UNITED STATES GEOLOGICAL SURVEY

J. W. POWELL, DIRECTOR

LAKE BONNEVILLE

BY

GROVE KARL GILBERT

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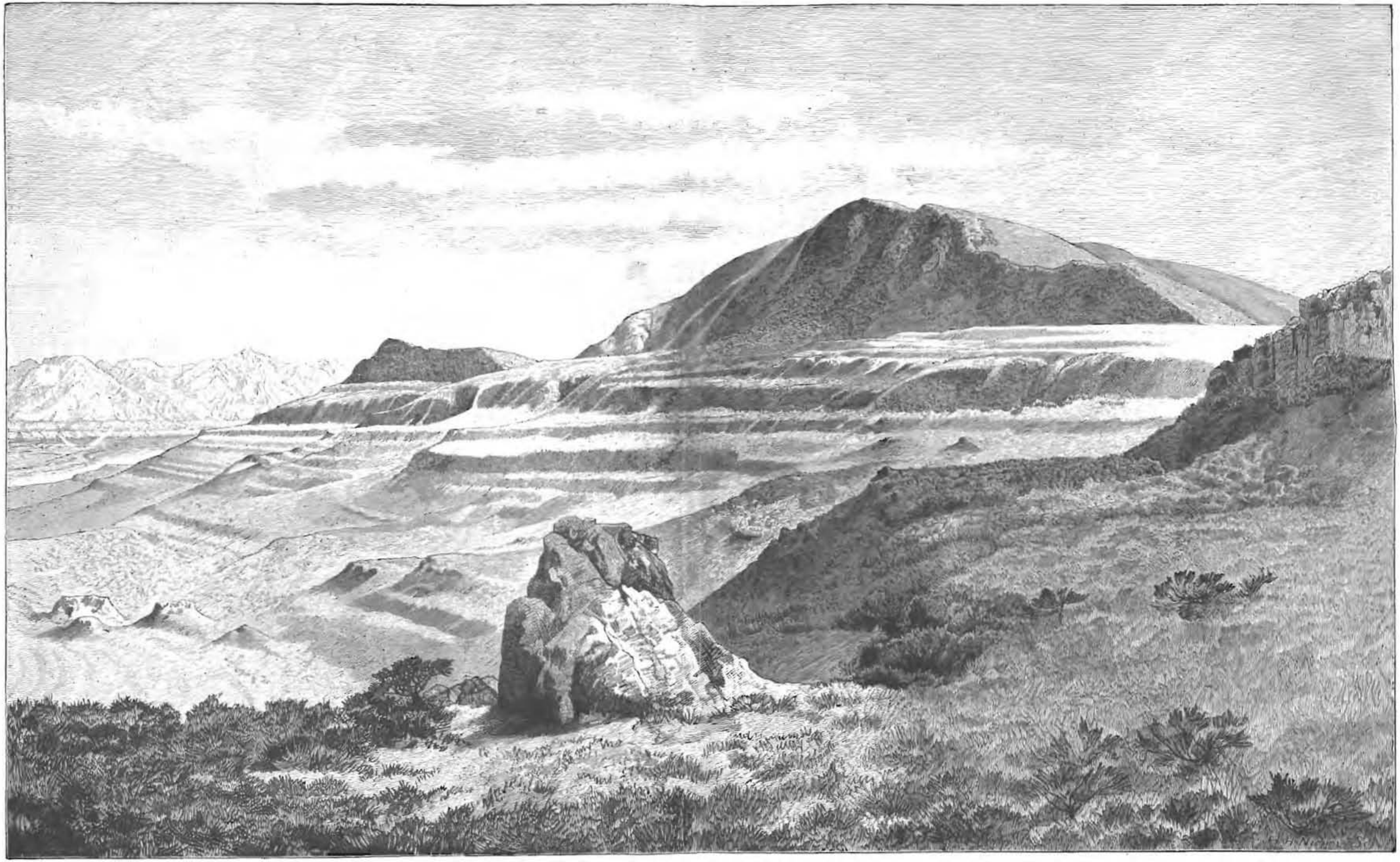

SHORE-LINES ON THE NORTH END OF THE OQUIRRH RANGE, UTAH.

Drawn by W. H. Holmes.

UNITED STATES GEOLOGICAL SURVEY

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UNITED STATES GEOLOGICAL SURVEY,
DIVISION OF THE GREAT BASIN,
Washington, D. C., June 29, 1889.

SIR: I have the honor to transmit herewith the manuscript of a final report on Lake Bonneville.

To yourself, and to the Hon. Clarence King, under whose direction a large part of the investigation was conducted, I am indebted not only for the facilities which have rendered the research possible, but also for never-failing kindness and encouragement, that have added zest and pleasure to the work.

Very respectfully, your obedient servant,

G. K. GILBERT,
Geologist in Charge.

HON. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

PREFACE.

When the Geological Survey was created, in 1879, it had for its field of operations the country west of the Great Plains. In its original organization, under the directorship of Clarence King, the Division of the Great Basin was established, with headquarters at Salt Lake City, and the Division undertook as its first large work the investigation of the Pleistocene lakes.

Afterward the field of operations of the Survey was extended over the entire United States, and as the appropriations of funds were not correspondingly increased, a re-organization became necessary. One factor of that re-organization was the abolition of the Great Basin Division. Its last field examinations were made in 1883, and the publication of the present volume closes its work.

The preparation of the volume was begun before the re-organization, and many of the plates for its illustration were then engraved. It was planned to be chiefly descriptive and to be restricted to the single lake whose name it bears. All general discussions were to be deferred until many lakes had been studied. But when it became necessary to bring the work to a close, the plan of publication was changed, and it was determined to include in this volume such generalizations as were permitted by the material gathered.

This change of plan is in part responsible for the great delay in the completion of the manuscript, but the chief cause of delay has been the assumption by myself of new duties before old ones were fully discharged.

Portions of the material of the volume have already received publication in various ways. An outline of the history of Lake Bonneville appeared in the Second Annual Report of the Survey. A partial discussion of the deformation of the plane of the Bonneville shore-line was presented to the American Society of Naturalists at its Boston meeting, 1885. The Fifth Annual Report contained a paper on the topographic features of lake shores. The subjects of the first and second of these publications are here greatly amplified. The text of the third is in large part repeated in the second chapter of this volume; but the specialist will find new matter on pages 25–26, 30–31, 39, 42–45, 53–55, 63–65, 71, 80–83. He will also note that the discussion of rhythmic embankments takes a new form in another chapter.

To those assistants, colleagues, and fellow students who have contributed to my store of material I have endeavored to give credit in the pages of the text, but it has been impossible there to acknowledge my multifarious obligations for friendly aid, advice, and criticism. To numerous citizens of Utah and Nevada I am indebted for substantial favors, and some parts of the work would have been very difficult without the special facilities afforded by the railways of Utah.

G. K. G.

ABSTRACT OF VOLUME.

CHAPTER I: INTRODUCTION.—Diastrophic processes tend to the formation of closed basins; atmospheric, to their destruction. In arid regions formative processes prevail; in humid, destructive.—The Great Basin is the chief North American district of interior drainage, but is inferior to those of other continents. Its dry climate is caused by certain relations of winds and ocean currents.—The Pleistocene lakes of the Great Basin have been previously studied by Stansbury, Beckwith, Blake, Simpson, Engelmann, Whitney, King, Hague, Emmons, Hayden, Bradley, Poole, Howell, and Peale.—The Bonneville Basin is the northeastern part of the Great Basin, and includes one-fourth its area.—The term Pleistocene is preferred to Quaternary, as being less connotive.

CHAPTER II: TOPOGRAPHIC FEATURES OF LAKE SHORES.—The waves and shore currents of lakes are produced by the same winds. They work together in littoral transportation. Where a shore current is accelerated, littoral erosion occurs; where it is retarded, littoral deposition. Where the current departs from the shore a spit is built.—The delta formation has three parts. The upper and middle parts are coarser than the lower; the bedding of the middle is more highly inclined than that of the upper and lower.—An adolescent coast is marked by narrow terraces and absence of shore drift and embankments; numerous embankments mark the mature coast.—Wave work renders coast lines less tortuous.—Cliffs, terraces, and ridges, due to shore processes, may be distinguished from similiar features produced otherwise by the study of their forms, structures, and relations.

CHAPTER III: SHORES OF LAKE BONNEVILLE.—The Bonneville shore-line is about 1,000 feet above Great Salt Lake, and compasses an area of 19,750 square miles. The Provo shore-line contours the basin 375 feet lower, and is the strongest marked of all the shore-lines. Between the Bonneville and the Provo are the Intermediate shore-lines.—The synchronism of the entire Bonneville shore-line is shown by its series of embankments.—The Intermediate embankments are ryhthmic products of the irregular oscillations of the water surface.—Deltas belong chiefly to the Provo shore-line.—Tufas were deposited just below the water surface.—The chronologic order of the shore-lines is (1) Intermediate, (2) Bonneville, (3) Provo.

CHAPTER IV: OUTLET.—At the level of the Bonneville shore-line the lake overflowed, sending a stream from the north end of Cache Valley northward to the Snake River. The sill of the outlet was of alluvium, but with a limestone ledge beneath. The alluvium was easily washed away, and a prism of water about 375 feet deep went out by a debacle, lowering the lake to the level of the limestone ledge. This level coincides with the Provo shore-line.

CHAPTER V: BONNEVILLE BEDS.—Within the circle of the Bonneville shore-line are lake sediments of the same date. The White Marl, relatively thin and calcareous, lies above the Yellow Clay, relatively thick and aluminous.—They are separated by a plane of erosion, testifying to a dry epoch between two humid epochs. The calcareous character of the upper member is theoretically connected with the burial of salts during the dry epoch.—The strata contain fresh-water shells of living species.—They are divided by a system of parallel joints, ascribed to earthquake shocks.

CHAPTER VI: HISTORY OF BONNEVILLE BASIN.—Previous to the Bonneville history the basin was arid. The first rise of the lake was without overflow, and was long maintained; the Yellow Clay was then deposited. The second rise went 90 feet higher, causing overflow, but was of shorter duration; the White Marl was then deposited. The final drying divided the basin into a dozen independent basins, the largest of which contains Great Salt Lake. Since 1845 that lake has repeatedly risen and fallen through a range of 10 feet.—The history of Lake Bonneville is paralleled by that of Lake Lahontan, and each is connected with a history of glaciation in adjacent mountains. This connection, the depauperation of the fossil shells, and an analysis of the climatic conditions of glaciation, lead to the conclusion that the lacustrine epochs were epochs of relative cold.

CHAPTER VII: LAKE BONNEVILLE AND VOLCANIC ERUPTION.—The group of small craters and basaltic lava fields near Fillmore, Utah, are closely related to the lake history. Some eruptions took place beneath the water of the lake, others since its disappearance, and others again during the inter-lacustrine epoch.—Numerous basaltic eruptions occurred in the lake area before the lake period, and at still earlier dates rhyolite was extravasated.

CHAPTER VIII: LAKE BONNEVILLE AND DIASTROPHISM.—Orogenic change during a period subsequent to the lake is shown by fault scarps. The formation of fault scarps is accompanied by earthquakes.—Epeirogenic change during a period subsequent to the lake is shown by the deformation of the planes of the shore-lines. Under the postulate that the doming of the planes is due to the drying away of the lake, it is concluded that the strains induced by the unloading of the areas exceeded the elastic limit of the material and caused viscous distortion of the earth's crust. This result, taken in connection with the phenomena of mountain uplift, leads to an estimate of the strength of the crust.

CHAPTER IX: AGE OF THE EQUUS FAUNA.—The Equus fauna at its type locality is contained in lake beds correlated by physical relations with the uppermost of the Lahontan and Bonneville beds, The fauna, previously called later Pliocene, is thus shown to have lived in late Pleistocene time.

LAKE BONNEVILLE.

BY G. K. GILBERT.

CHAPTER I.

INTRODUCTION.

This volume is a contribution to the later physical history of the Great Basin. As a geographic province the Great Basin is characterized by a dry climate, by interior drainage, and by a peculiar mountain system. Its later history includes changes of climate, changes of drainage, volcanic eruption, and crustal displacement. Lake Bonneville, the special theme of the volume, was a phenomenon of climate and drainage, but its complete history includes an account of contemporaneous eruption and displacement.

When the work of the geologist is finished and his final comprehensive report written, the longest and most important chapter will be upon the latest and shortest of the geologic periods. The chapter will be longest because the exceptional fullness of the record of the latest period will enable him to set forth most completely its complex history. The changes of each period—its erosion, its sedimentation, and its metamorphism—obliterate part of the records of its predecessor and of all earlier periods, so that the order of our knowledge of them must continue to be, as it now is, the inverse order of their antiquity.

The great importance of the chapter on the latest period lies in the fact that it will contain the key for the decipherment of the records of the earlier. The records of those periods consist of the products of various processes of change, and these products are to be interpreted only through a knowledge of the processes themselves. Many of the processes can be directly observed at the present time, and it is by such observation, combined with the study of freshly formed and perfectly preserved products, that the relation of product to process is learned. It is through the study of the phenomena of the latest period that the connection between present processes of change and the products of past changes is established.

In view of these considerations the Bonneville study has been conducted with a double object, the discovery of the local Pleistocene history and the discovery of the processes by which the changes constituting this history were wrought.

INTERIOR BASINS.

In physical geography the terms "basin" and "drainage district" are synonymous, and are used to indicate any area which is a unit as to drainage. The basin of a stream is the tract of country it drains, whether the stream is a great river or the most insignificant tributary to a river. We thus speak of the basin of the Ohio and of the basin of the Mississippi, and say that the latter includes the former. And it may be said in general that the basin of any branching stream includes the basins of all its tributaries.

The basin of a lake is the tract of country of which it receives the drainage, and it includes not only the basins of all affluent streams but the area of the lake itself. The term "lake basin" is also applied to the depression occupied by the water of a lake and limited by its shores, and where confusion might arise from the double use, the wider sense is usually indicated by the adjective "hydrographic" or its equivalent. If the lake has an outlet its basin is a part of the basin of the effluent stream, but if it has no outlet its basin is complete in itself, and is wholly encircled by a line of water-parting. In such case it is called a *continental*, or *interior*, or *closed*, or *shut*, or *drainless* basin.

If an interior basin exists in a climate so arid that the superficial flow of water, which constitutes drainage, is only potential and not actual, or else is occasional only and not continuous, it contains no perennial lake and is called a dry basin.

The boundaries separating basins are water-partings or divides, and these are of all characters, from the acute crests of mountain ranges to low rolls of the plain scarcely discernible by the eye. Interior basins are completely encircled by lines of water-parting.

The existence of interior basins depends on two conditions: a suitable topographic configuration and a suitable climate. The ordinary process of land sculpture by running water does not produce cup-like basins, but tends on the contrary to abolish them. Wherever a topographic cup exists the streams flowing toward it deposit within it their loads of detritus, and if they are antagonized by no other agent eventually fill it. If the cup contains a lake with outlet the outflowing stream erodes the rim of the basin, and eventually the lake is completely drained.

The work of streams occasionally produces topographic cups by the rapid formation of alluvial deposits where two streams meet. If the power of one stream to deposit is greatly increased, or if the power of the other stream to erode is greatly diminished, the one may build a dam athwart the course of the other and thus produce a lake basin.

The great agent in the production of lake basins, or the agent which has produced most of the large basins, is diastrophism,[1] and in a majority of the cases in which basins are partitioned off by the alluvial process just described, the change in the relative power of the streams is brought about by diastrophism.

Other basin-forming agencies are volcanic eruption, limestone sinks, wind waves, dunes, land slides and glaciers. By far the greatest number of topographic cups are due to glaciers; but with these we are not now concerned.

The basins of ordinary lakes are distinguished from interior basins by overflow, and that depends on climate. The rainfall of each basin is or may be disposed of by three processes: first, evaporation from the soil and

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[1] I find it advantageous to follow J. W. Powell in the use of *diastrophism* as a general term for the process or processes of deformation of the earth's crust. The products of diastrophism are continents, plateaus and mountains, ocean beds and valleys, faults and folds. Diastrophism is coordinate with volcanism, and is the synonym of *displacement* and *dislocation* in the more general of the two geologic meanings acquired by each of those words. Its adjective is *diastrophic*.

It is convenient also to divide diastrophism into orogeny (mountain-making) and epeirogeny (continent-making). The words *epeirogeny* and *epeirogenic* are defined in the opening paragraph of chapter VIII.

from the vegetation supported by it; second, evaporation from a lake surface; third, outflow. If the rainfall is sufficiently small, it is all returned to the air by evaporation from the soil and vegetation, and the basin is dry. If it is somewhat larger, the portion not directly evaporated accumulates in the lowest depression, forming a lake, from the surface of which evaporation is more rapid. The area of the lake surface is determined by the area of the basin, the rainfall and the local rates of evaporation. The basin is closed so long as a lake sufficient for the purpose of evaporation does not require such an extent as to cause it to discharge at the lowest point of the rim. The area enclosed by a contour passing through the lowest point of the rim, the total area of the basin, and the local climate are the three factors which determine whether a given topographic cup shall constitute an interior basin. If the area of a topographic cup and the area of the maximum lake it can contain are nearly identical, it may constitute an interior basin in a region of humid climate. If the contour through the lowest point of the rim encloses an area very small in comparison with the entire basin, the maintenance of an outlet is not inconsistent with an arid climate.

If there were no erosion and sedimentation, unchecked upheaval and subsidence would greatly multiply the number of basins. On the contrary, if all displacement should cease, and the foundations of the earth become stable, erosion and sedimentation would merge all basins into one. The actual state of the earth's surface is therefore at once the result and the index of the continuous conflict between subterranean forces on the one hand and atmospheric on the other. The two processes which destroy basins are conditioned by climate. In an arid basin the inwashing of detritus is slow and there is no outflow to corrade the rim; but with abundant rainfall the accumulation of detritus is rapid and corrasion conspires with it to diminish the inequality between center and rim. In arid regions, therefore, the formative subterranean forces are usually victorious in their conflict with the destructive atmospheric forces, and as a result closed basins abound; in humid regions the destructive agencies prevail and lake basins are rare. In the present geologic age it is necessary to restrict this generalization to lands in the lower latitudes, because the glaciation of the last geologic period created an immense number of lake basins in humid regions of high latitude, and running water has as yet made little progress in their destruction.

