In areas of loamy soil where the annual rainfall is about 45 cm. there is a much greater variety of associated shrubs, annual and perennial herbs, and several species of moss.

Plants of Saline Plains

The vegetation of the plains is diverse in different localities, but usually forms well defined combinations of species called plant association. A plant association is a group of plants of more or less definite botanical composition that is continuous over extended areas and dominated by a single species or two or three species which impart a characteristic appearance to the area as a whole and which is a stable type of vegetation not replaced by other types. The association is the culmination of plant succession.

Greasewood-shadscale association. The combination of greasewood and shadscale is the most extensive vegetation on the saline plains of this region. The general aspect shows a shrubby vegetation three to five feet in depth, the dominantly gray background of shadscale spotted with the dark green of the greasewood. The greasewood is an erect shrub, usually three to five feet tall with a much branched stem having white or grayish shreddy bark, green wood, numerous small spiny branches and narrow, fleshy, dark green leaves. Its roots penetrate the soil to a depth of fifteen feet and it is a ground water indicator. The shadscale is a round-topped shrub usually a foot and a half to two feet high with broad leaves covered with silvery-gray scurfy scales of waxy material. Its roots are shallow and it will grow in very dry places. The composition of this association varies in different localities, each area having certain less dominant plants that may not be present in other areas.

Herbs occupy the spaces between the shrubs and with the exception of certain annuals they do not assume a dominant role. The species are numerous and scattered.

Annual plants assume a dominant role in the spring imparting to the greasewood-shadscale association a brighter green appearance. The spring aspect is dominated by grasses and small mustards. Cheat-grass grows everywhere in the state and in this region dominates the spring flora above all other plants. Pepper grass is the most common mustard although the introduced *Malcolmia africana* (Willd.) A. Br., is assuming dominance in many places.

The shadscale association. On dry, mildly saline plains and slopes extending toward the foothills shadscale dominates the vegetation and greasewood is practically absent. It merges with the greasewood-shadscale association toward the more saline regions and with sagebrush or bunch grass associations toward the foothills. The general aspect shows a scattered growth of grayish shrubs, often with exposed ground between, and more scattered herbs. Many of the herbs present are those familiar to the foothills.

The Kochia flat association. Winter fat or white sage dominates the aspect in some localities.

Kochia-Erotia communities and *Kochia-Suaeda communities* are of less extent and occur locally as variations of other communities.

The rabbit brush communities. Several species of rabbitbrush are conspicuous in many places and may dominate the aspect in local areas, but are seldom continuous. Most species indicate ground water.

Dunes

Locally, sand dunes are formed along some of the eastern shores of Great Salt Lake and on the plains and foothills bordering the salt desert to the west. Those near the lake are composed of whitish calcareous oolites, while those farther removed are tawny colored and composed of mixed silaceous and ferromagnesium grains. The botanical composition varies somewhat on different dunes.

Plants of Dunes

Shrubs are lacking on the dunes at Black Rock, but on the dunes in the Lakeside mountains and Stansbury Island areas greasewood, fourwinged salt bush and rabbitbrush are prominent. Standing out very conspicuously is the white rabbitbrush, creating a whitish background spotted with the darker green of greasewood and twisted-leaved rabbitbrush. At the northern end of the dunes Utah juniper is dominant and is an outstanding feature in that it extends to the old shoreline of the lake and marks the closest approach a tree makes to the lake.

The usual sand-loving species are present in most of the dunes although varying in the different localities.

PLANTS ON THE SMALL ISLANDS OF THE GREAT SALT LAKE

General Description

A 1974 study by the Utah Division of Wildlife Resources recommended that consideration be given to protecting some of the islands of the Great Salt Lake for the benefit of colonial-nesting birds, particularly the American white pelican. In 1976 a second study was conducted to evaluate the importance of the smaller islands of the Great Salt Lake as bird rookeries. The following material was extracted from the sections of this report describing the islands and their vegetation.

Badger Island

Badger Island, which is approximately six acres in size, is located off the northwest point of Stansbury Island (figure 1) in township 2 north, range 7 west in Tooele County. It is connected to Stansbury Island by a dike and roadway built by N. L. Industries Inc.

Vegetation

The predominent vegetative types of Badger Island are greasewood and shadscale (figure 2). Badger Island supports a very low ridge which is only a couple of feet higher than the remainder of the island. The ridge runs in a northwest and southeast direction and lies north of center toward the northeast shoreline.

There is very little understory growing in the desert shrub type north of the ridge, but on the south side, between the ridge and the road which traverses the southern portion of the island, are found pockets of fairly dense growth of alfileria and bur buttercup. There is a dense growth of salt grass along the south shore south of the road.

Vegetative Types on Badger Island

	Scientific Name	Common Name
Grasses		
	Bromus tectorum	Cheatgrass brome
	Distichlis spicata stricta	Inland saltgrass
	Festuca ovina	Sheep fescue
	Poa sanbergii	Sandberg bluegrass
Forbes		
	Amsinckia intermedia	Fireweed fiddleneck
	Erodium circutarium	Alfileria
	Hutchinsia procumbens	Mustard
	Lappula redowskii	Annual stickseed
	Ranunculus testiculatus	Bur buttercup
Shrubs		
	Atriplex confertifolia	Shadscale
	Grayia spinosa	Spiny hopsage
	Sarcobatus Spp.	Greasewood

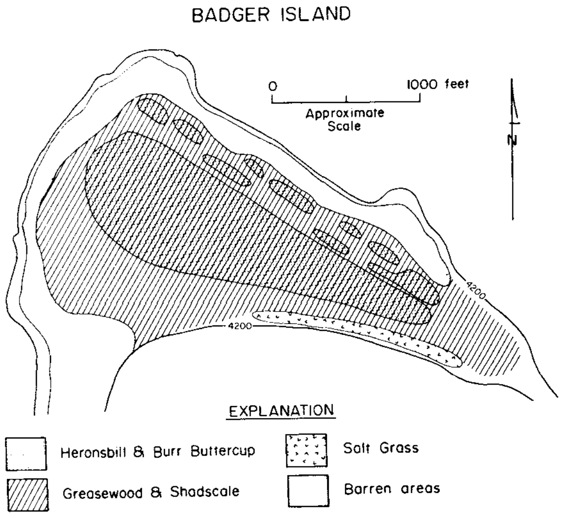


Figure 2. Vegetative types on Badger Island

Carrington Island

Carrington Island is 1,767 acres in size and is located in township 3 north, ranges 6 and 7 west in Tooele County. It is the largest of the islands considered in this article. It is located in the west portion of the Great Salt Lake northwest of Stansbury Island and in low-water periods is connected by sandbars with Badger Island, approximately five miles south of it (figure 1).

Carrington is a rocky island that is quite high in the center with sloping sides. Its high point is 4,727 feet. In low-water years extensive sandbars exist to the west as well as to Badger Island.

Vegetation

The vegetative type of Carrington Island is predominently grass. The northern crown of the island is covered with perennial grasses. The south side of the crown supports a more dense stand of cheatgrass with some sagebrush. The west, north, and east skirts of the island are covered with a mixture of cheatgrass, desert shrubs, and Indian ricegrass with some patches of sagebrush on the east skirt. The south skirt is predominently greasewood, shadscale, and Indian ricegrass (figure 3).

Vegetative Types on Carrington Island

	Scientific Name	Common Name
Grasses		
	Agropyron-Elymus	Wheatgrass-wildrye cross
	Agropyron spicatum	Bearded bluebunch wheatgrass
	Bromus rubens	Foxtail brome
	Bromus tectorum	Cheatgrass brome
	Distichlis spicata stricta	Inland saltgrass
	Hilaria jamesii	Galleta
	Oryzopsis hymenoides	Indian ricegrass
	Poa sandbergii	Sandberg bluegrass
	Sitanion hystrix	Bottlebrush squirreltail
Forbes		
	Abronia salsa	Sandverbena
	Amsinckia tessellata	Fiddleneck
	Calochortus nuttalli	Sego lily mariposa
	Castilleja hispida	Northwestern painted-cup
	Cirisium spp.	Thistle
	Cryptantha humilis	Cryptantha
	Erodium cicutarium	Alfileria
	Halogeton glomeratus	Halogeton
	Lomatium grayi	Desert parsley
	Sphaeralcea spp.	Globemallow
	Stephanomeria spinosa	Wirelettuce
Shrubs		
	Allenrolfea occidentalis	Iodine bush
	Artemisia tridentata	Big sagebrush
	Atriplex canescens	Fourwing saltbush
	Chrysothamus nauseosus	Rabbitbrush
	Grayia spinosa	Spiny hopsage
	Leptodactylon pungens	Prickly phlox
	Sarcobatus vermiculatus	Greasewood
	Xanthocephaleum sarothrae	Broom snakeweed

Hat Island

Hat Island (sometime referred to as Bird Island) is 22 acres in size and is roughly shaped like a hat with a crown and brim. The high point of Hat Island is at 4,275 feet. This rocky island is located in township 4 north, range 7 west of Box Elder County. Hat Island lies approximately five miles straight north of Carrington Island (figure 1).

Vegetation

The vegetative type of Hat Island was determined to be predominently annuals. The northern half and part of the south half of the island are covered mainly with mustards. The remainder of the south half with the exception of the south shore is predominently sunflowers. The south shore supports mainly greasewood and rabbit brush (figure 4).

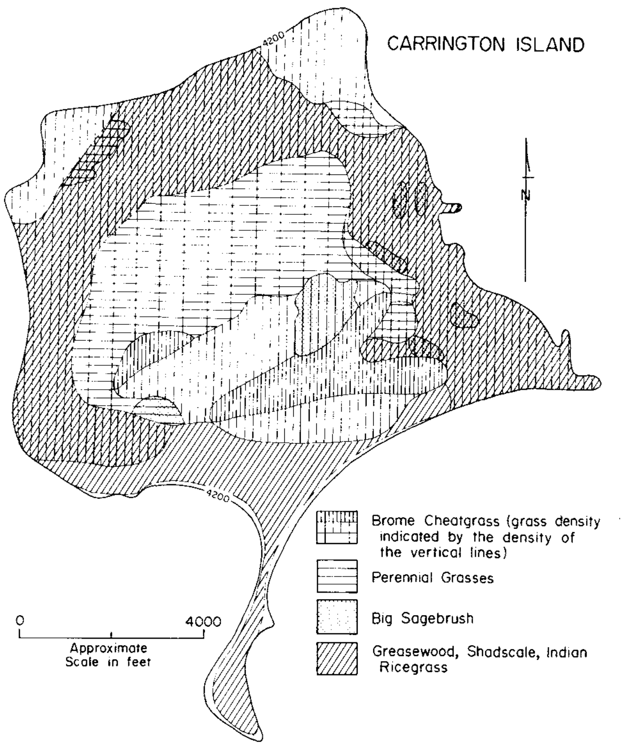


Figure 3. Vegetative types on Carrington Island

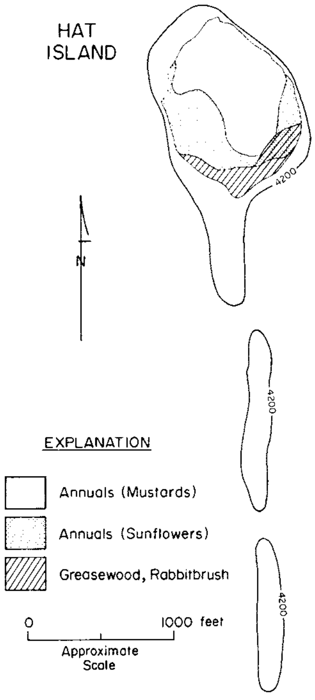


Figure 4. Vegetative types on Hat Island

Vegetative Types on Hat Island

	Scientific Name	Common Name
Grasses		
	Bromus tectorum	Cheatgrass brome
Forbes		
	Amsinckia tessellata	Fiddleneck
	Chenopodium album	Lambsquarters, goosefoot
	Descurainia pinnata	Pinnate tansymustard
	Descurainia richardsonii	Richardson tansymustard
	Descurainia sophia	Flaxweed tansymustard
	Halogeton glomeratus	Halogeton
	Kochia scoparia	Belvedere summer cypress
	Lactuca serriola	Prickly lettuce
	Monolepis nuttalliana	Nuttall monolepis
	Oenothera alyssoides	Alyssum evening-primrose
	Salsola kali	Russian thistle
	Sisymbrium altissimum	Tumblemustard
Shrubs		
	Sarcobatus vermiculatus	Greasewood

Gunnison Island

Gunnison Island is located in township 7 north, range 9 west of Box Elder County. Its highest point is at an elevation of 4,492 feet. It is some nine miles north of the railroad trestle on the west side of the lake and is roughly twenty-five miles from Promontory Point (figure 1). Its long axis extends in a north-south direction. The island is about one hundred and sixty-three acres in size. Its shoreline is irregular with several small embayments and is about three miles in extent. A rocky backbone runs the length of the island, sloping down to the sandy shores. Near the middle of the island are two low saddles.

Vegetation

Vegetation is typical of the cold desert community and is of the desert shrub type (figure 5).

The island slopes are rather thickly covered with shrubs such as greasewood, shadscale, pickleweed, and spiny sage.

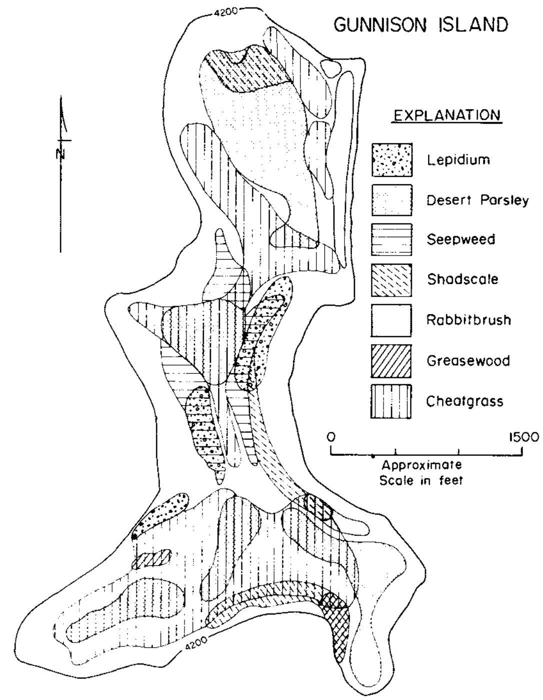


Figure 5. Vegetative types on Gunnison Island

Vegetative Types on Gunnison Island

	Scientific Name	Common Name
Grasses	*Bromus rubens*	Foxtail brome
	Bromus tectorum	Cheatgrass brome
	Distichlis spicata	Saltgrass
	Oryzopsis hymenoides	Ricegrass
	Poa Sandbergii	Sandberg bluegrass
	Sitanion hystrix	Bottlebrush squirreltail
Forbes	*Allenrolfea occidentalis*	Pickleweed
	Allium ssp..	Wild onion
	Amsinckia spp.	Fiddleneck
	Bassia hyssopifolia	Fivehook bassia
	Camissonia boothii	Alyssum evening-primrose
	Erigeron pumilus	Low fleabane
	Erodium cicutarium	Alfileria
	Halogeton glomerata	Halogeton
	Lactuca serriola	Prickly lettuce
	Lepidium spp..	Pepperweed
	Lomatium grayii	Desert Parsley
	Salsola kali	Russian thistle
	Suaeda torreyana	Torrey seepweed
	Tragopogon dubius	Goatsbeard

Shrubs		
	Atriplex confertifolia	Shadscale
	Atriplex rosea	Saltbrush
	Chrysothamnus nauseosus	Rabbitbrush
	Grayia spinosa	Spiny hopsage
	Sarcobatus vermiculatus	Greasewood

Dolphin Island

Dolphin Island is the northernmost of the Great Salt Lake islands. It lies close to the west shore of the lake, eleven and a half miles northwest of Gunnison Island. Dolphin Island is approximately 60 acres in size. Its highest point is at 4,275 feet. It is located in township 9 north, range 10 west of Box Elder County.

Vegetation

The vegetative type of Dolphin Island is predominently desert shrub. It will be noted from the vegetative map that the area above 4,205 feet is basically covered with shadscale, sagebrush, and cheatgrass. The area below 4,205 feet is mainly rabbitbrush, greasewood, and ricegrass except for a strip of salt grass at the water's edge along the south shore (figure 6).

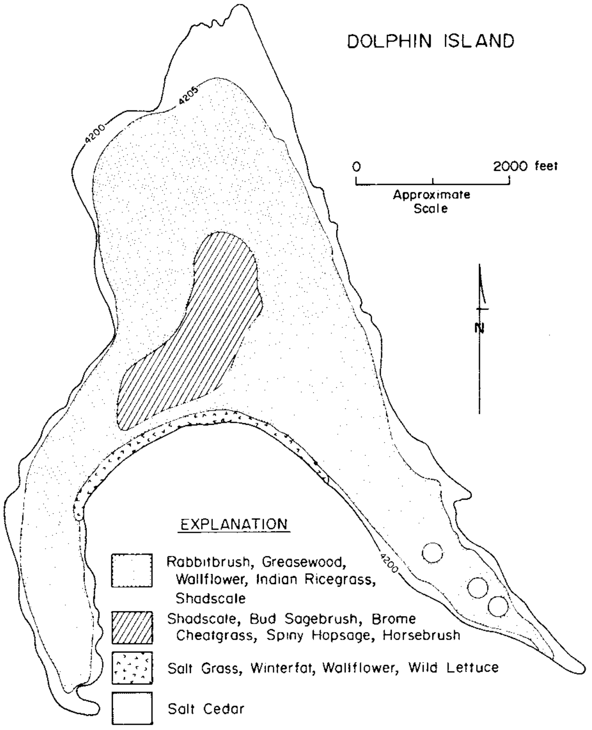


Figure 6. Vegetative types on Dolphin Island

Vegetative Types on Dolphin Island

	Scientific Name	Common Name
Grasses		
	Bromus tectorum	Cheatgrass brome
	Distichlis spicata stricta	Inland saltgrass
	Oryzopsis hymenoides	Ricegrass
	Poa sandbergii	Sandberg bluegrass
	Sitanion hystrix	Bottlebrush squirreltail
Forbes		
	Allium nevadensis	Nevada onion
	Cryptantha humilis	Cryptantha
	Erigeron pumilus	Low fleabane
	Eriogonum ovalifolium	Cushion eriogonum
	Erysimum argillosum	Plains erysimum

Gilia leptomeria	Gilia
Halogeton glomeratus	Halogeton
Lactuca serriola	Prickly lettuce
Lappula redowskii	Annual stickseed
Mentzelia albicaulis	Whitestem mentzelia
Monolepis nuttalliana	Nuttall monolepis
Oenothera alyssoides	Allyssum evening-primrose
Sphaeralcea spp.	Globemallow
Stanleya pinnata	Desert princesplume
Townsendia florifer	Townsendia

Shrubs

Allenrolfea occidentalis	Iodine bush
Artemisia spinescens	Bud sagebrush
Atriplex concertifolia	Shadscale
Chrysothamus nauseosus	Rabbitbrush
Grayia spinosa	Spiny hopsage
Leptodactylon pungens	Prickly phlox
Sarcobatus vermiculatus	Greasewood
Tamarix tetrandra	Fourstamen tamarisk
Tetradymia spinosa	Cottonhorn horsebrush
Xanthocephaleum sarothrae	Broom snakeweed

Egg Island

Egg Island (township 4 north, range 4 west) is a small rocky mass devoid of vegetation that is located an eighth of a mile off the northern tip of Antelope Island (see figure 1). A long sand bar extends southeast from Egg Island toward Antelope Island at low water stages. The area of Egg Island is less than an acre. The island is roughly circular in outline and is perhaps fifty to seventy-five yards in diameter. The island is essentially a great mass of boulders but there are flat spaces intervening.

White Rock

White Rock (township 3 north, range 4 west), also devoid of vegetation, is a hugh rock jutting out of White Rocky Bay which is located on the west side of the north end of Antelope Island (figure 1). The top measures about twenty-five feet long and fifteen feet wide. All sides but the east are precipitous; the latter slopes toward the water.

PLANTS IMPORTANT TO WILDLIFE

Of those plants occurring in the Great Salt Lake area several are important to wildlife for both food and cover. Among the more important of these plants are:

Dry Land Areas

Junipers. Their twigs and foliage are used extensively by hoofed browsers, small fruit produced is also used by bluebirds, grosbeaks, jays, waxwings, and most types of small mammals.

Saltbush. The small seeds are used by small mammals and birds. Twigs and foliage are eaten by rabbits and hoofed browsers.

Serviceberry. Berrys are used extensively by songbirds especially the thrashers, thrushes, towhees and magpie. Twigs and foliage are a preferred food of hoofed browsers.

Mountain Mahogany. Value to wildlife is primarily as a browse for deer.

Maples. They provide food for birds and small mammals especially grosbeaks, finches, porcupines, squirrels, chipmunks. Twigs and foliage are used by hoofed browsers.

Prickly pears. They are utilized by many wildlife species including thrashers, wrens, rabbits, chipmunks, ground squirrels, and kangaroo rats.

Sagebrush. This plant not only covers extensive areas, but it is also used extensively as both food and cover by many animals including sage grouse, jack rabbits, cottontail rabbits, ground squirrels, gophers, antelope, and deer.

Bromegrass. This annual grass covers extensive portions in the Great Salt Lake study area and is used for food by several species of sparrows, Hungarian partridge, chuckar, chipmunks, gophers, pocket mice and deer.

Wheatgrass. Several species of this grass occur in the study area and are used for food by pheasants, rabbits, ground squirrels, antelope, and deer.

Ricegrass. While often grazed extensively by deer, this grass is also used by mourning doves and chipmunks.

Carex. In addition to providing cover, this marsh plant also provides food for many species of wildlife including the mallard, greenwinged and cinnamon teal, snipe, pheasant, and several species of sparrows.

Polygonum. The large seeds and large distribution of this plant make it a valuable food source for the mourning dove, Hungarian partridge, redwing blackbird, horned lark, all sparrows, porcupine, chipmunks and ground squirrels.

Goosefoot. These plants are a food item relished by sparrows, juncos, larks, mourning doves, ground squirrels and kangaroo rats.

Rabbitbrush. Besides furnishing cover, the seeds and foliage are eaten by wildlife, especially deer, antelope and rabbits.

Ragweeds. These annual plants produce enormous amounts of seeds in addition to their foliage which makes them a valuable plant used extensively by sparrows, mourning doves, Hungarian partridge, blackbirds, juncos, goldfinch, chipmunks and ground squirrels.

Marsh and Aquatic Plants

Algae. It is used in large amounts by gadwall, coot, and widegeon, and to a lesser extent by pintail, mallard, redhead, shoveller, and teal.

Muskgrass. It is used principally by the diving birds: coot, redhead, scaup, ruddy, and also by widgeon, pintail, teal and mallards.

Cattails. Although these plants may be used as cover, they have little value to waterfowl other than geese which eat the roots, and are, therefore, usually regarded as undesirable since they take the place of more desirable plant species.

Pondweeds. These plants are without exception the most valuable single food plant for waterfowl, particularly for whistling swan, Canada goose, redhead, canvasback, scaup, coot, mallard, shoveller, gadwall, widgeon, and teal. It is also used by shore birds such as avocets, godwits, and dowitchers.

Widgeon grass. This grass is often associated with pondweeds. This plant rates as one of the most valuable species of marsh plants used by the same species that utilize pondweeds in a similar degree.

Saltgrass. This is a valuable plant used for resting and food by shoveller and cinnamon teal and for food by Canada geese and ground squirrels.

Bulrushes. These are used extensively for cover and food by canvasback, mallard, gadwall, pintail, redhead, ruddy, shoveller, teal, Canada and snow geese, godwits, and rails.

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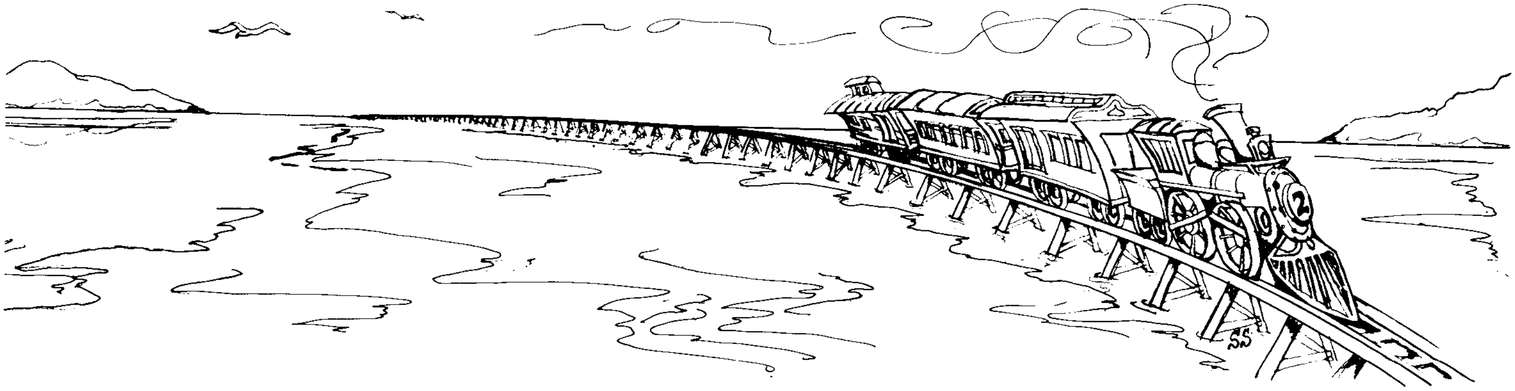
ENGINEERING



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VII.ENGINEERING

GEOTECHNICAL ASPECTS OF DEVELOPMENT IN THE VICINITY OF GREAT SALT LAKE

by Bruce N. Kaliser

Chief, Urban and Engineering Geology Section, UGMS

ABSTRACT

The shoreline of Great Salt Lake is a geologically hostile environment. Geotechnical problems are many and diverse. Preponderance of weak earth materials and high water content make it difficult to utilize standard site exploration techniques. Virtually all structures require careful placement and custom tailored foundation designs based upon *in-situ* conditions.

Not the least of geotechnical problems is that of aggravated shaking from probable earthquakes. Liquefaction possibilities are real and ground deformation is not altogether predictable. Only planning and consideration of geotechnical factors will assure a site with minimized risk of failure.

INTRODUCTION

Greater interest in the industrial and recreational potential of the Great Salt Lake will require that increasing attention be paid to the siting of facilities in the vicinity of its shoreline. Industrial and commercial expansion in Utah's megalopolis (Box Elder, Weber, Davis and Salt Lake counties) is westward, towards the lake (for example, the International Center in Salt Lake County). Siting problems to be addressed include the strength and stability of foundation supporting materials; seismic effects, to include horizontal acceleration and ground response, liquefaction, clay sensitivity, tectonic deformation and other contributors to ground surface subsidence; and construction problems related to erosion control, dewatering, sources of material, placement of fill, subsurface exploration techniques, material sampling, shoring and embankment stability.

SUPPORT MATERIALS

Strength

Strength of geologic materials to support a given facility without failure is a foremost geotechnical consideration. Predominant sediments in the area around Great Salt Lake are likely to contain considerable organic matter, and their natural moisture contents are likely to be high and to vary significantly from stratum to stratum vertically as well as laterally. Peat deposits are known to occur in the subsurface deltaic environments.

At the Arthur V. Watkins Dam (constructed as the Willard Dam), an earth structure was built across an eastward extension of Great Salt Lake. The structure was constructed to the unprecedented height of 35 feet on highly compressible organic silts and clays. Subsequently heave occurred beyond the toes of the eleven mile long embankment, indicating shear failure of the foundation materials; the earth embankment itself did not fail, however, due to the dissipation of porewater pressures (primary consolidation) during construction. Secondary settlements were also significant, gradually and persistantly occurring for many years after loading.

Stability

Stability of excavation walls has particular relevance to human safety. The intercalated, fine, unconsolidated sediments of the lacustrine and deltaic sequences found in the vicinity of the lake shore are quite vulnerable to failure on exposure. Fine, granular soils may flow into the excavation, aided by groundwater pressure. With the support of the overlying cohesive materials removed, instantaneous failure may be deemed likely.

SEISMIC EFFECTS

Seismic Situation

Dynamic response of soils to earthquakes is of primary consideration in any construction around Great Salt Lake, which is situated in the heart of the Intermountain Seismic Belt. The Wasatch Fault zone, to the east of the lake, is an active fault system with a north-south trend. There is reason to believe that faulting, largely parallel to the Wasatch system, if not a part of it, transects the Great Salt Lake. Physiography strongly suggests the occurrence of structural grabens (see Stokes, this volume). Several thousands of feet of sediments have accumulated in the down faulted blocks and much of this sediment is geologically unconsolidated and high in moisture content.

Horizontal acceleration and ground response

The preliminary map of Utah showing horizontal acceleration in rock (figure 1) indicates maximum values for the lake and its immediate vicinity. More recent mapping of ground response for the Salt Lake City area by the USGS (1978) shows that ground surface response tends to be high, by a factor of 3 to 10, compared to bedrock terrain, for sites underlain by thick sequences of geologically unconsolidated deposits. Maximum values have been demonstrated to occur at sites where thick beds of saturated to semi-saturated, fine sediments exist.

Two stations for monitoring ground response have been located in the vicinity of Great Salt Lake, one at the Salt Lake International Airport and one farther west, at the Morton Salt Plant on the lake shore. Difficult-to-predict differences in ground response may be expected to occur around the lake's shoreline due to such factors as lateral interfacing of lacustrine and deltaic sediments, sequences and thicknesses of differing grain size materials, varying moisture contents, buried bedrock profiles, distribution of algal reef rock, and abrupt changes of materials across faults.

Liquefaction

Geologic and hydrogeologic conditions appear to be perfectly suited over a large percentage of the lake shore area for ground failure and subsidence due to liquefaction. Fine, uniform sands at shallow depth, together with a shallow water table and intercalated clays and silts as confining aquicludes, offer suitable conditions for liquefaction.

Field evidence for liquefaction in the form of a vertical sand dike was found by the writer in the summer of 1978, while engaged in a geotechnical study for a state facility west of the State Fairgrounds in Salt Lake County. Under the cyclic, vibratory motion created during earthquakes, all strength is lost in the granular supporting material, and structures may settle, sometimes uniformly, sometimes differentially. Hydraulic structures such as water and wastewater treatment plants are particularly vulnerable to this phenomenon.

Clay sensitivity

Since clay sensitivity can be another cause of ground failure in dynamic loading situations, a considerable number of field vane shear tests were run by the U.S. Bureau of Reclamation for the Arthur V. Watkins Dam. It was found that the ratio of undisturbed to remolded vane shear strength (an index of sensitivity) averaged 1.92. From a number of other sources, data indicate that sensitivity values for Great Salt Lake vicinity materials do not exceed 5 to 6 and rarely 10. These are low values, when compared with values of 200 or so found elsewhere in the world's problem areas, and would appear to indicate little if any problem from clay sensitivity.

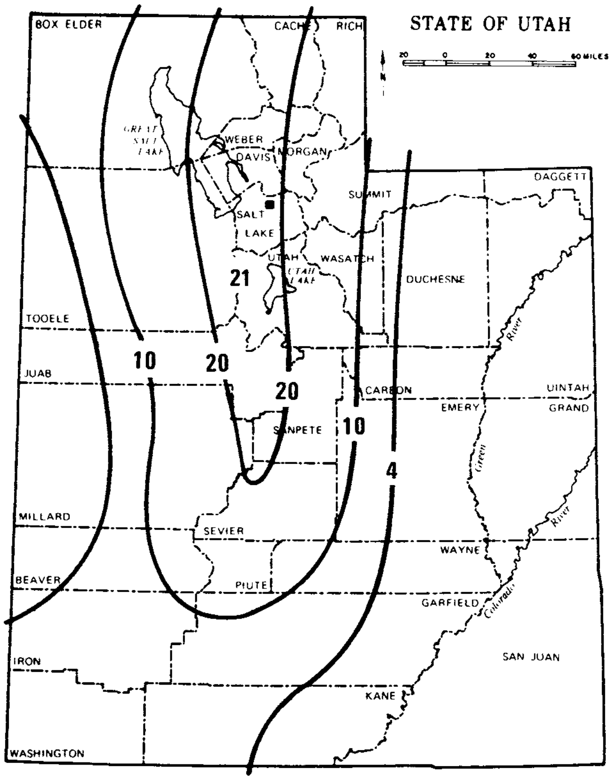


Figure 1. Preliminary map of horizontal acceleration (expressed as percent of gravity) in rock with 90 percent probability of not being exceeded in 50 years. (from U. S. G. S.)

Tectonic deformation

Faults are known to occur across the Great Salt Lake, and sudden displacements along any fault may trigger a seiche wave. Minor readjustments along any number of faults, or even creep, can result in earth surface deformation, largely in tilt. With a body of water as shallow and as broad as the Great Salt Lake the consequences are obvious, and perhaps more consideration is warranted than has heretofore been granted. Public facilities, in particular, must show regard for the potential hazard of seiche waves.

Photos, courtesy of Dames & Moore.

Figure 2. Preparing foundation soil with vibrating drum compactor.

Figure 3. Water erosion of solar pond dike.

CONSTRUCTION PROBLEMS

Sources of Material

Impervious material for core zones of impoundment structures, if not present locally, may be acquired from the lake bottom, acknowledging the fact, however, that handling and placement may be difficult and expensive. Granular materials (sand & gravel) can be hauled to the site from areas where the beach facies of ancient Lake Bonneville are found.

Placement

The method of placement of construction materials requires careful testing and planning. For example, the lower portion of the Watkins Dam was constructed with a rolled earth fill rather than a hydraulic fill when site tests showed that greater compaction could be achieved by the former method. Continual monitoring of conditions while undergoing loading is desirable. Construction in stages may allow time for foundation consolidation to occur. Surcharging, (allowing time for pore water pressure to dissipate) may be another technique to be applied. Because of the soft nature of the lake bottom material, use of heavy equipment must be carefully planned. Several spring flows were developed in the borrow areas near the site of the Watkins Dam because of "pumping" action caused by heavy equipment traveling over the area and exerting pore water pressures. One such flow is reported to have produced 0.5 gpm for a period of 36 hours.

Erosion control

Construction in the body of the lake (such as earth dikes) or along the shore, including the potential shoreline of highest lake level, must guard against erosion. The destructive power exerted by waves in Great Salt Lake has been repeatedly demonstrated, as was illustrated in the case of the Antelope Island causeway which was washed away by wave action simultaneous with the rise in the level of the lake. Rip rap protection should be considered as essential. The 2.5 to 1 upstream slope of the Watkins Dam embankment is protected with 8 feet of rip rap (measured horizontally). Rip rap sources will vary, of course, depending upon the location of the facility. Highly fractured and pulverized material from the Wasatch Fault zone should be avoided but jointed bedrock from ranges in and near the lake may prove suitable. Cost considerations should be weighed at the time the project siting is being contemplated. Extra protection must be included in the design of dikes and the placement of rip rap to allow for foundation settlement or rising of lake level which will lower the freeboard.

Subsurface exploration techniques

The subsurface environment is complex and a variety of subsurface exploration techniques may be necessary to yield all of the requisite geotechnical parameters.

Material sampling may be done by core drilling, hand augering, split-spoon penetration, or with thin wall samplers. In-situ material testing can be done with penetration resistance equipment and vane shear tests. Observation wells are recommended for groundwater levels, especially to acquire data on the seasonal fluctuations and recharge characteristics of an area. Hydraulic testing of aquifers for purposes of foundation dewatering may also be desirable.

Exploration trenches may be of considerable value for material sampling and determining the layering and structural characteristics of the sediments, except in areas with a high water table. Subsurface structure, such as faulting and sediment deformation, may be exposed by high resolution seismic reflection profiling.

For sensitive structures, such as water impoundments, instruments may be installed in the foundation prior to site activity in order to observe the foundation and embankment before, during and after construction. For example, piezometer tips installed for observation of pore-water pressures may offer significant clues on foundation and embankment behavior.

CONCLUSIONS

In conclusion, it may be seen that neglect of geotechnical aspects of Great Salt Lake vicinity development can spell economic disaster if not worse. Under static conditions the near shore geologic environment is sensitive and must not be regarded as stable; under dynamic conditions, mobility and instability may be almost assured. Yet, careful planning for the geotechnical aspects in and near Great Salt Lake should enable most types of structures to be satisfactorily sited and constructed to serve their intended purpose for their intended lifetime.

DIKE DESIGN AND CONSTRUCTION GREAT SALT LAKE - STANSBURY BASIN

by S. C. Johnson

Pond Superintendent, N. L. Industries, Inc.

ABSTRACT

The original solar pond constructed by N. L. Industries used a simple berm or dike, placed by a dragline, to prevent the concentrated pond brine from returning to the lake. However, continuing rise of the lake level made construction of a much larger dike necessary to keep lake water from flooding the pond. Two alternate methods of protecting the new dike were investigated. Although rip-rap construction is the more conventional method of protecting dikes from wave action, N. L. chose to use beach sand facing because it is less costly. The materials of construction are readily available and plentiful near the pond, and tests showed it can withstand the stresses required of it..

INTRODUCTION

N. L. Industries became interested in the extraction of magnesium from the Great Salt Lake in 1963. An original feasibility study resulted in N. L.'s decision in 1967 to begin production. The Stansbury Basin (figure 1) was chosen as the site for the solar ponds, based on the availability of adequate land, minimal annual rainfall and the most desirable soil conditions for solar pond construction at minimal cost.

The ponds cover an area of approximately 25,000 acres, perhaps the largest solar ponding complex in the world. The construction cost per acre of evaporation area was very low because the relatively large flat area chosen was almost enclosed by Stansbury Island to the east and a natural rise in land elevation to the west. Only 13 miles of dike were required to complete the enclosure of the ponds. A dike 2.5 miles long was built by a dragline from the northern tip of Stansbury Island northward to Badger Island. To complete the pond, a second dike was built 10.5 miles almost straight west from Badger Island, to a natural soil barrier.

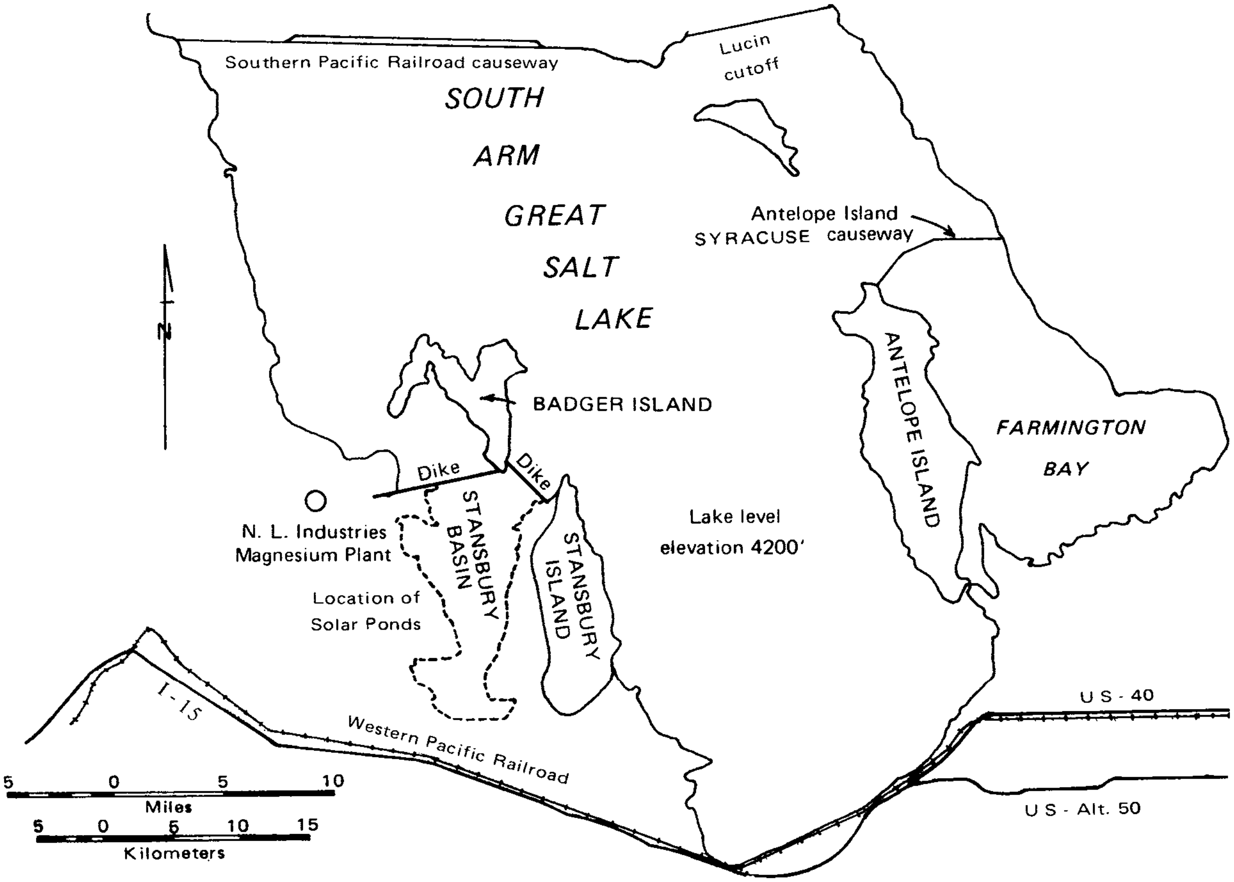


Figure 1. Location of N.L. Industries Magnesium Plant solar ponds in the Stansbury Basin.

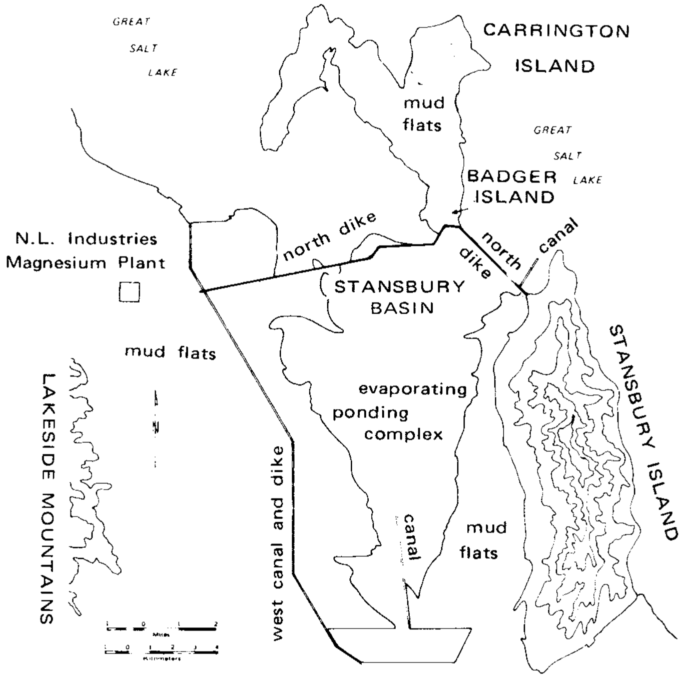


Figure 2. N. L. Industries solar pond area with associated dikes and canals.

As the proposed surface elevation of the impounded brines was originally higher than that of the lake waters, the original purpose of the dike or berm was to keep the brine in the pond. A canal approximately two miles long was dug northward from the north dike near Stansbury Island, to the lake. Brine was pumped from the lake into the pond through this canal (see figure 2).

The pond complex was protected from water runoff from Skull and Tooele Valleys by a drainage canal, dug with a dragline along the southern end and western sides of the ponding area. The material borrowed from the canal was used to enclose the ponds on the south and west. The canal conveyed the runoff water into the Great Salt Lake.

From 1967 to 1971 lake water was pumped into the pond, but in 1971 it became evident to N. L. that the lake level, which was 4191.5 in 1961, would rise above that of the ponds. The lake continued to rise to a level of 4199 in 1972 (see figure 3), and was now higher than the pond level. This required the operation of the ponds to be changed as follows:

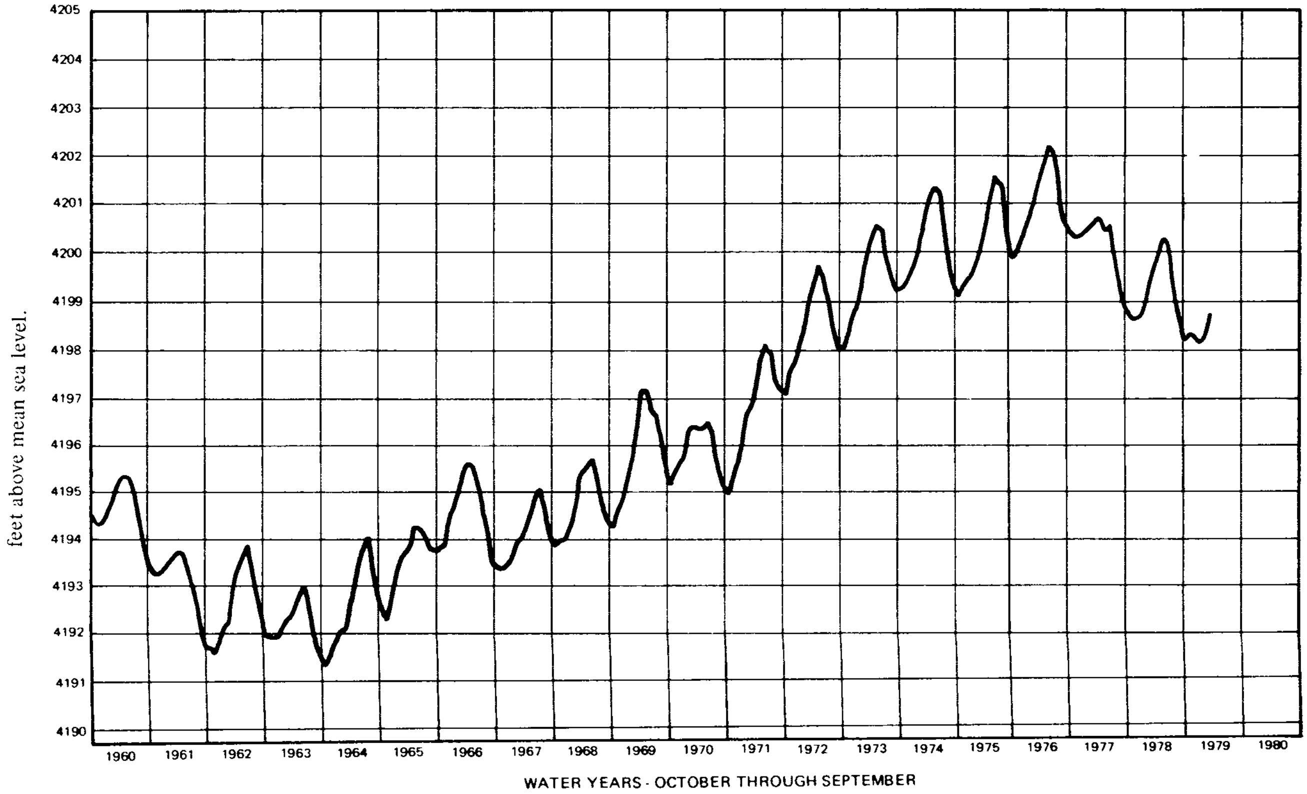


Figure 3. Hydrograph of the Great Salt Lake - water years 1960 - 1979.

1. The north dike now served the purpose of keeping the Great Salt Lake from flooding the ponds. This obviously required a new concept of dike design and construction.

2. The ponds were now fed by gravity flow, eliminating the need for a pumping station at the lake to feed the ponds.

3. The runoff water from Skull and Tooele Valleys, originally on a gravity flow, had to be pumped to the lake from the canal to prevent it from backing up and overflowing into the ponds.

Therefore in 1971 outside engineering firms were contacted to evaluate the most desirable method of dike construction to prevent the ponds from being flooded by the lake. The soil conditions and other parameters were evaluated to make preliminary design and cost estimates on possible alternatives for an effective diking system.

TYPES OF DIKES

Many types of dikes or levees may be constructed for the purpose of either impounding water or preventing water from inundating the impounded area. Only earthen fill dikes protected by rip-rap and earthen fill dikes protected by beach sand were considered in this study.

Dikes Protected by Rip-Rap

The earthen fill protected by rip-rap is the more conventional type of dike construction. Figure 4 shows a cross-section diagram of a dike faced with rip-rap material. The design must be such that the force of the waves is completely dissipated by the time the water passes through the rock fill and reaches the inner earthen fill. If the waves are allowed to reach the earth fill, the fill will be carried out with the undercurrent as the water washes down the face of the dike. This will undercut the rock face or rip-rap and permit it to collapse, resulting in a breach in the dike.

The construction of a dike with rip-rap requires that the rock size be properly chosen, and shaped and placed by hand. The larger rocks are placed first, with smaller rocks on top to fill up voids in the larger rock fill. The choice and slope of the filter media is critical to prevent seepage through the dike which could ultimately lead to piping and loss of dike by undercutting.

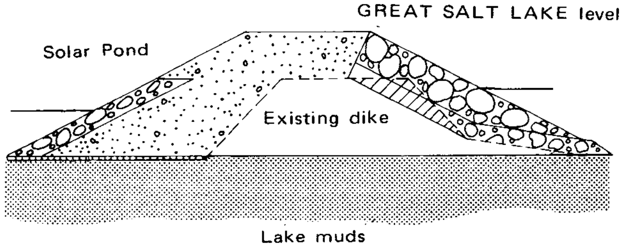


Figure 4. Cross section of dike faced with rip-rap material - no scale.

Dikes Protected by Sand Beach

In contrast, the construction of an earthen fill dike protected by a sand beach is far less complex, and the cost is approximately one half that of the rip-rap method. Tests were made to determine if this type of dike would be adequate to protect the solar ponds from invasion by the waters of the Great Salt Lake.

There are basically four types of failure associated with such dikes. They are:

1. Shear of supporting soils.
2. Piping or seepage.
3. Topping due to high waves.
4. Erosion of dike due to littoral drift.

To determine if failure due to shear of the existing supporting soil would occur, soil borings were taken and analyzed in the laboratory. This proved not to be a problem for the loading that was calculated for an earthen dike protected by a sand beach, and no further studies or alternates were considered necessary.

The rate of piping or seepage is a function of the permeability of the soils and of the H or elevation difference across the dike. Soil samples of the fill and sand material to be used for beaching were taken and permeability tests run. The permeability coefficient had a wide variation from 0.003 to 0.042 cm/sec. At a head difference of three feet and using a permeability coefficient of 0.20 cm/sec (a safety factor of 5), the seepage quantity was calculated to be 98 cubic feet per day per foot of dike. The velocity of the brine through the dike at this seepage rate is not sufficient to carry away the soil and sand and hence there is no danger of erosion breaching the dike. However, at a static head of 6 feet and the same permeability coefficient the flow through the dike was calculated to be 199 cubic feet per day per foot of dike. The velocity at this seepage rate is sufficient to carry away the material and would probably result in a dike failure.

During periods of high winds, the head difference across the dike reaches the calculated failure difference of six feet. However, failure by piping during windstorms has never occurred because of the relatively short duration of the high winds. Although the seiching or water pile-up usually lasts for several hours after a storm before equilibrium is reached, the increased elevation due to wave action is relatively short lived and is dissipated very shortly after the winds subside. Therefore, the static head of six feet or more is reduced to two or three feet within a matter of hours and the dike is not subjected to high seepage rates for enough time to cause failure by piping.

Should the lake approach an elevation of 4205 feet creating a head difference of six feet, N.L. will have to review again their dike design, and possibly add a clay core to the dike to prevent piping. However, the addition of clay will affect the soil loading and introduce the possibility of dike failure from shear and may perhaps necessitate an entirely different approach to the dike design.

The third and fourth means of dike failure, those of topping and erosion, are due to high wave action and require a complete analysis of wind velocities and wave forces. Dr. J. W. Johnson, Professor of Hydraulic Engineering Emeritus of the University of California at Berkeley, made such a study and in summary concluded the following:

1. The wave height caused by the winds of the velocity that occur over the lake could be approximated by using a factor of 0.78 times the water depth at the toe of the beach. This factor includes build up due to water pile-up (see tables 1, 2 and 3).

2. The dike between Badger and Stansbury Islands would require continual maintenance because of the littoral drift of the sand caused by the angle at which the waves break against the beach.

3. Oolitic sand particles were of the proper size range (0.4 to 1.03 mm), to substantiate a beach with slope between 7:1 to 12:1. Figure 5 shows the size distribution of sand grains from four borings along the north dike area and figure 6 shows the relationship between beach slope and grain size. (Johnson 1956, p. 2166).

The material used for the beach must be adequate in grain size so as not to be carried away from the beach by wind generated waves, and the beach must be built

Table 1. Winds from the N, NE, and E, Badger Island

Month	Percentage of time of winds in the N-E Sector	Percentage of time that winds exceed 16 mph
Jan. 1972	25	0
Feb. 1972	*	*
March 1971	39	1
April 1971	48	7
May 1971	43	4
June 1971	56	9
July 1971	62	8
August 1971	52	7
September 1971	*	*
October 1971	*	*
November 1971	24	0
December 1971	*	*

*Data too limited for inclusion

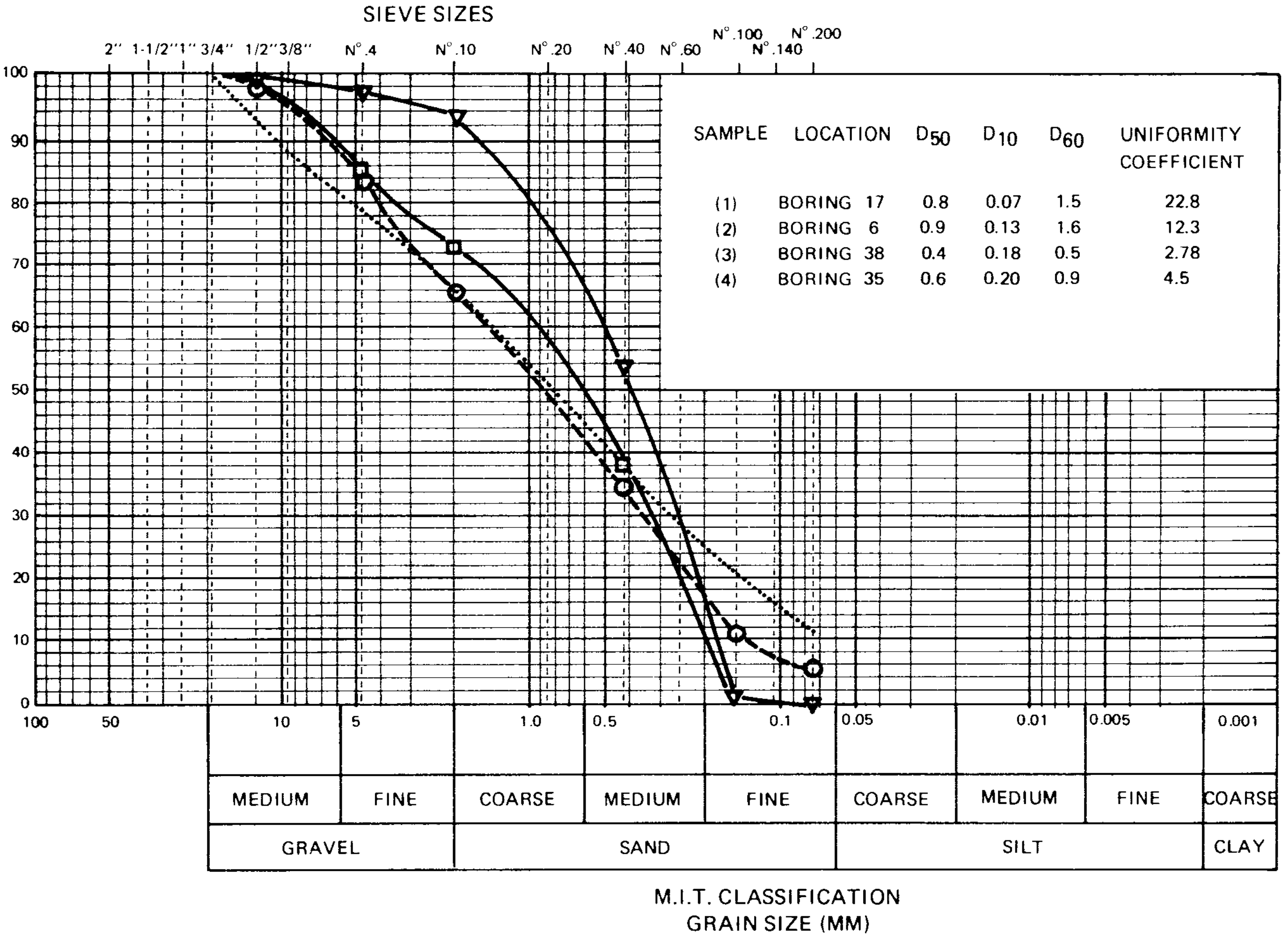
Table 2. Maximum wind speeds for various months Badger Island Station.