THE GREAT BASIN.

The major part of the North American continent is drained by streams flowing to the ocean, but there are a few restricted areas having no outward drainage. The largest of these was called by Fremont, who first achieved an adequate conception of its character and extent, the "Great Basin," and is still universally known by that name. It is not, as the title might suggest, a single cup-shaped depression gathering its waters at a common center, but a broad area of varied surface, naturally divided into a large number of independent drainage districts. It lies near the western margin of the continent and is embraced by rivers tributary to the Pacific Ocean. On the north it is bounded by the drainage basin of the Columbia, on the east by that of the Colorado of the West, and on the west by the basins of the San Joaquin, the Sacramento, and numerous minor streams. The central portion of the western water-parting is the crest of the Sierra Nevada, one of the greatest mountain masses of the United States, and farther south high mountains constitute much of the boundary. The northern half of the eastern boundary is likewise high, winding through the region of the High Plateaus. The remainder of the boundary does not follow any continuous line of upland, but crosses mountain ranges and the intervening valleys without being itself marked by any conspicuous elevations. It is defined only through a study of the drainage. The general form of the area, as exhibited on Plate II, is rudely triangular, with the most acute angle southward. The extreme length in a direction somewhat west of north and east of south is about 880 miles, the extreme breadth from east to west, in latitude 40° 30′, is 572 miles, and the total area is approximately 210,000 square miles. Of political divisions it includes nearly the whole of Nevada, the western half of Utah, a strip along the eastern border of California and a large area in the southern part of the State, another large area in southeastern Oregon, and smaller portions of southeastern Idaho and southwestern Wyoming. The southern apex extends into the territory of Mexico at the head of the peninsula of Lower California.

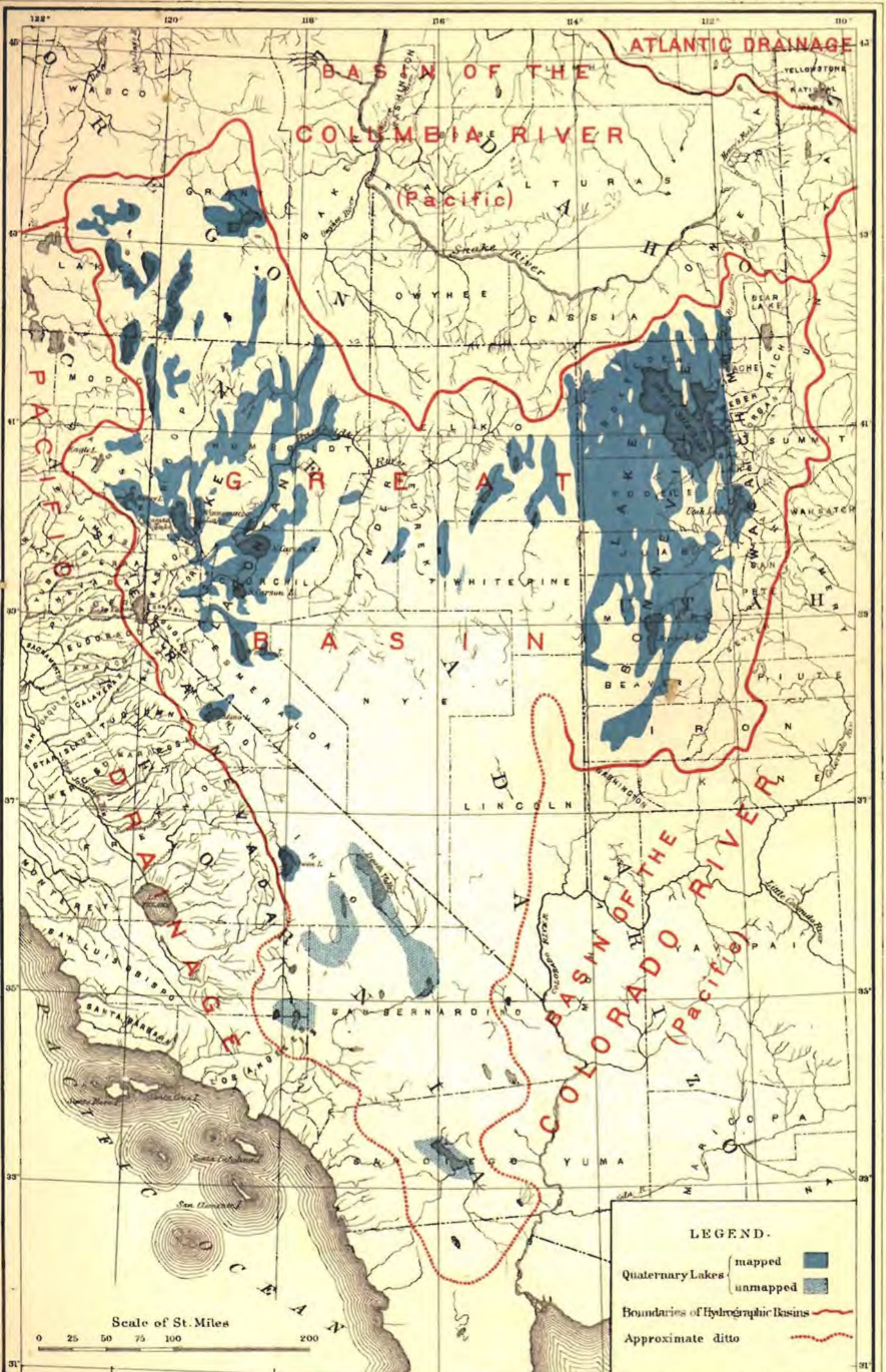
The region is occupied by a number of mountain ridges which betray system by their parallelism and by their agreement in a peculiar structure.

Their general trend is northerly, inclining eastward in the northern part of the basin and westward at the south. The individual ridges are usually not of great length, and they are so disposed en echelon that the traveler winding among them may traverse the basin from east to west without crossing a mountain pass. The type of structure is that of the faulted monocline, in which the mountain ridge is produced by the uptilting of an orogenic block from one side of a line of fracture, and it has been named (from the region) the Basin Range type. Its distribution, however, does not coincide perfectly with the district of interior drainage. On the one hand the Great Basin includes along its eastern margin a portion of the Plateau province, with its peculiar structural type, and on the other the Basin Range province extends southward through Arizona to New Mexico and Mexico.

Between the ranges are smooth valleys, whose alluvial slopes and floors are built of the débris washed through many ages from the mountains. In general they are trough-like, but in places they coalesce and assume the character of plains. The plains occupy in general the less elevated regions, where an exceptional amount of detritus has been accumulated. In the local terminology they are called deserts. The largest are the Great Salt Lake and Carson deserts at the north and the Mojave and Colorado deserts at the south. The Escalante, the Sevier, the Amargosa, and the Ralston are of subordinate importance.

Where the basin is broadest, the general elevation of its lowlands is about 5,000 feet, but they are somewhat higher midway between the eastern and western margins, so as to separate two areas of relative depression, the eastern marked by the Great Salt Lake and Sevier deserts, and the western by the Carson desert. Southward there is a gradual and irregular descent to about sea-level, and limited areas in Death Valley and Coahuila Valley lie lower than the surface of the ocean.

The aridity of the region is shown instrumentally by the records of rainfall and atmospheric humidity. On the broad plain bounded east and west by the Appalachian Mountains and the Mississippi River, 43 inches of of rain falls in a year. On the lowlands of the Great Basin there falls but 7 inches. In the former region the average moisture content of the air is 69 per cent of that necessary for saturation; in the lowlands of the Great



Julius Bien & Co. lith

THE GREAT BASIN AND ITS LAKES

Basin it is 45 per cent.[1] From the surface of Lake Michigan evaporation removes each year a layer of water 22 inches deep.[2] The writer has estimated that 80 inches are yearly thus removed from Great Salt Lake,[3] and Mr. Thomas Russell has computed from annual means of temperature, vapor tension, and wind velocity that in the lowlands of the Great Basin the annual rate of evaporation from water surfaces ranges from 60 inches at the north to 150 inches at the south.[4]

The variation with latitude exhibited by the evaporation is found also, inversely, in the rainfall, but is not clearly apparent in the humidity. In the southern third of the Basin the lowland rainfall ranges from 2 to 5 inches. On the line of the Central Pacific Railroad, between the 40th and 42d parallels, it averages 7 inches; in the Oregonian arm at the north, 15 inches. The average lowland precipitation for the whole area is between 6 and 7 inches. With the relative humidity approximately constant, the evaporation rate varies directly and the rainfall inversely with the temperature, and both latitude and altitude here make the lowland temperature fall toward the north. The sympathy of rainfall with temperature is likewise shown in the greater precipitation of the mountains as compared with adjacent valleys. Mountain stations proper are wanting, but rain-gauge records on the flanks and in the passes of mountains show a marked advantage over those in neighboring lowlands. An estimate based on these, on the records at high points in the Sierra Nevada, and on approximate knowledge of the heights and areas of the mountains and plateaus of the Great Basin, places the average precipitation for the whole district at 10 inches.

The story of climate is more eloquently told by the hydrography and the vegetation. In the valleys of the northwestern arm of the basin there are numerous lakes, drainless and of varying extent, but fed by streams from mountain ranges of moderate size. In the middle region the only perennial lakes are associated with mountain masses of the first rank. The

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[1] These figures and those in the preceding sentences are based on data compiled by the U. S. Signal Service. Through the courtesy of Gen. A. W. Greely, Chief Signal Officer, the writer has had access to manuscript data as well as printed.

[2] D. Farrand Henry, in a report on the meteorology of the Laurentian lakes. Rept. of Chief of Engineers for the year 1868. Washington, 1869, p. 980.

[3] Report on the lands of the Arid Region . . . , J. W. Powell, 2d ed., Washington, 1879, p. 73.

[4] MS. report to the Chief Signal Officer.

great Sierra forming the western wall of the basin receives each winter a heavy coating of snow—the greater part on the side of the great Californian valley, but enough east of the water-parting to maintain a line of lakes in the marginal valleys of the Great Basin. The Wasatch range and its associated plateaus, overlooking the Basin from the east, are less favored than the Sierra, but still receive an important precipitation, and by gathering the drainage from a large area, support Great Salt Lake, the largest of the Basin's water sheets. The East Humboldt Range, standing midway, and one of the largest mountain masses within the basin area, catches enough moisture to feed at one base two small lakes and at the other the Humboldt River. The neighboring and smaller mountains are whitened every winter by snow, a large share of which either evaporates without melting or, if melted, is absorbed by the soil, to be returned to the thirsty air without gathering in drainage ways. Many of them are without perennial streams; some even lack springs; and of the mountain creeks, few are strong enough to reach the valleys before succumbing to the ravenous desert air. The Humboldt itself, though fairly entitled to the name of river, dwindles as it goes, so that its remnant after a course of two hundred miles is able to sustain an evaporation lake barely twenty-five square miles in extent. Most of the small closed basins are without permanent creek or lake, containing at the lowest point a playa or "alkali flat"— a bare, level floor of fine saline earth, or perhaps of salt, over which a few inches of water gather in time of storm.

In the southern half of the Basin there are no lakes dependent for their water on the interior ranges. At the east the most southerly lake is Sevier, in latitude 39°; the last of the lakes sustained by the Sierra is Owens, between the 36th and 37th parallels. Then for three hundred miles evaporation is supreme. Playas abound, streams are almost unknown, and springs are rare. Death Valley, with its floor of salt spread lower than the surface of the ocean, is overlooked on either side by mountains from 5,000 to 10,000 feet high, but they yield it no flowing stream, and more than one traveler has perished from thirst while endeavoring to pass from spring to spring. The Mohave "river" is a hundred miles long, but it preserves its life only by concealment, creeping through the gravel of the desert and betraying its existence only where ledges of rock athwart its course force it to the surface.

As in other desert regions, precipitation here results only from cyclonic disturbance, either broad or local, is extremely irregular, and is often violent. Sooner or later the "cloud-burst" visits every tract, and when it comes the local drainage-way discharges in a few hours more water than is yielded to it by the ordinary precipitation of many years. The deluge scours out a channel which is far too deep and broad for ordinary needs and which centuries may not suffice to efface. The abundance of these trenches, in various stages of obliteration, but all manifestly unsuited to the every-day conditions of the country, has naturally led many to believe that an age of excessive rainfall has but just ceased—an opinion not rarely advanced by travelers in other arid regions. So far as may be judged from the size of the channels draining small catchment basins, the rare, brief, paroxysmal precipitation of the desert is at least equal while it lasts to the rainfall of the fertile plain.

A line of cottonwoods marks the course of each living stream, but otherwise the lowlands are treeless. So are most of the alluvial foot-slopes and some of the smaller mountains, especially at the south. Except on the high plateaus in central Utah, there is little that may be called forest. The greater mountains have much timber in their recesses, but are not clothed with trees. The growth is so irregular and interrupted that the idea of a tree limit could not have originated here, but it may be said that only the straggling bush-like cedar passes below 6,000 feet at the north or 7,000 feet at the south. Only conifers are of such size and abundance as to have economic importance. Oak and maple grow commonly as bushes, forming low thickets, but occasionally rank as small trees, along with the rarer box-elder, ash, locust, and hackberry. The characteristic covering of the lowlands is a sparse growth of low bushes, between which the earth is bare, excepting scattered tufts of grass. Toward the north, and especially on the higher plains, the grass is naturally more abundant and the bushes occupy less space, but the introduction of domestic herds favors the ascendency of the bushes. At the south the bushes are partly of different species, and they are partially replaced by cactuses and other thorny plants. The playas are bare of all vegetation and are usually margined by a growth of salt-loving shrubs and grasses. A single southern bush bears leaves of deep green, but with this exception the desert plants are grey, like the desert soil. These, and the persistent haze whose grey veil deadens all the landscape, weary the eye with their monotony, so that the vivid green marking the distant spring is welcome for its own sake as well as for the promise of refreshment to the thirsty traveler.

The causes of this arid climate lie in the general circulation of the atmosphere, in the currents of the Pacific Ocean, and in the configuration of the land. There is a slow aerial drift from west to east, so that the air coming to the Basin has previously traversed a portion of the Pacific, to which its temperature and humidity have become adjusted. Off the west coast of the United States there is a southward current, believed to be the chief branch of the Kuro Siwa. Prof. George Davidson[1] estimates its width at about 300 miles, and finds that its temperature rises with southward advance only one degree Fahrenheit for each degree of latitude. Being derived from a north-moving current, it reaches our coast with a temperature higher than that normal to the latitude, while at the south its temperature is below the normal. As pointed out by Dutton,[2] the air passing from it to the land at the north is cooled by the land and precipitates moisture, while the similar air-current at the south is warmed by the land and converted to a drying wind. The Great Basin falls within the influence of the drying wind, its southern part being more affected than its northern. At the extreme south and the extreme north the mountains between the ocean and the Basin do not greatly interfere with the eastward flow of air, but between latitudes 35° and 41° the Sierra Nevada forms a continuous wall, rarely less than ten thousand feet high. In rising to pass this obstruction the air loses much of its stored moisture, especially in winter, and it descends to the Basin with diminished humidity. The Basin is further influenced by deviations of the air-currents from the eastward direction, and its southern part falls in summer within the zone of calms theoretically due to a descending current at the margin of the northern trade-wind; but observational data are too meager for the discussion of these factors.

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[1] Letter to the writer.

[2] Cause of the Arid Climate of the western portion of the U. S., Capt. C. E. Dutton: Am. Jour. Sci., 3d ser., vol. 22, p. 249.

The southern portions of Arizona and New Mexico and the western part of Texas resemble the Great Basin in climate, and they contain a number of small interior basins. These are not so fully determined in extent as the Great Basin, but several of them may be approximately indicated. One of the largest lies between the Rio Grande and its eastern branch, the Pecos, extending from latitude 35° in central New Mexico to latitude 31° in western Texas. In its broadest part it is bounded on the west by the San Andreas and Organ Mountains, and on the east by the Sacramento and Guadaloupe. Its area, of which two-thirds lies in New Mexico, is about 12,500 square miles. Southwest of the Rio Grande, in Mexico, there is a larger tract of interior drainage, containing a number of saline lakes, and to one of these, Lake Guzman, the valley of the Mimbres River of New Mexico descends. Other basins adjacent on either side to that of the Mimbres are believed to bear the same relation to Lake Guzman, sloping gently toward it, but contributing no water unless during periods of rare and exceptional storm. Yet other basins without exterior drainage are contiguous to these, and unite to form in southwestern New Mexico an arm of the Mexican district of interior drainage, the area within New Mexico probably falling between 7,000 and 7,500 square miles. North of this, and intersected centrally by the 103d meridian and the 34th parallel, lies a smaller basin, including the plain of San Augustin. Its area is about 1,800 square miles. In southeastern Arizona a slightly smaller basin lies between the Caliyuro and Dragoon Mountains on the west and the Pinaleño and Chiricahua Mountains on the east, including the Playa de los Pimas. Another and still smaller basin is known to exist in the Hualapi Valley of northwestern Arizona, and it is probable that others occur in the western part of the Territory, both north and south of the Gila River. When all have been determined and measured, it is estimated that the total area of the interior basins of the United States, additional to the Great Basin, will be found equal to 25,000 square miles, making the grand total for the United States about 232,000 square miles—the thirteenth part of our territory. Mexico contains other inland districts besides the one mentioned above, and the total area in that country may be one-third as great as ours. It is probable that the remainder of the continent drains to the ocean.

Large as are these districts, it is nevertheless true that North America, as compared with other continents, is not characterized by interior drainage. According to data compiled by Murray, the closed basins in Australia aggregate 52 per cent of its area, those of Africa 31 per cent, of Eurasia 28 per cent, of South America 7.2 per cent, of North America 3.2 per cent.[1] The Great Basin is great only in comparison with similar districts of our own continent. The interior district of the Argentine Republic and Bolivia is half as large again, and that of central Australia exceeds the Great Basin seven times; Sahara exceeds it sixteen times, and the interior district of Asia twenty-three times.

HISTORY OF INVESTIGATION.