Month	Speed mph	Direction (Azimuth)
January 1972	10	200
February 1972	*	*
March 1971	30	290
April 1971	33	330
May 1971	30	270
June 1971	39	220
July 1971	28	50
August 1971	30	290
September 1971	*	*
October 1971	*	*
November 1971	10	200
December 1971	*	*

*Inadequate data

Table 3. Maximum wave height at north dike.

Lake level* (feet)	Water depth at toe of dike (feet)	Breaker height (feet)
4196	1	0.8
4198	3	2.4
4200	5	3.9
4202	7	5.5
4204	9	7.



SAMPLE	LOCATION	D_{50}	D_{10}	D_{60}	UNIFORMITY COEFFICIENT
(1)	BORING 17	0.8	0.07	1.5	22.8
(2)	BORING 6	0.9	0.13	1.6	12.3
(3)	BORING 38	0.4	0.18	0.5	2.78
(4)	BORING 35	0.6	0.20	0.9	4.5

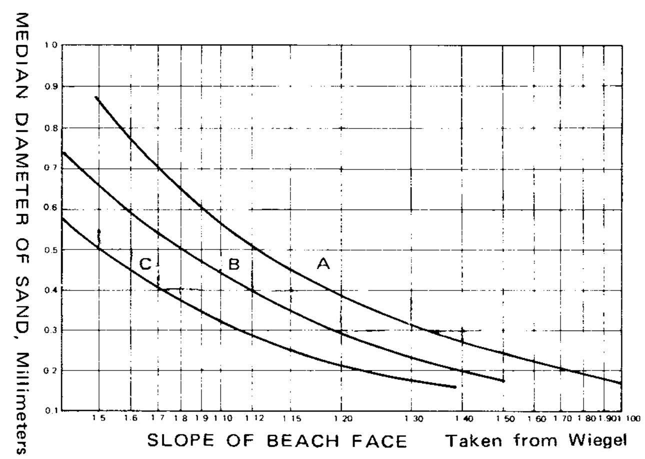
Figure 5. Size distribution of sands from four north dike area borings. After J. W. Johnson.

high enough to prevent the waves from going over the top. The wave height data, generated for engineering studies, is a function of wind velocity, duration, fetch and water depth. In addition to the wave height itself, seiching or water pile-up and wave run-up must be taken into consideration in designing the height of the beach. N.L. has provided a two foot freeboard safety factor in the design chosen for the dike.

A final decision to use the beach sand facing rather than the more conventional rip-rap method of dike construction, for lake elevations up to 4205, was based on the following factors:

1. Cost - approximately 50 percent less than that of rip-rap.

2. Beach with sand was more practical because it was available and plentiful, and appeared to be satisfactory for the purpose.



A. Average slope of exposed beaches

B. Average slope of moderately protected beaches

C. Average slope of protected beaches

Figure 6. Relationship between beach slope and grain size - taken from Johnson (1956, p. 2166).

3. A dike faced with rip-rap must be constructed with a great deal of care and expertise or wave action will cause it to fail. N.L. was not convinced that they had the expertise nor that they could obtain it locally.

DIKE CONSTRUCTION

The construction of the dike was relatively simple. Borrowed material that had adequate compaction capacity was hauled from Stansbury Island and placed on the east end of the dike; material was hauled from the Lakeside mountains to construct the west end. This material proved adequate to support vehicle traffic. The dike was then faced with sand to prevent topping and to provide a beach of a 10:1 slope.

Dredge Operation

To build and later to maintain the dike, N.L. purchased a 14 inch Ellicott dredge (figure 7 and 8). This dredge provides the most economical means of handling the large quantity of material to be used. The dredge was anchored approximately 350 feet north of the toe of the dike; oolitic sand was pumped from the bottom of the lake and conveyed to the face of the dike by a 12 inch floating pipeline (figure 9). Care was taken not to cut into the clays below the sand, to prevent any clay from becoming part of the beach material.

The Ellicott 14 inch Super Dragon (figure 7) has a 14 inch suction pipeline, a 12 inch discharge, and a centrifugal pump with a 34 inch impeller. This pump is capable of handling approximately 6000 gpm with a capacity of 600 yards per hour. The average material movement is 250 yards per hour, including the down time for moving the dredge. The pump is driven by a D-346 Caterpillar diesel engine with self contained cooling system using lake water for the external cooling source. The hydraulic system, which operates the winches, spuds, ladder and the cutter head, is driven by a D-333 Caterpillar diesel engine with the same cooling system as the D-346.

The dredge is operated by setting the digging spud (figures 8 and 9) and moving the ladder and cutter head from side to side by means of the starboard and port side winches, pulling against anchors set approximately 200 feet at a 45 degree angle from the dredge. The dredge has the capability of making a cut 120 feet wide and 26 feet deep. The dredge is moved forward during the digging operation by the spuds. When not digging, the dredge can be moved either by a tug boat or by pulling against the anchors with the winches.

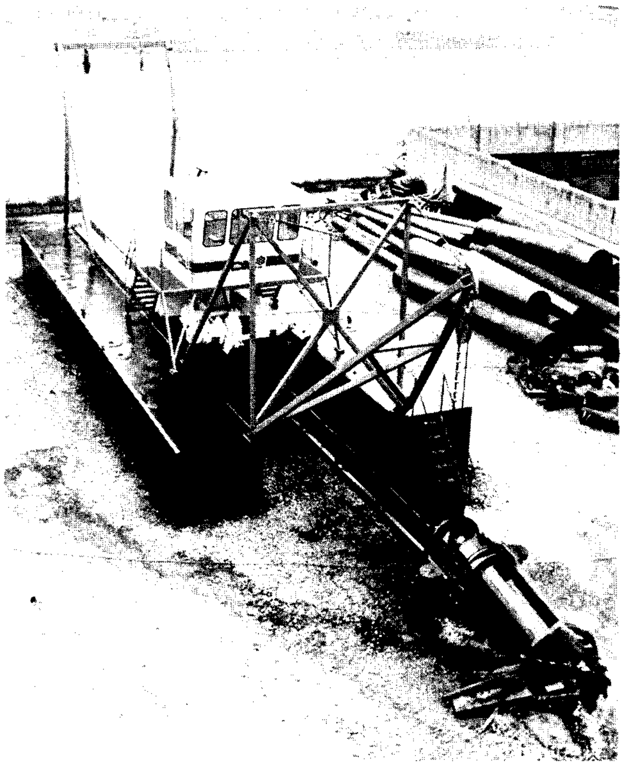


Figure 7. Ellicott 14 inch Super Dragon Dredge.

Alternate method of dike construction

An alternate method used to face the dike with sand was to push the material with bulldozers (see figure 10) west from Badger Island, where there was adequate sand and the soil to support the equipment. The sand was pushed over the top of the dike along the face of the dike. In this location this method proved to be much faster and less costly than the dredge.

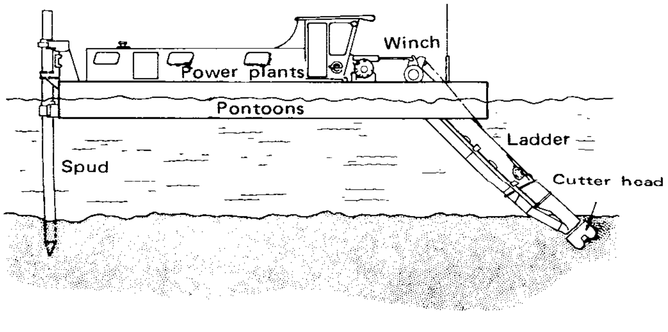
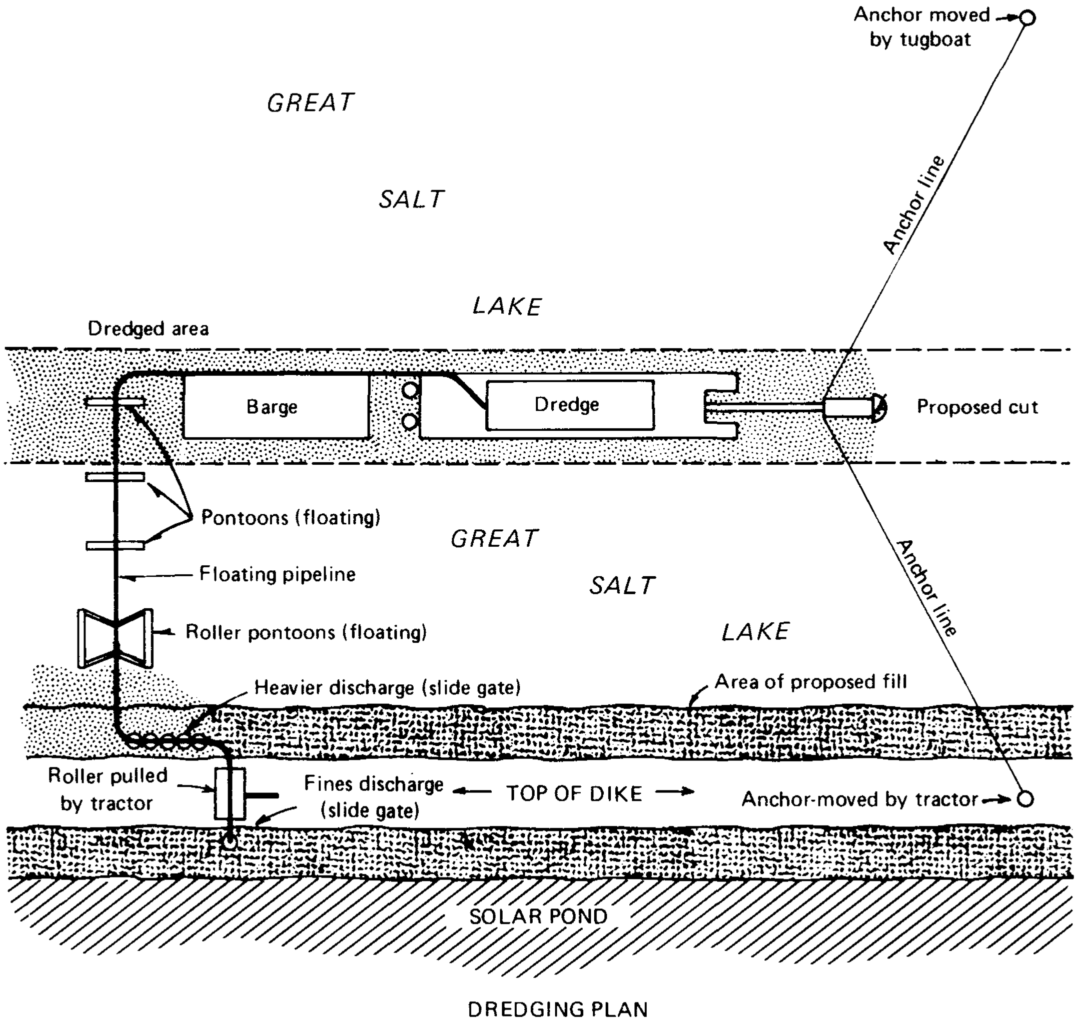


Figure 8. Schamatic of Ellicott dredge in working position.



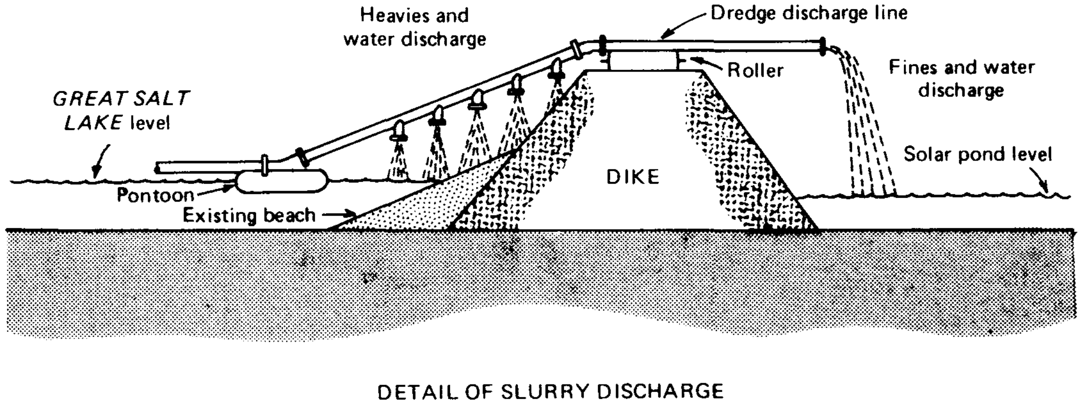


Figure 9. Schematics of dredging plan and slurry discharge - No scale.

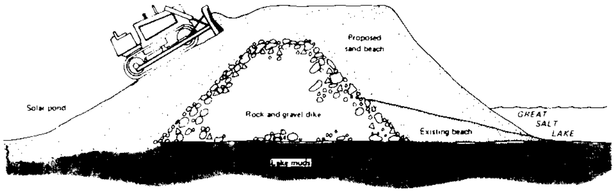


Figure 10. Moving dike-facing sand with bulldozer.

DIKE MAINTENANCE

Dike maintenance is required because of the compaction of the dike due to vehicular traffic and to the erosion of the beach by wave action. The quantity of material required for repair due to compaction is relatively small and not too costly. This material is usually moved by vehicle. On the other hand, considerable repair is required to replace sand moved along the face of the dike, or clays and silts which are completely suspended and washed away by wave action.

Waves which strike the beach at an angle cause littoral drift or movement of the sand along the dike. The angle and force of the wave are a function of the wind velocity, direction and fetch.

No littoral drift has been observed on the dike and beach between Badger Island and the west canal, nor was any predicted by the study made by Dr. Johnson. However, considerable movement of sand has been observed on the dike between Badger and Stansbury Islands, in a southeasterly direction, as was predicted by Dr. Johnson's study. Continual maintenance has been required in this section.

The littoral drift of material can be minimized by constructing groins, at right angles with the approaching waves, extending from the beach into the lake for approximately 100 feet. N.L. has not tried this approach because the repair costs thus far have not warranted it.

REFERENCE

Johnson, J. W., 1956, Dynamics of nearshore sediment movement: American Association of Petroleum Geologists Bulletin v. 40, pp 2211 - 2232.

SOLAR PONDING ADJACENT TO THE GREAT SALT LAKE, UTAH

by J. Wallace Gwynn and Paul A. Sturm

INTRODUCTION

Solar ponding began when primitive man impounded estuaries of saline bodies to produce salt for his own needs and for commercial trade. Improvements have been made in solar ponding techniques until today highly sophisticated solar ponding complexes are capable of producing a variety of products from natural brine constituents. With rising energy costs the importance of solar ponding adjacent to the Great Salt Lake is steadily increasing, since the salts and metals now being produced from Great Salt Lake require from a seventy to one hundred-fold increase in the concentration of the original brine.

The use of solar evaporation ponds for the extraction of minerals from Great Salt Lake brines was not employed until about 1870 (Clark, 1971). About 1888 the process of fractional crystallization was first employed in Utah to produce salt that was not bitter to the taste (Clark, 1971). Today a combination of these processes is the key to selectively and economically producing a variety of salt species and brines from the lake. The lake's mineral extraction industries, using solar energy, have expanded from the sole production of sodium chloride to include magnesium metal, chlorine gas, potassium and sodium sulfate, and magnesium chloride brine. Other compounds of magnesium, lithium, bromine, boron, and other elements can potentially be extracted.

RESOURCE EXTRACTION ON THE GREAT SALT LAKE

Potential Resources of the Great Salt Lake

The Great Salt Lake provides an almost limitless supply of brine for use by the present as well as the possible future mineral extraction industries. The brine in the northern arm of the lake, north of the Southern Pacific Railroad causeway, has become more concentrated than the brine in the southern arm. The north arm has little fresh water inflow and is essentially a large concentration pond. The south arm, in contrast, is density stratified, the upper 22-24 feet (6.7 - 7.3 m) being less dense than the brine below that depth. The reason for the existence of these layered brines has not been fully explained.

The chemical compositions and respective densities of the three brine types are given in table 1 (UGMS -October, 1978, data):weight percent on dry weight basis (total dry solids, grams/liter). The three brine types are chemically similar except that sodium and chloride are relatively more abundant, on a dry weight basis, in the north arm brine and in the deep south arm brine.

The volume of the lake is dependent upon its surface elevation, which fluctuates on a seasonal basis by as much as three feet (.9 m) and on a long term basis by as much as 20 feet (6 m). Historically, it has fluctuated cyclically between a high of 4,211.6 feet (1,283.7 m) in 1873 to a low of 4,191.4 (1,377 m) in 1963. The surface area at the high elevation was about 2,425 square miles (6,280 km^2), and 915 miles^2 (2,369 km^2) at the lowest elevation. On October 15, 1978 (which corresponds to the date of the chemistry given in table 1), the surface elevation of the two arms of the lake, the volumes of the three brine types, and the surface areas of the two bodies were as shown in table 2.

The difference in surface elevation that is noted between the two arms of the lake is because first, the majority of fresh water inflow to the lake enters the south arm and is somewhat "impounded" by the causeway, and second, a natural hydrostatic head is maintained across the causeway due to the density differences between the two bodies of water.

The total amount of dissolved salts in the Great Salt Lake has been estimated to be 4.6 billion tons (4.17 x 10^9 mt in 1976). This salt load total is dependent upon the concentration of the north and south arm brines. If a portion of the salt load is precipitated out of solution, it is not available in the form of brine for industrial use.

Present day extraction industries

Currently there are six mineral extraction industries operating on the Great Salt Lake, producing either salts or brines by solar evaporation (see figure 1). There is also one experimental, nonproducing solar pond complex. Table 3 lists these industries, the arm of the lake from which they draw their feed brine, the products they currently produce and the surface area covered by their solar ponding complexes (Data from Searle, 1976, p. 91).

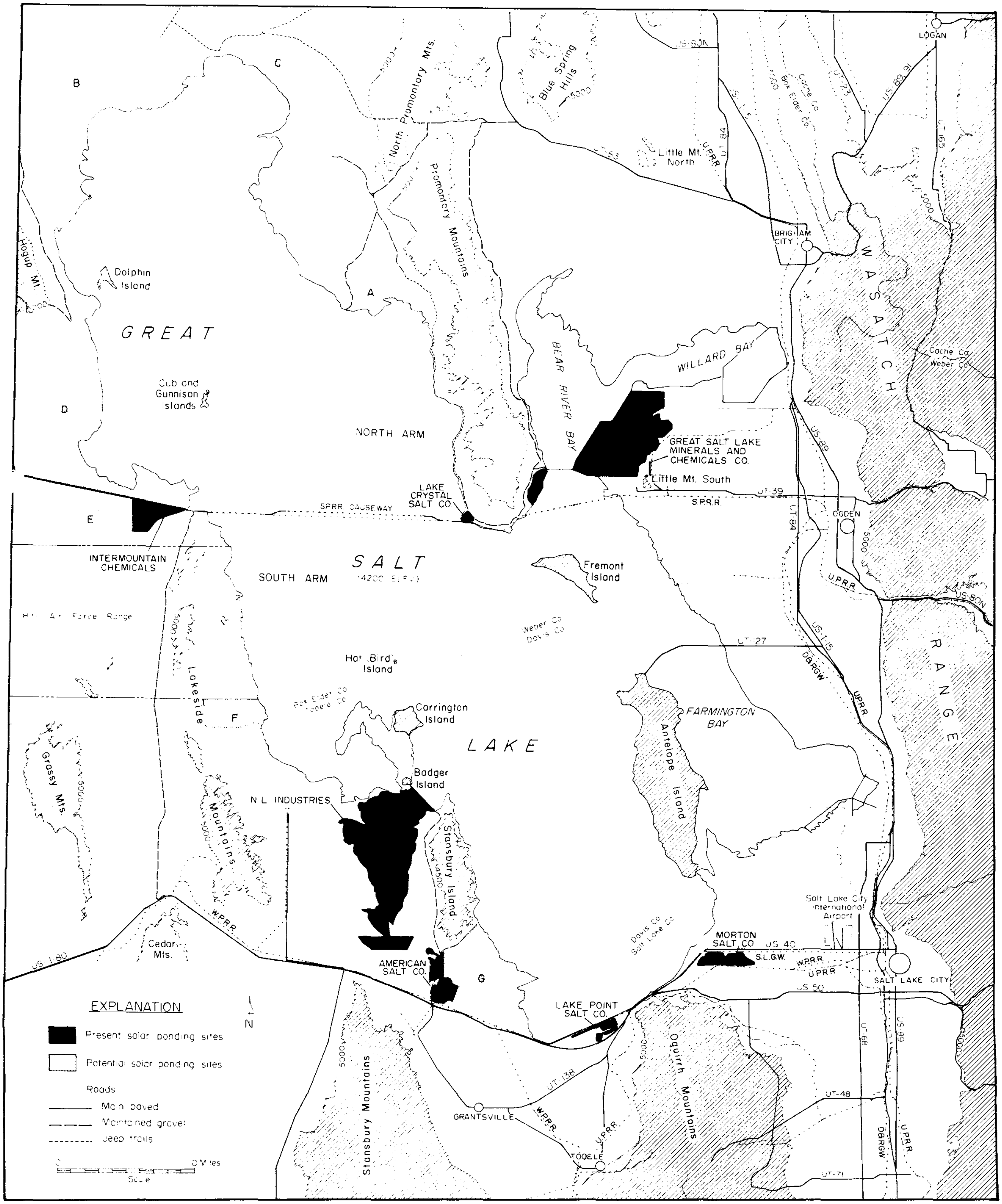


Figure 1. Map showing present (black areas) and potential (grey with letters; see Table 4) ponding areas and transportation routes around the Great Salt Lake, Utah.

Table 1. Chemical composition of Great Salt Lake brines - on a dry weight basis; Total dissolved solids (TDS).

Brine	Sodium	Magnesium	Potassium	Calcium	Chloride	Sulphate	TDS
So. Arm Upper	31.9	3.5	2.2	0.2	55.4	6.9	132.0
So. Arm Lower	34.3	3.6	2.3	0.2	59.6	7.6	240.9
North Arm	33.9	3.6	2.4	0.1	60.3	7.2	306.3

Table 2. Lake elevations, volumes and surface areas, October 15, 1978

Brine	Date Date	Elevation Elevation	Volume*	Area*
North Arm	10-15-78	4197.35' (1279.35m)	4.88 (6.02)	331 (1339)
South arm (upper brine)	10-15-78	4198.45' (1279.68m)	7.87 (9.67)	491 (1987)
South Arm (lower brine)	10-15-78	4175.45' (1272.67m)	1.33 (1.63)	(NA)

* Volume in acre feet x 10^6 (cubic meters x 10^9). Area in acres x 10^3 (km^2), south arm data given without Farmington and Bear River Bays being included.

Table 3. Extractive industries, brine source, products and pond areas.

Company	Arm	Products	Pond Area
N.L. Industries	South	Magnesium, Chlorine	25,000ac. (101.17 Km^2)
American Salt Company	S	Sodium Chloride	4,500ac. (18.21 Km^2)
Lakepoint Salt Company	S	Sodium Chloride	1,267ac. (5.12 Km^2)
Morton Salt Company	S	Sodium Chloride	1,500ac. (68.79 Km^2)
Great Salt Lake Mineral & Chemicals	North	Potassium and Sodium Sulfate, sodium chloride	17,000ac. (68.79 Km^2)
Lake Crystal Salt Company	N	Sodium chloride	300ac (1.21 Km^2)
Intermountain Chemical	N	Experimental	1,350ac (5.46 Km^2)

To date, all of the industrial solar ponding complexes around the lake have been built on the mudflats in near proximity to the lake; N. L. Industries' ponds were formed by diking off the shallow West Bay area of the lake, west of Stansbury Island and south of Carrington Island (figure 1). The best planning efforts were made to design and build these above future predicted lake levels. In spite of this however, the level of the lake has exceeded the elevations expected by some of the industries, and has become a serious and costly problem in terms of dike erosion and flooding.

Future Resource Development

The factors which could dictate the expansion of present industrial solar ponding complexes include: (1) development of new or larger markets for current products, (2) the need for larger ponding areas if salinity of the south and north arm brines declines, (3) new ponding areas made necessary by rising lake levels, (4) new ponding areas needed when present ponds are filled with undesirable salts, and (5) the development of new products. The persistant decline in the salinity of the south arm may create an immediate need for increased ponding area to maintain present production levels for south arm industries. The establishment of new extraction industries on the lake, or other industries requiring evaporative facilities, will also require new solar ponding complexes.

SOLAR POND LOCATION AND DESIGN PARAMETERS

The following is a review of a number of factors relative to the siting, design, and construction of solar ponds discussed by Garrett (1966 a and 1966 b).

Site Location - Social and Economic Parameters

Though not physically related to the siting, design and construction of an extraction industry's solar ponding complex, the social and economic factors of markets, transportation, energy sources and labor must be considered.

Markets

The limiting factor for the distribution of solar salt is the cost of transportation. Helgren (1979) states that "the Utah salt market, except for large industrial bulk users, is essentially serving the Intermountain West. The bulk of the market is from the borders of Canada and Mexico to California and Nebraska. Movement of solar salt is increasing to the east due to the competitive advantage of reduced energy cost of solar salt versus solution or underground mined salt."

Only a fraction of the magnesium produced from the lake is used within the state; the remainder is shipped east and west in the United States, and some is exported. Chlorine, a by-product of magnesium production, is marketed both within and beyond Utah. The majority of both the potassium and sodium sulfate produced from solar evaporated lake brine is shipped out of state, and even to foreign markets.

Transportation

The area adjacent to the Great Salt Lake is serviced by major highway, railroad and air transportation facilities. The major highways serving the area include the east-west Interstate 80, which crosses the State at the south end of the lake, and north-south Interstate 15 which serves the Wasatch Front communities east of the lake. The areal distribution of state highways and other major access roads leading to the lake is shown on figure 1. Four railroads operate in the vicinity of the lake. The Western Pacific Railroad crosses the state along the southern shore of the lake, and both the Union Pacific and the Denver and Rio Grande railroads parallel the Wasatch Front east of the lake. The Southern Pacific runs west from Ogden and crosses the lake on the causeway (figure 1). Both N.L. Industries and Great Salt Lake Minerals are served by spurs from one or more of the railroads. Air service is available at the Salt Lake City International airport, located on the southeastern edge of the lake. The western and northern shores of the lake are nearly inaccessible.

Energy Sources

The main sources of energy other than solar radiation used by or available to extractive industries on the Great Salt Lake are natural gas and electricity (figure 2). Auxiliary fuel sources such as propane and fuel oil are maintained for emergency use. The route of an 8-inch petroleum products line is also shown on figure 2.

Labor and Services

An ample labor supply is available from the cities and towns along the Wasatch Front: Grantsville, Toole, Magna and Salt Lake City lie to the south and southeast of the lake, and Ogden and Brigham City lie to the east. These, plus many small towns, form a nearly continuous population pool for almost 50 miles (80 km). Utah's labor market offers a complete spectrum of available professional, technical, and skilled to unskilled personnel in a wide variety of disciplines.

The area also provides abundant services in the fields of design and construction, research, education, transportation, business and others.

Site Location - Physical Parameters

Physical factors related to the design, construction, and operation of a solar ponding complex for the production of a given type and quantity of product or products include: topography and land area, soil characteristics, sources of fresh water, weather and evaporation rates, lake fluctuations and groundwater conditions.

Topography and Land Area

Relatively flat, large and contiguous areas of land are desirable for the construction and operation of solar ponding complexes. The mud flats around the Great Salt Lake best fulfill these requirements, and enable a ponding complex to be built so that pond brines can be maintained at shallow depths to optimize evaporation through more efficient absorption of solar radiation.