The history of the early geographic exploration of the Great Basin has been carefully detailed by Simpson in the introduction to the report of his own expedition. In 1776 it was penetrated by Padre Escalante from the southeast, and about the same time its southern rim was crossed by Padre Graces, but it does not appear that they discovered the peculiarity of its drainage. From about 1820 to 1835 the northern and broader portion of the basin was gradually explored by Indian-traders, who learned of the existence of undrained lakes and passed the account from mouth to mouth, but made no maps and published no accounts of their discoveries. Capt. Bonneville, an army officer on leave, traveling in the interest of the fur trade but with the spirit of exploration, took notes of geographic value (1833), which were put in shape and published after a lapse of some years by Washington Irving, and his map is probably the first which represents interior drainage. While Irving's account was in press, Fremont was engaged in his justly celebrated exploration which afforded to the world the first clear conception of the hydrography of the region.[2] Since that time numerous expeditions, public and private, have contributed details, so that now the external boundary of the Great Basin is well known except at the extreme south, and its internal configuration has been described and mapped throughout four-fifths of its extent.

[1] The total annual rainfall of the land of the globe, and the relation of rainfall to the annual discharge of rivers. By John Murray. Scottish Geog. Mag. vol 3, pp. 65–77.

[2] Report of the Exploring Expedition to the Rocky Mountains in the year 1842 and to Oregon and North California in the years 1843–'44, by Brevet-Capt. J. C. Fremont. Washington, 1845.

Our knowledge of that lacustrine history to which the present volume is a contribution begins with Stansbury. Fremont, finding a line of drift-wood a few feet above the water of Great Salt Lake, inferred a small variation of its level, but appears to have overlooked the ancient shore-lines terracing the mountains round about. He described the coating of tufa on the valley sides near Pyramid Lake, and the thought that it might be a lacustrine deposit occurred to him, but was deemed inadmissible on account of the thickness of the formation.

Stansbury in 1849 and 1850 made an elaborate survey of Great Salt Lake and its vicinity, meandering its shore, determining its depth by a series of soundings, and controlling his work by a system of triangulation. In his itinerary, while describing the plain where now stands Lakeside station of the Central Pacific railway, he says:

> This extensive flat appears to have formed, at one time, the northern portion of the lake, for it is now but slightly above its present level. Upon the slope of a ridge connected with this plain, thirteen distinct successive benches, or water-marks, were counted, which had evidently, at one time, been washed by the lake, and must have been the result of its action continued for some time at each level. The highest of these is now about two hundred feet above the valley, which has itself been left by the lake, owing probably to gradual elevation occasioned by subterraneous causes. If this supposition be correct, and all appearances conspire to support it, there must have been here at some former period a vast inland sea, extending for hundreds of miles; and the isolated mountains which now tower from the flats, forming its western and southwestern shores, were doubtless huge islands similar to those which now rise from the diminished waters of the lake.[1]

One of his sketches of Fremont Island, reproduced in a lithograph facing page 102 of his report, exhibits terraces of the same sort, and he says in another place that the island, which is "at least 800 or 900 feet high," presented "the appearance of regular beaches, bounded by what seemed to have been well-defined and perfectly horizontal water-lines, at different heights above each other, as if the water had settled at intervals to a lower level, leaving the marks of its former elevation distinctly traced upon the hillside. This continued nearly to the summit, and was most apparent on the northeastern side of the island."[2]

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[1] Exploration and Survey of the Valley of the Great Salt Lake of Utah, ... by Howard Stansbury, Capt. Top. Eng., Philadelphia, 1852, p. 105.

[2] Ibid. p. 160.

Beckwith, who led a geographic expedition across the Great Basin in 1854, makes the next advance in the description of the lacustrine phenomena, and his contribution is so important that I quote it entire:

The old shore-lines existing in the vicinity of the Great Salt Lake present an interesting study. Some of them are elevated but a few feet (from five to twenty) above the present level of the lake, and are as distinct and as well defined and preserved as its present beaches; and Stansbury speaks, in the Report of his exploration, pages 158–160, of drift-wood still existing upon those having an elevation of five feet above the lake, which unmistakably indicates the remarkably recent recession of the waters which formed them, whilst their magnitude and smoothly-worn forms as unmistakably indicate the levels which the waters maintained, at their respective formations, for very considerable periods.

In the Tuilla Valley, at the south end of the lake, they are so remarkably distinct and peculiar in form and position that one of them, on which we traveled in crossing that valley on the 7th of May, attracted the observation of the least informed teamsters of our party—to whom it appeared artificial. Its elevation we judged to be twenty feet above the present level of the lake. It is also twelve or fifteen feet above the plain to the south of it, and is several miles long; but it is narrow, only affording a fine roadway, and is crescent-formed, and terminates to the west as though it had once formed a cape, projecting into the lake from the mountains on the east—in miniature, perhaps, not unlike the strip of land dividing the sea of Azoff from the Putrid sea. From this beach the Tuilla Valley ascends gradually towards the south, and in a few miles becomes partly blocked up by a cross-range of mountains, with passages at either end, however, leading over quite as remarkable beaches into what is known, to the Mormons, as Rush Valley, in which there are still small lakes or ponds, once, doubtless, forming part of the Great Salt Lake.

The recessions of the waters of the lake from the beaches at these comparatively slight elevations, took place, beyond all doubt, within a very modern geological period; and the volume of the water of the lake at each subsidence—by whatever cause produced, and whether by gradual or spasmodic action—seems as plainly to have been diminished; for its present volume is not sufficient to form a lake of even two or three feet in depth, over the area indicated by these shores, and, if existing, would be annually dried up during the summer.

These banks—which so clearly seem to have been formed and left dry within a period so recent that it would seem impossible for the waters which formed them to have escaped into the sea, either by great convulsions, opening passages for them, or by the gradual breaking of the distant shore (rim of the Basin) and draining them off, without having left abundant records of the escaping waters, as legible at least as the old shores they formed—are not peculiar to the vicinity of this lake of the Basin, but were observed near the lakes in Franklin Valley, and will probably be found near other lakes, and in the numerous small basins which, united, form the Great Basin.

But high above these diminutive banks of recent date, on the mountains to the east, south and west, and on the islands of the Great Salt Lake, formations are seen, preserving, apparently, a uniform elevation as far as the eye can extend—formations on a magnificent scale, which, hastily examined, seem no less unmistakably than the former to indicate their shore origin. They are elevated from two or three hundred to six or eight hundred feet above the present lake; and if upon a thorough examination they prove to be ancient shores, they will perhaps afford (being easily traced on the numerous mountains of the Basin) the means of determining the character of the sea by which they were formed, whether an internal one, subsequently drained off by the breaking or wearing away of the rim of the Basin—of the existence of which at any time, in the form of continuous elevated mountain chains, there seems at present but little ground for believing—or an arm of the main sea, which, with the continent, has been elevated to its present position, and drained by the successive stages indicated by these shores.[1]

A year earlier Blake explored the Colorado desert between San Diego and Fort Yuma, finding unmistakable evidence of its former occupation by a lake. He observed a shore line, tufa deposits, and lacustrine clays, and in the clays and tufa, as well as scattered over the surface of the desert, he found fresh-water shells, and a single brackish shell, *Gnathodon*. His description and discussion are full and eminently satisfactory, but his explanation takes the lake he describes out of the field of present interest, for he shows that only its disappearance and not its origin is to be ascribed to climate. The lake basin was created by the growth of the delta of the Colorado River, which was built across the Gulf of California, separating a portion of its upper end. When the river, shifting on its delta, is turned to the right, a lake is maintained behind the barrier, a lake with outlet to the Gulf, and therefore fresh. When the river turns to the left, it flows directly to the Gulf, and the lake is dried away. The latter is the present and historic condition, but occasionally at extreme flood a portion of the river's water has been known to flow for many miles toward the desiccated basin.[2]

Simpson, exploring for wagon routes in the broadest part of the Great Basin, in 1859,[3] observed in Cedar and Rush valleys the same water lines that had been seen by Stansbury farther north; and Henry Engelmann, the geologist of his party, noted not only shore terraces but lacustrine silt and tufa and fresh-water shells. He points out that the saltness of the

[1] Explorations . . . from the mouth of the Kansas River, Mo., to the Sevier Lake, in the Great Basin. By Lieut. E. G. Beckwith. Foot note to p. 97. In Pacific Railroad reports, vol. 2, Washington, 1855.

[2] Geological Report, by William P. Blake. In Pacific Railway Reports, vol. 5, 1856, pp. 97–99, 236–239.

[3] Explorations across the Great Basin of the Territory of Utah for a direct wagon-route from Camp Floyd to Genoa, in Carson Valley, in 1859, by Captain J. H. Simpson. Washington, 1876.

Basin lakes is inconsistent with the prevalent impression that they possess subterranean outlets, and comparing their former with their present extent, refers the difference to climate. He argues that the present geographic conditions tend to the diminution of rainfall, and that under them the basin has become progressively more and more arid. But there is nothing in his discussion serving to explain the greater humidity of the preceding age.

The reports of Simpson and Engelmann, though prepared in manuscript immediately after the completion of their exploration, were not printed until 1878, and in the mean time many observers saw the lake vestiges and wrote upon them. Whitney, visiting Mono Lake in 1863, and noticing old shore-lines rising in a series to the height of 600 feet above the water, raised the question—for many years unanswered—whether the old lake was confined to the Mono Valley or communicated with lakes in other valleys of the Great Basin, and pointed out that whatever conditions produced the ancient glaciers of the adjacent Sierra were competent to expand the lake.[1] Hayden in 1870 examined the old shore-lines in the immediate vicinity of Great Salt Lake, correctly correlated them with lacustrine deposits at various points, showed their recency as compared to the later Tertiary beds of the vicinity, and referred them to the Quaternary. He also found shells in the deposits, and from their character recognized the freshness of the old lake.[2] Bradley, two years later, recognized the broad terraces flanking Ogden River and other streams of the vicinity as deltas built by the same streams in the ancient lake, observed that the Ogden delta deposits extended into the mountain canyon of the river, and drew the important conclusion that before the age of the high terraces Great Salt Lake was not far, if at all, above its present level.[3] About the same time Poole made additional observations on the shore-lines of the same basin and traced them as far westward as the Deep Creek Mountains.[4]

The observations of Hayden, Bradley, and Poole were independent and original, and by reason of priority of publication they belong to the

[1] Geol. Surv. of California, Geology, vol. 1, by J. D. Whitney. Philadelphia 1865, pp. 451–452.

[2] U. S. Geol. Surv. of Wyoming. . . 1870, by F. V. Hayden. Washington, 1872, pp. 169, 170, 172, 175.

[3] Report of Frank H. Bradley, in U. S. Geol. Surv. of the Territories, Rept. for 1872. Washington, 1873, pp. 192, 196.

[4] The Great American Desert, by Henry S. Poole: Proc. Nova Scotia Inst. Nat. Sci., vol. 3, pp. 208–220.

history of the subject, but, as already mentioned, they were partially anticipated by those of Simpson and Engelmann, and wholly anticipated by those of King, Hague and Emmons, the geologists of the Fortieth Parallel Exploration. The work of this corps covered a belt one hundred miles broad, spanning the Great Basin in its broadest part, and within this belt the Pleistocene lakes were studied and for the first time approximately mapped. It was shown that the corrugated surface of the Great Basin in this latitude is higher in the middle than at the east and west margins, warranting a general subdivision into the Utah Basin, the Nevada Plateau and the Nevada Basin; that the Utah Basin formerly contained a large lake, Bonneville, extending both north and south beyond the belt of survey; that the Nevada Basin contained a similar lake, Lahontan, likewise exceeding the limits of the belt; and that the valleys of the central plateau held within the belt no less than eight small Pleistocene lakes. The mechanical sediments and chemical deposits of the lakes were studied, and were ascertained to overlie subaerial gravels, thus proving that a dry climate had preceded the humid climate of the lake epoch; and it was inferred from the chemical deposits of Lake Lahontan that the lake had been twice formed and twice dried away.[1]

The field work that afforded this important body of information was performed chiefly in the years 1867–70, but publication was delayed till 1877–78. In 1872 Howell and the writer, traveling with topographic parties of the Wheeler Survey, traversed the Utah Basin on many lines, and our reports, printed in 1874 and 1875, contained an account of Lake Bonneville, the extent of which we were able to indicate with inconsiderable error, and to which the writer gave a name.[2] Thus, by an accident of publication, King and his colleagues lost that literary priority in regard to Lake Bonneville to which they were fairly entitled by priority of investigation.

[1] Geol. Expl. of the 40th Parallel. Vol. 1, Systematic Geology, by Clarence King. Washington, 1878; vol. 2, Descriptive Geology, by Arnold Hague and S. F. Emmons. Washington, 1877.

[2] Prelim. Geol. Rept. by G. K. Gilbert; Appendix D to Progress Rept. Expl. and Sur. W. of the 100th Mer. in 1872. Washington, 1874, pp. 49–50.

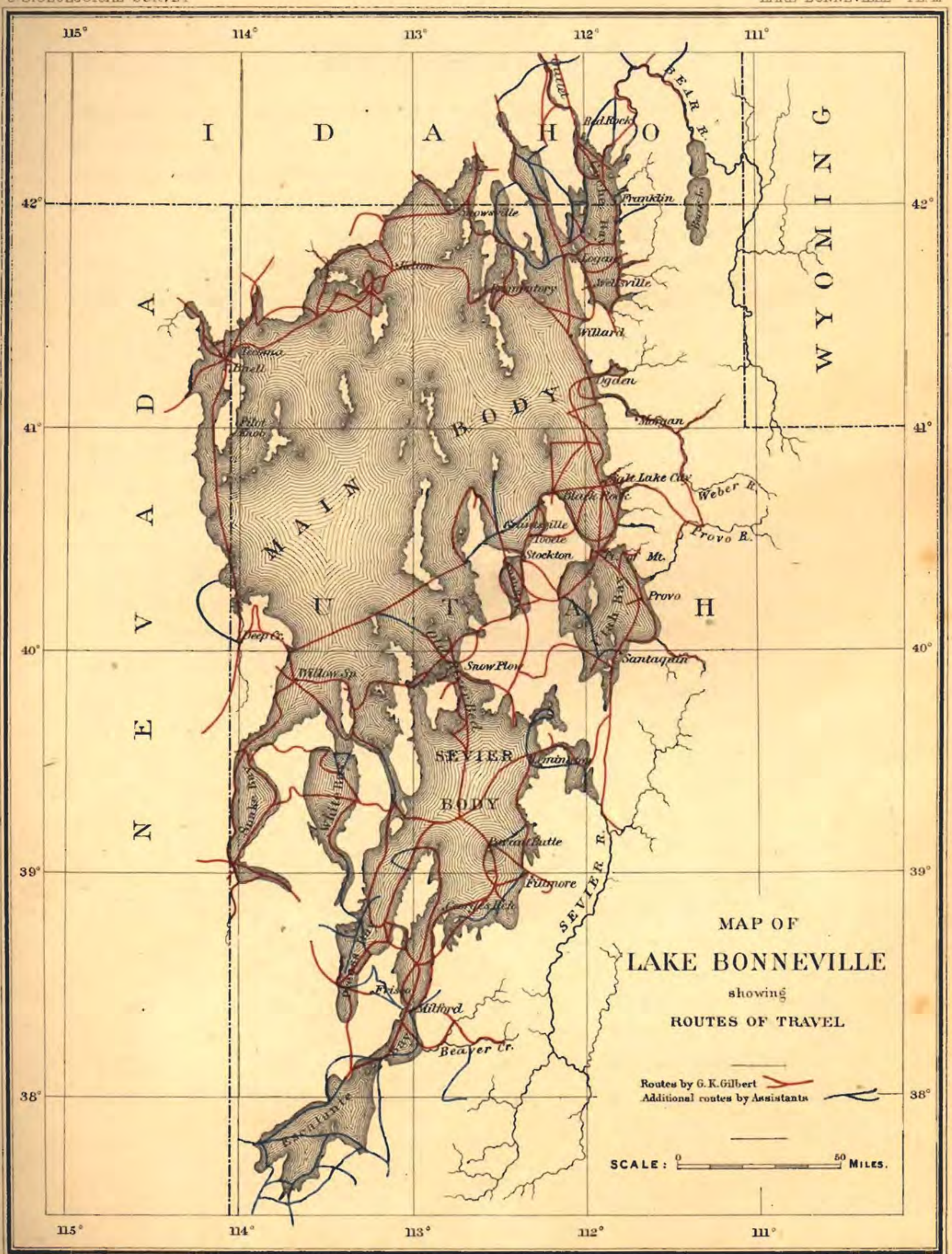
Explorations and Surveys west of the 100th Meridian, vol. 3, Geology. Washington, 1875. Part 1, by G. K. Gilbert, treats of Lake Bonneville on pp. 88–104. Part 3, by Edwin E. Howell, treats of Lake Bonneville on pp. 249–251.

In 1877 Peale observed shore terraces in various parts of Cache valley.[1]

From 1875 to 1878 I spent each summer in Utah as a member of the Powell survey, and found many opportunities in connection with other work to continue the study of Lake Bonneville. This was especially the case in 1877, when the duty of gathering information as to the irrigable land of the basin of Great Salt Lake led me all about the margin of the Salt Lake desert. When the corps for western surveys were reorganized in 1879, I was placed in charge of the Division of the Great Basin, with the understanding that the Pleistocene lakes, previously investigated only in an incidental way, should form a principal subject of study. Late in the season some months were spent in the field, with Mr. W. D. Johnson as assistant; and a corps was organized the following year. Of this corps, Mr. Israel C. Russell was principal assistant, and he remained with the work from first to last, being assigned independent investigations after the first season. Messrs. H. A. Wheeler, W. J. McGee, and Geo. M. Wright took part in the geologic work for shorter periods. Messrs. Gilbert Thompson, Albert L. Webster, Willard D. Johnson, and Eugene Ricksecker, associated with the work at various times as topographers, and Messrs. Fred. D. Owen, J. B. Bernadou, and E. R. Trowbridge, temporarily attached to field parties as general assistants, all contributed to the mapping and illustration of the lake phenomena.

The field work of the year 1880 was in the Bonneville Basin, and little was afterward done in that area. In 1881 Mr. Russell made a preliminary examination of the vestiges of Lake Lahontan in the Nevada Basin and of the Mono Basin, and in the following spring extended his reconnaissance to the lake basins of southeastern Oregon. I was called to Washington in the spring of 1881 on duty supposed to be temporary, but remained there until the following year, when the work of the Survey, previously restricted to the western Territories, was extended by Congress to the eastern States also. As the enlargement of field and function was not accompanied by an equivalent increase of funds, it became necessary to curtail the western work of the Survey, and it was decided to stop the investigation of the Pleistocene lakes as soon as this could be done without great sacrifice of

[1] Report of A. C. Peale, in U. S. Geol. Surv. of the Territories for 1877, Washington, 1879, pp. 603–606.



Julius Bien & Co, lith. Drawn by G. Thompson

material already acquired. Mr. Russell completed the study of the Lahontan and Mono Basins by the close of the season of 1883 and then returned east. I made a single excursion in the summer of 1883, devoting a few weeks to supplementary observations in the Bonneville, Lahontan, and Mono Basins, and visiting Owens Valley to examine the geologic features of the Inyo earthquake. The examination of the more southerly valleys of the Great Basin, the study of the brines and saline deposits, and the elaborate measurement of post-Pleistocene displacements, are indefinitely deferred.

The results of the investigation have been communicated in a series of reports, essays, and memoirs. An outline of the Bonneville history was published by me in 1882,[1] and an essay on shore topography in 1885.[2] Russell's results have appeared in a preliminary report on Lake Lahontan,[3] reports on the Oregon basins[4] and the Mono Basin,[5] and a monograph on Lake Lahontan.[6] An essay on the Pleistocene fresh-water shells was prepared and published by Call,[7] and one on the pseudomorph thinolite by Dana.[8] The present publication completes the series.

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[1] Contributions to the history of Lake Bonneville: Second Ann. Rept. U. S. Geol. Survey. Washington, 1882, pp. 169–200.

[2] The topographic features of lake shores: Fifth Ann. Rept. U. S. Geol. Survey. Washington, 1885, pp. 75–123.

A discussion of post-Bonneville displacement appeared in an address "The Inculcation of Scientific Method by Example," read to the American Society of Naturalists Dec. 27, 1885, and printed in the Am. Jour. Sci., vol. 31, pp. 284–299. A description of the jointed structure of the Bonneville beds was printed in the Am. Jour. Sci., 3d Series, Vol. 23, 1882, pp. 25–27.

[3] Sketch of the Geological History of Lake Lahontan: Third Ann. Rept. U. S. Geol. Survey. Washington, 1883, pp. 189–235.

[4] A geological reconnaissance in Southern Oregon: Fourth Ann. Rept. U. S. Geol. Survey. Washington, 1885, pp. 431–464.

[5] Quaternary history of Mono Valley, California: Eighth Ann. Rept. U. S. Geol. Survey. Washington, 1880, pp. 261–394.

[6] Geological History of Lake Lahontan: Mon. U. S. Geol. Survey, No 11, Washington, 1885, pp. 302.

Other publications by Mr. Russell containing portions of the same material are—

Lakes of the Great Basin: Science, vol. 3, 1884, pp 322–323.

Deposits of Volcanic Dust in the Great Basin: Bull. Phil. Soc., Washington, vol. 7, 1885, pp. 18–20.

Notes on the Faults of the Great Basin, . . .: Bull. Phil. Soc. Washington, vol. 9, 1887, pp. 5–8.

The Great Basin. In Overland Monthly, 2d Series, vol. 11, 1888, pp. 420–426.

[7] On the Quaternary and Recent Mollusca of the Great Basin, with descriptions of new forms. By R. Ellsworth Call. Introduced by a Sketch of the Quaternary Lakes of the Great Basin, by G. K. Gilbert. Bull. U. S. Geol. Survey No. 11, 1884, 56 pp.

[8] A Crystallographic Study of the Thinolite of Lake Lahontan. By Edward S. Dana. Bull. U. S. Geol. Survey No. 12, 1884, 29 pp.

THE BONNEVILLE BASIN.

The Great Basin comprises a large number of subsidiary closed basins, each draining to a lake or playa. About sixty of these could be enumerated from present knowledge, and the full number may be as high as one hundred. In the last geologic epoch a more humid climate converted many, or perhaps all, of these playas into lakes, and enlarged all the lakes. Some lakes overflowed the rims of their basins, becoming tributary to others; and the lakes of adjacent basins in many instances expanded until they became confluent. A few of the overflowing lakes discharged across the rim of the Great Basin, thus becoming tributary to the ocean, and subtracting their catchment basins from the district of interior drainage. In the remaining portion of the district the number of independent drainage areas was reduced by coalescence.

The largest of the confluent lakes were formed at the eastern and western margins of the Great Basin, being separated by the plateau of eastern Nevada. Lake Lahontan at the west was fed chiefly by the snows of the Sierra Nevada, Lake Bonneville at the east by those of the Wasatch and Uinta mountains.

The catchment basin of Lake Bonneville comprises that part of the Great Basin lying east of the Gosiute, Snake, and Piñon mountains of eastern Nevada—an oblong area embracing about five degrees of latitude and three of longitude, and containing about 54,000 square miles, or the fourth part of the area of the Great Basin. Its western two-thirds may be described as a plain ranging in altitude from 4,200 to 5,500 feet above tide, and more or less interrupted by short mountain ranges trending north and south. At the north, where the mountains are comparatively few and small, the barren plain is called the Great Salt Lake Desert, and similar open stretches at the south are named the Sevier Desert and the Escalante Desert. The eastern third is much higher, including the lofty Wasatch Range and its dependencies, the western end of the still loftier Uinta Range, and the western part of the district of the High Plateaus. Several peaks of the Wasatch and Uinta Mountains rise above the level of 12,000 feet, and the High Plateaus culminate near Beaver in the Tushar ridge with peaks of similar altitude.

The eastern uplands are the only important condensers of moisture, and from them flow a system of rivers whose waters are evaporated in the salt lakes of the lowlands. The Bear, the Weber, and the Provo-Jordan have their principal sources in the Uinta Mountains, and break through the Wasatch Range on their way to Great Salt Lake. One of the upper valleys traversed by the Bear River contains Bear Lake, a body of fresh water; and Utah Lake, likewise fresh, receives the Provo and discharges the Jordan. The Sevier River, after flowing 150 miles northward among the plateaus, receives the San Pete from the north and then turns westward to Sevier Lake, the saline of the Sevier Desert.

The eastern uplands are better timbered than any other part of the Great Basin. The upland valleys are fertile, but having a climate too cool for agriculture are devoted to grazing and maintain only a scant population. The western plain is infertile by reason of aridity, and is almost without inhabitants. The lower valleys of the rivers, where they issue from the uplands upon the plain, have a climate suited for agriculture, are rendered fertile by irrigation, and constitute a habitable zone, over which the Mormon community has spread.

To understand fully the topographic relations described above, the reader should examine the large map of Lake Bonneville (in a pocket attached to the cover of this volume), where the reliefs are expressed by contour lines at each 1,000 feet; and also Plate XII, whereon are marked the boundary of the Bonneville Basin and the boundaries of the equivalent group of smaller basins as they exist at the present time. He will find also that the plate supplements the expression of the distribution of the uplands, by contrasting the area above 7,000 feet with the area below; and he can learn from it more readily than through words the relation of the basin to the political divisions of the country. By turning again to Plate II he will see that the Bonneville basin adjoins interior drainage only on the west; its northern rim parts it from the basin of Snake River, a branch of the Columbia, its eastern and southern from the basin of the Colorado of the West. The more important streams heading near the northern rim and flowing to the Snake are the Salt, Blackfoot, Portneuf, Bannack, and Raft. In the eastern rim rise Black's Fork, the Uinta, and the Price, all tributary to the Green before it joins the Colorado, and the San Rafael, Fremont, and Escalante, immediate tributaries of the Colorado. The Paria, Kanab, and Virgen flow to the Colorado from the southern rim.

CHRONOLOGIC NOMENCLATURE.

The geologic period to which the Bonneville history has been referred has three names in good standing, Quaternary, Pleistocene, and Glacial. Each name varies more or less in scope as used by different authors, but as ordinarily understood the three are strictly synonymous. In earlier writings I have preferred Quaternary, in the present I prefer Pleistocene.

No vital principle is involved in either preference, and indeed I am not of those who clamor for the rights of words. In my judgment words have no rights which the users of words are bound to respect. The claim of a word for preference rests only on its utility—its convenience for the communication of thought.

Glacial connotes glaciers, and was a convenient name while it was supposed that a cold climate marked the whole period. But now that interruptions of that climate are recognized, it is more convenient to speak of glacial epochs and interglacial epochs of the Quaternary or Pleistocene period.

Quaternary connotes a fourfold classification, and is coordinate with Tertiary. *Pleistocene* suggests by its termination coordination with the subdivisions of the Tertiary. Using the scale of time-nouns adopted by the International Congress of Geologists, the Quaternary is an era, having the classificatory rank of the Tertiary era, and the Pleistocene is a period, ranking with the Eocene period. It is generally believed that the Pleistocene is comparable in point of duration with one of the periods of the Tertiary era, being less rather than greater, and those who advocate the employment of the name Quaternary recognize the Quaternary era as one containing but a single period. The time division with which we have to deal is, then, from every point of view, a "period," and it is believed that the use of the name Pleistocene Period involves a minimum amount of implication as to higher classification, a subject whose discussion is not here contemplated.

CHAPTER II.

THE TOPOGRAPHIC FEATURES OF LAKE SHORES.

It has been assumed in the preceding pages that valleys from which lakes have recently disappeared are characterized by certain features whereby that fact can be recognized. Perhaps no one observant of natural phenomena will dispute this. But there is, nevertheless, some diversity of opinion as to what are the peculiar characters to which lakes give rise; and especially has the true interpretation of certain local topographic features been mooted, some geologists ascribing them to waves, and others to different agencies.

In the investigation of our ancient lake, it has been found necessary not only to discriminate from all other topographic elements the features created by its waves, but also to ascertain the manner in which each was produced, so as to be able to give it the proper interpretation in the reconstruction of the history of the lake. It is proposed in this chapter to present the more general results of this study, describing in detail the various elements which constitute shore topography, explaining their origin, so far as possible, and finally contrasting them with topographic features of other origin which so far simulate them as to occasion confusion.

The play of meteoric agents on the surface of the land is unremitting, so that there is a constant tendency to the production of the forms characteristic of their action. All other forms are of the nature of exceptions, and attract the attention of the observer as requiring explanation. The shapes wrought by atmospheric erosion are simple and symmetric and need but to be enumerated to be recognized as normal elements of the sculpture of the land. Along each drainage line there is a gradual and gradually increasing ascent from mouth to source; and this law of increasing acclivity applies to all branches as well as to the main stem. Between each pair of adjacent drainage lines is a ridge or hill, standing midway and rounded at the top. Wherever two ridges join there is a summit higher than the adjacent portion of either ridge; and the highest summits of all are those which, measuring along lines of drainage, are most remote from the ocean. The crests of the ridges are not horizontal but undulate from summit to summit. There are no sharp contrasts of slope; the concave profiles of the drainage lines change their inclination little by little and merge by a gradual transition in the convex profiles of the crests and summits.

The factor which most frequently, and in fact almost universally, interrupts these simple curves is heterogeneity of terrane. Under the influence of this factor, just as in the case of a homogeneous terrane, the declivities adjust themselves in such way as to oppose a maximum resistance to erosion; and with diversity of rock texture this adjustment involves diversity of form. Hard rocks survive, while the soft are eaten away. Peaks and cliffs are produced. The apices are often angular instead of rounded. Profiles exhibit abrupt changes of slope. Flat-topped ridges appear, and the distribution of maximum summits becomes in a measure independent of the length of drainage lines.

A second factor interrupting the continuity of erosion profiles is upheaval; and this produces its effects in two distinct ways. First, the general uprising of a broad tract of land affects the relation of the drainage to its point of discharge or to its base level, causing corrasion by streams to be more rapid than the general waste of the surface and producing canyons and terraces. Second, a local uprising by means of a fault produces a cliff at the margin of the uplifted tract; and above this cliff there is sometimes a terrace.

A third disturbing factor is glaciation, the cirques and moraines of which are distinct from anything wrought by pluvial erosion; and a fourth is found in eruption.

The products of all these agencies except the last have been occasionally confused with the phenomena of shores. The beach-lines of Glen Roy have been called river terraces and moraine terraces. The cliffs of the Downs of England have been ascribed to shore waves. Glacial moraines in New Zealand have been interpreted as shore terraces. Beach ridges in our own country have been described as glacial moraines, and fault terraces as well as river terraces have been mistaken for shore-marks.

In the planning of engineering works for the improvement and protection of harbors, it is of prime importance to understand the natural processes by which coast features are produced and modified, and this necessity has led to the production by engineers of a large though widely scattered literature on coast-forming agencies. Geologists also require for the interpretation of strata originating as coast deposits an understanding of the methods of coastal degradation and coastal deposition, and from their point of view there has arisen an independent literature on the subject. The physical theory of water waves required alike by engineers and geologists has been developed by physicists, and has its own literature. The three groups of writers have so thoroughly traversed the subject of shore processes that the present chapter would have need to demonstrate its raison d'être were it not that the general subject has as yet received no compendious and systematic treatment in the English language.

It happens, moreover, that the present treatment of the subject has its own peculiar point of view, and is in large part independent. During the progress of the field investigation I was unaware of the greater part of the literature mentioned above, having indeed met with but one important paper, that in which Andrews describes the formation of beaches at the head of Lake Michigan, and I was induced by the requirements of my work to develop the philosophy of the subject ab initio. The theories here presented had therefore received approximately their present form and arrangement before they were compared with those of earlier writers. They are thus original without being novel, and their independence gives them confirmatory value so far as they agree with the conclusions of others.

The peculiarity of the point of view lies in the fact that the phenomena chiefly studied are fossil shore-lines instead of modern. The bodies of water to which they pertain having disappeared, the configuration of the submerged portion is directly seen instead of being interpreted from laborious soundings. There are, moreover, natural sections of the deposits, exposed by subsequent erosion, and these reveal features of internal structure or anatomy quite as important to the geologist as the features of morphology.

The literature of shore-lines is so feebly connected by cross reference, and portions of it have been discovered in places so unexpected, that the writer fears many important contributions have escaped his attention. Within the range of his reading, the earliest discussions of value are by Beaumont[1] and De la Beche,[2] and it must be admitted that the writers of geologic manuals now in use have improved very little upon their presentation. Fleming, in an essay on the origin and preservation of the harbor of Toronto,[3] set forth the process of littoral transportation with admirable clearness; and Andrews, who appears to have reached his conclusions by independent observation, added to the theory of littoral transportation an important factor in the theory of littoral deposition.[4] Mitchell, in an essay on tidal marshes,[5] incidentally describes the growth of the protecting barrier. A general treatise by Cialdi[6] gives a systematic discussion of coast processes from the engineer's point of view, and reviews the Italian literature of the subject; and a shorter paper by Keller[7] has a similar scope. Richthofen, in his manual of instruction to scientific travelers, treats analytically and at length of the work of waves in conjunction with tides, and discusses a subsiding continent.[8] The theory of waves has been developed experimentally by a committee of the British Association, with J. Scott Russell as reporter;[9] and it is analytically treated by Airy[10] and Rankine.[11]

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[1] Leçons de geologie pratique. Par Elie de Beaumont. Vol. 1, pp. 221–253, Paris, 1845.

[2] A Geological Manual. By Henry T. De la Beche. 3d edition, enlarged, London, 1833, pp. 67–91. The Geological Observer. By the same. London, 1851, pp. 49–117.

[3] Toronto Harbor—its formation and preservation. By Sandford Fleming, C. E.: Canadian Journal, vol. 2, 1854, pp. 103–107, 223–230. Reprinted with additions as Report on Preservation and Improvement of Toronto Harbor. In Supplement to Canadian Journal, 1854, pp. 15–29.

[4] The North American Lakes considered as chronometers of post-Glacial time. By Dr. Edmund Andrews. Trans Chicago Acad. Sci., Vol. 2, pp. 1–23.

[5] On the reclamation of tide-lands and its relation to navigation. By Henry Mitchell. Appendix No. 5, to Rept. U. S. Coast Survey for 1869. Washington, 1872, pp. 75–104.

[6] Sul moto ondoso del mare e su le correnti di esso specialmente su quelle littorali. Alessandro Cialdi, Roma, 1866.

[7] Studien uber die Gestaltung der Sandkusten, etc., H. Keller, Berlin, 1881.

[8] Führer für Forschungsreisende, von Ferdinand Freiherr von Richthofen. Berlin, 1886, pp. 336–365.

[9] Report of the Committee on Waves, by Sir John Robinson, and John Scott Russell, Reporter: Rept. British Ass. Adv. Sci., 7th meeting, 1837, pp. 417–496.

[10] G. B. Airy, Vol. V, Ency. Metrop.

[11] W. J. McQ. Rankine, Philos. Trans. Royal Soc. London, vol. 153, 1863, pp. 127–138.

In the following treatment of the subject the description and analysis of the elements of shore topography will be followed by a comparison of certain of these elements with simulating features of different origin. First, however, a few words will be devoted to the consideration of shore shaping as a division of the more general process of earth shaping.

The earth owes its spheroidal form to gravity and rotation. It owes its great features of continent and ocean bed to the unequal distribution of the heterogeneous material of which it is composed. Many of its minor inequalities can be referred to the same cause, but its details of surface are chiefly molded by the circulation of the fluids which envelope it. This shaping or molding of the surface may be divided into three parts—subaerial shaping (land sculpture), subaqueous shaping, and littoral shaping. In each case the process is threefold, comprising erosion, transportation, and deposition.

In subaerial or land shaping the agents of erosion are meteoric—rain, acting both mechanically and chemically, streams, and frost. The agent of transportation is running water. The condition of deposition is diminishing velocity.

In subaqueous shaping, or the molding of surface which takes place beneath lakes and oceans, currents constitute the agent of erosion. They constitute also the agent of transportation; and the condition of deposition is, as before, diminishing velocity.

In littoral shaping, or the modeling of shore features, waves constitute the agent of erosion. Transportation is performed by waves and currents acting conjointly, and the condition of deposition is increasing depth.

On the land the amount of erosion vastly exceeds the amount of deposition. Under standing water erosion is either nil or incomparably inferior in amount to deposition. And these two facts are correlatives, since the product of land erosion is chiefly deposited in lakes and oceans, and the sediments of lakes and oceans are derived chiefly from land erosion. The products of littoral erosion undergo division, going partly to littoral deposition and partly to subaqueous deposition. The material for littoral deposition is derived partly from littoral erosion and partly from land erosion.