The seven solar ponding complexes currently in use around the lake are built on mud flats, and seven more potential sites have been identified. The locations of these sites, principally along the northern and western edges of the lake, are identified as A through G on figure 1. The approximate topographic slope of each area in feet/100 feet (meters/100 meters) and its size in acres (km^2) are shown on table 4. The slope is broken down into two elevation ranges (in feet above mean seal level): (I) 4200 feet to 4205 feet (1280.3 m to 1281.7 m) and (II) 4205 feet to 4210 feet (1281.7 m to 1283.2 m).

The area required for a solar ponding complex depends on the type and quantity of product(s) to be produced and the concentration of the starting brine. Based on data from the industries currently operating on the lake, Searle (1976, p. 98, 105, 109), presents the approximate ponding areas required for the production of given quantities of sodium chloride, potas-

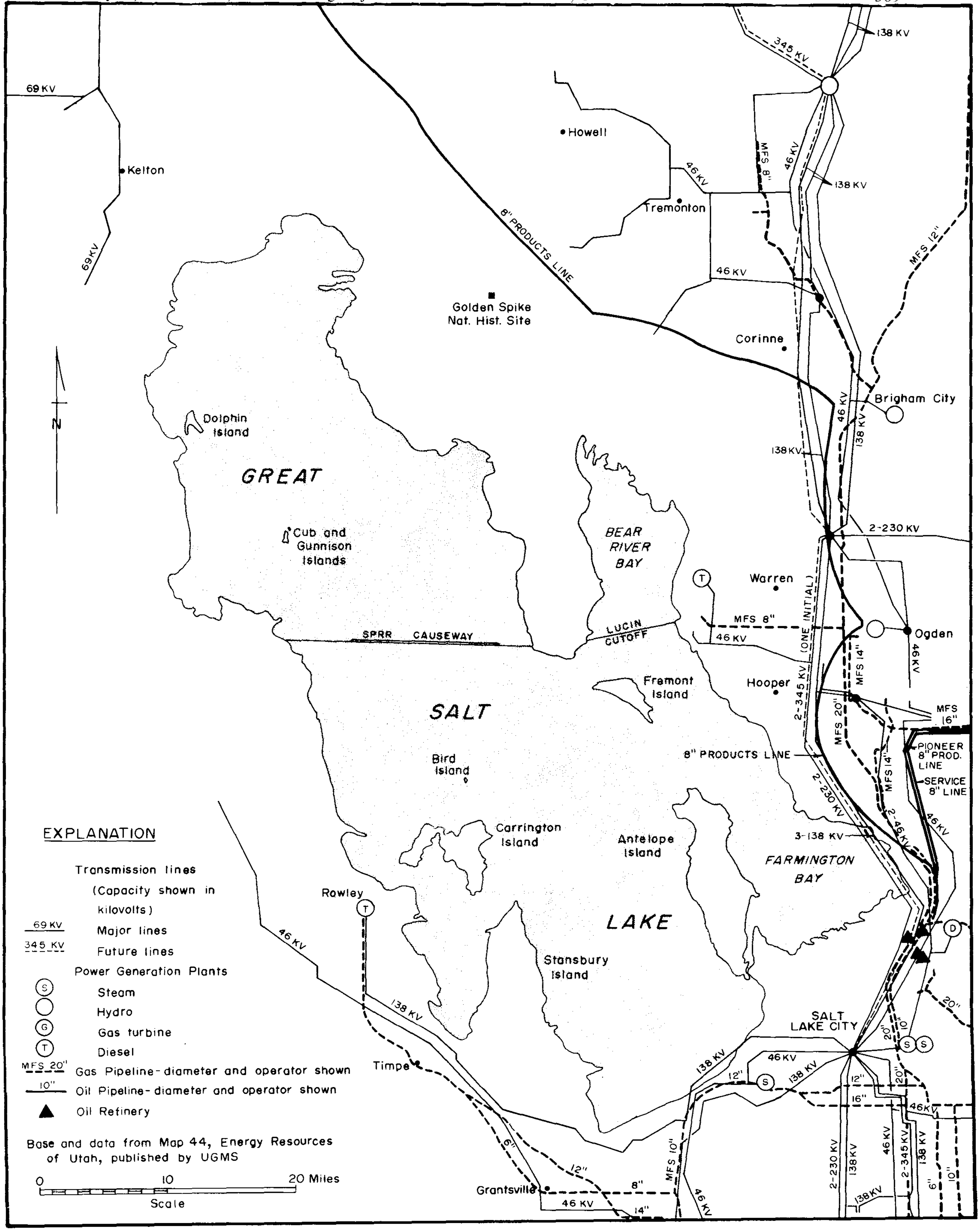


Figure 2. Location of power and energy sources around the Great Salt Lake.

Table 4. Potential ponding sites - slope, area.

Site	Slope (I) feet / 100	Slope (II) feet / 100	Total Area Acres	Total Area km²
A	.139	.222	3,675	14.87
B	.038	.084	42,900	173.61
C	.116	.094	9,000	36.42
D	.066	.046	21,850	88.42
E	- - -	.031	15,100	61.10
F	.074	.079	11,250	45.52
G	.076	.020	17,350	70.21

sium sulfate and magnesium metal with varying concentrations of brine. Ponding areas currently being used for the production of sodium chloride, potassium sulfate, and magnesium cover up to 4,500 acres (18.21 km^2), 17,000 acres (68.79 km^2) and 25,000 acres (101.17 km^2) respectively.

Soil Characteristics

Once potential areas of favorable topography and size have been selected, tests must be conducted to determine the engineering design properties of the soils within these areas. These properties include permeability, bearing strength, mineralogy and chemistry, and soil layering.

The permeability of the soils, or the rate at which a fluid will flow through them, is used in determining the brine leakage rate from the solar ponding system. Permeability is largely dependent upon the proportion of clay or fine silt contained within the soils. Those soils with high clay contents have lower permeabilities than those with low clay content. For successful solar pond design and operation, Glauser (1975) suggests that the soils should contain a minimum of 40 percent clays and fine silts within the upper six feet of soil. The permeability of unconsolidated soils can vary both laterally and vertically. Once permeability rates are determined throughout a potential ponding area, the solar ponding complex can be designed so that the more permeable areas contain the ponds with less concentrated brines and the tightest soils have the ponds for the more valuable production brines.

The bearing strength of the soils, throughout a prospective ponding area, is required to design dikes, and to determine both position and dimensions of roads, buildings and other structures. It is also used to determine if pond floors will support harvesting and maintenance equipment for pond operations. If a salt floor is required, the bearing strength of the soils will determine the thickness of salt floor necessary to support the equipment weight.

The determination of soil mineralogy and chemistry, in conjunction with other tests, is made to find the compatibility of the soils with the concentrated brines. Under some conditions, as discussed by Turk (1974), cracking occurs in clays when they are subjected to highly saline pond brines, resulting in the loss of brines through leakage.

The nature of the vertical layering and the areal extent of relatively impermeable clays and fine silts or relatively permeable sands and gravels must also be determined for a prospective ponding site. Permeable layers can become conduits for pond leakage. In the mud flats surrounding the Great Salt Lake, there are areas where extensive sand lenses occur through which a solar ponding complex could loose brine. These criteria are used in pond layout, and in dike and canal design to aid in selecting construction materials, siting barrow material areas within the ponds, and in determining settling rates of pond structures.

Sources of Fresh Water

All extraction industries on the lake require good quality water for culinary use. In addition, a large quantity of water of lesser quality is necessary for washing harvest salts, industrial processing, and desalting and washing pumps and equipment. Large quantities of fresh or very low salinity water are also required by some industries to flush ponds into which thousands or even millions of tons of salt are deposited each year but are not harvested. Unless the salts are flushed or removed mechanically, or the confining dikes raised, those ponds fill with salts and become inserviceable.

Sources of fresh water include the major tributaries to the lake, springs, wells which tap groundwater, impounded spring runoff, and the Willard Reservoir. For some purposes, less concentrated brines from Farmington Bay or even the south arm of the lake might be used.

The Bear River is the major source of fresh water currently being used. Great Salt Lake Minerals (GSLM) uses this water during the winter months to flush its extensive pond system. GSLM also obtains process water from Willard Reservoir which in turn derives its water from the Weber River.

As no fresh water from tributaries is available near the undeveloped portions of the lake, other sources must be found in the form of springs, groundwater or through the impoundment of spring runoff. For data on these water resources, the reader is referred to the series of Technical Publications, listed in the references, that are published by the Utah Division of Water Rights.

Weather and Evaporation

The effective solar ponding season on the Great Salt Lake, when evaporation substantially exceeds precipitation, is restricted to the four summer months of June through September. Initial brine pumping and final product harvesting by the lake industries take place before and after this time, respectively. Waddell and Fields (1977, p. 7) have shown, on a monthly basis, the fraction of the mean annual precpitation (figure 3) and of the mean annual evaporation (figure 4) on the Great Salt Lake for the period 1951 and 1960.

The amount of precipitation in the vicinity of the lake is greater at the southeast end of the lake than at the northwest end, and the rate of evaporation on the lake is greater at the northwest end than at the southeast end. Waddell and Fields (1977, p. 5) show lines of equal average annual precipitation over the lake (figure 5), and (p. 8) the lines of equal annual freshwater-lake evaporation over the lake (figure 6). Freshwater-lake evaporation is equal to pan evaporation times a pan coefficient. But the evaporation rate of lake brines is somewhat lower than that of fresh water under similar conditions, and the more concentrated the brine becomes, the more pronounced is this relationship. The evaporation rate, throughout 1966, at Great Salt Lake Minerals, for brines of various concentrations, is given by Butts (1972) in figure 7. Note that these data represent evaporation rates at a given locality for a given time period only. Since 1966, with the increase in lake elevation and subsequent increase in the size of the Bear River Bay, there has been a substantial alteration in these evaporation curves for the Great Salt Lake Minerals solar ponding complex.

Lake Fluctuations

Three types of lake-level fluctuations on the Great Salt Lake include long term, seasonal, and seiching or short-term fluctuations associated with winds. Historically, the lake's south arm elevation has fluctuated some twenty feet (6.1 m). The seasonal fluctuation of the lake level is much more predictable and has averaged about 1.9 feet (0.57 m) during the past thirteen years. Its largest fluctuation during this time was 3.1 feet (0.94 m) and occurred in Water Year 1971. Seiching (wind tides), can cause fluctuations in the level of the lake as much as two to three feet (Lin, 1976, p. 17-26). Both seasonal and seiching-related level fluctuations of the lake must be accounted for in designing solar ponds. The long term, cyclic rise and fall, however, cannot be predicted.

Ground Water

The occurrence of near surface ground water or

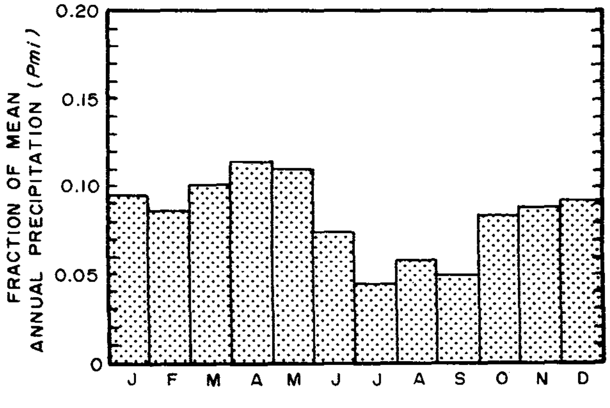


Figure 3. Average monthly distribution of precipitation on Great Salt Lake, 1951 - 60. Taken from Waddell and Fields, 1977.

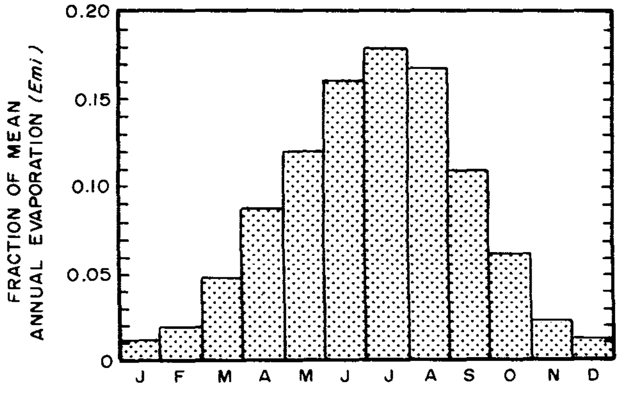


Figure 4. Average monthly distribution of evaporation on Great Salt Lake, 1950 - 60. Taken from Waddell and Fields, 1977.

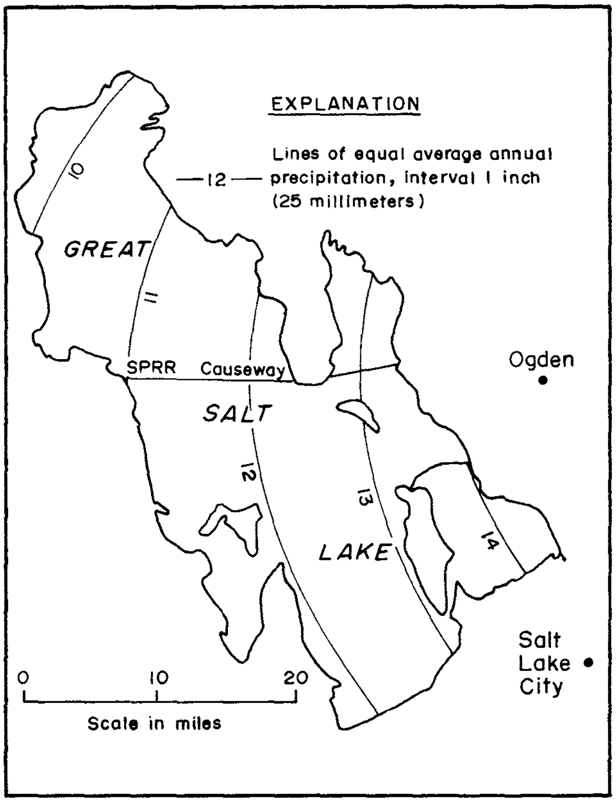


Figure 5. Map showing average annual precipitation on Great Salt Lake, 1931 - 73. Modified from Waddell and Fields, 1977.

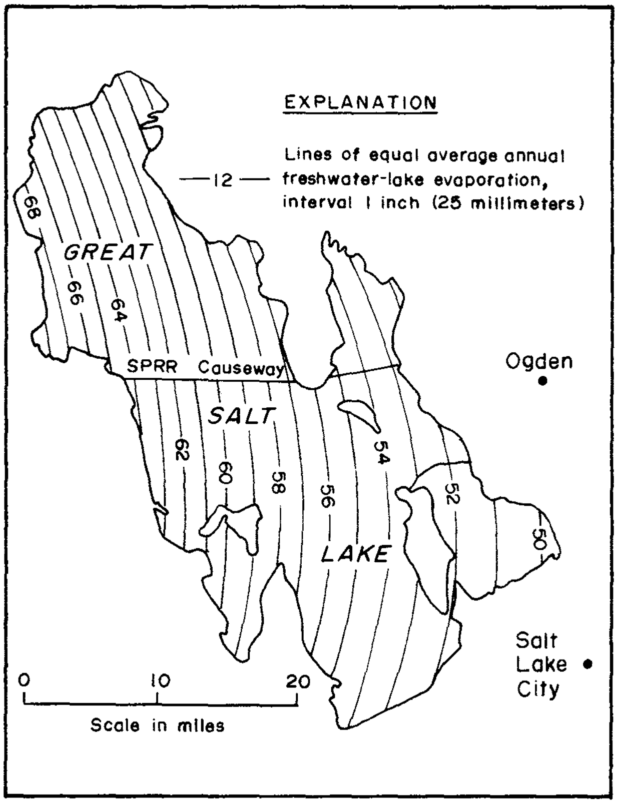


Figure 6. Map showing average annual freshwater - lake evaporation for Great Salt Lake, 1931 - 70. Modified from Waddell and Fields, 1977.

springs is detrimental to solar ponding operations because of dilution to concentrating brines. This is especially serious within ponds holding highly concentrated potash and magnesium brines where such dilution can affect the types and quality of salts deposited. Springs in harvesting areas create holes in the salt floors which make harvesting or other activities difficult and sometimes dangerous. Flowing water can undermine the floors of solar ponds and cause structural failure when heavy harvesting equipment passes over the weakened area. When this happens the underlying mud contaminates large harvest areas and decreases recovery of the final product. Ground water can also cause structural failure of dikes, roads and other facilities by decreasing the bearing strength of the supporting sediments or by washing away the structural support material.

Pond Layout

The goal of good pond layout is to make use of the available space in the most effective and economical manner. The preliminary data discussed in "site location" are used to plan the physical area, subdivision, and arrangment of a solar ponding complex. The efficient arrangement of roads, canals, and other operating facilities must also be considered.

Optimum Ponding Area

The ultimate size of a ponding complex is dependent upon the quantity and type of product(s) to be produced. Based on these two factors, Garrett (1966, p.

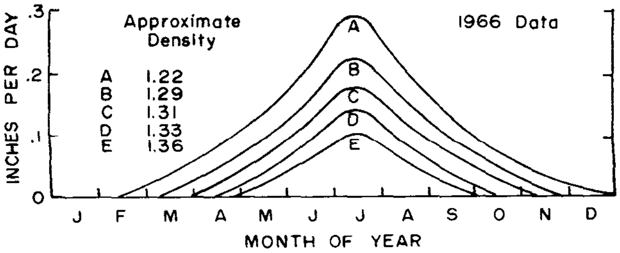


Figure 7. Graph showing evaporation rate in inches per day versus the month of the year for brines of various densities. Modified from Butts, 1972.

170) lists feed brine density, pond seepage rates, and the applicable evaporation rates as three essential parameters to be accessed in determining the size of a solar ponding complex. Scaleup factors as well as variations in feed brine density and weather must also be considered. Using these basic parameters, Garrett calculates the area required to produce a given quantity of sodium chloride.

Calculations become more complex, however, to determine the area required for the production of potassium and magnesium salts and/or brines. The brines for these additional salts normally require two to four times the area necessary for sodium chloride production, all other things being equal. Because this increased area results in a decreased overall evaporation rate due to a factor known as pond effect, relatively more ponding area is required to produce a specific amount of material. As the brines increase in concentration, the lowered vapor pressure also results in a decreased evaporation rate. And, as salts precipitate in solar ponds, voids develop in the crystals which are filled with brine, thus effectively eliminating that brine from further salt production. All of these factors combined necessitate a solar ponding area from four to six times that required for the production of sodium chloride alone.

Subdivision of Ponding Area

A ponding area is subdivided to maintain control of the brine from the time it enters the system. Four factors govern pond subdivision: the elevation, topography and geometry of the area; the need to control pond depths; the need to eliminate dead areas or short circuiting; and the prevention of wave damage (Garrett, 1966a, p. 170-171). When dealing with the more concentrated brines, the subdivision of ponds is critical for controlling the chemistry of the brines and deposited salts. The subdivisions of the harvest ponds also facilitate harvesting the salts, and draining of the pond and entrained brines prior to the harvest. Subdivision also provides space for "stacking" of harvest pond bitterns in pond areas not currently being harvested. It also is an insurance against such disasters as flooding or structural failure.

Pond subdivision should take advantage of the natural topography to ensure the most uniform brine depth possible within each pond. This is especially important in harvest ponds where uniform depositional thicknesses of salt(s) are required to prevent contamination with the salt from the floor during harvesting. Proper pond subdivision and topographic control also prevent brine "dead areas" which deposit uneven or undesireable salt, and short circuiting which prevents the total available area of the pond from being utilitized effectively for evaporation. Pond subdivision reduces the unbroken surface area exposed to winds and thereby reduces the wave action within the ponds which can damage dikes and other structures.

Pond Arrangement

Garrett (1966 a, p. 173) makes the following three suggestions regarding pond arrangements: first, to minimize wave damage, the narrow dimension of individual ponds should be oriented in the prevailing wind direction; second, ponds should be oriented to provide the most positive flow path, requiring the least number of controlling weirs and transfer pumps, and third, those ponds containing the most concentrated brines should be located in the areas containing the tightest soils and those least likely to be flooded.

The harvest ponds within a solar ponding complex should be located nearest the stockpiling or processing areas to minimize transport costs while initial concentrating ponds should be located near the brine source to reduce overall pumping costs.

Canals, Roads, and Other Facilities

Brines are moved to the high points within a solar ponding system by canals with the aid of lift pumps. The brines then gravity-flow through the evaporation ponds. The canal parameters to be considered include: carrying capacity (which can be decreased by the deposition of salts), length, rate of leakage and ease of cleaning/flushing if salting occurs. Garrett (1966 a, p.173) suggests that provisions be made for canals to bypass ponds that are being harvested or are otherwise inoperative, and that their positioning be coordinated with that of roads. Canals may be replaced by pipes or culverts at intersections with roads.

Roads within a solar ponding complex are used for main product haulage, principal access, and minor maintenance (Garrett, 1966 a, p. 173). Those used for hauling harvest salts must be capable of withstanding heavy loads over sustained periods of time, and be serviceable during all kinds of weather. Principal access roads must provide efficient access throughout the ponding system. Minor maintenance roads must service all parts of the system where dike repair is likely to be needed, and where weirs and pumps are located.

Of necessity, roads are usually confined to the tops of dikes and are often located adjacent to canals. In the vicinity of the Great Salt Lake, it has been found satisfactory to surface pond roads with gravel or salt. Clay-type dike materials do not make serviceable all-weather roads. Oiled surfaces are too expensive, and do not hold up under the heavy use. Oiled surfaces are also of concern in that oil leached from the roads might enter the ponds and form a thin film that would restrict or even stop evaporation. The oil may also interfere with the product processing. Concrete roads are too expensive and do not hold up well in a saline environment.

Dike design and construction

Three types of dikes within a solar ponding complex are: main perimeter dikes surrounding the entire complex; main interior dikes, which often carry roads; and minor interior dikes, used to separate or subdivide ponds. Perimeter dikes are ultimately responsible for confining the concentrating brines within the pond system. They may also be required to keep unwanted lake water or fresh water from entering the ponding complex.

Perimeter dikes must be designed to prevent the lateral transport of brine or water in the soils beneath the dike, and the dike itself must be impermeable. Because these dikes are subjected to internal wave action from their impounded waters, or possibly from exterior bodies of water, they must be designed to resist erosion. And those dikes which serve as road foundations must be designed to withstand the heavy, continual stresses placed upon them by heavy equipment.

To prevent the lateral leakage of fluids through the soils beneath or through perimeter dikes, cutoff or seal trenches can be constructed as follows. A trench approximately 2.5 feet (.75 m) wide and 6 feet (1.8 m) deep is cut below ground level, along the course of the proposed dike, and then filled with an impermeable material. The top of the cutoff trench is then constructed above the highest level of fluid encountered by the dike. The dikes are built on either side and on top of the cutoff trenches (see figure 8). The impermeable material stops the lateral flow of fluids into or out of the ponding area by disrupting permeable soil layers. The material that was originally excavated from the trench is thoroughly mixed, and replaced in the trenches or, if that material is too sandy, clay from borrow areas within or without of the ponding area can be used. An impermeable membrane, such as butyl rubber sheeting, may also be used (Garrett, 1966 a, p. 174). The sheeting is placed vertically along the length of the trench prior to refilling. A seal ditch may also be used, as described by Ecton and MacDonald (1962). This is a ditch bounded on both sides by a dike, each of which is underlain by a cutoff trench. During pond operations, the ditch is filled with brine to a level just above the brine level in the evaporation pond. The combination of the two cutoff trenches and the hydrostatic pressure of the brine in the seal ditch have proved effective in preventing leakage (see figure 9).

The fill material generally used for the completion of the body of the dike is the soil from either side of the seal trench or proposed dike route. If borrowing dike material from within the pond system will damage the integrity of the floors, material for the dikes must be hauled in from outside sources. The final configuration of the dike is trapezoidal, wide at the bottom, narrow at the top, with sloping sides. The width of the base of the dike is dependent upon the bearing strength of the soils,

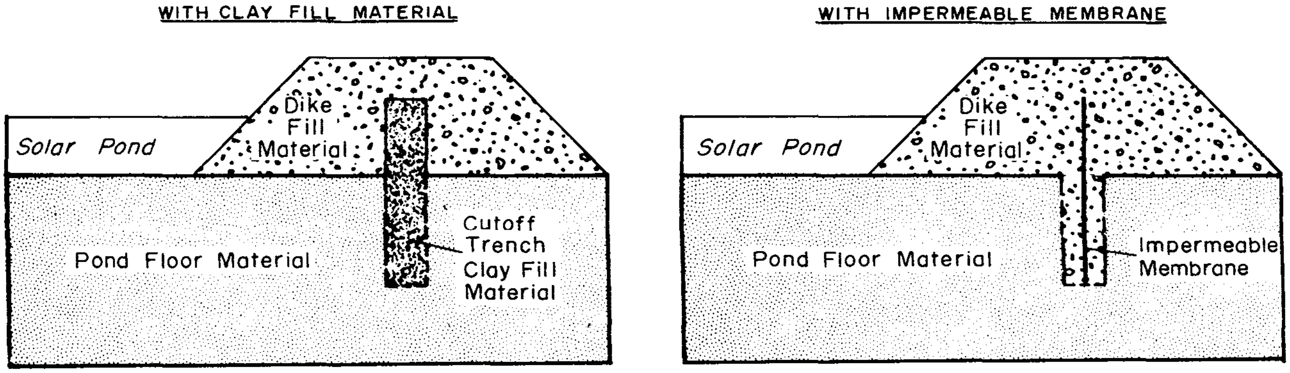


Figure 8. Schematic cross sections of two types of cutoff or seal trenches (with clay fill material and with impermeable membrane).

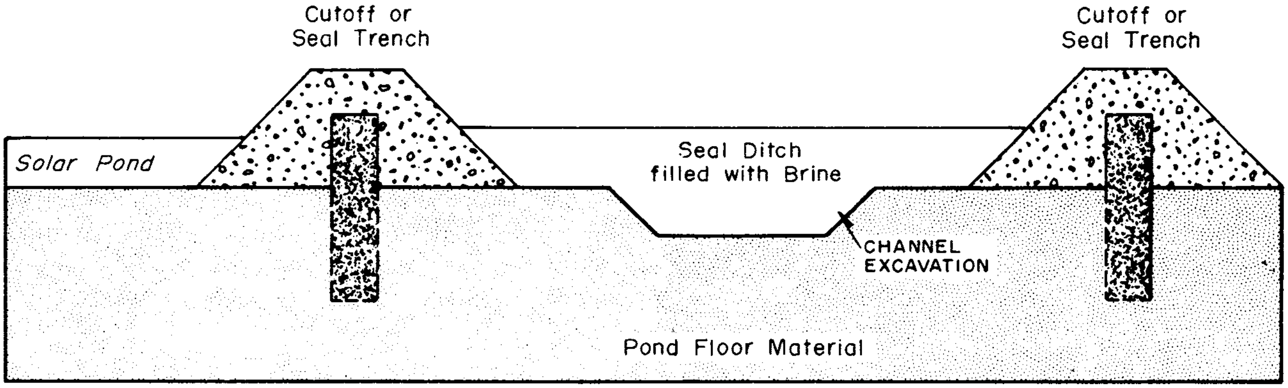


Figure 9. Schematic cross section of typical hydrastatic seal ditch. Modified from Ecton and McDonald, 1962.

the expected height of the structure, and its intended load or purpose.

Garrett (1966, p. 175) states that "Normally steep slopes (i.e., 2:1) on the sides provide better wave resistance than very shallow slopes, and rip-rapping of some type is necessary to provide a comparatively long maintenance-free life." The height to which the dikes are built is dependent upon the fluid level to be confined, the accumulated depth of salt deposition that is anticipated, and the amount of freeboard (distance out of the water) that is to be maintained. The amount of freeboard depends upon the wave height that is expected inside the ponds or from adjoining bodies of water. Glauser (1975) suggests two feet (.6 m) of freeboard for perimeter dikes, except for those restraining the Bear River which were set at five feet (1.5 m). Garrett (1966 a, p. 175) suggests four feet (1.2 m).

Dikes within the ponding system are usually built without underlying seal trenches unless sand lenses, high groundwater, etc. warrant their construction. Interior dikes are similar to perimeter dikes with the exception that their freeboard is less. Glauser suggest a one foot freeboard (0.3 m) while Garrett suggest 2 feet (0.6 m).

CONCLUSIONS

Successful solar pond design and construction embodies both economical and technical considerations, and is an essential part of building a mineral extraction industry on the Great Salt Lake. Each new solar ponding site is unique, and much testing and site evaluation must be done in order to optimize the effectiveness of the completed ponding complex.