That is to say, the detritus worn from the land by meteoric agents is transported outward by streams. Normally it is all carried to the coast, but owing to the almost universal complication of erosion with local uplift, there is a certain share of detritus deposited upon the basins and lower slopes of the land. At the shore a second division takes place, the smaller portion being arrested and built into various shore structures, while the larger portion continues outward and is deposited in the sea or lake. The product of shore erosion is similarly divided. A part remains upon the shore, where it is combined with material derived from the land, and the remainder goes to swell the volume of subaqueous deposition.

The forms of the land are given chiefly by erosion. Since the wear by streams keeps necessarily in advance of the waste of the intervening surfaces, and since, also, there is inequality of erosion dependent on diversity of texture, land forms are characterized by their variety.

The forms of sea beds and lake beds are given by deposition. The great currents by which subaqueous sediments are distributed sweep over the ridges and other prominences of the surface and leave the intervening depressions comparatively currentless. Deposition, depending on retardation of current, takes place chiefly in the depressions, so that they are eventually filled and a monotonous uniformity is the result.

The forms of the shore are intermediate in point of variety between those of the land and those of the sea bed; and since they alone claim parentage in waves, they are sui generis.

Ocean shores are genetically distinguished from lake shores by the cooperation of tides, which modify the work accomplished by waves and wind currents.

The phenomena of ocean shores are therefore more complicated than those of lake shores, and an exhaustive treatment of the subject would include the discussion of their distinguishing characteristics. They fall, however, without the limits of the present investigation, and in the analysis which follows, the influence of tides is not considered. It is perhaps to be regretted that the systematic treatment here proposed could not be so extended as to include all shores, but there is a certain compensation in the fact that the results reached in reference to lake shores have an important negative bearing on tidal discussions. It was long ago pointed out by Beaumont[1] and Desor[2] that many of the more important features ascribed by hydraulic engineers to tidal action, are produced on the shores of inland seas by waves alone; and the demonstration of wave work pure and simple should be serviceable to the maritime engineer by pointing out those results in explanation of which it is unnecessary to appeal to the agency of tides.

The order of treatment is based on the three-fold division of the process of shore shaping. Littoral erosion and the origin of the sea-cliff and wave-cut terrace will be first explained, then the process of littoral transportation with its dependent features, the beach and the barrier, and finally the process of littoral deposition, resulting in the embankment, with all its varied phases, and the delta.

WAVE WORK.

LITTORAL EROSION.

In shore sculpture the agent of erosion is the wave. All varieties of wave motion which affect standing water are susceptible of producing erosive effect on the shore, but only those set in motion by wind need be considered here. They are of two kinds: the wind wave proper, which exists only during the continuance of the wind; and the swell, which continues after the wind has ceased. It is unnecessary to discriminate the effects of these upon the shore further than to say that the wind wave is the more efficient and therefore the better deserving of special consideration. In the wind wave two things move forward, the undulation and the water. The velocity of the undulation is relatively rapid; that of the water is slow and rhythmic. A particle of water at or near the surface, as each undulation passes, describes an orbit in a vertical plane, but does not return to the starting point. While on the crest of the wave it moves forward, and while in the trough it moves less rapidly backward, so that there is a residual advance.[3]

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[1] Leçons de géologie pratique, vol. 1, p. 232.

[2] E. Desor, Geology of Lake Superior Land District by Foster & Whitney, Washington, 1851, vol. 2, pp. 262, 266.

[3] The theory of wave motion involved in this and the following paragraphs is based partly on observation but chiefly on the discussions of J. S. Russell, Airy, Cialdi, and Rankine.

This residual advance is the initiatory element of current. By virtue of it the upper layer of water is carried forward with reference to the layer below, being given a differential movement in the direction towards which the wind blows. This movement is gradually propagated to lower aqueous strata, and ultimately produces movement of the whole body, or a wind-wrought current. So long as the velocity of the wind remains constant, the velocity of the current is less than that of the wind; and there is always a differential movement of the water, each layer moving faster than the one beneath. The friction is thus distributed through the whole vertical column, and is even borne in part by the lake bottom. The greater the depth the smaller the share of friction apportioned to each layer of water and the greater the velocity of current which can be communicated by a given wind.[1] The height of waves is likewise conditioned by depth of water, deep water permitting the formation of those that are relatively large.

When the wave approaches a shelving shore its habit is changed. The velocity of the undulation is diminished, while the velocity of the advancing particles of water in the crest is increased; the wave length, measured from trough to trough, is diminished, and the wave height is increased; the crest becomes acute, with the front steeper than the back; and these changes culminate in the breaking of the crest, when the undulation proper ceases. The return of the water thrown forward in the crest is accomplished by a current along the bottom called the *undertow*. The momentum of the advancing water contained in the wave crest gives to it its power of erosion. The undertow is efficient in removing the products of erosion.

The retardation of the undulation by diminishing depth of water changes the direction of its axis or crest line—excepting when the axis is parallel to the contours of the shoaling bottom—and the phenomena are analogous to those of the refraction of light and sound. As a wave passes obliquely from deep water to a broad shoal of uniform depth, the end first entering shoal water is first retarded and the crest line is for the moment bent. When the entire crest has reached shoal water it is once more straight, but with a new trend, a trend making a narrower angle with the line of separation

[1] This is a matter of observation rather than theory. It implies that the friction between contiguous films of water increases in more than simple ratio with the differential velocity of the films.

between deep and shallow water. The wave has been refracted. When a wave passes obliquely from deep water to shoal water whose bottom gradually rises to a shore, the end nearer the shore is the more retarded at all stages of progress and the crest line is continuously curved. When the wave breaks and the undulation ceases, the crest line is nearly parallel to the shore. It results that for a wide range of wind direction there is but small range in the direction of wave trend at the shore. It results also, as has been often noted, that when the wind blows normally into a circling bay, the waves it brings are diversely turned, so as to beat against both sides as well as the head of the bay.

When the land at the margin of the water consists of unconsolidated material or of fragmental matter lightly cemented, the simple impact of the water is sufficient to displace or erode it. The same force is competent also to disintegrate and remove firmer rock that has been superficially weakened by frost or is partially divided by cracks, but it may be doubted whether it has any power to wear rock that is thoroughly coherent. The impact of large waves has great force, and its statement in tons to the square foot is most impressive; but, so far as our observation has extended, the erosive action of waves of clear water beating upon firm rock without seams is practically nil. On the shores of Lake Bonneville, not only was there no erosion on the faces of cliffs at points where the waves carried no detrital fragments, but there was actually deposition of calcareous tufa; and this deposition was most rapid at points specially exposed to the violence of the waves.

The case is very different when the rock is divided by seams, for then the principle of the hydrostatic press finds application. Through the water forced into the seams, and sometimes through air imprisoned and compressed by the water, the blow struck by the wave is applied not merely to large surfaces but in directions favorable to the rending and dislocation of rock masses.

It rarely happens, however, that the impact of waves is not reinforced by the impact of mineral matter borne by them. The detritus worn from the shore is always at hand to be used by the waves in continuance of the attack; and to this is added other detritus carried along the shore by a process presently to be described.

The rock fragments which constitute the tool of erosion are themselves worn and comminuted by use until they become so fine that they no longer lie in the zone of breakers but are carried away by the undertow.

The direct work of wave erosion is restricted to a horizontal zone dependent on the height of the waves. There is no impact of breakers at levels lower than the troughs of the waves; and the most efficient impact is limited upward by the level of the wave crests, although the dashing of the water produces feebler blows at higher levels. The indirect work has no superior limit, for as the excavation of the zone is carried landward, masses higher up on the slope are sapped so as to break away and fall by mere gravity. Being thus brought within reach of the waves, they are then broken up by them, retarding the zonal excavation for a time but eventually adding to the tool of erosion in a way that partially compensates.

Let us now consider what goes on beneath the surface of the water. The agitation of which waves are the superficial manifestation is not restricted to their horizon, but is propagated indefinitely downward. Near the surface the amount of motion diminishes rapidly downward, but the rate of diminution itself diminishes, and there seems no theoretic reason for assigning any limit to the propagation of the oscillation. Indeed, the agitation must be carried to the bottom in all cases where the depth operates as a condition in determining the magnitude of waves, for that determination can be assigned only to a resistance opposed by the bottom to the undulation of the water.

During the passage of a wave each particle of water affected by it rises and falls, and moves forward and backward, describing an orbit. If the passing wave is a swell, the orbit of the particle is closed,[1] and is either a circle or an ellipse; but in the case of a wind wave the orbit is not closed. The relative amounts of horizontal and vertical motion depend on the depth of the particle beneath the surface, and on the relation of the total depth of the water to the size of the wave. If the water is deep as compared to the wave-length, the horizontal and vertical movements are sensibly equal, and their amount diminishes rapidly from the surface downward. If the depth

[1] This is strictly true only while the swell traverses deep water. It is pointed out by Cialdi that in passing to shoal water the swell is converted into a wave of translation, and the particles no longer return to their points of starting.

is small, the horizontal motion is greater than the vertical, but diminishes less rapidly with depth. Near the line of breakers, the vertical motion close to the bottom becomes inappreciable, while the horizontal oscillation is nearly as great as at the surface. This horizontal motion, affecting water which is at the same time under the influence of the undertow, gives to that current a pulsating character, and thus endows it with a higher transporting power than would pertain to its mean velocity. Near the breaker line, the oscillation communicated by the wave may even overcome and momentarily reverse the movement of the undertow. Inside the breaker line no oscillation proper is communicated. The broken wave crest, dashing forward, overcomes the undertow and throws it back; but the water returns without acceleration as a simple current descending a slope.

It should be explained that the increment given by pulsation to the transporting power of the undertow depends upon the general law that the transporting power of a current is an increasing geometric function of its velocity. Doubling the velocity of a current more than doubles the amount it can carry, and more than doubles the size of the particles it is able to move.

The transporting power of the undertow diminishes rapidly from the breaker line outward. That part of its power which depends on its mean velocity diminishes as the prism of the undertow increases; that part which depends on the rhythmic accelerations of velocity diminishes as the depth of water increases.

The pulsating current of the undertow has an erosive as well as a transporting function. It carries to and fro the detritus of the shore, and, dragging it over the bottom, continues downward the erosion initiated by the breakers. This downward erosion is the necessary concomitant of the shoreward progress of wave erosion; for if the land were merely planed away to the level of the wave troughs, the incoming waves would break where shoal water was first reached and become ineffective at the water margin. In fact, this spending of the force of the waves where the water is so shallow as to induce them to break, increases at that point the erosive power by pulsation, and thus brings about an interdependence of parts. What may be called a normal profile of the submerged terrace is produced, the parts of which are adjusted to a harmonious interrelation. If some exceptional temporary condition produces abnormal wearing of the outer margin of the terrace, the greater depth of water at that point permits the incoming waves to pass with little impediment and perform their work of erosion upon portions nearer the shore, thus restoring the equilibrium. If exceptional resistance is opposed by the material at the water margin, erosion is there retarded until the submerged terrace has been so reduced as to permit the incoming waves to attack the land with a greater share of unexpended energy. Conversely, if there is a diminution of resistance at the water margin, so as to permit a rapid erosion, the landward recession of that margin causes it to be the less exposed to wave action. Thus the landward wear at the water margin and the downward wear in the several parts of the submerged plateau are adjusted to an interdependent relation.

The Sea-Cliff.—Wave erosion, acting along a definite zone, may be rudely compared to the operation of a horizontal saw; but the upper wall of the saw cut, being without support, is broken away by its own weight and falls in fragments, leaving a cliff at the shoreward margin of the cut. This wave-wrought cliff requires a distinctive name to avoid confusion with cliffs of other origin, and might with propriety in this discussion be called a lake-cliff; but the term *sea-cliff* is so well established that it appears best to retain it.

One of the most noteworthy and constant characters of the sea-cliff is the horizontality of its base. Being determined by wave erosion the base must always stand at about the level of the lake on which the waves are formed. The material of the cliff is the material of the land from which it is carved. Its declivity depends partly on the nature of that material and partly on the rate of erosion. If the material is unconsolidated, the inclination cannot exceed the normal earth slope; if it is thoroughly indurated, the cliff may be vertical or may even overhang. If the rate of wave erosion is exceedingly rapid, the cliff is as steep as the material will permit; if the rate is slow, the inclination is diminished by the atmospheric waste of the cliff face.

Figure 1 represents a cliff on the shore of Great Salt Lake. The material in this case is arenaceous limestone. At the base of the cliff may be seen a portion of the accompanying wave-cut terrace, and the foreground exhibits a portion of the associated beach. The large bowlders of the foreground have an independent origin, but the shingle and other material of the beach were derived from the erosion of the cliff and transported to their present position by the waves. Sheep Rock is overlooked by the northern face of the Oquirrh mountain range, on which the Bonneville shores are traced, and the partial view of the mountain face given in the frontispiece shows a line of ancient sea-cliffs, originally as precipitous as Sheep Rock but now shattered by frost and partially draped by talus.

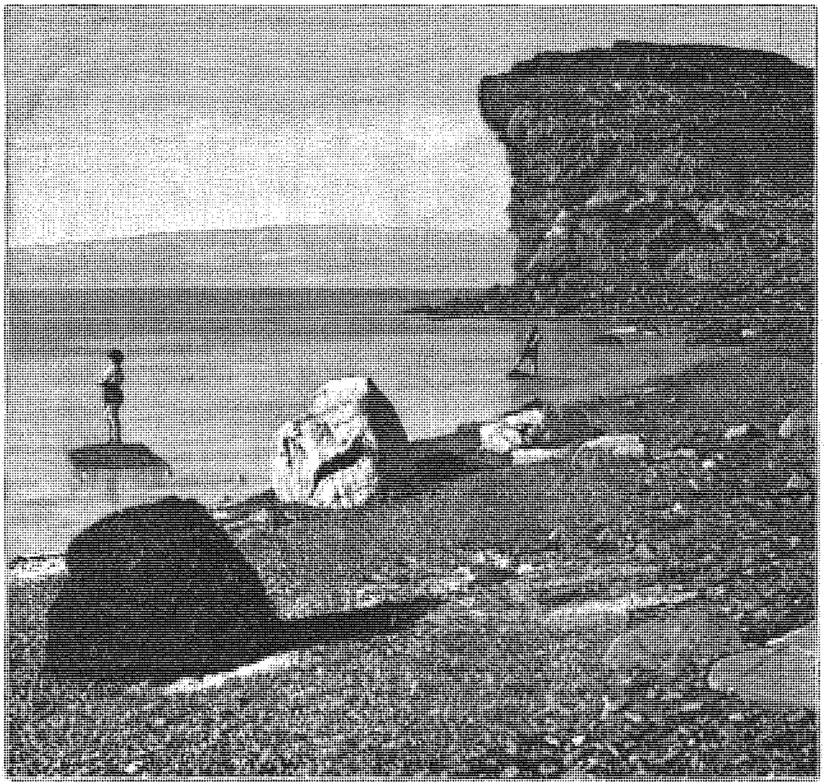

FIG. 1.—Sheep Rock, a Sea-Cliff on the shore of Great Salt Lake. From a photograph by C. R. Savage.

It will appear in the sequel that the distribution of sea-cliffs is somewhat peculiar, but this cannot be described until the process of littoral transportation has been explained.

The Wave-Cut Terrace.—The submerged plateau whose area records the landward progress of littoral erosion, becomes a terrace after the formative lake has disappeared, and, as such, requires a distinctive name. It will be called the *wave-cut terrace.*

Its prime characteristics are, first, that it is associated with a cliff; second, that its upper margin, where it joins the cliff, is horizontal; and, third, that its surface has a gentle inclination away from the cliff. There is an exceptional case in which an island or a hill of the mainland has been completely pared away by wave action, so that no cliff remains as a companion for the wave-cut terrace; but this exception does not invalidate the rule. The lakeward inclination is somewhat variable, depending on the nature of the material and on the pristine acclivity of the land. It is greater where the material is loose than where it is coherent; and greater where the ratio of terrace width to cliff height is small. It is probably conditioned also by the direction of the current associated with the wind efficient in its production; but this has not been definitely ascertained.

The width of the terrace depends on the extent of the littoral erosion, and is not assignable. Its relative width in different parts of a given continuous coast depends entirely on the conditions determining the rapidity of erosion, and the discussion of these at this point would be premature.

Sometimes a portion of the eroded material gathers at the outer edge of the terrace, extending its profile as indicated in Figure 4.[1]

Figures 2 and 3 show ideal sections of cliffs and terraces, carved in one case from soft material, in the other from hard. The station of the artist

FIG. 2.—Section of a Sea Cliff and Cut-Terrace in Incoherent Material.

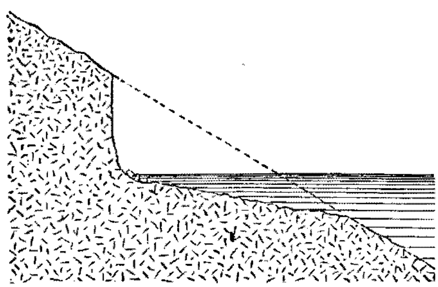

FIG. 3.—Section of a Sea Cliff and Cut-Terrace in Hard Material.

in sketching the view represented in the frontispiece was on a cut-terrace, and a portion of it appears in the foreground.

[1] I. C. Russell. Geological History of Lake Lahontan, p. 89.

LITTORAL TRANSPORTATION.

Littoral transportation is performed by the joint action of waves and currents. Usually, and especially when the wind blows, the water adjacent to the shore is stirred by a gentle current flowing parallel to the water margin. This carries along the particles of detritus agitated by the waves. The waves and undertow move the shallow water near the shore rapidly to and fro, and in so doing momentarily lift some particles, and roll others forward and back. The particles thus wholly or partially sustained by the water are at the same moment carried in a direction parallel to the shore by the shore current. The shore current is nearly always gentle and has of itself no power to move detritus.