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TP no. 12, 1965, Tooele Valley
TP no. 18, 1968, Skull Valley
TP no. 25, 1969, Curley Valley
TP no. 26, 1969, Sink Valley
TP no. 30, 1971, Park Valley
TP no. 31, 1971, Salt Lake County
TP no. 33, 1979, Hansel Valley
TP no. 34, 1971, Salt Lake County
TP no. 35, 1972, East Shore area (Box Elder, Davis and Weber Counties)
TP no. 38, 1972, Promontory Mountains
TP no. 42, 1973, Great Salt Lake Desert
TP no. 44, 1974, Lower Bear River Drainage
TP no. 45, 1974, Curlew Valley

ENGINEERING PROBLEMS OF GREAT SALT LAKE, UTAH, MARINE OIL DRILLING OPERATION

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ABSTRACT

On June 24, 1978, Amoco Production Company, Denver, began oil or gas well drilling operations about 11 km (7 miles) from shore on the first "marine" well in Great Salt Lake. This paper covers some of the engineering problems encountered while preparing for this operation. The operation is unique in that (1) there is little prior data; (2) there is no local supply; (3) there is a desire to carry out marine drilling on both sides of the Southern Pacific causeway, which is an effective bar to a marine crossing; (4) there is considerable speculation on the effect of the heavy north arm brine as to wave forces and corrosion; and (5) it was necessary to use truckable units to assemble a barge strong enough to withstand the operation.

INTRODUCTION

Amoco Production Company obtained oil and gas leases to over 242,000 hectares (600,000 acres) of the Great Salt Lake from the state of Utah in 1973. From then until drilling started in June 1978 many studies were completed. Figure 1 shows the general operation and the location of the first Amoco well, Indian Cove Unit No. 1. The specific results of some of the studies will probably be subjects for technical papers. This paper will quickly review the types of studies and present highlights.

To start with, the process of carrying out a marine drilling operation in Great Salt Lake has obviously never been done before. In sheer engineering problems, only the Southern Pacific causeway is in the same category: The causeway faced some of the same problems; some were solved in similar ways, some in a quite different manner (See paper by J. E. Newby, this volume).

The biggest problem of this type operation is logistics. Nothing in the Great Salt Lake area provides for the needed materials and equipment although the area does have an excellent labor pool. Amoco was fortunate to be able to use the Little Valley Harbor which was constructed for the railroad causeway.

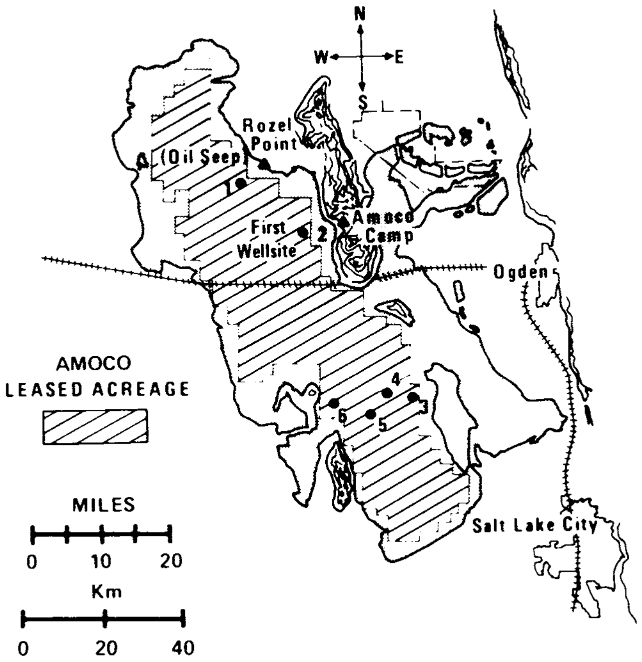

Figure 1. Amoco's Great Salt Lake operations. Numbers represent six proposed drilling locations approved by the State (from Gits, 1978). Used by permission.

Engineering problems investigated and the purpose for the investigation are:

1. Geotechnical data of the lake bottom.
   This data is needed to determine:
   (a) if friction piles will safely hold a platform;
   (b) if piles can develop strength for lateral loads, especially for anchors or earthquake activity;
   (c) if the soil might liquify under earthquake loading; and
   (d) whether the first tubular goods used in drilling can be used safely.

2. Wind and wave data.
   This information is needed prior to the drilling operation as input to theoretical and tank tests on proposed floating equipment. It is needed as history on which to base weather forecasts which include expected wave data. If oil or gas production is found, the data will be needed to design a platform capable of withstanding the wind and wave forces.

3. Seismic activity (Earthquake probability).
   This data is needed to determine the risk of damage to structures such as a platform or pipeline which might be installed and to allow for proper design to minimize such risk.

4. Marine engineering.
   These investigations use the results of wind-wave data and model tank tests to design the structural engineering on the barge and derrick. They also cover the method of mooring a drilling barge.

5. Corrosion.
   These studies are needed to evaluate the metallurgy and corrosion protection needed on all items subject to the salt water corrosion. These include mooring system, floating units, and propulsion units.

6. Shore site.
   These investigations include bathymetry, bottom conditions, available installations, etc, of suitable sites in both the north and south arm to use as a harbor and staging area to support the marine operation.

7. Marine Fleet.
   The choice of the proper marine fleet includes investigations of propulsion units, expected loads, operating conditions, etc.

8. Pollution Control Equipment.
   The studies on pollution equipment require information on the interaction of expected wind and wave; oil spill trajectory; vessel response, and the required equipment to keep a spill from reaching shore.

9. Governmental Agencies.
   Most applications to governmental agencies require engineering back-up and sometimes require their own engineering studies. The engineering involvement for this purpose has increased drasically in recent years.

Not covered in this paper are the engineering studies required to place drilling equipment designed for land drilling on a very limited barge area for use in a hostile environment of waves, horizontal motions, rolling motion, and attack by corrosive water spray. Also not included are the special studies made on well head connections and the means to maintain the drilling derrick "lined up" with the well being drilled.

Although these problems are all normal to offshore operations, we usually expect some phases to have been covered by prior operations. There is no "file" for past Great Salt Lake operations.

GEOTECHNICAL DATA

The first question was, what does the bottom of the lake look like? Casagrande's classic paper (Casagrande, 1965) covering the causeway gave us an inkling over a small area. Mikulich (1974), using shallow seismic work, extended data from the causeway but neither study gave the type data needed nor the coverage. Our library research turned up no geotechnical data of any but very shallow penetration studies (such as Buck, 1977; Oliver, 1974). (NOTE: Both here and for other subjects discussed in this paper, such information may exist, but we didn't locate it).

Also needed are detailed shear strength data for pile supported platforms, for the design of anchoring systems and for the first strings of conductor pipe or casings.

1974-75 Soil Boring Program

Two 6 m x 20 m (21 feet by 68 feet) catamaran barges were mobilized in 1974 to drill core holes using a Failing 1500 core rig. One barge was equipped with the drill rig; the other served as a landing area for a small helicopter. Two core holes were drilled to 91 m, (300 feet) in each arm of the lake. Figure 2 shows the typical stratigraphy. Four more borings were made the next year (1975).

No unsolvable problems arose in this program. Crew changes were made with the helicopter. The catamaran's twin 75 kw (100 HP) engines proved undesirable for the operation. No drilling mud problems arose. There were no gas or water flows (the latter seemed possible based on available on-shore shallow well data). There was no lost circulation.

The boring sites were located with radio ranging equipment from land stations located at USGS triangulation stations on the nearby mountains. This equipment is considered accurate to 3 meters and reproducible to probably 1 meter.

The geotechnical data from the borings verified the expectations of zero strength material (ooze or goop!!) at the mud line, building slowly with depth to normally consolidated deposition. Age dating reported

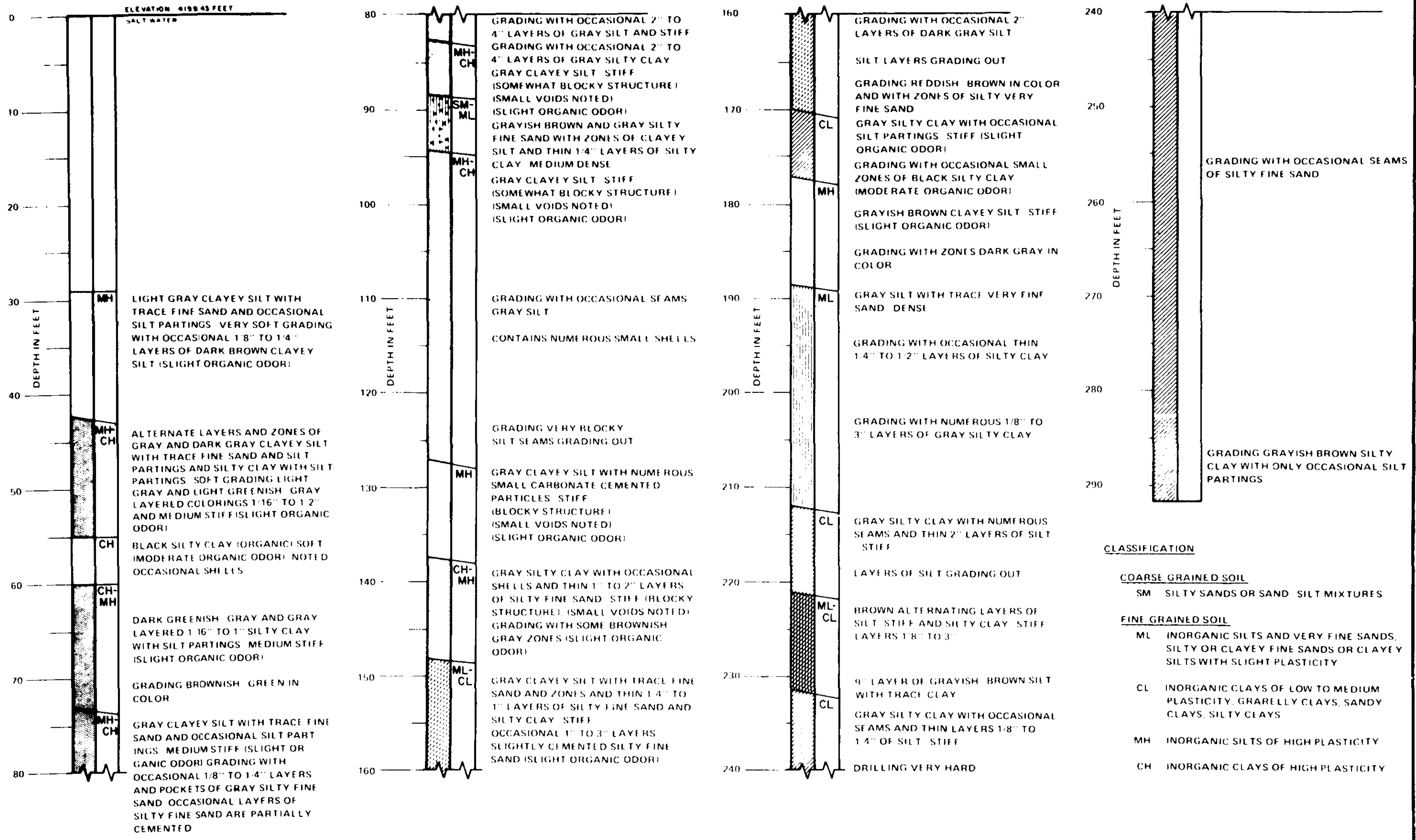

Figure 2. Typical stratigraphy in Great Salt Lake sediments of a 300 foot soil boring in an area free of bedded salt.

by Eardley (1966, 1960) indicates deposition has occurred near the rate of 1000 feet per million years with nearsurface nearer 800 feet per million years.

The lake bottom is strong enough to support a properly designed structure although the interaction of the piling with the soil under earthquake conditions must be carefully watched for liquifaction. Figure 3 is a generalization of the shear strengths.

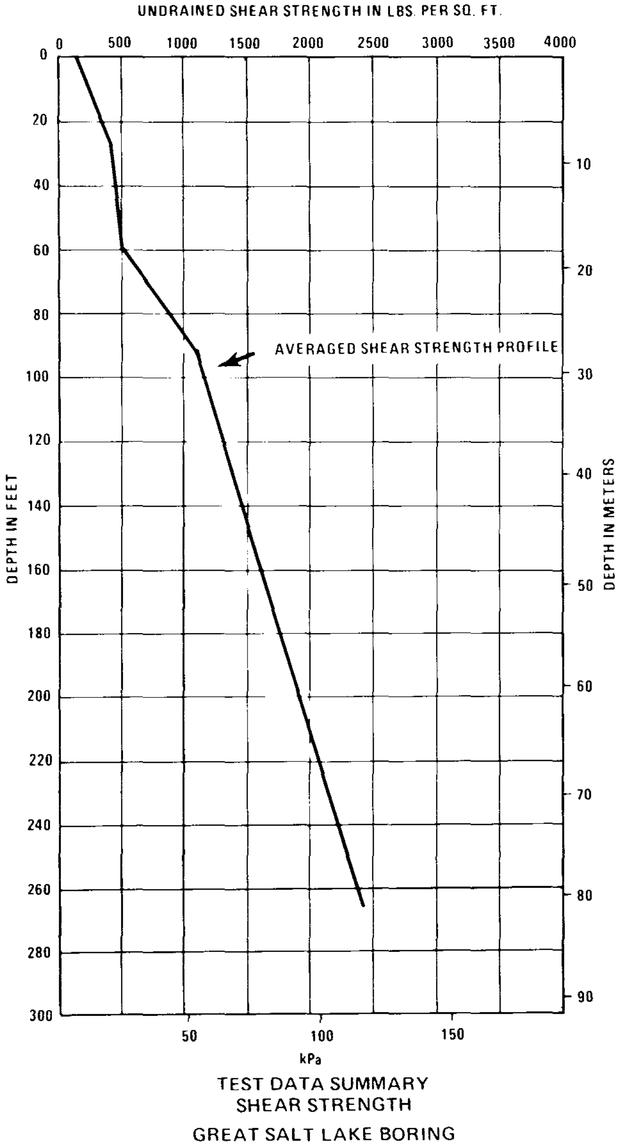

Figure 3. Typical shear strength versus depth below Great Salt Lake. Note absence of strength at the mudline and slow increase with depth.

The 1974 north arm borings initially penetrated a 2-3 m (6-8 foot) layer of halite on the floor of the lake. The halite had very consistent crystal size approximately 5 to 6 mm (3/16 inch to ¼ inch). The crystals were either lightly cemented or not cemented at all. With the continued lake rise, however, the water "freshened". State personnel working on the lake reported that the salt completely dissolved and then, in the fall, 1977, they reported new salt precipitation.

1978 Sampling

We tried unsuccessfully to obtain a salt sample of this layer in the second quarter of 1978, using hand tools. We assumed (incorrectly, it turned out) there might have been a hard veneer of sodium sulfate overlying the halite, which could create problems.

This led to a more drastic attack: driving a thick wall 15 cm (6 inch) pipe into the salt. The resulting sample was somewhat of a surprise: 1 m (3 to 4 feet) of uncemented halite, with crystal size 3 to 4 mm (1/8 inch to 3/16 inch). There are no "dirt" layers, although there might be sodium sulfate bedding. We believe that the salt might have "rained" down when the lake level was very low, somehow being seeded, then falling slowly through the brine, growing as it fell. The salt would, by this speculation, "rain" so fast that there was no chance for cementation to occur.

In the fall, 1977, we had planned on a muck bottom. We were now faced with, in essence, a "gravel" bottom, with the "gravel" composed of halite. On the strength of the reported precipitation in the fall, 1977, we began work on an alternate anchor system - as will be explained later.

WIND AND WAVE DATA

Great Salt Lake lies inside a rather broad National Weather Service net. Primary stations are at Salt Lake City and Wendover, Utah; and at Burley, Idaho.

During the soil boring program, it became obvious that the forecasts of the National Weather Service at the Salt Lake City Airport were not forecasts of the activity on the Great Salt Lake. Many times the wind on the lake was 180° out of phase with that in the city and velocities varied significantly. Salt Lake City winds are obviously mountain directed to give a preference to winds from the south. After frontal passage from the west the wind shifts to the north but is moderated by the land before reaching the airport.

Based on the little wind and wave data obtained while doing the soil boring and seismograph work, we could estimate that the significant wave* height in feet would equal one-tenth the wind velocity in mph. We made the following estimates:

> A 0.5 m (1.5 foot) significant height wave could be expected daily.
>
> A 1 m (3 foot) significant height wave could be expected at least once weekly.
>
> A more than 1.5 m (5 foot) wave could be expected at least once quarterly.

The wind-wave relationship compared reasonably with the accepted shallow wave lake forecasts. Thus, there seemed to be no unusual effect from either the heavy salt water nor the drastic light air-heavy wave relationship.

Yet there remained nagging questions:

> How much energy is in the waves?
>
> Are the waves random (as we see in the ocean) or were they "marching soldiers," each like the one in front?
>
> How fast does the wave respond to the wind?
>
> Really, what is the weather regime on the lake, especially compared to that in Salt Lake City?

Weather Tower Installation

Amoco decided to install weather monitoring equipment. In December, 1977, we activated two wind and wave measurement stations in the lake plus one weather station on the north end of the lake. Some combination of wave height, wind velocity and direction, barometric pressure, air temperature, and water current velocity are measured at each station. Figure 4 shows the location of each station and the data measured. Except for water current velocity, which apparently is below instrument threshold, data retrieval has approached 100%. In a few instances, on the south tower, the recording cassette tape ran out before it was replaced.

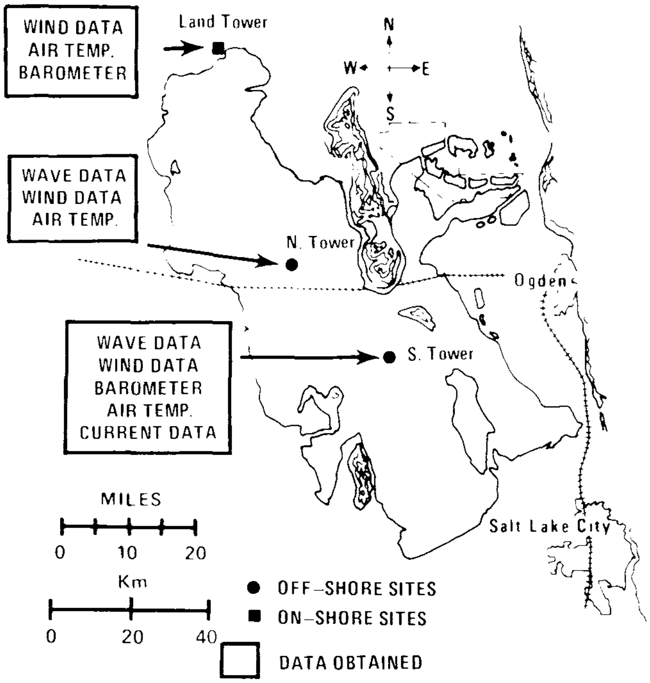

Figure 4. Location and data retrieved from Amoco's Lake and on land weather stations. The reader should compare these locations with a topo map to see how much wind is mountain directed.

The weather tower design was approached in the same manner as a typical offshore platform. (We wish to acknowledge here that the Utah Geological Survey furnished very helpful drawings of a tower which they installed 3 kilometers (2 miles) from the south shore). The platform design approach forced us to evaluate some aspects of our operation in detail at an early stage. We "overdesigned" the tower so that it should withstand 160 km/hr (100 mph) winds and 3.6 meter (12 foot) waves from any direction. The photograph in figure 5 shows part of the completed design.

Wind Data

Figure 6A and 6B are "wind roses" at the two towers for the period December, 1977 through July, 1978. Short term weather data should be used with caution and we emphasize there is no history to evaluate these data. Comparing the south tower wind rose with a 5 year wind rose available from the National Weather Service for Salt Lake City shows the following:

> Wind velocities are possibly higher in storms, relatively, than expected from Salt Lake City data.

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* Significant wave height is the average height of the highest one-third of all waves.

Winds from the northeast are much more persistant than at Salt Lake City. This might be expected from mountain directed winds at this lake location.

High velocity south winds are about the same.

High velocity north winds exceed those measured at the airport, in velocity as expected, but also in persistance. (This condition is further accentuated at the north tower location).

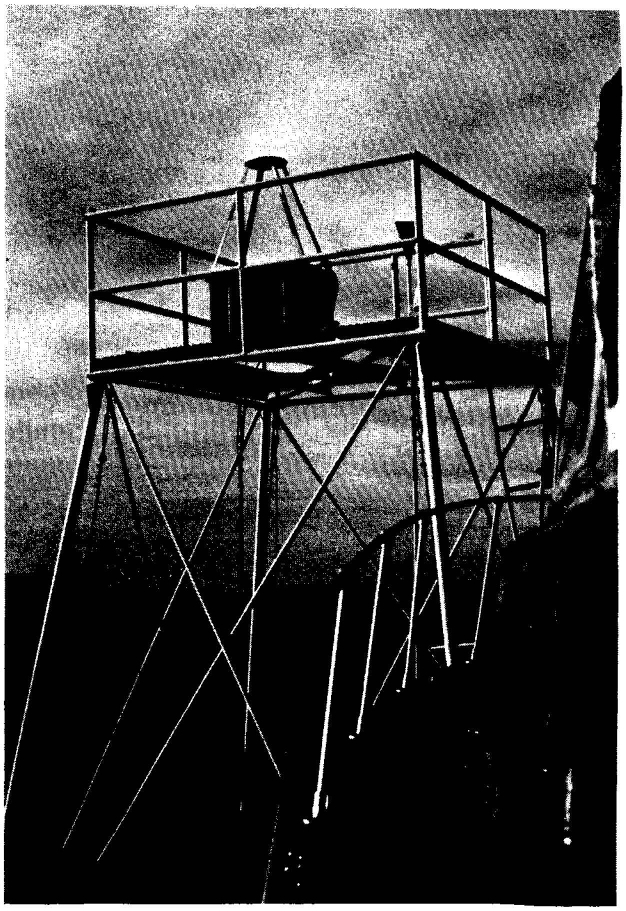


Figure 5. Photo shows the south weather tower in place. Structure design can be noted. The tower is free standing in 9 meters (30 feet) of water against 160 km/hr (100 mph) winds and 3.7 meter (12 foot) waves.

Comparison of Figures 6A and 6B show the difference in the wind regime between the two towers. (Incidentally, other data show a possible 20° shift between the two recordings which effectively shifts the north tower counter-clockwise relative to the south tower). It is also apparent that storms – more than 48 km/hr (30 mph) winds – were recorded from all but the east during the recorded period.

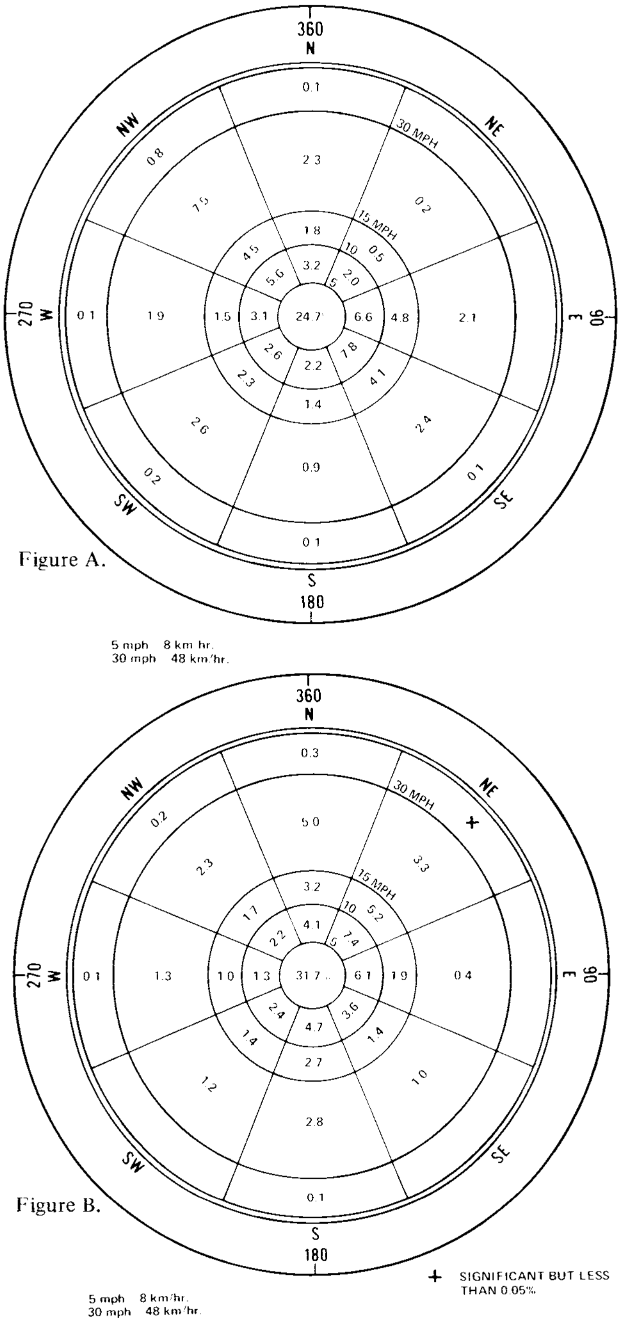


Figure 6. Modified wind rose for the north tower (A) and the south tower (B). All winds below 8 km/hr (5 mph) are plotted as calm. Note wind at south tower from the northeast - down the Bear River Valley. Data base is limited to December, 1977 to July, 1978.

The wind-wave relationship at the north tower is shown in figure 7. These represent selected waves in storms from the north quadrant only, after the wave had been built up. That is, the wind had been blowing steadily long enough to develop the wave at near maximum height.

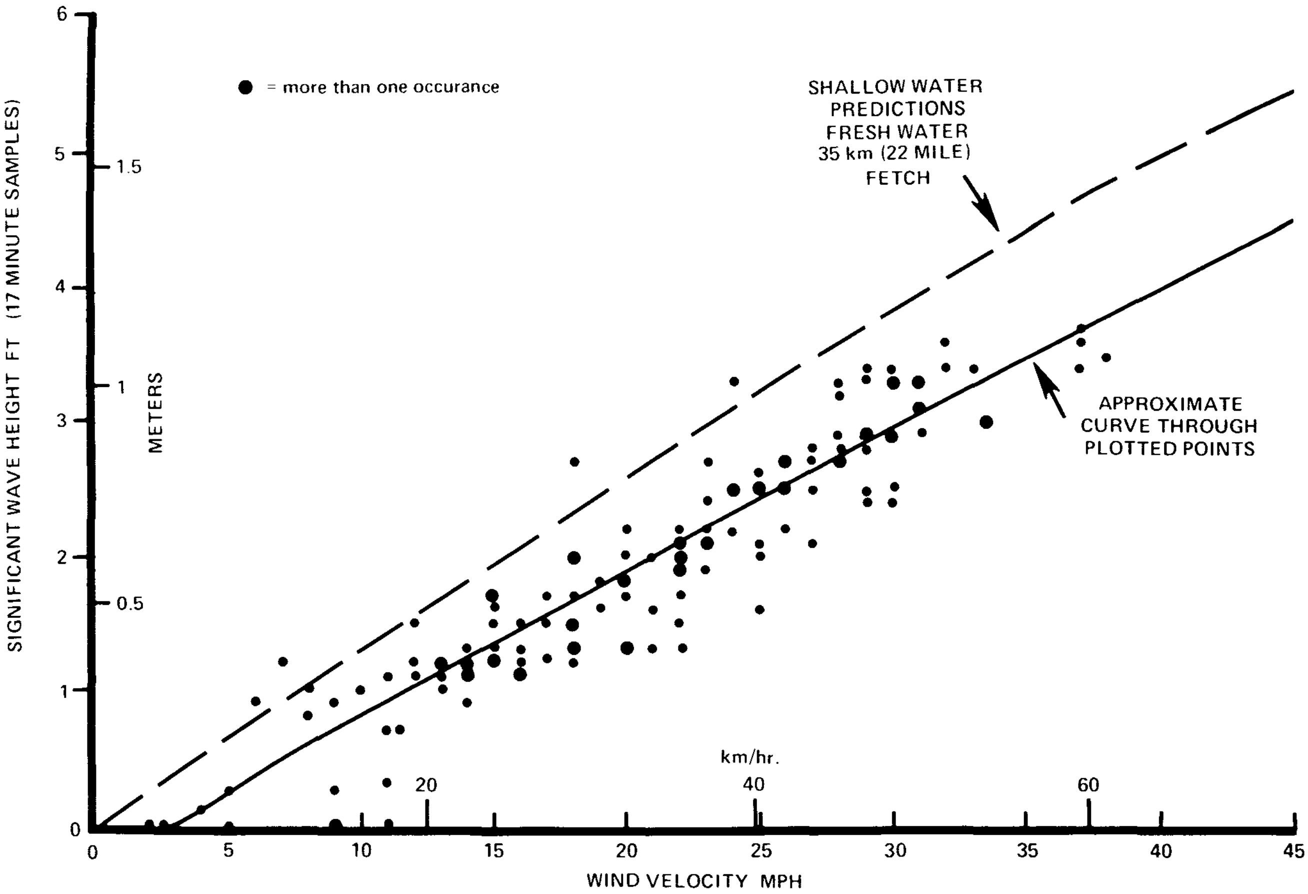


Figure 7. Wind-wave relationship at the north tower from north quadrant winds and developed waves. Fetch is 35 km (22 miles); water depth at site is 8 meters (26 feet). Great Salt Lake waves seem lower than predicted fresh water waves by approximately the specific gravity of the water.

Note in this curve and other general wave data, wave height is the significant wave height, defined as the average height of the highest one-third of all waves. This definition approaches what a person "thinks" is the wave height from visual observation and is used universally in marine work (See also figure 8).

Realizing that figure 7 represents a preliminary not-in-depth review of data just now available, the following comments seem appropriate:

The wave heights are lower than those predicted for shallow fresh water. The north arm (figure 7) superficially appears to be below forecast by the specific gravity difference. (As far as we can determine, no one has made detailed studies of the effect of specific gravity on wave development).

There is a relative lack of wave development at wind velocities below 8 km/hr (5 mph). This might be the result of instrument sensitivities.

The south arm data (not shown) does not follow the predictive curve as closely but there is an indication that waves in this fresher water more nearly approach the predicted fresh water waves than is true in the heavier water north arm.

The 1 to 10 ratio 4 - foot wave in 40 mph wind is a reasonable approximation (up to 40 mph).

As an aside, wave energy is a function of wave height and specific gravity. If one were exposed to the same height wave in both Great Salt Lake and the ocean, the energy difference absorbed would be the difference in specific gravities. Since the south arm is now below a sp. gr. of 1.1 and ocean water is about 1.03, an equal height wave would have about 5% to 7% more energy. Waves from the north arm would show 25% or so more energy. If, as figure 7 may imply, the developed wave height is decreased by a factor equal to the specific gravity, then the energy in a wave developed by, say, a 64 km/hr (40 mph) wind would be equal to that of waves developed in the north arm or in any fresh water lake. The wave in Great Salt Lake would not be as high, but would have more mass. Note that this reasoning is speculative. Data from the weather towers might be used to investigate a wind-wave relationship for varying specific gravities.

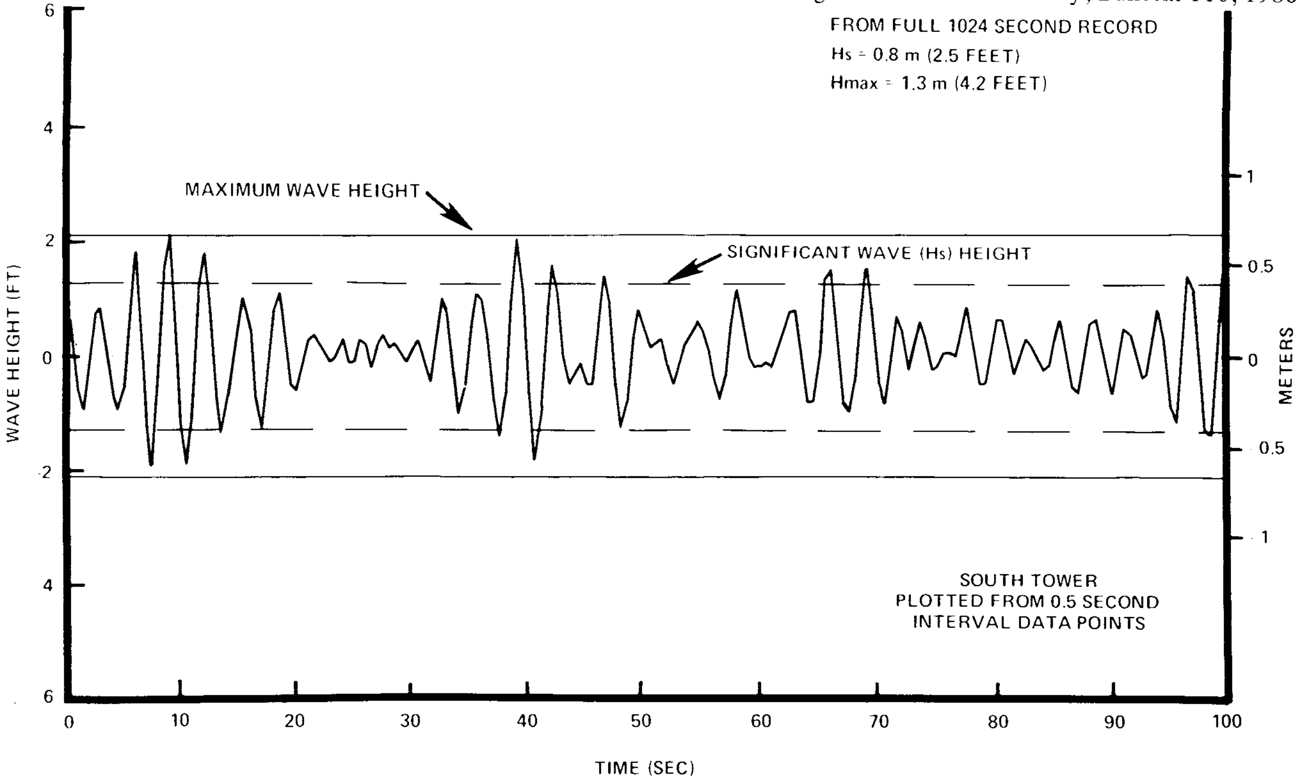


Figure 8. 100 second trace of storm waves from 35 km/hr (22 mph) west winds. Note relationship of the significant height to maximum wave height. Note also high waves at 10, 40, 70 and 100 seconds with much lower waves between.

Figure 8 is a 100 second record of storm waves. One can see from inspection there are "beats" in the wave train. Thus, the waves are not "marching soldiers".

In the open ocean, the maximum single wave in a storm varies from 1.4 to 2.0 times the significant height, increasing with the storm duration. The maximum wave in Great Salt Lake seems to be 1.5 times the significant height (again based on our limited data).

Because our choice of operation results in less detailed information at the north tower, we cannot make a detailed comparison of north arm data with south arm data. Visual comparison, however, shows little difference, certainly no more than the difference in water specific gravity. Figure 9 is a time plot showing wind and waves at both the north and south towers during a "strong" wind. Note that with similar winds, the wave height is almost the same. Since the fetch for a north wind is less at the south tower, wave heights should be somewhat lower than if the fetches were equal, but the fresher water permits an offsetting higher wave.

Wind is measured at the Amoco towers one minute out of every 20 minutes. The highest one minute velocity has been 82 km/hr (51 mph). This compares with the recorded all time high at Salt Lake City of 114 km/hr (71 mph). (Highest one minute winds in Salt Lake City are based on continuous recording and have exceeded 78 km/hr (49 mph) in each month. These winds are from the northwest or west except in December, January and February when the city peak winds were from the south). Significant waves are measured over a period of 17 minutes in each 20 minutes. The highest 17 minute significant height has been 1.6 meters (5.2 feet). Since the maximum wave is measured only if the 17 minute interval is recorded, and since we do not record every 17 minute interval, we miss the details in some storms. The highest one recorded single wave, neither preceeded nor followed by a wave of similar height has been 2.7 meters (8.8 feet).

A probability curve for waves is shown as figure 10. This shows that:

6% of the waves exceed	0.6 m (2 feet)	(significant height)
0.5% "	1.0 m (3 feet)	"
0.1% "	1.2 m (4 feet)	"

This also says that 94% of the time, waves are less than 0.6 meter (2 feet) significant height. Using 1.5 as the factor to determine maximum waves will give the reader an idea of the probability of experiencing a

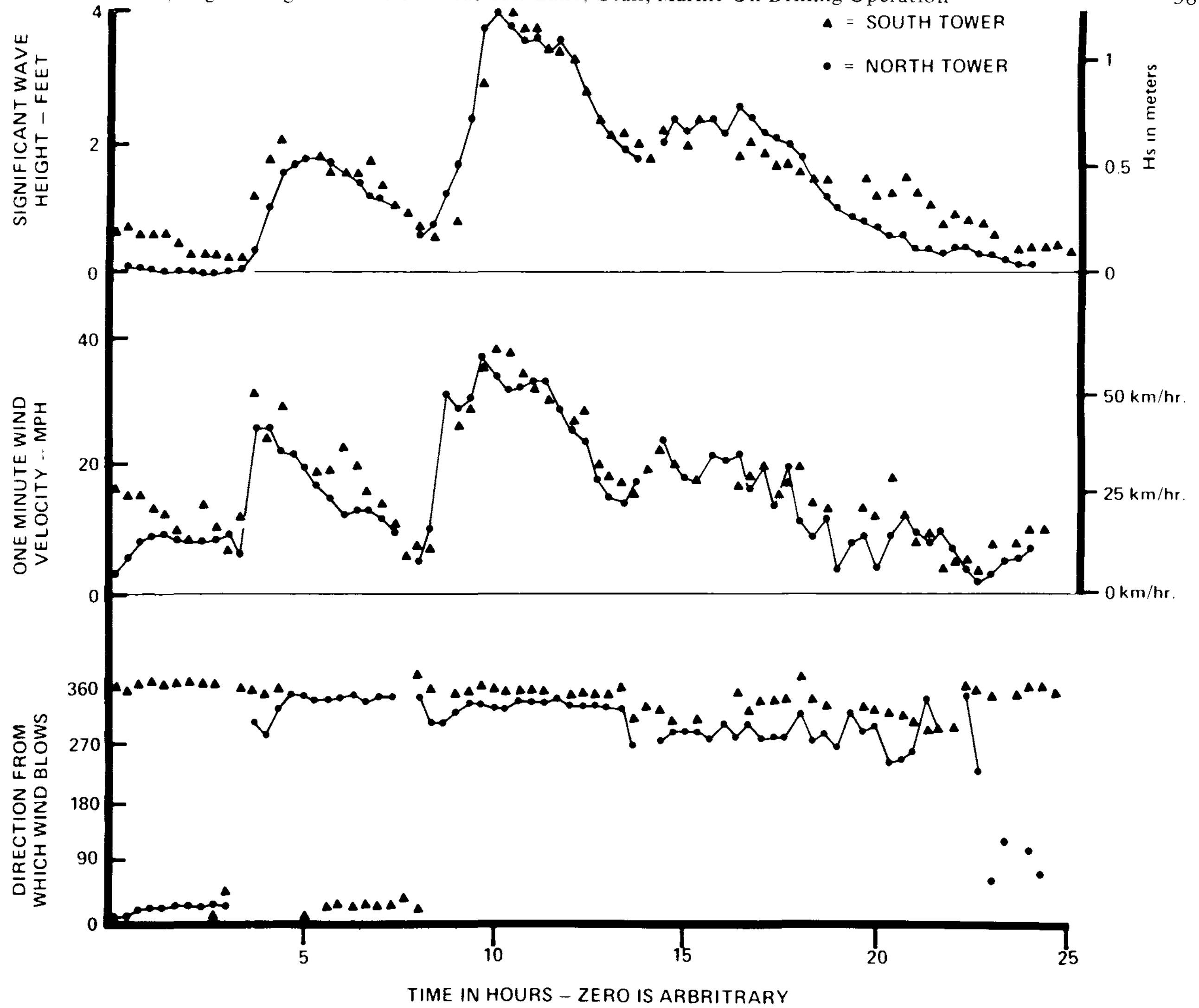


Figure 9. This figure compares data taken at the North and South towers during a rather severe storm. The time of peak wave (near 10 hours) has been made the same for both records. Note relative consistency of data between 5 and 20 hours yet discrepancy below 5 and more than 20 in wind velocity or direction. Differences in wind direction 5 to 15 hours possibly instrument error.

given maximum wave. Note again that this is limited to data obtained in the first half 1978. We do not recommend extrapolation of the probability curve for the extreme event. For example, the 1.6 meter (5.2 foot) significant wave represents only one event in 17,000 recorded events. More extreme-event data are needed for high wave and wind probability.

SEISMIC ACTIVITY

Great Salt Lake is in an active earthquake zone. This is indicated by very recent activity near Magna and a strong quake (magnitude 6.1) on the Utah-Idaho border on March 28, 1975.

In 1974, little detailed analysis of the earthquake probability for the Great Salt Lake had been published although some work had been done along the Wasatch front. Amoco used the known data to determine its own seismic risk. More recent (Algermissen, 1976; Donovan, 1976) work has been published which justifies our 1974 seismic risk approach. Specific studies have also been made recently for Salt Lake vicinity buildings.

We have assumed that any structure built in the Salt Lake should be designed for seismic loading. This creates problems when that structure is to be installed in the low strength mud bottom.

Recent studies funded by the petroleum industry for Alaska offshore earthquakes show that the attenuation of seismic forces in marine deposits is different from attenuation on land in Southern California: the resulting forces are less in the marine sediments. Whether this result would be valid in Great Salt Lake (Lake Bonneville) sediments is conjectural.

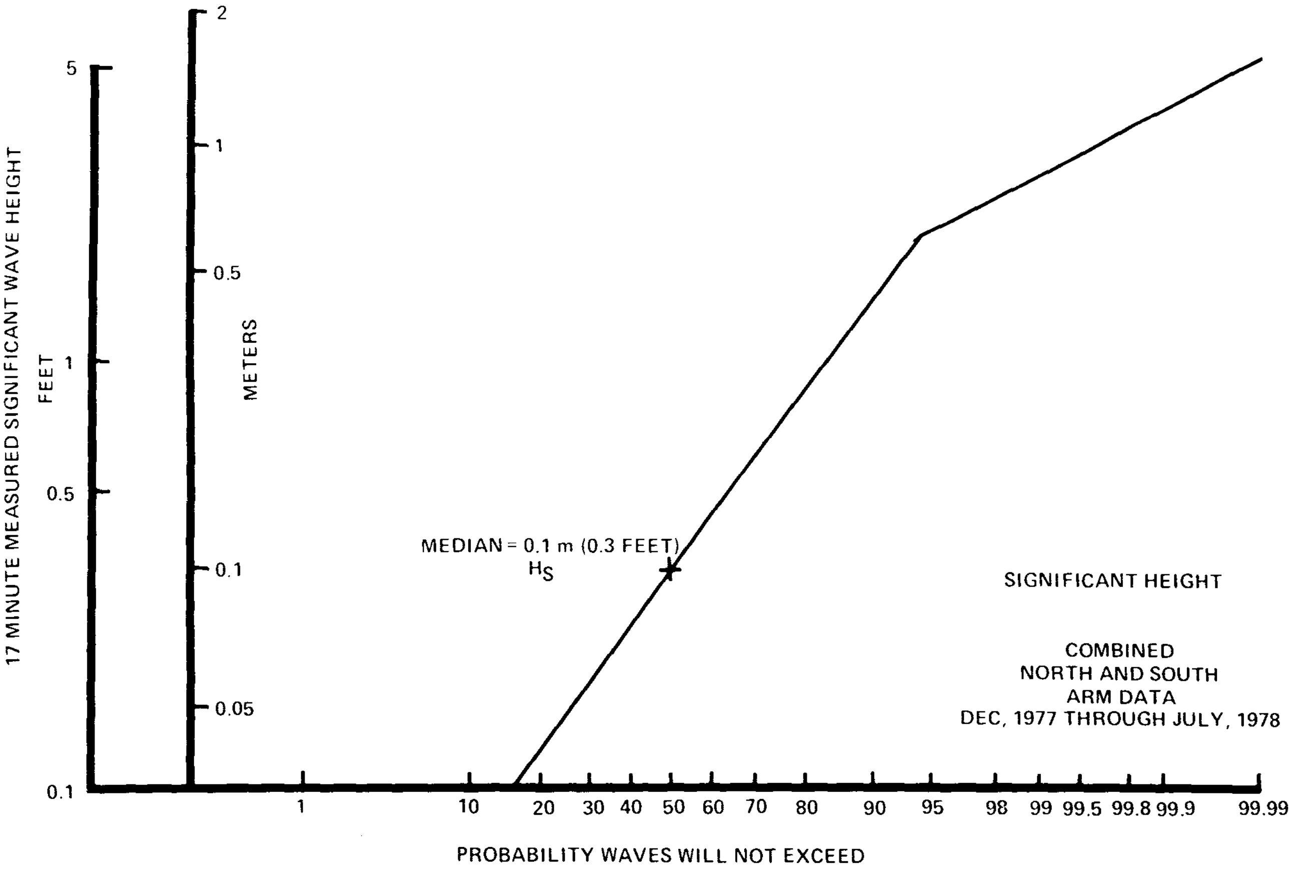


Figure 10. Log-normal probability plot of H_S. Based on short term data. Upper limits will have very low confidence levels.

STRUCTURAL ENGINEERING

Drilling Platform Selection

Three types of drilling platforms are generally available for marine drilling:

A structure fabricated to "sit" on piles driven into the soil below the water;

A structure which is floated to location, then rests on bottom;

A moored floating vessel.

We had to consider the desire to drill at more than one location on each side of the Southern Pacific causeway. This required that equipment (1) be mobilized (in our case) on the north arm, (2) be partially demobilized to move all the drilling equipment to the south arm, (3) remobilized on the south arm and finally (4) be demobilized on the south arm.

Pile Supported Platform

Amoco retained a consultant engineering firm to design a pile supported platform. The combination of very low soil strength plus seismic loads when combined with the high loads of a drilling operation make designing a fixed platform difficult. The problem is increased when crane lifts are restricted by the probable available equipment. For example, we imposed a 23 metric ton (25 ton) single lift: this compares to routine 450 metric ton (500 ton) lifts in the Gulf of Mexico and 900 to 1800 metric ton (1000 to 2000 ton) lifts elsewhere in the world. The result of the study was that platform construction was feasible albeit difficult.

Bottom Founded Structure

The second method, a structure which is floated in and then set on bottom, is unacceptable in Great Salt Lake. In the first place, there is no vessel of this type which could be moved to Salt Lake. Further, if one were available, the soil at the bottom of the lake can not support this type load.

Floating Vessel

The third alternate is a moored floating vessel. Our 1974 evaluation seemed to rule out this alternate. However, in the Spring 1977, Cleary Petroleum Company, Oklahoma City, drilled a well at Lake Texoma on the Texas-Oklahoma border using an assembled barge. There are many differences between the Texoma and Salt Lake operations, but the successful Cleary operation led to a more detailed evaluation.

The outcome of a 1977 study was that a fabricated barge could be sufficently strengthened to withstand the wave loading expected in a 50 year storm and with proper precautions could take a 100 year storm. A companion study indicated the barge could be successfully anchored.

The decision on the drilling structure was further complicated by factors involved in petroleum production: (a) how would we convert wells to production if a discovery were made? and (b) could we directionally drill from a fixed platform? (Directional drilling requires that the drill bit be forced away from vertical to a target some distance horizontally from the surface location). Typically the horizontal distance could equal the vertical distance in competent rock. In pre-drilling studies, the probable sediments in the first 600 to 1200 meters (2000 feet to 4000 feet) of drilling were considered unable to stand up in a slanted hole, making directional drilling potentially impractical. Therefore the problem is academic.

Amoco re-evaluated the two viable alternates:

1) A limited use fixed platform and

2) A moored barge.

The second alternate was chosen, mainly to provide flexibility in drilling wells at acceptable locations. The resultant barge is 27 m x 54 m (90 feet x 180 feet), dimensions which represent a compromise between maximum size for acceptable strength and minimal size for drilling operations. Figure 11 is a photograph of the designed barge in use.

MARINE ENGINEERING

Drilling Barge

Amoco retained a marine engineering firm to do the structural engineering of an assembled barge which would withstand the Great Salt Lake wind and wave environment. The barge is assembled from interconnecting units, all 7 feet (2.1 m) deep, with deck areas of either 10 feet by 20 feet (3 m by 6 m) or 10 feet by 40 feet (3 m x 12 m). The units were trucked to the lake from the Houston fabricator.

Nominal assembly of the units with their male and female connectors is relatively easy. The result, however, is a "beam" 55 m long by 2 m deep (180 feet by 7 feet) which has considerable play in the connectors. The long slender "beam" required considerable strengthening to carry the heavy drilling derrick loads through the various loadings of wave action. Since the strengthening included extensive welding to connect many of the individual units, design consideration had to also account for "undoing" this welding for the move to the south arm.

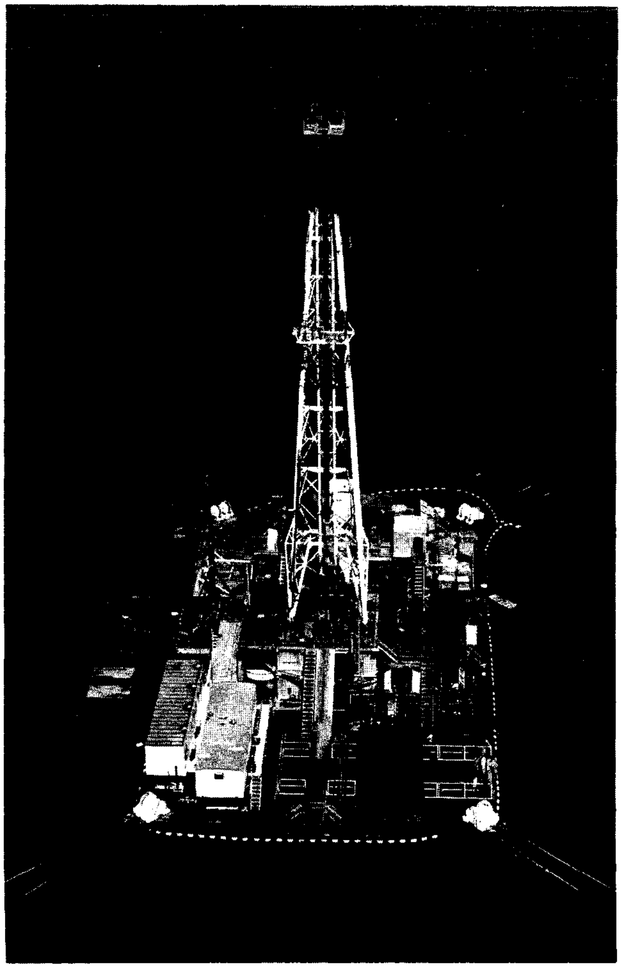


Figure 11. Anchored 27 m x 55 m (90' x 180') drilling barge operating at the Indian Cove Well No. 1.

Barge Mooring

The drilling barge is of no value as a drilling structure unless it can be held over the well. In our case, permissible horizontal motion while drilling was limited to less than 0.5 m (1.5 foot) from the well, which turns out to be very restrictive. Greater motion will occur in major storms (continued winds above, say, 80 km/hr (50 mph); a safety disengagement procedure has been developed for this eventuality.

A mooring study indicated the magnitude of the problem. Several solutions based on theoretical barge motion were evaluated and rejected. The accepted mooring scheme uses a so-called taut moor. There are 8 mooring lines, two on each corner of the barge (See figure 11). Each line is nominally 2000 feet of 1½ inch (600 m of 3.8 cm) high strength wire cable. After construction stretch was taken out by pulling 350 to 450 newtons (80,000 to 100,000 pounds), the cables are held at 90 newtons (20,000 pound pull) under non-storm conditions. No adjustment is made during storms. The breaking strength of each cable is above 800 newtons (180,000 pounds).

Tank Test

Proposed mooring plans were checked on a model in a wave tank. The only tank available developed sinusoidal waves and not random waves. Thus any condition near the natural frequency of the barge modeled higher motions than expected in true life. The wind and wave section above shows that lake waves are not constant amplitude waves (See figure 8). The first wave data from the towers was available before the mooring design was completed. Thus we were able to set the tank-test determined mooring stresses higher than would be encountered on the lake. Similarly, actual vessel motion would be less than modeled.

Anchoring

A study was made to determine what type anchors would hold the taut moored barge in the soft bottom conditions, known from the soil borings. Commercial anchors generally used offshore are heavy for our handling (20 ton anchors are normal). Even if we could use them the holding power in soft formations is low, and would require using many anchors. Therefore a special plate anchor was designed and model tested.

At about this time (1977), we were told about the reprecipitation of salt in the north arm. We now had some new problems:

Was the salt the same as our 1974 sample?

Could we design any anchor to hold in salt?

How thick was the salt?

Could we break through, or wash out the salt to set the anchor in the underlying mud?

What would the salt layer do to our mooring cable?

We immediately changed our priority to an anchor design using driven piles. A pile can easily be designed to take the lateral load. But there were still some questions: how thick was the salt? how strong? and could we drive a pile successfully? What precautions were needed to handle the pile as soon as the salt was penetrated? The most nagging question, would the salt act as a "pulley" to our mooring line and create a vertical force for which the pile is not designed, instead of the horizontal force?

The final design is a driven 30 inch (76 cm) diameter pile with 180 feet of 6 inch (55 m of 16 cm) anchor chain between the pile and the end of the 1½ inch (3.8 cm) wire cable. The chain is in the salt section to take the abrasion. It also accepts an easier connection to the pile.

Through the storms up to the time this is written, the entire mooring system has worked as predicted. Barge motion has been very low: maximum motion less than several inches and rolling motion low.

The total system is designed for storms considerably more extreme than have yet been experienced.

CORROSION

The mooring system is imbedded or immersed in a potentially hostile environment of salt or salt water. The floating equipment rides on the same water. We needed to consider (1) the corrosiveness of the south arm dense layer (Gwynn, 1977);(2) whether the saturated north arm is more or less corrosive than the fresher south, and (3) if the south arm will cause problems. Water chemical properties are available from Waddell (1973), Whelan (1977), and Gwynn (1977).

Water samples analyzed in our lab show that the low oxygen content of the water offsets the increased salinity on a *rusted* surface. Inspection of the Southern Pacific sheet steel unpainted barge "Sacramento", which is trapped between the trestle and the causeway, shows no adverse corrosion at the waterline. This barge is in relatively quiet water.

Inspection of metal pieces around the Little Valley Harbor and the ship canal also indicate low corrosion except where metal choice might have been questionable.

We concluded that corrosion would be no worse than is normal to warm weather ocean operation.

The mooring cable, however, is not normal sheet steel: it is high strength steel alloy. This metal might be subject to attack by both the saturated brine and by the sulfide in the south arm dense layer.

We chose a drawn galvanized wire which is coated with a chemical substance capable of at least short term protection. Since there is no laboratory data for this cable in Great Salt Lake water, its utility will be determined by inspection. As additional protection we have added an impressed electrical current system. However, as of this writing this has not been completely lined out.

A complete back up set of mooring cables was purchased at start up in case of line failure, or in case inspection indicates the corroded wire should not be reused on later wells.

SHORESITE

As indicated earlier, Amoco upgraded existing facilities at Little Valley Harbor for the north arm operations. There are no facilities for industrial use in the south arm. Therefore, a jetty plus bulkhead dock will be constructed for south arm operations.

This installation is proposed for the area just east of Promontory Point. As this is written, we are in the leasing and permitting phases with construction set for October, 1978. The resulting installation will be left as a "safe haven" for recreation boats after drilling is completed.

The problem here is to design a usable installation from native material at an acceptable cost. The State Department of Transportation has been helpful by discussing its problems with the Antelope Island Causeway. The Division of Parks and Recreation updated us on the problems at the State Marina at Silver Sands (on the south shore). We have also had considerable help from the Great Salt Lake Division, including its studies (Anon, 1976).

MARINE FLEET

The choice of floating equipment is a three way problem between needs, availability, and utility in Great Salt Lake.

The marine fleet on September 1, 1978 consisted of:

1 drilling barge, 27 m x 54 m (90 feet x 180 feet).