When the play of the waves ceases, all shore action is arrested. When the play of the waves is unaccompanied by a current, shore action is nearly arrested, but not absolutely. If the incoming waves move in a direction normal to the shore, the advance and recoil of the water move particles toward and from the shore, and effect no transfer in the direction of the shore; but if the incoming waves move in an oblique direction the forward transfer of particles is in the direction of the waves, while the backward transfer, by means of the undertow, is sensibly normal to the shore, and there is thus a slow transportation along the shore. If there were no currents a great amount of transportation would undoubtedly be performed in this way, but it would be carried on at a slow rate. The transporting effect of waves alone is so slight that only a gentle current in the opposite direction is necessary to counteract it. The concurrence of waves and currents is so general a phenomenon, and the ability of waves alone is so small, that the latter may be disregarded. The practical work of transportation is performed by the conjoint action of waves and shore currents.

In the ocean the causes of currents are various. Besides wind currents there are daily currents caused by tides upon all coasts, and it is maintained by some physicists that the great currents are wholly or partly due to the unequal heating of the water in different regions. But in lakes there are no appreciable tides, and currents due to unequal heating have never been discriminated. The motions of the water are controlled by the wind.

A long-continued wind in one direction produces a set of currents harmoniously adjusted to it. A change in the wind produces a change in the currents, but this adjustment is not instantaneous, and for a time there is lack of harmony. The strong winds, however, bring about an adjustment more rapidly than the gentle, and since it is to these that all important littoral work is ascribed, the waves and currents concerned in littoral transportation may be here regarded as depending on one and the same wind.

A wind blowing directly toward a shore may be conceived of as piling the superficial water against the shore, to be returned only by the undertow, but, in fact, so simple a result is rarely observed. Usually there is some obliquity of direction, in virtue of which the shoreward current is partially deflected, so as to produce as one of its effects a flow parallel to the shore, or a littoral current. The littoral current thus tends in a direction harmonious with the movement of the waves, passing to the right if the waves tend in that direction, to the left if the waves tend thither.

To this rule there is a noteworthy exception. The undertow is not the only return current. It frequently occurs that part of the water driven forward by the wind returns as a superficial current somewhat opposed in direction to the wind. If this current follows a shore it constitutes a littoral current whose tendency is opposed to that of the waves. Thus the littoral current may move to the right while the waves tend to the left, and vice versa. In every such case the direction of transportation is the direction of the littoral current.

The waves and undertow accomplish a sorting of the detritus. The finer portion, being lifted up by the agitation of the waves, is held in suspension until carried outward to deep water by the undertow. The coarser portion, sinking to the bottom more rapidly, can not be carried beyond the zone of agitation, and remains as a part of the shore. Only the latter is the subject of littoral transportation. It is called *shore drift.*

With the shifting of the wind the direction of the littoral current on any lake shore is occasionally, or it may be frequently, reversed, and the shore drift under its influence travels sometimes in one direction and sometimes in the other. In most localities it has a prevailing direction, not necessarily determined by the prevailing direction of the shore current, but rather by the direction of that shore current which accompanies the greatest waves. This is frequently but not always the direction also of the shore current accompaning the most violent storms.

The source of shore drift is two-fold. A large part is derived from the excavation of sea-cliffs, and is thus the product of littoral erosion. From every sea-cliff a stream of shore drift may be seen to follow the coast in one direction or the other.

Another part is contributed by streams depositing at their mouths the heavy part of their detritus, and is more remotely derived from the erosion of the land. The smallest streams merely reinforce the trains of shore drift flowing from sea-cliffs, and their tribute usually cannot be discriminated. Larger streams furnish bodies of shore drift easily referred to their sources. Streams of the first magnitude, as will be explained farther on, overwhelm the shore drift and produce structures of an entirely different nature, known as deltas.

The Beach.—The zone occupied by the shore drift in transit is called the *beach*. Its lower margin is beneath the water, a little beyond the line where the great storm waves break. Its upper margin is usually a few feet above the level of still water. Its profile is steeper upon some shores than others, but has a general facies consonant with its wave-wrought origin. At each point in the profile the slope represents an equilibrium in transporting power between the inrushing breaker and the outflowing undertow. Where the undertow is relatively potent its efficiency is diminished by a low declivity. Where the inward dash is relatively potent the undertow is favored by a high declivity. The result is a sigmoid profile of gentle flexure, upwardly convex for a short space near its landward end, and concave beyond.

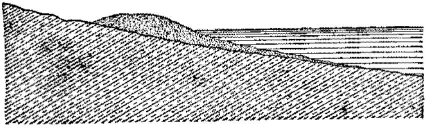

FIG. 4.—Section of a Beach.

In horizontal contour the beach follows the original boundary between land and lake, but does not conform to its irregularities. Small indentations are filled with shore drift, small projections are cut away, and smooth, sweeping curves are given to the water margin and to the submerged contours within reach of the breakers.

The beach graduates insensibly into the wave-cut terrace. A cut-terrace lying in the route of shore drift is alternately buried by drift and swept bare, as the conditions of wind and breaker vary. The cut-and-built terrace (Figure 5), which owes its detrital extension to the agencies determining the beach profile, may be regarded as a form intermediate between the beach and the cut terrace.

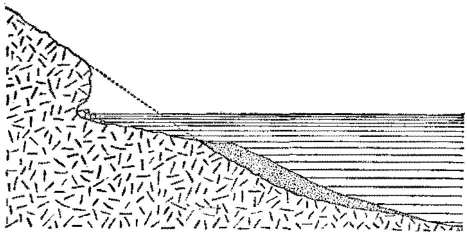

FIG. 5.—Section of a Cut-and Built Terrace.

The Barrier.—Where the sublittoral bottom of the lake has an exceedingly gentle inclination the waves break at a considerable distance from the water margin. The most violent agitation of the water is along the line of breakers; and the shore drift, depending upon agitation for its transportation, follows the line of the breakers instead of the water margin. It is thus built into a continuous outlying ridge at some distance from the water's edge. It will be convenient to speak of this ridge as a *barrier*.

FIG. 6.—Section of a Barrier.

The barrier is the functional equivalent of the beach. It is the road along which shore drift travels, and it is itself composed of shore drift. Its lakeward face has the typical beach profile, and its crest lies a few feet above the normal level of the water.

Between the barrier and the land a strip of water is inclosed, constituting a lagoon. This is frequently converted into a marsh by the accumulation of silt and vegetable matter, and eventually becomes completely filled, so as to bridge over the interval between land and barrier and convert the latter into a normal beach.

The beach and the barrier are absolutely dependent on shore drift for their existence. If the essential continuous supply of moving detritus is cut off, not only is the structure demolished by the waves which formed it, but the work of excavation is carried landward, creating a wave-cut terrace and a cliff.

The principal elements of the theory of shore-drift deposits here set forth are tacitly postulated by many writers on the construction of harbor and coast defenses. According to Cialdi[1] the potency of currents in connection with waves was first announced by Montanari; it has been concisely and, so far as appears, independently elucidated by Andrews.[2]

Still water level is the datum with which all vertical elements of the profile of the beach and barrier are necessarily compared; and, referred to this standard, not only does the maximum height of the beach or barrier vary in different parts of the same shore, but the profile as a whole stands at different heights.

The explanation of these inequalities depends in part on a principle of wide application, which is on the one hand so important and on the other so frequently ignored that a paragraph may properly be devoted to it, by way of digression. There are numerous geologic processes in which quantitative variations of a causative factor work immensely greater quantitative variations of the effect. It is somewhat as though the effect was proportioned to an algebraic power of the cause, but the relation is never so simple. Take, for example, the transportation of detritus by a stream. The variable cause is the volume of water; the variable effect is the amount of geologic work done—the quantity of detritus transported. The effect is related to the cause in three different ways: First, increase of water volume augments the velocity of flow, and with increase of velocity the size of the maximum particle which can be moved increases rapidly. According to Hopkins, the size of the maximum fragment which can be moved varies as the sixth power of the velocity, or (roughly) as the $\frac{3}{2}$ power of the volume of water. Second, the increase of velocity enlarges the capacity of the water to transport detritus of a given character; that is, the per cent of load to the unit of water is increased. Third, increase in the number of unit volumes of water increases the load pro rata. The summation of these three tendencies gives to the flooded stream a transporting power scarcely to be compared with that of the same stream at its low stage, and it gives to the exceptional flood a

[1] Loc. cit., p. 394, et seq. Cialdi himself maintains at great length that the work is performed by waves, and that the so-called shore current, a feeble peripheral circulation observed in the Mediterranean, is qualitatively and quantitatively incompetent to produce the observed results. Whether he would deny the efficiency of currents excited by the same winds which produce the waves is not clearly apparent.

[2] Trans. Chicago. Acad. Sci., vol. 2, p. 9.

power greatly in excess of the normal or annual flood. Not only is it true that the work accomplished in a few days during the height of the chief flood of the year is greater than all that is accomplished during the remainder of the year, but it may even be true that the effect of the maximum flood of the decade or generation or century surpasses the combined effects of all minor floods. It follows that the dimensions of the channel are established by the great flood and adjusted to its needs.

In littoral transportation the great storm bears the same relation to the minor storm and to the fair-weather breeze. The waves created by the great storm not only lift more detritus from each unit of the littoral zone, but they act upon a broader zone, and they are competent to move larger masses. The currents which accompany them are correspondingly rapid, and carry forward the augmented shore drift at an accelerated rate. It follows that the habit of the shore, including not only the maximum height of the beach line and the height of its profile, but the dimensions of the wave-cut terrace and of various other wave products presently to be described, is determined by and adjusted to the great storm.

It should be said by way of qualification that the low-tide stream and the breeze-lifted wave have a definite though subordinate influence on the topographic configuration. After the great flood has passed by, the shrunken stream works over the finer debris in the bed of the great channel, and by removing at one place and adding at another shapes a small channel adjusted to its volume. After the great storm has passed from the lake and the storm swell has subsided, the smaller waves of fair weather construct a miniature beach profile adapted to their size, superposing it on the greater profile. This is done by excavating shore drift along a narrow zone under water and throwing it up in a narrow ridge above the still water level. Thus, as early perceived by De la Beche[1] and Beaumont,[2] it is only for a short time immediately after the passage of the great storm that the beach profile is a simple curve; it comes afterward to be interrupted by a series of superposed ridges produced by storms of different magnitude.

Reverting now to the special conditions controlling the profiles of beach or barrier at an individual locality, it is evident that the chief of these is the

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[1] Manual of Geology, Philadelphia, 1832, p. 72.

[2] Leçons, p. 226 and plate IV.

magnitude of the largest waves breaking there. The size of the waves at each locality depends on the force of the wind and on its direction. A wind blowing from the shore lakeward produces no waves on that shore. One from the opposite shore produces waves whose height is approximately proportional to the square root of the distance through which they are propagated, provided there are no shoals to check their augmentation. For a given force of wind, the greatest waves are produced when the direction is such as to command the broadest sweep of water before their incidence at the particular spot, or in the technical phrase, when the *fetch* is greatest.

A second factor is found in the configuration of the bottom. Where the off-shore depth is great the undertow rapidly returns the water driven forward by the wind, and there is little accumulation against the shore; but where the off-shore depth is small the wind piles the water against the shore, and produces all shore features at a relatively high level.

The Subaqueous Ridge.—Various writers have mentioned low ridges of sand or gravel running parallel to the shore and entirely submerged. As the origin of such ridges is not understood, they have no fixed position in the present classification, and they are placed next to the barrier only because of similarity of form. The following description was published by Desor in 1851:

> An example of this character occurs on the northern shore of Lake Michigan, not far from the fish station of Bark Point (Pointe aux Écorces), under the lee of a promontory, designated on the map as Point Patterson. Here, the shore, after running due east and west for some distance, bends abruptly to the northeast. The voyageur coming from the west, after having passed Point Patterson, is struck by the appearance of several bands of shallow water, indicated by a yellowish tint. These bands, which appear to start from the extremity of the point, are caused by subaqueous ridges, which spread, fan-like, to the distance of nearly half a mile to the east, being from three to ten yards wide, and from five to ten feet above the general bed of the lake, at this point. They are not composed, like the flats, of fine sand, but of white limestone pebbles, derived from the adjacent ledges, with an admixture of granitic pebbles, some of which are a foot in diameter. It is difficult to conceive of currents sufficiently powerful to transport and arrange such heavy materials, and yet we know of no other means by which this aggregation could have been accomplished.
>
> These subaqueous ridges afford, on a small scale, an interesting illustration of the formation of similar ridges now above water. If the north coast of Lake Michigan were to be raised only twenty feet, such a rise would lay dry a wide belt of almost level ground, on which these ridges would appear conspicuously, not unlike those which occur on the south shores of lakes Erie and Ontario, and thus confirm the views of Mr. Whittlesey, that most of these ridges are not ancient beaches, but have been formed under water, by the action of currents.[1]

[1] Foster and Whitney's "Geology of the Lake Superior Land District." Part 2, p. 258.

Whittlesey describes no examples on existing coasts, but refers to them as familiar features and relegates to their category numerous inland ridges associated with earlier water surfaces in the basins of Lakes Erie, Ontario, and Michigan. He says that "their composition is universally coarse water-washed sand and fine gravel", while beaches consist of "clean beach sand and shingle"; and also that beaches are distinguished from subaqueous ridges by the fact "that the former are narrow and are steepest on the lake side, resembling miniature terraces."[1]

Having personally observed many of the inland ridges described by Whittlesey and recognized them as barriers, having failed or neglected to observe ridges of this subaqueous type in the Bonneville Basin, and having independent reason to believe that the waters of Lakes Michigan, Erie, and Ontario have recently advanced on their coasts, I leaped to the conclusion that the ridges seen by Desor beneath the water of Lake Michigan, as well as the subaqueous ridges mentioned without enumeration by Whittlesey, were formed as barriers or spits at the water surface and were subsequently submerged by a rise of the water.[2] In so doing I ignored an important observation by Andrews, who, writing of the beach at the head of Lake Michigan, describes "a peculiarity in the contour of the deposit, which is uniform in all the sand shores of this part of the coast. As you go out into the lake, the bottom gradually descends from the water line to the depth of about five feet, when it rises again as you recede from the shore, and then descends toward deep water, forming a subaqueous ridge or 'bar' parallel to the beach and some ten or twenty rods from the shore."[3] It is impossible to regard this sand ridge as a beach or barrier submerged by the rise of the lake, for it stands within the zone of action of storm waves, and no mole of loose debris can be assumed to successfully oppose their attack. It is to be viewed rather as a product of wave action, or of wave and current action, under existing relations of land and lake.

The subject is advanced by Russell, who visited the eastern shore of Lake Michigan in 1884. He says:

> Bars of another character are also formed along lake margins, at some distance from the land, which agree in many ways with true barrier bars, but differ in being

[1] Fresh-water Glacial Drift of the Northwestern States. By Charles Whittlesey. Smithsonian Contribution No. 197. Washington, 1866, pp. 17, 19.

[2] Fifth Ann. Rept. U. S. Geol. Survey, p. 111.

[3] Trans. Chicago Acad. Sci., vol. 2, p. 14.

composed of homogeneous, fine material, usually sand, and in not reaching the lake surface.

The character of structures of this nature may be studied about the shores of Lake Michigan, where they can be traced continuously for hundreds of miles. There are usually two, but occasionally three, distinct sand ridges; the first being about 200 feet from the land, the second 75 or 100 feet beyond the first, and the third, when present, about as far from the second as the second is from the first. Soundings on these ridges show that the first has about 8 feet of water over it, and the second usually about 12; between, the depth is from 10 to 14 feet. From many commanding points, as the summit of Sleeping Bear Bluff, for example, these submerged ridges may be traced distinctly for many miles. They follow all the main curves of the shore, without changing their character or having their continuity broken. They occur in bays as well as about the bases of promontories, and are always composed of clean, homogeneous sand, although the adjacent beach may be composed of gravel and boulders. They are not shore ridges submerged by a rise of the lake, for the reason that they are in harmony with existing conditions, and are not being eroded or becoming covered with lacustral sediments.

In bars of this character the fine debris arising from the comminution of shore drift appears to be accumulated in ridges along the line where the undertow loses its force; the distance of these lines from the land being determined by the force of the storms that carried the waters shoreward. This is only a suggested explanation, however, as the complete history of these structures has not been determined.[1]

In the survey of these lakes by the U. S. Engineers, numerous inshore soundings were made, and while these do not fall near enough together to determine the configuration of subaqueous ridges, they serve to show whether the profile of the bottom descends continuously from the beach lakeward. A study of the original manuscript sheets, which give fuller data than the published charts, discovers that bars similar to those described by Russell occur along the eastern coast of Lake Michigan wherever the bottom is sandy, being most frequently detectible at a depth of 13 feet, but ranging upward to 3 feet and downward to 18 feet. At the south end of the lake they are not restricted to the 5-foot zone indicated by Andrews, but range to 13 feet. A single locality of occurrence was found on the shore of Lake Erie, but none on Lake Ontario.

These ridges constitute an exception to the beach profile, and show that the theory of that profile given above is incomplete. Under conditions not yet apparent, and in a manner equally obscure, there is a rhythmic action along a certain zone of the bottom. That zone lies lower than the trough between the greatest storm waves, but the water upon it is violently oscil-

[1] Geol. Hist. of Lake Lahontan. pp. 92–93.

lated by the passing waves. The same water is translated lakeward by the undertow, and the surface water above it is translated landward by the wind, while both move with the shore current parallel to the beach. The rhythm may be assumed to arise from the interaction of the oscillation, the landward current, and the undertow.

LITTORAL DEPOSITION.

The material deposited by shore processes is, first, shore drift; second, stream drift, or the detritus delivered at the shore by tributary streams Increasing depth of water is in each case the condition of littoral deposition. The structures produced by the deposit of shore drift, although somewhat varied, have certain common features. They will be treated under the generic title of *embankments.* The structures produced by the deposit of stream drift are *deltas.*

EMBANKMENTS.

The current occupying the zone of the shore drift and acting as the coagent of littoral transportation has been described as slow, but it is inseparably connected with a movement that is relatively rapid. This latter, which may be called the off-shore current, occupies deeper water and is less impeded by friction. It may in some sense be said to drag the littoral current along with it. The momentum of the off-shore current does not permit it to follow the sinuosities of the water margin, and it sweeps from point to point, carrying the littoral current with it. There is even a tendency to generate eddies or return currents in embayments of the coast. The off-shore current is moreover controlled in part by the configuration of the bottom and by the necessity of a return current. The littoral current, being controlled in large part by the movements of the off-shore current, separates from the water margin in three ways: first, it continues its direction unchanged at points where the shore-line turns landward, as at the entrances of bays; second, it sometimes turns from the land as a surface current; third, it sometimes descends and leaves the water margin as a bottom current.