2 supply barges, 9 m x 36 m (30 feet x 120 feet), one with 1-300 HP (223 KW) supercharged engine propulsion units and one with 2 of these drives (See figure 12).

3 Crew and work boats, 2 with two-125 HP (93 KW) engines, 1 with somewhat larger engine.

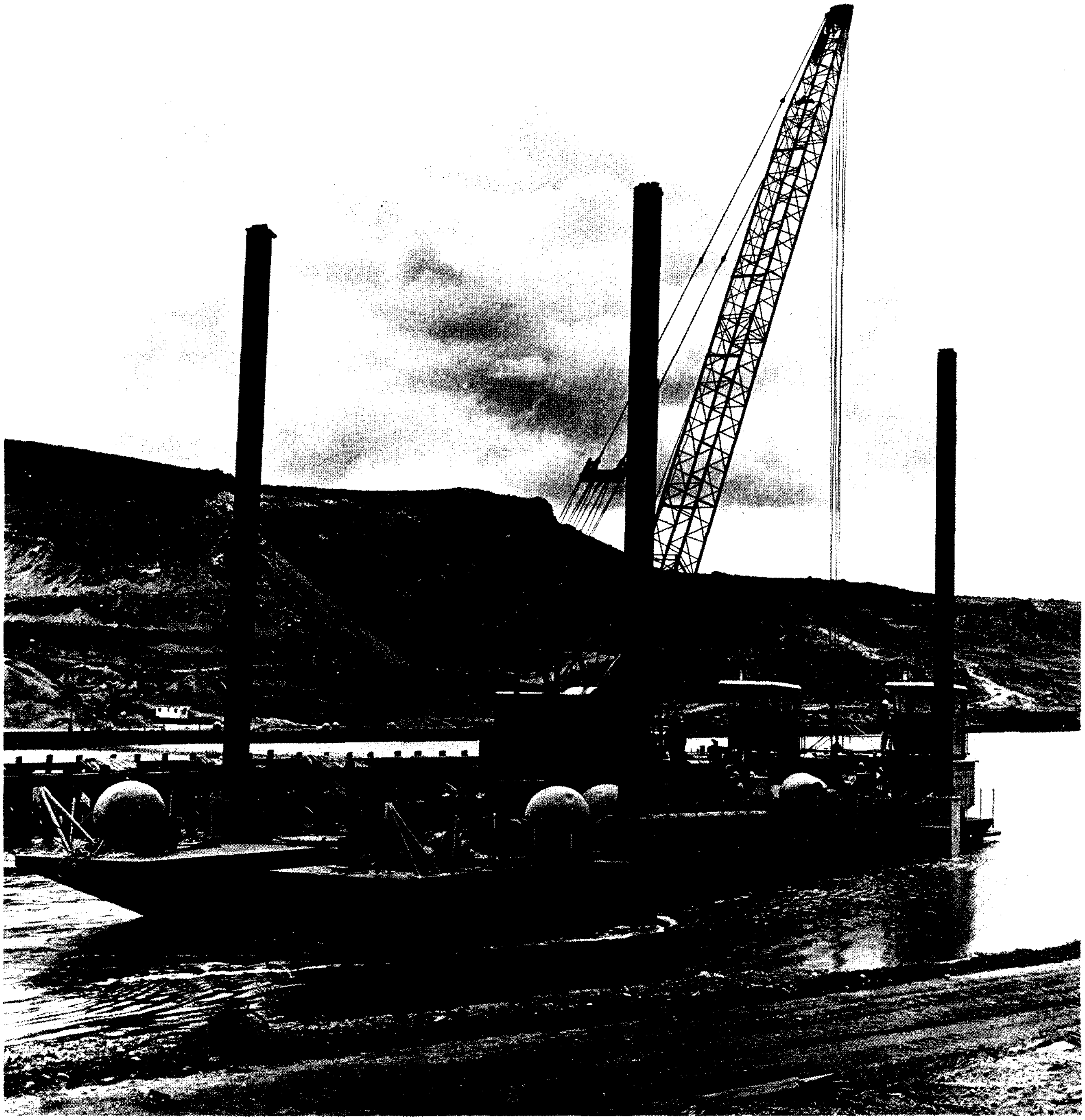
1 pollution barge 6 m x 21 m (21 feet x 68 feet) catamaran with 1-125 HP (93 KW) propulsion unit.

1 mud barge 6 m x 21 m (21 feet x 68 feet) tied to the drilling barge to catch drilling cuttings which must be taken to shore to satisfy EPA (Environmental Protection Agency) regulations.

All propulsion units have been designed to withstand the corrosion problems and salt deposition on the marine heat exchangers. We have experienced no adverse problems with the marine heat exchangers nor corrosion. Salt build-up is, of course, a continual process. No aluminum has been used because of a concern over corrosion in the welding material. (We do not state that there will be a problem, but did not have time to do laboratory research before the deadline to-order equipment).

POLLUTION CONTROL

Oil spill control in Great Salt Lake is relatively easier than in the oceans. The maximum sea conditions are much less; the probability of significant waves greater than 0.6 meters (2 feet) (the approximate limit of some pollution control equipment) is very low; the



Note: All photographs by Bob Lynn, Amoco.

Figure 12. 9 m x 36 m (30' x 120') supply barge.

normal lake currents approach zero, meaning the oil spill trajectory will be wind determined rather than current determined; and distances from shore are short enough to get quick response but still far enough to provide response time.

Working with the advice of response team personnel from other and rougher sea areas, Amoco obtained the following pollution control equipment:

> A floating boom which encircles the drilling barge. This boom primarily contains the accidental spills from the barge which have very low volume.
>
> A heavy floating boom which is stored on the pollution barge. This boom would be deployed for an oil spill which is relatively large and outside the drilling barge boom. Its purpose is to contain the oil spill. In operation, the boom would be deployed down stream of the spill (probably down wind in Great Salt Lake) by one of the crew boats and pulled into a circle around the spill.
>
> An oil recovery system located on the pollution barge composed of a 180 m (600 foot) loop of material which absorbs oil, and a mechanism to pull this loop onto the pollution barge, where the loop feeds through wringers which squeeze out the oil. The loop is returned to the water to pick up more oil.
>
> Absorbant material and other material and equipment to remove oil from the shore line in the unlikely event that oil got to shore.

Personnel working on the job have been trained for first response to an oil spill. Expert crews are available by plane within a few hours if needed for a major spill.

Historically, oil spills from exploratory wells have been very few in the entire world. Even though there is a very low probability of need, Amoco has oil spill cleanup capability at Great Salt Lake which exceeds, on a relative basis, equipment located in many marine areas.

SUMMARY

The success of the drilling operation at Great Salt Lake is the result of much engineering investigation. It is also the result of co-operation between the many parts of an oil company organization, both intra-company and inter-company. The freely exchanged data, knowhow, and techniques of the petroleum industry from its worldwide operation served as background and expertise to design a drilling system to fit the very unique conditions of Great Salt Lake. State of Utah officials were very cooperative in providing specific available data on the lake.

The success or failure of the venture in terms of oil or gas discovery is not known at this time. We believe, however, that the information obtained, most of which will be deposited with the State of Utah, should aid in understanding this great body of water.

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GREAT SALT LAKE RAILROAD CROSSING

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INTRODUCTION

The Great Salt Lake has long been an obstacle to transportation from the eastern to the western part of the United States. In frontier days, wagon trains took a long, tortuous detour around the lake to the north. In 1869, when the first transcontinental railroad was being rushed to completion, the possibility of constructing a crossing of the Great Salt Lake was investigated by the exploration survey parties of both Union Pacific and Central Pacific (now Southern Pacific) Railroads. The engineers for both companies came to the same decision -- that construction directly across the lake was beyond feasibility because of cost, lack of information regarding the lake bottom, depth of lake, weight of water, and uncertainty as to long-term changes in the lake levels. The railroads completed the transcontinental line on May 10, 1869, at Promontory Summit, but it was necessary to build to the north of the lake, with grades up to 2.2 percent and many sharp curves.

FIRST CROSSING

It was agreed the Central Pacific, which had built from the West, would take over the line to Ogden.

In March 1902, some years after the Pioneer Central Pacific was incorporated into the Southern Pacific, work was begun on the construction of an embankment across the lake. Under the direction of Chief Engineer William Hood, Southern Pacific construction crews set out from both shores to build a rock embankment by dumping materials from railroad cars. At that time, the lake level had dropped approximately 16 feet from the maximum in 1868. Bear River Bay was spanned by construction of an embankment, but only after considerable trouble. Rock-embankment construction was started from both the west shore and Promontory Peninsula, but numerous and repeated land slides required construction of an 11-mile timber trestle -- extended later to 12 miles -- to close the gap (See map, figure 1). The building of the trestle, an epochal event in railroad engineering, enabled Southern Pacific forces to complete the crossing on March 8, 1904.

Over 3,000 men were employed during the construction of the crossing. Rock was excavated for the embankments with five-yard steam shovels and hauled by 40-yard dump ore-cars over a temporary construction trestle. This rock was hauled from quarries at each end until foundation failures halted the operation, and only then did the construction of the wooden trestle begin. Rambo Fill, built from the western shore, alone required about 3,700,000 cubic yards of rock material.

Nineteen pile-driver rigs were used to drive 38,000 piles for the wooden trestle. Although the lake was no more than 20 to 35 feet in depth, 120-foot long

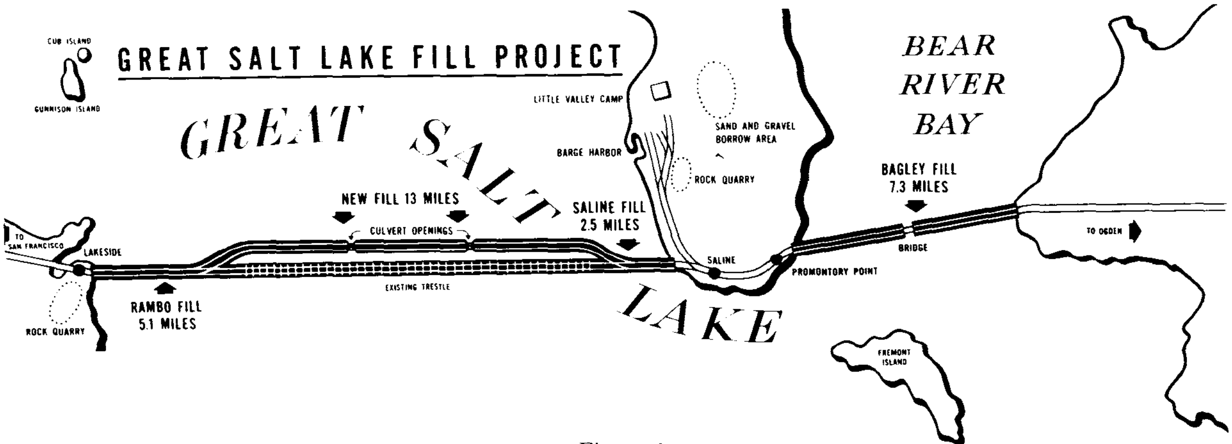


Figure 1.

wooden piles were required to develop enough friction to support the light trestle for 11,000 feet on the western portion and 1,500 feet on the eastern portion. The remainder of the trestle rested on shorter piles driven to refusal on a salt formation. Extreme settlements of the eastern 4,000 feet of Rambo Fill, on the west side of the lake, were so serious that this 4,000 feet of original embankment had to be replaced with additional trestle, extending trestle construction to 12 miles in length (figure 2).

The original trestle deck was replaced between 1920 and 1927. A limited number of helper piles and replacement piles were added from time to time. In 1943 and 1946, a number of additional piles were driven, increasing the number of piles in all of the single track bents from 5 to 7 and the passing track bents from 9 to 11. About 2,038 bracing piles, battered in the direction of trestle, were driven to support some 1,019 bents which were leaning, and to provide additional longitudinal stiffness to the trestle. A system of 8-inch by 8-inch horizontal struts under the stringers, and blocked between the caps, was installed in 1924 to improve the longitudinal integrity of the structure after an emergency stop of a train had caused the trestle to pull apart at one point. Due to severe checking of the stringers installed between 1920-1927, it has been necessary to install 5,400 helper stringers at various points along the trestle.

In 1942, at the request of the War Production Board, the alternate northern trackage between Lucin on the west and Corinne Junction, north of Ogden, was abandoned and the rails removed. Overland Route service of the Southern Pacific became entirely dependent on the single track wood trestle being maintained in service.

Figure 2. Pilings used on original causeway. Photo by David Miller.

PRELIMINARY STUDY OF ALTERNATE STRUCTURE

With time, it became obvious that construction of a full, permanent earthfill crossing of the lake was essential.

Maintenance costs on the wooden trestle mounted steadily under heavier loadings, the wear and stress of the elements, and 50 years of use. The trestle was not braced in the lower 70 percent of its depth, causing considerable sway with heavier traffic. Train speeds were restricted to 20 miles per hour to reduce impact and the sway action.

By 1953, Southern Pacific made a detailed structural inspection and analysis of the existing trestle, and it was estimated that the deck or superstructure above the pile caps should be replaced during the next six or seven years, and that the piles would require replacing within 25 to 30 years. To complete repairs of the 12-mile structure within those seven years it would have been necessary to take the trestle out of service a minimum of six hours every day. Such a plan was not acceptable from an operating and traffic viewpoint, and Southern Pacific decided that a more searching investigation be undertaken to examine in detail the feasibility and economics of constructing a crossing of the lake on several possible bases. These included solid fill and a completely new concrete trestle, as opposed to timber.

On August 24, 1953, Southern Pacific entered into a contract with International Engineering Company, Inc., a subsidiary of Morrison-Knudsen Company, to study all the various engineering and economic factors in connection with the required reconstruction of replacement of the existing trestle. Based on preliminary investigations, it was concluded that it would be most economical to construct a solid fill parallel to the existing trestle.

The preliminary investigation included two lines of sounding on courses 750 feet and 1,500 feet north of and parallel to the existing trestle; undisturbed soil samples from six 100-foot borings, and investigation into suitable quarry and gravel borrow sites. The water in the lake near the site of embankment was a maximum of 30 feet deep and was saturated with Glauber's salt or mirabilite ($Na_2SO_4+10H_2O$). When the lake level falls to elevation 4196.5 (USGS), the lake water becomes saturated with NaCl and Na_2SO_4 (a saturated solution is about 27.6 percent).

A seismic survey outlined a layered deposit of crystalline Glauber's salt at about the center one-third of the distance along the proposed alignment of fill, lying 20 to 30 feet below the lake bed. No subsurface rock was found, and the bottom sediments, other than the salt layer, were mainly clays, oolites and calcareous algae deposits with about one-third of the sediments composed of rod-shaped fecal pellets of the brine shrimp *Artemia gracilis.*

DESIGN

On May 26, 1955, a contract was awarded to International Engineering Company to design the embankment under the direction of a board of consultants and review by Southern Pacific. The board of consultants consisted of Dr. Arthur Casagrande, Mr. R. R. Philippi, Mr. F. H. Kellogg, and Mr. S. D. Wilson.

Southern Pacific insisted that the new fill be constructed about 1,500 feet from the existing trestle to avoid the possibility of damage to the trestle and consequent interruption of traffic. Subsequent engineering and soil tests investigations confirmed the wisdom of this decision and the fill was constructed along this general alignment.

The investigation of foundation clays for design purposes consisted of conventional piston-type samples during the initial phases. In-site strength was measured by means of numerous vein and penetration tests. The strength results from such a variety of investigations checked each other remarkably well. To speed up these investigations and to obtain better undisturbed samples, a Swedish Foil Sampler was used which allowed the recovery, in one operation, of continuous cores up to 60 feet in length wrapped in sixteen thin axial metal foils to prevent friction between the wall of the sampler tube and clay specimen. Numerous cores taken of the salt layer showed it to be a very heterogeneous deposit, highly stratified with laminations of "rock" salt, soft salt, and clay seams. The salt layer also varied in thickness from one foot on the west end to a very great thickness of the east end of the layer.

A soils laboratory was set up at the job site, where unconfined compression tests, quick triaxial compression tests, consolidation tests, determinations of water content, density and Atterberg limits were made of both the construction material and undisturbed clay samples. Chemical analyses and special soil tests were made at other laboratories. Numerous piezometers and settlement gauges were installed and observations were taken on these before, during and after construction. Southern Pacific Soils Engineer J. E. Newby, Geotechnical Engineer, worked closely with the soil consultants and International Engineering on phases of the design, and maintained a program of records and observations after construction.

Based on the results from the foundation and construction materials tests, preliminary designs were prepared. Stability analyses of the cross sections were performed both by the sliding block method and by the slip circle method. Because of the very soft upper layers of clay and the resulting construction difficulties, it was determined it would be more economical to remove a certain amount of the upper clay layers by dredging and backfilling the dredged trench with sand and gravel. In this manner, somewhat stronger foundation materials were reached, and lateral resistance was obtained by the trench walls. On the salt layer, all overburden clays were to be removed by dredging. Extensive analyses were made to determine a satisfactory depth-width ratio for the dredge trench.

The dimension, determined by the analyses, was that the depth of dredging in clay should be 25 feet, with width varied in accordance with variations in the strength of the clay along the project. The depth of dredging on salt depended on the elevation of the top of the salt layer. The bottom width of the embankment ranged from 175 feet to 600 feet, with a top width of 38 feet at 12 feet above water surface. As a check of the testing and analysis, a number of prototype test fills were constructed to failure. These test fills and further field and laboratory investigations led to modifications in the cross sections while construction was in progress. In general, the modifications lessened the cost of the project.

In order to achieve maximum economy, the embankment was designed and constructed with a stability factor practically equal to unity. It was less costly to repair a few failures during construction than to increase the stability factor, which would have required a greater increase in total volume of fill for this large a project. A low factor of foundation stability was acceptable since progressive increases in strength of the soft clay would occur with time due to consolidation

A special consultant was obtained to determine the size of rip-rap required on the slopes of fill to armor plate it against the heavy water wave action. Also, a special consultant was obtained to determine the concrete mix design for the concrete boxes or culverts to resist the chemicals in the lake water. This required a very impermeable concrete, free from cracks, resistant to freezing and thawing, and highly resistant to sulfate action. To accomplish this result, a 2 ½ inch maximum size aggregate design was used with special type V cement. All aggregates were shipped to the site from Fair Oaks, California, and quartz sand from Monterey Bay, California. A special air-entraining agent was used. The box culverts were constructed at the harbor under very close supervision and floated to their permanent locations and sunk into place.

CONSTRUCTION

Determination of an economical design was a great task, but just as hard was determination of the most economical method of moving a mountain of material into the Great Salt Lake to form the roadbed. The project entailed the dredging of 16 million cubic yards of muck from the lake bottom and the placing of 45-½ million cubic yards of rock, sand, and gravel.

Actual construction started in June 1955, with the dumping of some fill material from railroad cars. Work was accelerated in March 1956, with the award of a $45 million contract to Morrison-Knudsen Company covering construction of the embankment and culvert.

Installation of railroad track and signal equipment -- by Southern Pacific's own forces -- cost about $2 million. With such other expenditures as those for exploration, engineering, testing and overhead, the cost of the project eventually was about $53 million.

A construction camp called Little Valley was established two miles north of Promontory Point, close to supplies of rock, sand and gravel. Included were storehouses, workshops, dining hall, barracks, facilities for 300 family trailers, a supermarket, clothing store, restaurant, post office and school. The camp was closed at the end of construction, in 1959, eliminating a city that had a population of over 1,300.

The first major job was the dredging of one million cubic yards of lake shore to build a half-mile-wide harbor and a channel to deep water three miles long and 15 feet deep. This dredging and the dredging along the fill was performed by 15-inch and 18-inch hydraulic dredges. A 44,000 volt power line was brought in from Ogden to supply the camp and operate various construction equipment, including electric shovels of eight cubic yard capacity.

A flotilla of barges, dredges, tugs and workboats bore the brunt of fill construction. It was fed by all forms of modern earth-moving equipment. An unusual aggregation of shovels, including the electric shovels, loaded mixed sand and gravel on 27-cubic-yard bottom dump trucks. These trucks fed the world's largest (in terms of tons per hour) belt conveyor to deliver up to 4,200 tons per hour to storage. In a separate operation, additional big shovels loaded trucks that transferred rock to bottom-dump and flat-deck scows for hauling direct to the core of the fill.

All equipment was moved by rail. Six of the largest bottom-dump barges ever constructed, each capable of holding 2,000 cubic yards, were fabricated at Napa, California, and shipped on railroad flatcars in 32 sections, weighing 10 to 30 tons each, for assembly and launching at the lake. Five flat-deck barges were constructed at Provo, Utah, to carry about 1,000 cubic yards each.

Six tugboats, each equipped with twin 500-horsepower engines, were built at Portland, Oregon; then halved down the centerline and moved by rail to the lake for reassembly and launching. Additional 600-horse-power tugs handled the flat-deck barges, while 300-horsepower tugs supplemented the larger vessels.

Material for the fill consisted of two types: Gravel, available at lower cost and better for contact with the soft clays, was used for the major part of the fill. Quarry-run rock was used from ten feet below water surface to the top of the embankment. Selected large rock from the quarry was used for a blanket over the gravel fill and for rip-rap on the slopes.

Sand and gravel came from a range of hills some two miles from the lake and about 400 feet above it. Three eight-cubic yard electric shovels loaded a fleet of 11 bottom-dump trucks for a short haul to a dumping station over the high-capacity belt conveyor. The sand and gravel, with plus eight-inch material scalped out and crushed, was loaded on the 54-inch-wide belt that traveled at the unusual speed of 850 feet per minute. Accelerating belts, 30 feet long and 60 inches wide, operated at 500 feet per minute, reduced stress and wear at the loading point and at the one transfer point required. This "dog-leg" conveyor system carried the materials 7,500 feet to a radial stacker near the barge harbor. The main conveyor had a regenerative braking system that produced power as it controlled the 400 feet downward movement of 4,000 tons of material per hour. Electricity was fed into the job power system.

During one 30-day period, the belt delivered an average of 83,333 tons a day, with surges as high as 5,000 tons an hour.

The stacker at the waterfront was used to build a semicircular stock pile of 70,000 cubic yards over two tunnels made from corrugated multiplate metal pipe of 180 inch diameter. Each tunnel had five openings for reclaiming material. A 72-inch wide conveyor in each tunnel delivered the gravel at a combined rate of 12,000 tons per hour, sufficient to load a barge of 2,000 cubic yards capacity in 15 minutes. When the material was moist, loading took appreciably longer.

The major part of the quarry rock and rip-rap came from the lake shore near the harbor. One of the principal features of interest regarding the quarry was the method of blasting the high rock face. A scheme was worked out in which two 5 by 7 foot main access tunnels, approximately 1,300 feet apart, were drilled straight into the side of a mountain. From the main access tunnels at 100-foot intervals, cross-connecting tunnels of the same size as the main access tunnels led off at right angles from the main tunnels. These drifts extended out a sufficient distance to leave only a 50-foot pillar of undrilled rock in the center of each pair of laterals. The rock was primarily quartz with 70-plus percentage of silica, requiring the use of tungsten carbide-type rock bits. The extremely hard drilling nature of the quartzite ruled out the use of large diameter vertical drilled holes.

The powder consisted of ammonium nitrate with about 25 percent of conventional explosives. The powder was piled in the cross-connecting tunnel drifts, beginning with a pocket at the end of each tunnel. After the powder was piled high, sand backfill was packed tightly over the top of the powder and against the roof of the tunnel. To prevent blast damage to the main access tunnels, the cross drifts were loaded with powder to within only 130 feet of the main tunnels and this area was packed with sand. All powder pockets were connected by two lines of reinforced Primacord.

The tunnels permitted the use of very large blasts. One of the blasts consisted of the detonation of 1.8 million pounds of explosives on July 21, 1957, and produced 4 million tons of quartzite rock (figure 3). Another blast consisted of 2.14 million pounds of explosives on January 5, 1958, and produced 5.9 million tons of the same rock. The rock was hauled by 17-cubic yard end-dump trucks to the harbor, where it was loaded into bottom-dump barges or on flat-deck scows. The hopper barges were loaded by first lowering material in skip buckets to provide a cushion and then dumping from the dock.

To provide rock for an economical train haul on the west end, a quarry on the west shore of the lake was established. This quarry consisted of hard limestone and a coyote-hole method of drilling and blasting was used. This rock was loaded directly into 30-cubic-yard side-dump railroad cars and hauled by train to the new fill.

Meanwhile, in the lake, the 15-inch and 18-inch dredges were excavating the trench into which the material was to be placed. The wide area was excavated and replaced with gravel fill, requiring some 400 to 500 cubic yards per linear foot. The dredges worked some 2,000 feet ahead of the fill operation, about the minimum distance permissible with equipment that could place as much as 50,000 cubic yards per day.

The bottom-dump barges were positioned over the trench and dumped by remote control from the bridge of the tug. Each barge had seven hoppers that could be controlled from the tug or from the deck house of the barge, and the hoppers could be opened all at one time or individually. The bottom-dump barges had a draft of 11 feet, so they could not be used when the fill came to within 12 to 15 feet of the surface (figure 4). For this work, the flat-deck barges were used; they were unloaded by tractors that pushed the material over the side. This procedure was supplemented by direct truck-haul operations at the east end of the project and by the train haul with side-dump cars from the western end.

Positioning of the loaded barges for dumping was under control of a Barge Control Engineer. The method used for control was by positioning towers on each side of the embankment and setting a string of targets above water level, all longitudinally perpendicular to the cut. This enabled the dumping to be accurate in regard to both offset and stationing. Pro-

Figure 3. Blast of July 1957 to obtain rock.

file of the underwater fill was checked daily, or after each dumping if necessary, by fathometers mounted in small boats.

The construction schedule called for the placement of up to 1.8 million cubic yards of embankment per month. For several consecutive months the production exceeded 2 million cubic yards, with the record month exceeding 2.2 million. The fill was placed from both ends toward the middle. The roadbed was completed July 1, 1959.

WEATHER

The Great Salt Lake is subject to sudden and violent storms with winds up to 60 knots, accompanied by waves up to 8 feet in water that weighs 76 pounds per cubic foot. The lake is so large that it has its own weather pattern. In less than an hour, a gentle southern breeze can change to a howling gale that arrives simultaneously with six-foot waves. Blinding snow storms and heavy fog are common in winter.

To protect the marine equipment and to prevent its being tossed into the existing railroad trestle the service of a consulting meteorologist in Salt Lake City was used and his advice was followed without question. This avoided potential disasters. In addition, wind directions and velocities were reported to the job site and to the meteorologist at regular intervals from both sides of the lake and from an automatic reporting station located at the north end of the lake.

TRACK AND SIGNAL

The installation of track and signals was under the immediate supervision of Division Construction Engineer H. J. Willard, who was stationed at the site of the project.

All track materials were distributed from the east end of the fill due to availability of equipment and storage space at this location. The cross ties were shipped to the site in banded bundles of 49 ties each. Seventeen-cubic-yard end dump trucks distributed the bundles of ties on the fill, hauling two bundles in each load.

Welded 78-foot rails were furnished for the construction of track. The distribution of the rail on the fill was by loading 22,78-foot rails on a special carrier. This carrier consisted of two tilt trailers separated by two rails as spacers. The carrier was constructed to enable towing from either end, thus eliminating the necessity of turning it around. The rails were loaded and unloaded by dragline type loader. All rail appurtenances were distributed by trucks.

The ballast was manufactured from the hard quartzite rock in the quarry on the east end of the project and placed in a stockpile. The distributing of ballast on the fill was by railroad cars after the rail was spiked. All track laying and surfacing was performed by modern mechanical equipment.

The track was built 7½ feet south of centerline of fill in order to leave sufficient room for a maintenance road. A 10,250-foot siding was constructed near the middle of the fill with Centralized Traffic Control switches on each end. The signal control wires are carried on a telegraph pole line constructed along the south edge of fill.

On July 27, 1959, the track work was completed and the new causeway was officially opened for freight traffic on the following day (Figure 5). By August 18, the ballast had been sufficiently traffic tamped and passenger trains were routed across the new track.

ANTICIPATED BEHAVIOR

The prototype test fills constructed to failure and other subsidences during construction caused mudheaves 150 to 200 feet from centerline of fill. It was determined during construction that placing berms on top or at locations where mud heaves would occur was the most effective method of obtaining stability. Excessive settlements or failures were not anticipated after completion of the fill, but if either should occur,

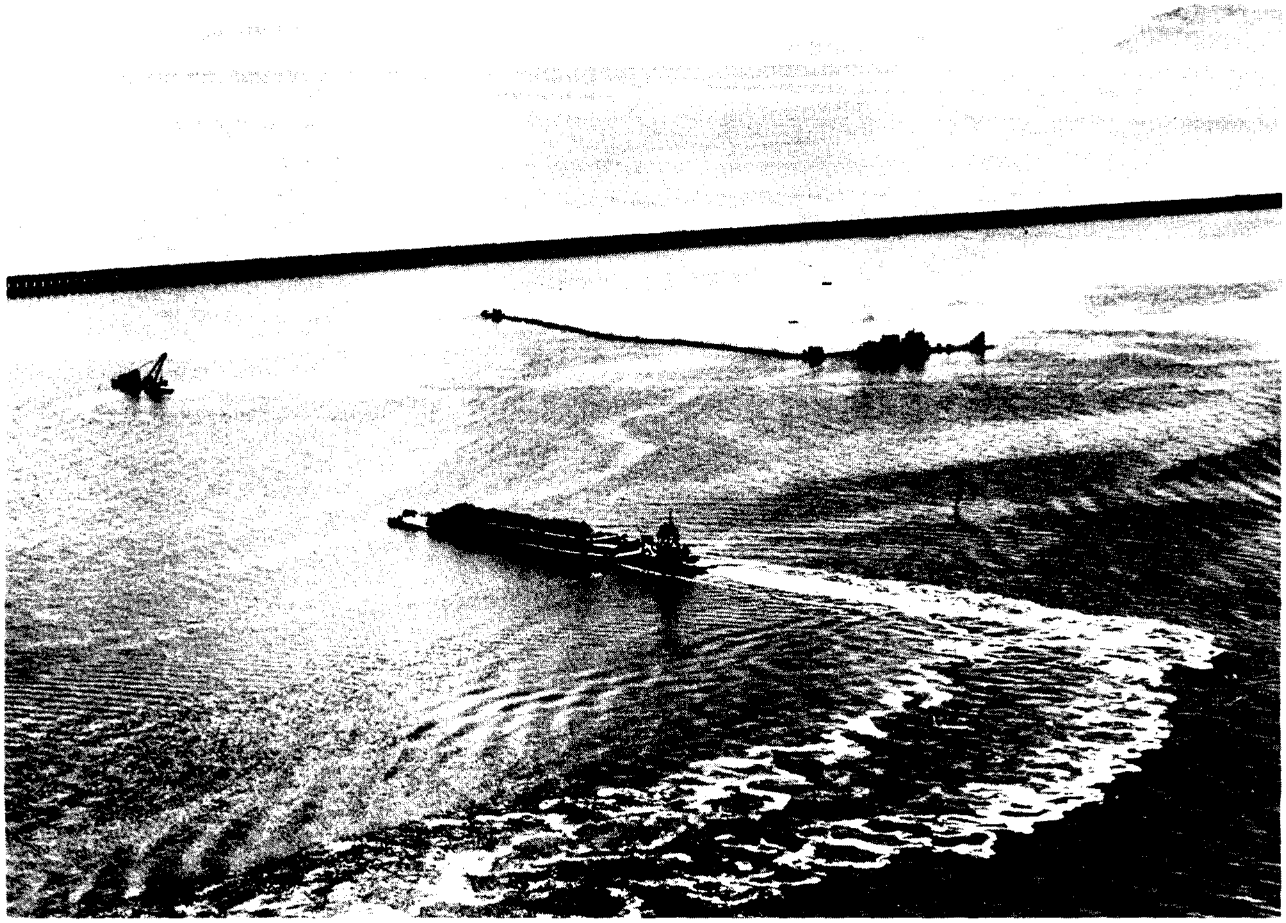


Figure 4. Bottom dump barge moves into position near dredge.

plans were made to correct them by construction of berms.

High rates of settlements were anticipated during the first few years after construction because the base of fill consists of either soft clays or salt layers underlain by soft clays. This was particularly true where subsidence occurred during construction due to disturbance of the base clays. Small settlements can be expected even 50 to 100 years after completion. In addition, the history of the lake's water surface elevations has been very erratic and the amount of rising or falling of the lake's surface elevation could not be predicted with any accuracy. Because settlements were expected and future water surface elevations are unknown, a required raising of the fill was anticipated and the fill was constructed of sufficient width to allow for a raise.

BEHAVIOR SINCE COMPLETION

The total average settlement of the fill after one year of operation was about one foot, after five years 2½ feet, and after ten years about four feet. The above rates of settlements were near or less than anticipated and have now decreased to a rate of about 2½ inches per year.

Total settlements plus the rise in water elevation required raising the subgrade back to its original elevation; this work was completed in 1971.

High water elevations have caused slope erosion problems during heavy storms, requiring replacement of rip-rap. The signal pole line was replaced with underground cable in 1974 due to storm damage to the pole line.

SUMMARY

The Great Salt Lake crossing had been a challenge to the Southern Pacific, and the completion of a low maintenance– cost embankment across the lake has brought to pass the dream of the early railroad pioneers. This was made possible by the combination of modern soil mechanics design techniques and modern mountain-moving construction equipment and technology. This was the most challenging soil mechanics and construction problem ever encountered at that time. Except for storm erosion caused by higher water elevation, the behavior of the embankment has been as anticipated.

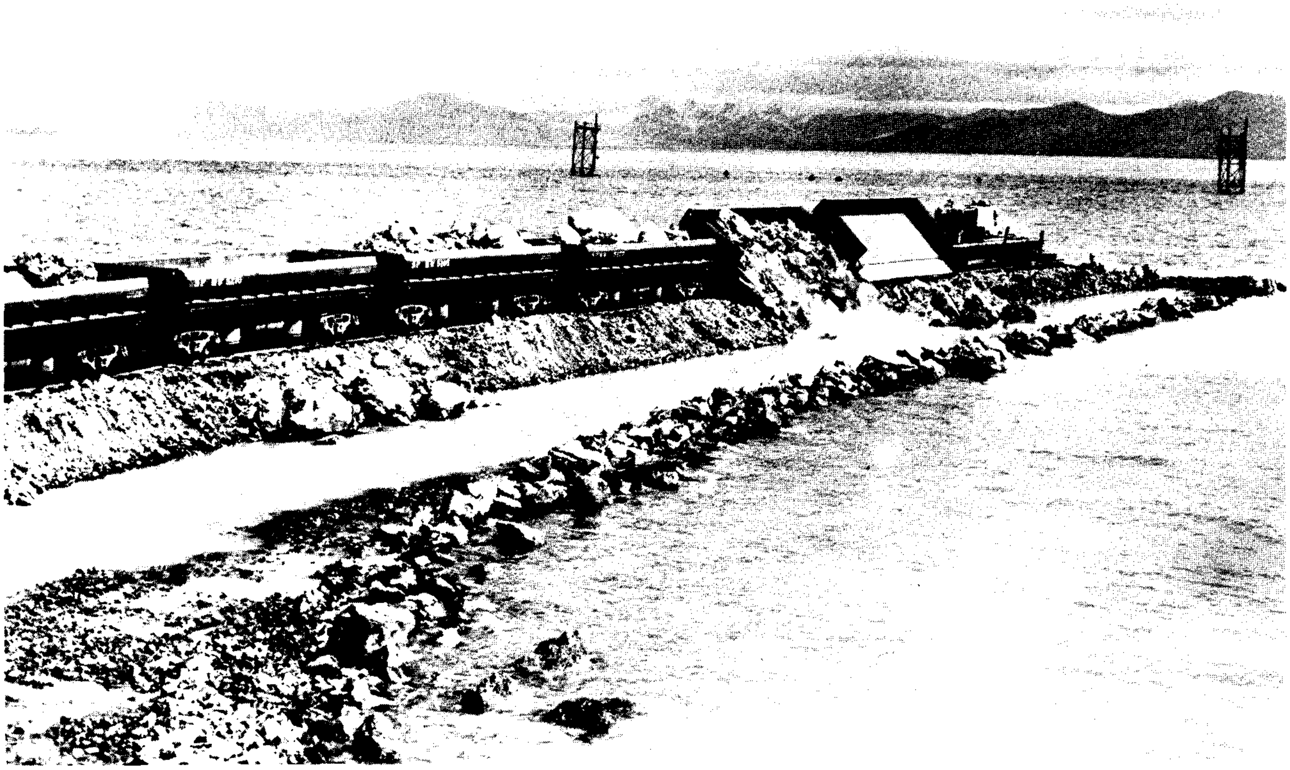
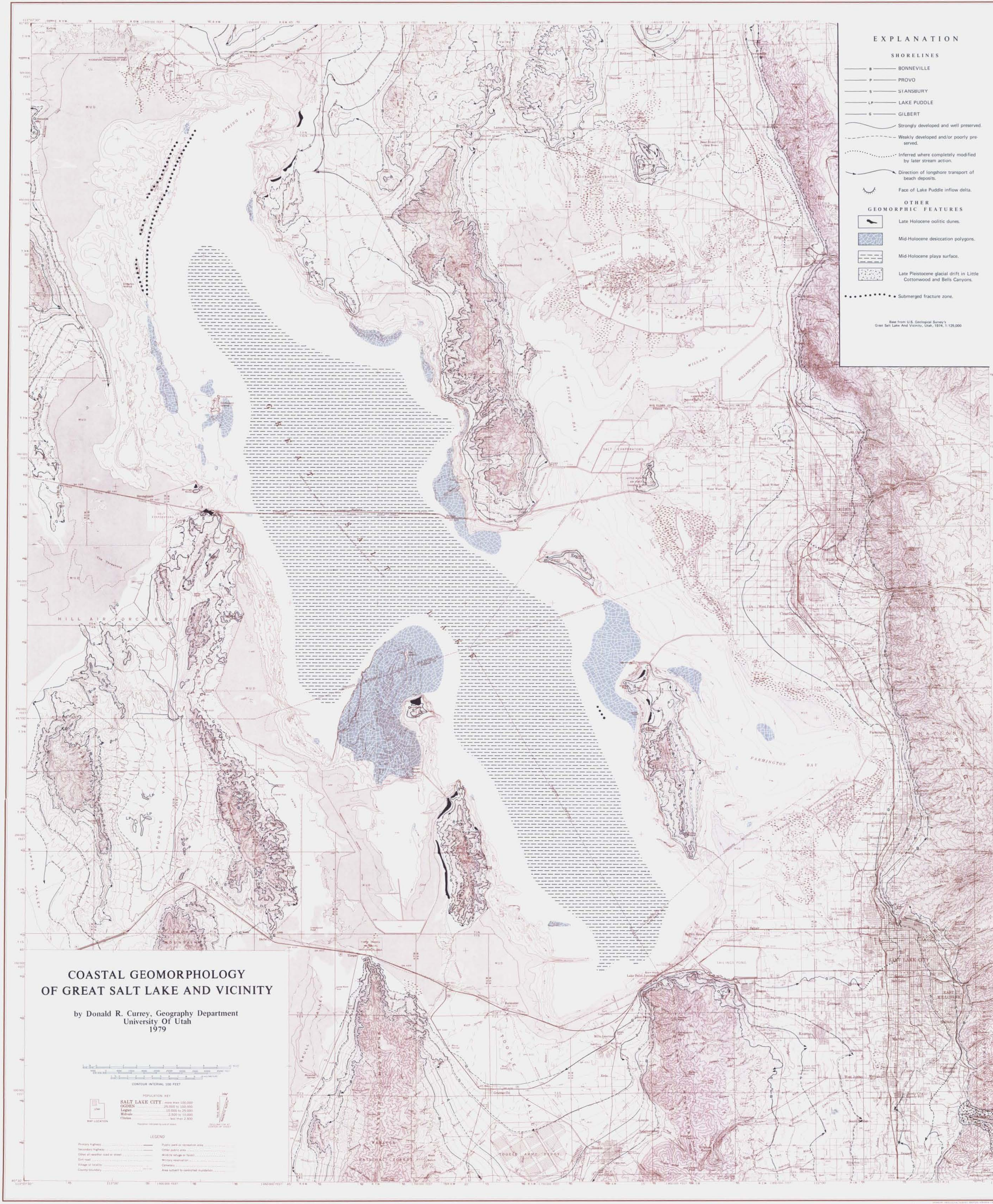


Figure 5. Rail dump cars used on west side of lake.

Archives Approval No. 8000142
Appropriations No. 01-61-03

STATE OF UTAH
Department Of Natural Resources
Utah Geological And Mineral Survey

Plate 1
Bulletin 116
Donald R. Currey, Coastal Geomorphology
Of Great Salt Lake And Vicinity



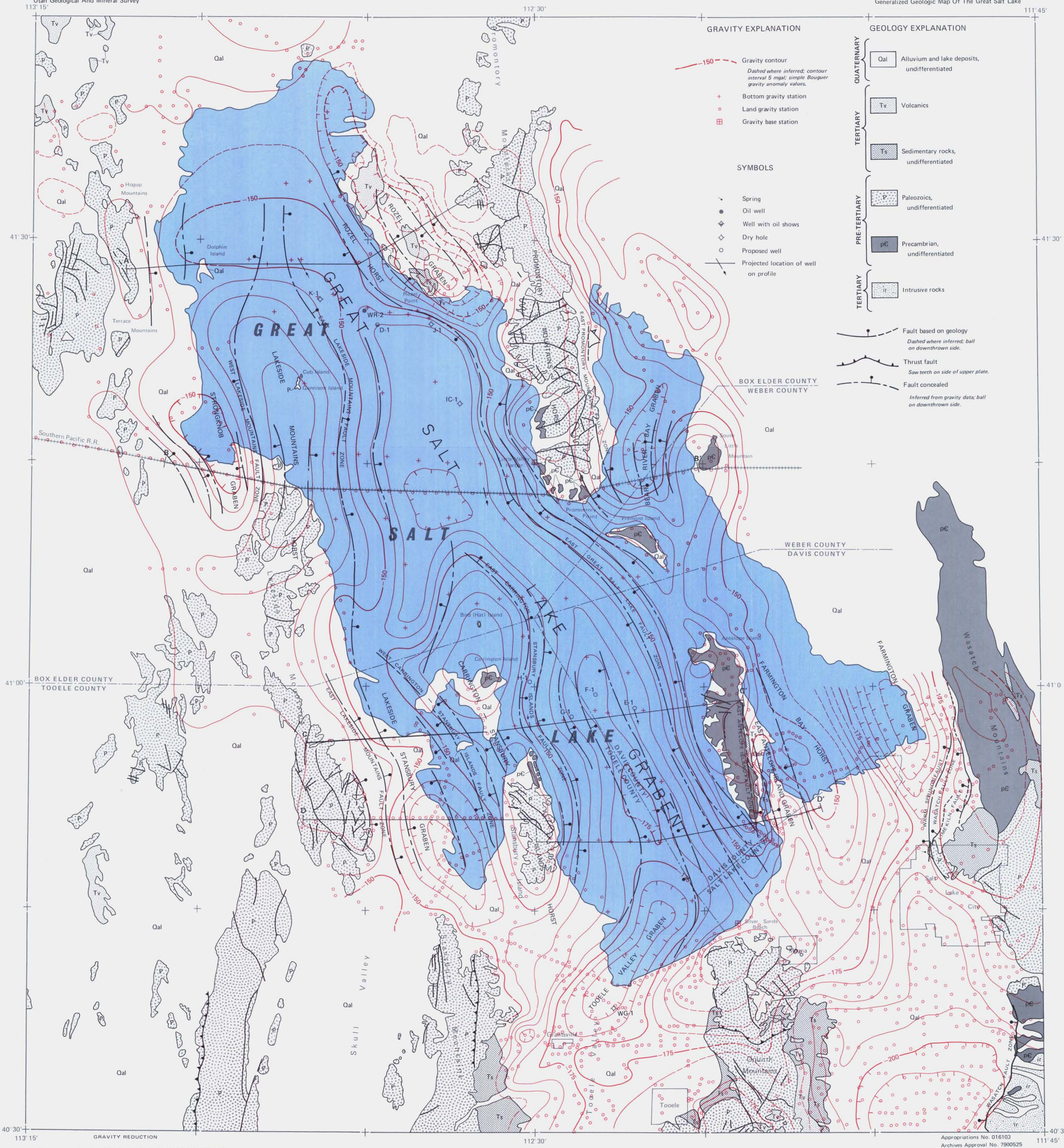
COASTAL GEOMORPHOLOGY OF GREAT SALT LAKE AND VICINITY

by Donald R. Currey, Geography Department
University Of Utah
1979

Appropriations No. 016103
Archives Approval No. 7900525

STATE OF UTAH
Department Of Natural Resources
Utah Geological And Mineral Survey

Plate 2
Bulletin 116
Simple Bouguer Gravity Anomaly And
Generalized Geologic Map Of The Great Salt Lake



GRAVITY REDUCTION

For Bouguer corrections, the following densities were assumed: a) 1.22 gm/cc for lake water; and b) 2.67 gm/cc for land from surface to mean sea level.

SOURCES OF GRAVITY DATA

Lake area—bottom gravity meter

Defense Mapping Agency, Hydrographic/Topographic Center (formerly U.S. Army Map Service), Washington, D.C. July - August, 1968.

Mainland area—land gravity meters

K.L. Cook, J.W. Berg, Jr., W.W. Johnson, and R.T. Novotny, 1966.

16½°
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN
DECLINATION, 1960

SCALE 1:250,000

5 0 5 10 15 Miles

5 0 5 10 15 Kilometers

CONTOUR INTERVAL 5 MILLIGALS
DATUM IS MEAN SEA LEVEL

Appropriations No. 016103
Archives Approval No. 7900525

Simple Bouguer Gravity Anomaly And Generalized Geologic Map Of The Great Salt Lake, Utah

by Kenneth L. Cook, Edward F. Gray, Robert M. Iverson,
and Martin T. Strohmeier
1979

Storm on the lake, with Antelope Island in the distance. Peter G. Czerny

THE MYSTERY PERSISTS

by Peter G. Czerny

Ever since word reached the world that a salt water lake existed in North America, it has generated global fascination and interest. Traveling Utahns are usually deluged with questions about the lake, and many tourists have made the Great Salt Lake a major objective. Even native Utahns, who generally consider the lake very negatively, will still flock to its shallow shores by the thousand on sunny weekends. And as locals and visitors look out over that vast body of water, they stand in amazement. Is that an island on the horizon? What's beyond those distant mountains? Surely some fish must live in the brine? What are the islands like? Does anyone live on them? You say, the lake shrinks?

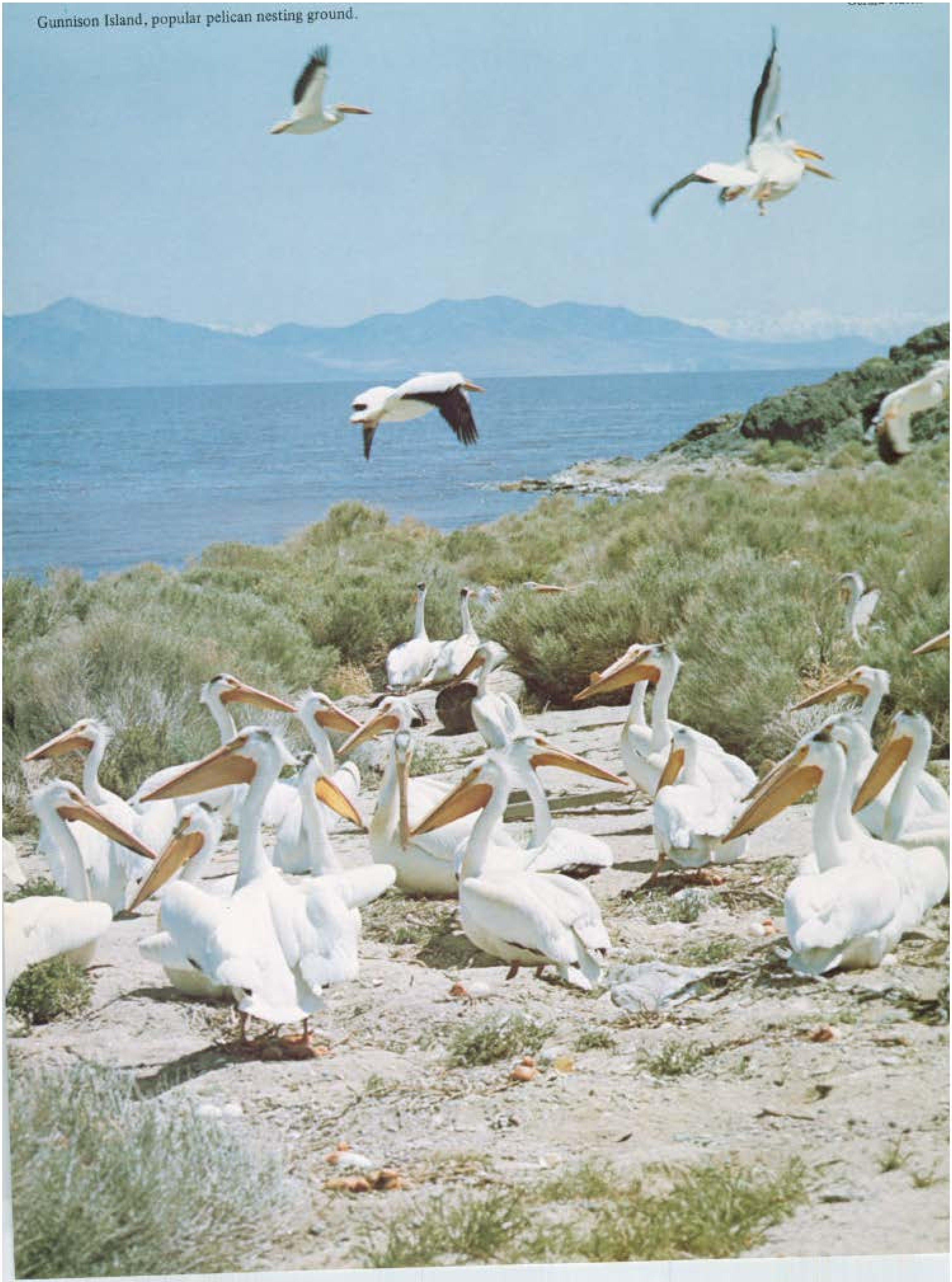
Although much has been written and read about the lake, when the visitor stands at its shore and is awed by a melted gold sunset, poured out over a deep-blue evening sky, reflected in a million parts by the rippling waves, all learning and reading seems forgotten. He is over-whelmed. What is this strange body of water where enchanting sunsets erupt as regularly as Old Faithful, and bathers aren't wrestled into the deep by gravity, but float, as if a law of nature had been suspended?

As awe inspring and beautiful as the lake may seem to the casual onlooker, it does have an ugly side as well. It has swallowed up airplanes, and then blinded the shore-seeking survivors and constricted their throats. Other victims are unsuspecting sunset seekers who sail west into the golden, lukewarm bosom of its water, as if flirting with a beguiling maiden, only to be trapped by a vicious storm when heeding her call. Yet, minutes later the raging tempest can subside, the foaming waves assuage and the surface sparkle and shine like an unblemished diamond.

Even in its beauty there is a paradox. From the distance, a bay may look exotic and inviting but when tempted to swim there, the bather may find himself walking through foul mud banks, foot-high drifts of smelly pupal shells, black clouds of brine flies and gnats, and then discover that the entire bay is only ankle deep and that his feet are surrounded by millions of tiny brine shrimp wiggling about in the water.

It wasn't too many years ago when I stood at the lake's shore, mystified by this aqueous stranger. I saw the distant mountains and islands and had the same

View from Fritsch to Stansbury Island. Peter G. Czerny



Gunnison Island, popular pelican nesting ground.

questions as the countless visitors before me. I read some books and articles about the lake but my curiosity was never satiated. I had to go, see, explore and find the answers myself. This was the beginning of my love affair with the lake, and a stormy one it has been.

I have experienced the lake's alluring pull, out into the open water, as the pleasant lukewarm brine lulled my senses, undulating waves caressed and rocked my body, and a gentle breeze pushed it further and further into the open sea. What a heavenly feeling! What a total way to relax!

What horror pierced my heart when I awoke from the trance as a wave broke over my head, right into my open mouth and eyes. I coughed violently, cleared my stinging eyes with saliva and looked about in panic. No shore in sight. The waves, frothing at their tops, danced around me like mad, vicious dogs. My frantic swimming attempts were futile against the howling wind. The billows roared. Caresses turned into face slaps, my eyes stinging from the salty spray. I swallowed more brine and was close to convulsions, spitting salt water and gasping for air at the same time. The brilliant sunset had faded into thick bands of black clouds moving menacingly above me. What if a thunderstorm hits?

View across Fremont Island, with Antelope Island in the background.

Gerald Hatch

Stark beauty on Fremont Island's west shore.

What if lightning electrifies the salty brine? Oh, if I were just back on the shore! I struggled violently.

I did make it back to the beach, after a merciful change in wind direction pushed me toward a submerged sandbar on which I walked to safety, the foaming waves still snapping at my thighs.

This harrowing experience became a valuable lesson. I have returned to float in the lake many times since then, but I know it too well to drift out far, or to feel so heavenly that I become oblivious to the realities around me.

Those who know the lake best, have learned to respect it, even fear it a bit. Weather warnings are taken seriously, hand-paddled canoes and dinghies keep close to shore, and bathers stay within easy calling distance and monitor their drifting. Even though you can't sink, higher waves splash over you, salt encrusting ears, nostrils and eyes, making directed swimming impossible.

Undaunted, I did keep exploring and savoring the lake and ultimately got to know its good sides, not just those paint-palette sunsets but the islands during their magic moment of emerald splendor, the fascinating shores, bays, Indian caves, rock formations and animal life. Most spectacular are the lake overlooks from lofty peaks and cliffs on some shores. To view the lake in a cinemascopic panorama from these high pinnacles with the water far below, as a fresh, revitalizing breeze pinches your cheeks and invigorates your mind, is a timeless, transcendental experience without comparison.

It was only natural to take cameras along and

Fremont Island, west shore view.

Spencer G. Lewis

View across the northern tip of Stansbury Island.

Peter G. Czerny

Flaming cacti on Fremont Island.

Peter G. Czerny

Spectacular view across the lake from

Evening launch at the Silver Sands Marina.

Peter G. Czerny

A private hunting club in the marshes of Farmington Bay.

Peter G. Czerny

Promontory Point. Peter G. Czerny

The Southern Pacific Railroad's causeway. Peter G. Czerny

record the splendor of this ageless, rugged beauty to share with others. Over ten years the Great Salt Lake became my second home and best friend as I really became acquainted with it, photographing every area, every season and every mood. I tried to capture the spirit of one of the last remaining wonders of the world.

Some of this work was published in my book, *The great Great Salt Lake*, (Brigham Young University Press, 1976,) which helped dispel a few of the mysteries and answered a few of the questions about those distant mountains and islands.

I had assumed that once the book was written and I had personally explored the lake and gotten wise to its insidious manners and unpredictable behavior, my fascination with it would subside. To the contrary, I find myself drawn back again and again. I've discovered new things to wonder about and to question, and somehow I feel that the lake has held back, that there are still secrets and mysteries out there that only repeated exploration and patience might uncover.

This feeling has already proven to be true. Recently I was hiking near the north end of Stansbury Island, climbing a steep, rocky mountain toward a jagged peak. As I stopped for a breath and looked up, I froze in amazement. The peak, high above me, was a beautifully formed profile of a buffalo's or bull's head, complete with horn and open eye. My excitement at the discovery of this quite impressive image, was one of great elation. I immediately named the mountain *Taurus Rock*, and returned soon after with my camera and telephoto lens. I had already started writing this article, and wanted to unveil *Taurus* to the world, in conjunction with this project. (Please see last page of color section).

As far as other Great Salt Lake mysteries are concerned. . . . .? Well – I'm going out there again next weekend.

Aardvark Arch on the west shore of the lake.

Peter G. Czerny

Sand Pebble Beach in 1972.

Peter G. Czerny

Sand Pebble beach in 1974, attests to the destructive power of the salt laden waves.

Peter G. Czerny

View from the Promontory Peninsula across Bear River Bay. Peter G. Czerny

Sandy Beach Bay on Stansbury Island is one of the best swimming beaches of the lake. Peter G. Czerny

Taurus Rock on Stansbury Island, (pupil-rock inserted by author). Peter G. Czerny

Antelope Island, west shore. Spencer G. Lewis