In each of these three cases deposition of shore drift takes place by reason of the divorce of shore currents and wave action. The depth to which wave agitation sufficient for the transportation of shore drift extends is small, and when the littoral current by leaving the shore passes into deeper waters the shore drift, unable to follow, is thrown down.

When the current holds its direction and the shore-line diverges, the embankment takes the form of a *spit*, a *hook*, a *bar*, or a *loop*. When the shore-line holds its course and the current diverges, whether superficially or by descent, the embankment usually takes the form of a *terrace*.

The Spit.—When a coast line followed by a littoral current turns abruptly landward, as at the entrance of a bay, the current does not turn with it, but holds its course and passes from shallow to deeper water. The water between the diverging current and coast is relatively still, although there is communicated to the portion adjacent to the current a slow motion in the same direction. The waves are propagated indifferently through the flowing and the standing water, and reach the coast at all points. The shore drift can not follow the deflected coast line, because the waves that beat against it are unaccompanied by a littoral current. It can not follow the littoral current into deep water, because at the bottom of the deep water there is not sufficient agitation to move it. It therefore stops. But the supply of shore drift brought to this point by the littoral current does not cease, and the necessary result is accumulation. The particles are carried forward to the edge of the deep water and there let fall.

In this way an embankment is constructed, and so far as it is built it serves as a road for the transportation of more shore drift. The direction in which it is built is that of the littoral current. It takes the form of a ridge following the boundary between the current and the still water. Its initial height brings it just near enough to the surface of the water to enable the wave agitation to move the particles of which it is constructed; and it is narrow. But these characters are not long maintained. The causes which lead to the construction of the beach and the barrier are here equally efficient, and cause the embankment to grow in breadth and in height until the cross-profile of its upper surface is identical with that of the beach.

The history of its growth is readily deduced from the configuration of its terminus, for the process of growth is there in progress. If the material is coarse the distal portion is very slightly submerged, and is terminated in the direction of growth by a steep slope, the subaqueous "earth-slope" of the particular material. If the material is fine the distal portion is more deeply submerged, and is not so abruptly terminated. The portion above water is usually narrow throughout, and terminates without reaching the extremity of the embankment. It is flanked on the lakeward side by a submerged plateau, at the outer edge of which the descent is somewhat steep. The profile of the plateau is that normal to the beach, and its contours are confluent with those of the beach or barrier on the main shore. Toward the end of the embankment its width diminishes, its outer and limiting contour turning toward the crest line of the spit and finally joining it at the submerged extremity.

The process of construction is similar to that of a railroad embankment the material for which is derived from an adjacent cutting, carted forward along the crest of the embankment and dumped off at the end; and the symmetry of form is often more perfect than the railway engineer ever accomplishes. The resemblance to railway structures is very striking in the case of the shores of extinct lakes.

As the embankment is carried forward and completed, contact between the current and the inshore water is at first obstructed and finally cut off, so that there is practically no communication of movement from one to the other at the extremity of the spit. At the point of construction the moving and the standing water are sharply differentiated, and there is hence no uncertainty as to the direction of construction. The spit not only follows the line between the current and still water, but aids in giving definition to that line, and eventually walls in the current by contours adjusted to its natural flow.

The Bar.—If the current determining the formation of a spit again touches the shore, the construction of the embankment is continued until it spans the entire interval. So long as one end remains free the vernacular of the coast calls it a *spit;* but when it is completed it becomes a *bar.* Figure 7 gives an ideal cross-section of a completed embankment.

The bar has all the characters of the spit except those of the terminal end. Its cross-profile shows a plateau bounded on either hand by a steep slope. The surface of the plateau is not level, but has the beach profile, is

BAR ON THE SHORE OF LAKE MICHIGAN.

From a photograph by I. C. Russell.

slightly submerged on the windward side and rises somewhat above the ordinary water level at the leeward margin. At each end it is continuous with a beach or barrier. It receives shore drift at one end and delivers it at the other.

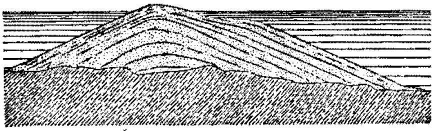


FIG. 7.—Section of a Linear Embankment.

The bar may connect an island with the shore or with another island, or it may connect two portions of the same shore. In the last case it crosses the mouth either of a bay or of a river. If maintained entire across the entrance to a bay it converts the water between it and the shore into a lagoon. At the mouth of a river its maintenance is antagonized by the outflowing current, and if its integrity is established at all it is only on rare occasions and for a short time. That is to say, its full height is not maintained; there is no continuous exposed ridge. The shore drift is, however, thrown into the river current, and unless that current is sufficient to sweep it into deep water a submerged bar is thrown across it, and maintains itself as a partial obstruction to the flow. The site of this submerged bar is usually also the point at which the current of the stream, meeting the standing water of the lake, loses its velocity and deposits the coarser part of its load of detritus. If the contribution of river drift greatly exceeds that of shore drift, a delta is formed at the river mouth, and this, by changing the configuration of the coast, modifies the littoral current and usually determines the shore drift to some other course. If the contribution of river drift is comparatively small it becomes a simple addition to the shore drift, and does not interrupt the continuity of its transportation. The bars at the mouths of small streams are constituted chiefly of shore drift, and all their characters are determined by their origin. The bars at the mouths of large streams are constituted chiefly of stream drift, and belong to the phenomena of deltas.

On a preceding page the fact was noted that the horizontal contours of a beach are more regular than those of the original surface against which it rests, small depressions being filled. It is now evident that the process of filling these is identical with that of bar construction. There is no trenchant line of demarkation between the beach and the bar. Each is a carrier of shore drift, and each employs its first load in the construction of a suitable road.

Plate IV represents a part of the east shore of Lake Michigan seen from the hill back of Empire Bluffs. In the extreme distance at the left stand the Sleeping Bear Bluffs, and somewhat nearer on the shore is a timbered hill, the lakeward face of which is likewise a sea-cliff. A bar connects the latter with the land in the foreground and divides the lagoon at the right from the lake at the left. The symmetry of the bar is marred by the formation of dunes, the lighter portion of the shore-drift being taken up by the wind and carried toward the right so as to initiate the filling of the lagoon.

Figure 8 is copied from the U. S. Engineer map of a portion of the south shore of Lake Ontario west of the mouth of the Genesee River. The orig-

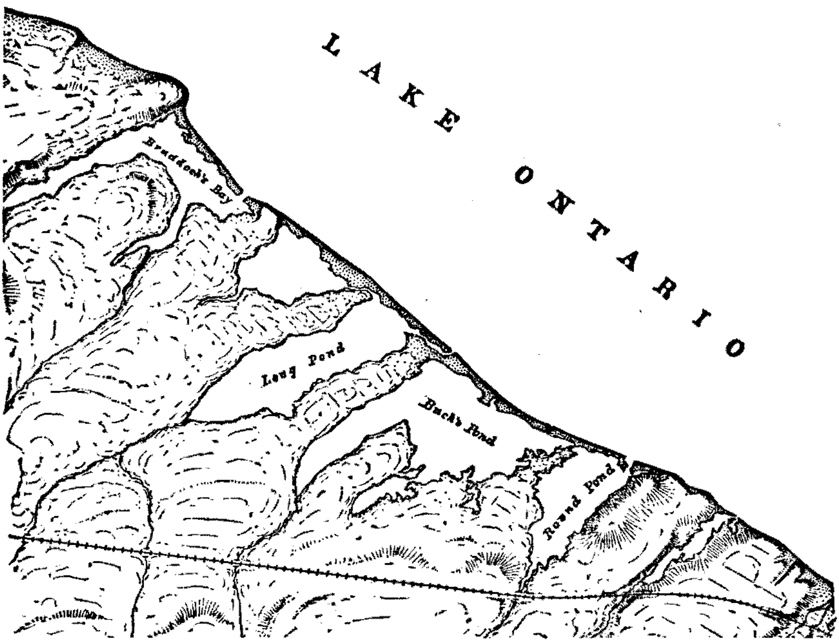


FIG. 8.—Map of Braddock's Bay and vicinity, N. Y., showing headlands connected by Bars.

inal contour of the shore was there irregular, consisting of a series of salient and reentrant angles. The waves have truncated some of the salients and have united them all by a continuous bar, behind which several bays or ponds are inclosed. The movement of the shore drift is in this case from northwest to southeast, and the principal source of the material is a point of land at the extreme west, where a low cliff shows that the land is being eaten by the waves.

The map in Figure 9 is also copied from one of the sheets published by the U. S. Engineers, and represents the bars at the head of Lake Superior. These illustrate several elements of the preceding discussion. In the first place they are not formed by the predominant winds, but by those which bring the greatest waves. The predominant winds are westerly, and produce no waves on thi scoast. The shore drift is derived from the south coast, and its motion is first westerly and then northerly. Two bars are exhibited, the western of which is now protected from the lake waves, and must have been completed before the eastern was begun. The place of deposition of shore drift was probably shifted from the western to the eastern by reason of the shoaling of the head of the lake. The converging shores should theoretically produce during easterly storms a powerful undertow, by which a large share of the shore drift would be carried lakeward and distributed over the bottom. The manner in which the bars terminate against the northern shore without inflection is explicable likewise by the theory of a strong undertow. If the return current were superficial the bars would be curved at their junctions with both shores.

FIG. 9.—Map of the head of Lake Superior, showing Bay Bars.

An instructive view of an ancient bar will be found in Pl. IX, representing a portion of the Bonneville shore line. The town of Stockton, Utah, appears at the right. The plain at the left was the bed of the lake. The storm waves, moving from left to right, carved the sea-cliff which appears at the base of the mountain at the left, and drifting the material toward the right built it into a great spit and a greater bar. The end of the spit is close to the town. The bar, which lies slightly lower, having been formed by the lake at a lower stage of its water, sweeps in a broad curve across the valley to the rocky hill on the opposite side, where the artist stood in making the sketch.

The Hook.—The line of direction followed by the spit is usually straight, or has a slight concavity toward the lake. This form is a function of the littoral current, to which it owes origin. But that current is not perpetual; it exists only during the continuance of certain determining winds. Other winds, though feebler or accompanied by smaller waves, nevertheless have systems of currents, and these latter currents sometimes modify the form of the spit. Winds which simply reverse the direction of the littoral current retard the construction of the embankment without otherwise affecting it; but a current is sometimes made to flow past the end of the spit in a direction making a high angle with its axis, and such a current modifies its form. It cuts away a portion of the extremity and rebuilds the material in a smaller spit joining the main one at an angle. If this smaller spit extends lakeward it is demolished by the next storm; but if it extends landward its position is sheltered, and it remains a permanent feature. It not infrequently happens that such accessory spits are formed at intervals during the construction of a long embankment, and are preserved as a series of short branches on the lee side.

It may occur also that a spit at a certain stage of its growth becomes especially subject to some conflicting current, so that its normal growth ceases, and all the shore drift transported along it goes to the construction of the branch. The bent embankment thus produced is called a *hook*.

The currents efficient in the formation of a hook do not cooperate simultaneously, but exercise their functions in alternation. The one, during the prevalence of certain winds, brings the shore drift to the angle and accumulates it there; the other, during the prevalence of other winds, demolishes the new structure and redeposits the material upon the other limb of the hook.

A HOOK. DUTCH POINT, GRAND TRAVERSE BAY, LAKE MICHIGAN.

From a photograph by I. C. Russell.

In case the land on which it is based is a slender peninsula or a small island, past which the currents incited by various winds sweep with little modification of direction by the local configuration, the hook no longer has the sharp angle due to the action of two currents only, but receives a curved form.

Hooks are of comparatively rare occurrence on lake shores, but abound at the mouths of marine estuaries, where littoral and tidal currents conflict.

Plate V represents a recurved spit on the shore of Lake Michigan, seen from a neighboring bluff. The general direction of its construction is from left to right, but storms from the right have from time to time turned its end toward the land and the successive recurvements are clearly discernible near the apex.

The mole enclosing Toronto harbor on the shore of Lake Ontario is a hook of unusual complexity, and the fact that its growth threatens to close the entrance to the harbor has led to its thorough study by engineers. Especially has its history been developed by Fleming in a classic essay to which reference has already been made. A hill of drift projects as a cape from the north shore of the lake. The greatest waves reaching it, those having the greatest fetch, are from the east (see Fig. 10), and the cooperating current flows from east to west. As the hill gradually yields to the waves, its coarser material trails westward, building a spit. The waves and currents set in motion by southwesterly winds carry the spit end northward, producing a hook. In the past the westward movement has been the more powerful and the spit has continued to grow in that direction, its northern edge being fringed with the sand ridges due to successive recurvements, but the shape of the bottom has introduced a change of conditions. The water at the west end of the spit is now deep, and the extension of the embankment is correspondingly slow. The northward drift, being no longer subject to frequent shifting of position, has cumulative effect on the terminal hook and gives it a greater length than the others. In the chart of the harbor (Fig. 11) the composite character of the mole is readily traced. It may

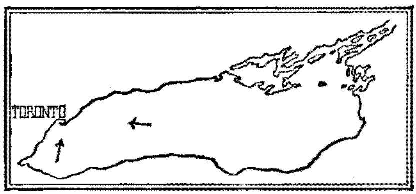


Fig. 10.—Diagram of Lake Ontario, to show the Fetch of Waves reaching Toronto from different directions.

also be seen that the ends of the successive hooks are connected by a beach, the work of waves generated within the harbor by northerly winds.[1] It will be observed furthermore that while the west end of the spit is continuously fringed by recurved ridges its eastern part is quite free from them. This does not indicate that the spit was simple and unhooked in the early stages of growth, but that its initial ridge has disappeared. As the cliff is eroded,

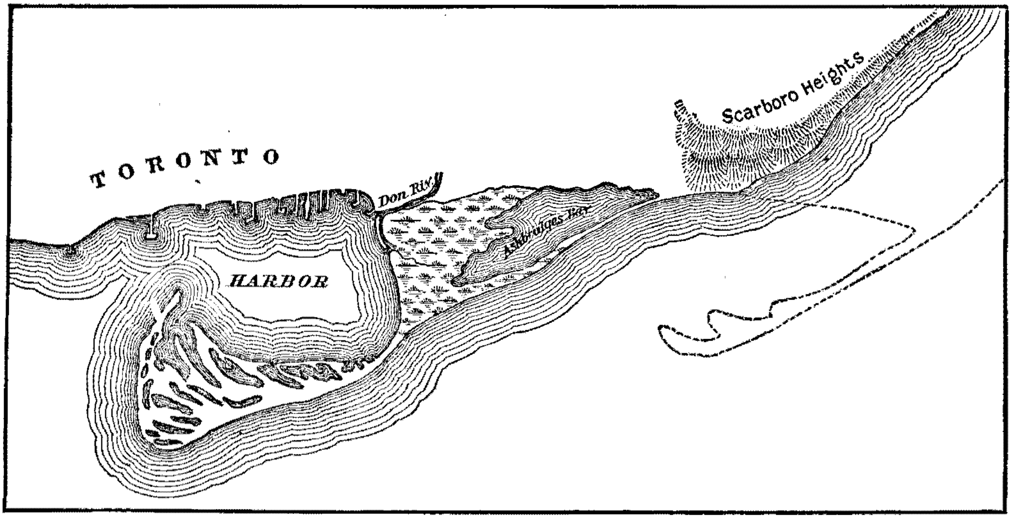


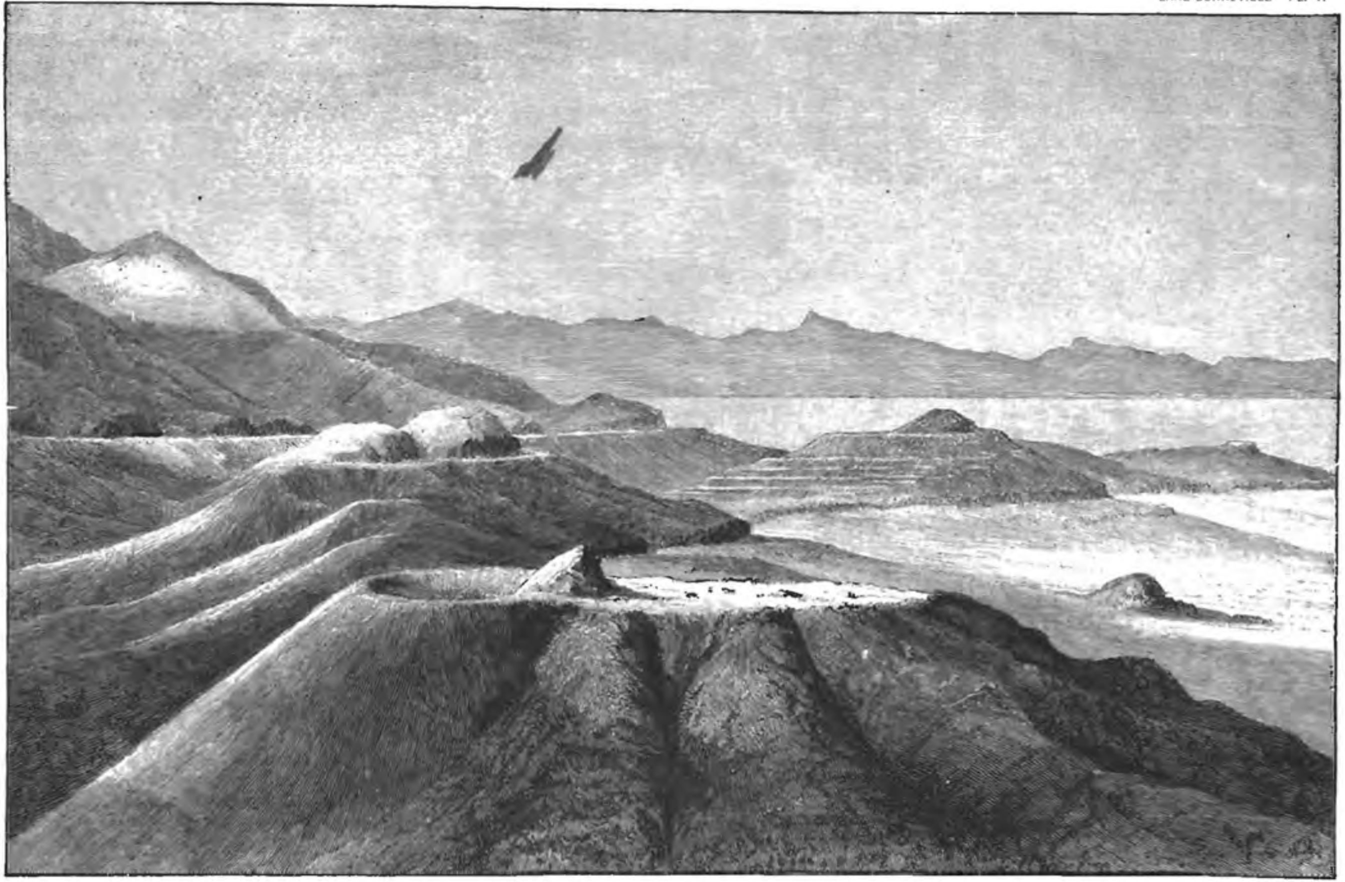
FIG. 11.—Map of the harbor and peninsula (Hook) at Toronto. From charts published by H. Y. Hind, in 1854.[2]

its position constantly shifts landward, the shore current follows, and the lakeward face of the spit is carried away so that the waves break over it, and then a new crest is built by the waves just back of the line of the old one.[3] By this process of partial destruction and renewal the spit retreats, keeping pace with the retreating cliff. At an earlier stage of the process the spit may have had the position and form indicated by the dotted outline, but whatever hooks fringed its inner margin have disappeared in the process of retreat.

[1] The marsh occupying part of the space between the spit and the mainland (Fig. 11) is only incidentally connected with the feature under discussion. A small stream, the Don, reaches the shore of the lake within the tract protected from waves by the hook and is thus enabled to construct a delta with its sediment.

[2] Report on the preservation and improvement of Toronto Harbor. In Supplement to Canadian Journal, 1854.

[3] At the present time the spit is divided near the middle, a natural breach having been artificially prevented from healing. The portion of the peninsula fringed by successive hooks stands as an island.



CUP BUTTE, A FEATURE OF THE BONNEVILLE SHORE-LINE.

The landward shifting illustrated by the Toronto hook affects many embankments, but not all. It ordinarily occurs when the embankment is built in deep water and the source of its material is close at hand. Wherever it is known that an embankment has at some time been breached by the waves, it may be assumed with confidence that retreat is in progress.

As retreat progresses the layers constituting the embankment are truncated at top, and new layers are added on the landward side. In the resulting structure the prevailing dip is landward (Fig. 12), and it is thereby distinguished from all other forms of lacustrine deposition. This structure was first described and explained by Fleming, who observed it in a railway cutting through an ancient spit.[1]

The Loop.—Just as the spit, by advancing until it rejoins the shore, becomes a bar, so the completed hook may with propriety be called a *loop* or a *looped bar.* There is, however, a somewhat different feature to which the name is more strikingly applicable. A small island standing near the main-land is usually furnished on each side with a spit streaming toward the land. These spits are composed of detritus eroded from the lakeward face of the island, against which beat the waves generated through the broad expanse. The currents accompanying the waves are not uniform in direction, but vary with the wind through a wide angle; and the spits, in sympathy with the varying direction of currents, are curved inward toward the island. If their extremities coalesce, they constitute together a perfect loop, resembling, when mapped, a festoon pendent from the sides of the island.

Such a loop in the fossil condition, that is, when preserved as a vestige of the shore of an extinct lake, has the form of a crater rim, the basin of the original lagoon remaining as an undrained hollow. The accompanying illustration (Pl. VI) represents an island of Lake Bonneville standing on the desert near what is known as the "Old River Bed." The nucleus of solid rock was in this instance nearly demolished before the work of the waves was arrested by the lowering of the water.

The Wave-built Terrace.—It has already been pointed out that when a separation of the littoral current from the coast line is brought about by a divergence of the current rather than of the coast line, there are two cases, in the

[1] Notes on the Davenport gravel drift. Canadian Journal, New Series, vol. 6, 1861, pp. 247–253.

first of which the current continues at the surface, while in the second it dives beneath the surface. It is now necessary to make a further distinction. The current departing from the shore, but remaining at the surface, may continue with its original velocity or it may assume a greater cross-section and a diminished velocity. In the first case the shore drift is built into a spit or other linear embankment. In the second case it is built into a terrace. The quantity of shore drift moved depends on the magnitude of the waves; but the speed of transit depends on the velocity of the current, and wherever that velocity diminishes, the accession of shore drift must exceed the transmission, causing accumulation to take place. This accumulation occurs, not at the end of the beach, but on its face, carrying its entire profile lakeward and producing by the expansion of its crest a tract of new-made land. If afterward the water disappears, as in the case of an extinct lake, the new-made land has the character of a terrace. A current which leaves the shore by descending, practically produces at the shore a diminution of flow, and the resulting embankment is nearly identical with that of a slackening superficial current.

The wave-built terrace is distinct from the wave-cut terrace in that it is a work of construction, being composed entirely of shore drift, while the wave-cut terrace is the result of excavation, and consists of the pre-existent terrane of the locality. The wave-built terrace is an advancing embankment, and its internal structure is characterized by a lakeward dip (Fig. 13). It is thus contrasted with the retreating embankment (Fig. 12).

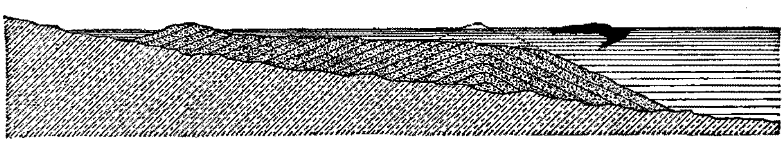


FIG. 12.—Section of a Linear Embankment retreating landward. The dotted line shows the original position of the crest.

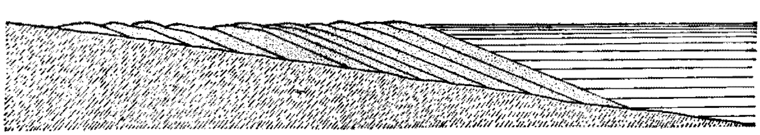


FIG. 13.—Section of a Wave-built Terrace.

The surface of the wave-built terrace, considered as a whole, is level, but in detail it is uneven, consisting of parallel ridges, usually curved. Each of these is referable to some exceptional storm, the waves of which threw the shore drift to an unusual height.

Where the shore drift consists wholly or in large part of sand, and the prevailing winds are toward the shore, the wave-built terrace gives origin to dunes, which are apt to mask its normal ribbed structure.

The locality most favorable for the formation of a wave-built terrace is the head of a triangular bay, up which the waves from a large body of water are rolled without obstruction. The wind sweeping up such a bay carries the surface of the water before it, and the only return current is an undertow originating near the head of the bay. The superficial advance of the water constitutes on each shore a littoral current conveying shore drift toward the head of the bay, and as these littoral currents are diminished and finally entirely dissipated by absorption in the undertow, the shore drift taken up along the sides of the bay is deposited. If the head of the bay is acute, the first embankment built is a curved bar tangent to the sides and concave toward the open water. To the face of this successive additions are made, and a terrace is gradually produced, the component ridges of which are approximately parallel. The sharpest curvature is usually at the extreme head of the bay.

The converging currents of such a bay give rise to an undertow which is of exceptional velocity, so that it transports with it not only the finest detritus but also coarser matter, such as elsewhere is usually retained in the zone of wave action. In effect there is a resorting of the material. The shore drift that has traveled along the sides of the bay toward its head, is divided into two portions, the finer of which passes out with the reinforced undertow, while the coarser only is built into the terrace.

The V-Terrace and V-Bar.—It remains to describe a type of terrace for which no satisfactory explanation has been reached. The shores of the ancient Pleistocene lakes afford numerous examples, but those of recent lakes are nearly devoid of them, and the writer has never had opportunity to examine one in process of formation. They are triangular in ground plan, and would claim the title of delta were it not appropriated, for they simulate the Greek letter more strikingly than do the river-mouth structures. They are built against coasts of even outline, and usually, but not always, upon slight salients, and they occur most frequently in the long, narrow arms of old lakes.

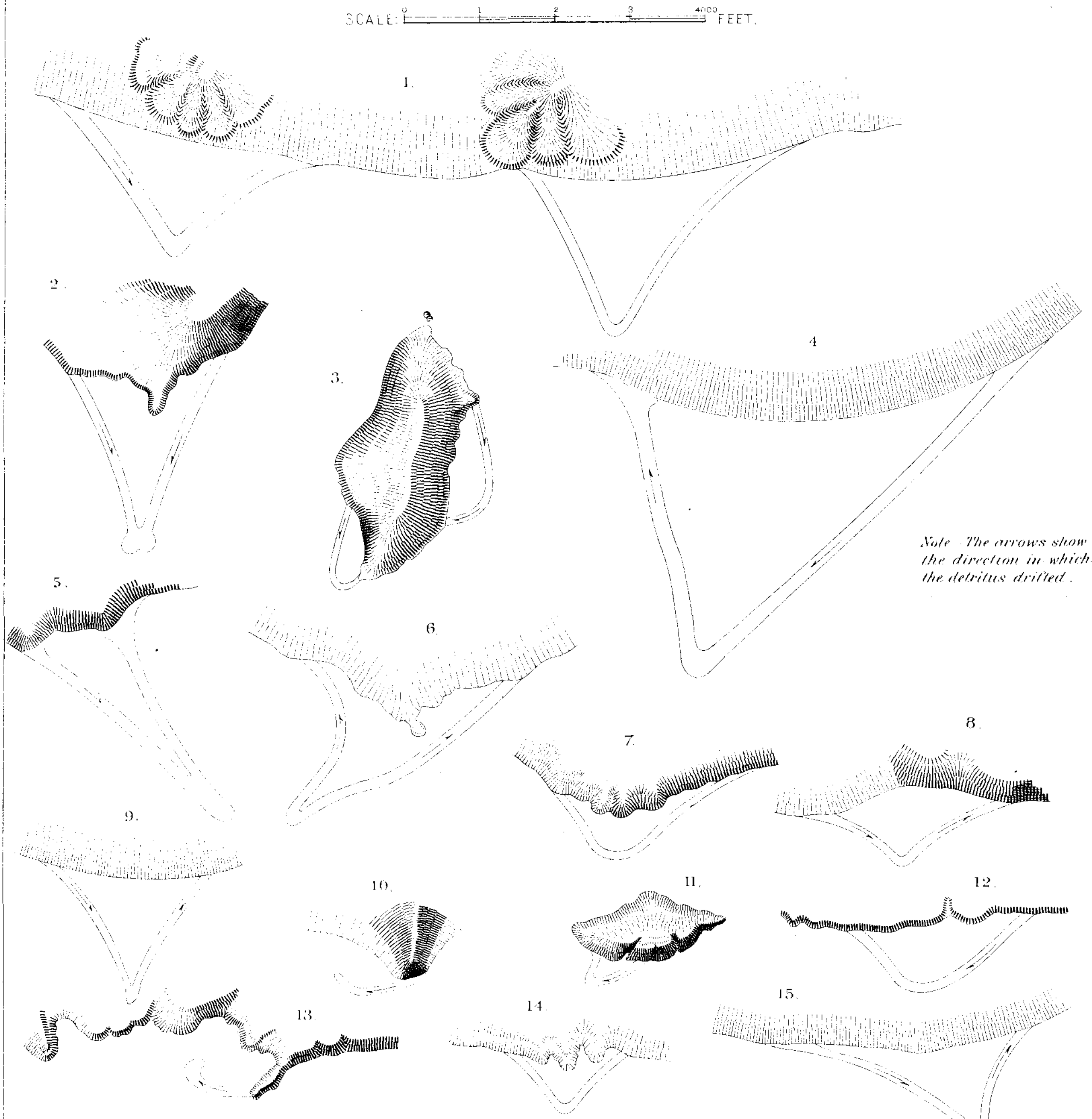
One side of the triangle rests against the land and the opposite angle points toward the open water. The free sides meet the land with short curves of adjustment, and appear otherwise to be normally straight, although they exhibit convex, concave, and sigmoid flexures. The growth is by additions to one or both of the free sides; and the nucleus appears always to have been a miniature triangular terrace, closely resembling the final structure in shape. In the Bonneville examples the lakeward slope of the terrace is usually very steep down to the line where it joins the preexistent slope of the bottom.

There seems no reason to doubt that these embankments, like the others, were built by currents and waves, and such being the case the formative currents must have diverged from the shore at one or both the landward angles of the terrace, but the condition determining this divergence does not appear.

In some cases the two margins appear to have been determined by currents approaching the terrace (doubtless at different times) from opposite directions; and then the terrace margins are concave outward, and their confluence is prolonged in a more or less irregular point. In most cases, however, the shore drift appears to have been carried by one current from the mainland along one margin of the terrace to the apex, and by another current along the remaining side of the terrace back to the mainland. The contours are then either straight or convex.

In Lake Bonneville it happened that after the best defined of these terraces had attained nearly their final width the lake increased in size, so that they were immersed beneath a few feet of water. While the lake stood at the higher level, additions were made to the terraces by the building of linear embankments at their outer margins. These were carried to the water surface, and a triangular lagoon was imprisoned at each locality. The sites of these lagoons are now represented by flat triangular basins, each walled in by a bar bent in the form of a **V**. These bars were at first observed without a clear conception of the terrace on which they were founded, and the name **V**-*bar* was applied. The **V**-bar, while a conspicuous feature of

PLATS OF LOOPED AND V-SHAPED EMBANKMENTS, OBSERVED ON THE SHORES OF LAKE BONNEVILLE.



1,	*Salt Marsh, Snake Valley.*	6,	*East Base, Deep Cr. Mts.*
2, 11,	*East Base of Beaver Creek Range.*	7, 14,	*side of Old River Bed.*
3,	*Reservoir Butte, Old River Bed.*	8, 9, 15,	*West Base of Frisco Mountain.*
4,	*Snowplow.*	10, 12	*Preuss Valley, near Wa-wa Spring.*
5,	*Point of the Mountain.*	13,	*Near Stockton.*

Julius Bien & Co. lith. Drawn by G. Thompson

the Bonneville shores, is not believed to be a normal feature of lakes maintaining a constant level.

DRIFTING SAND; DUNES.

The dune is not an essential shore feature, but is an accessory of frequent occurrence.

Dunes are formed wherever the wind drifts sand across the land. The conditions essential to their production are wind, a supply of sand, and sterility or the absence of a protective vegetal growth. In arid regions sterility is afforded by the climatic conditions, and the sand furnished by river bars laid bare at low water, and by the disintegration of sand rocks, is taken up by the wind and built into dunes; but where rain is abundant, accumulations of such sort are protected by vegetation, and the only sources of supply are shores, either modern or ancient.

Shore drift nearly always contains some sand, and is frequently composed exclusively thereof. The undertow carries off the clay, which might otherwise hold the sand particles together and prevent their removal by the wind; and pebbles and bowlders, which, by their superior weight oppose wind action, are less able to withstand the attrition of littoral transportation, and disappear by disintegration from any train of shore drift which travels a considerable distance. Embankments are therefore apt to be composed largely of sand; and the crests of embankments, being exposed to the air during the intervals between great storms, yield dry sand to the gentler winds.

The sand drifted from the crests of free embankments, such as barriers, spits, and bars, quickly reaches the water on one side or the other. What is blown to the lakeward side falls within the zone of wave action, and is again worked over as shore drift. What is blown to the landward side extends the area of the embankment, correspondingly encroaching on the lagoon or bay.

Sand blown from the crests of embankments resting against the land, such as beaches and terraces, will spread over the land if the prevailing wind is favorable. In cases where the prevailing wind is toward the lake the general movement of sand is, of course, in that direction, and it is merely returned to the zone of the waves and readded to the shore drift; but where the prevailing winds are toward the land, dunes are formed and slowly rolled forward by the wind. The supply of dry sand afforded by beaches is comparatively small, and dunes of magnitude are not often formed from it. The great sand magazines are wave-built terraces, and it is from these that the trains of sand so formidable to agriculture have originated.

The sands accumulated on the shores of lakes and oceans now extinct are sometimes so clean that vegetation acquires no foothold, and the wind still holds dominion. The "oak openings" of Western States are usually of this nature; and in the Great Basin there are numerous trains of dunes conveying merely the sand accumulated on the shores of the Pleistocene lakes.

One product of littoral deposition—the delta—remains undescribed; but this is so distinct from the embankment, not only in form but in process of construction, that its consideration will be deferred until the interrelations of the three processes already described have been discussed.

THE DISTRIBUTION OF WAVE-WROUGHT SHORE FEATURES.

Upon every coast there are certain tracts undergoing erosion; certain others receive the products of erosion, and the intervals are occupied by the structures peculiar to transportation. Let us now inquire what are the conditions determining these three phases of shore shaping.

It will be convenient to consider first the conditions of transportation. In order that a particular portion of shore shall be the scene of littoral transportation, it is essential, first, that there be a supply of shore drift; second, that there be shore action by waves and currents; and in order that the local process be transportation simply, and involve neither erosion nor deposition, a certain equilibrium must exist between the quantity of the shore drift on the one hand and the power of the waves and currents on the other. On the whole this equilibrium is a delicate one, but within certain narrow limits it is stable. That is to say, there are certain slight variations of the individual conditions of equilibrium, which disturb the equilibrium only in a manner tending to its immediate readjustment. For example, if the shore drift receives locally a small increment from stream drift, this increment, by adding to the shore contour, encroaches on the margin of the littoral current and produces a local acceleration, which acceleration leads to the removal of the obstruction. Similarly, if from some temporary cause there is a local defect of shore drift, the resulting indentation of the shore contour slackens the littoral current and causes deposition, whereby the equilibrium is restored. Or if the force of the waves is broken at some point by a temporary obstruction outside the line of breakers, as for example by a wreck, the local diminution of wave agitation produces an accumulation of shore drift whereby the littoral current is narrowed and thus accelerated until an adjustment is reached.

Outside the limits thus indicated everything which disturbs the adjustment between quantity of shore drift and capacity of shore agents leads either to progressive local erosion or else to progressive local deposition. The stretches of coast which either lose or gain ground are decidedly in excess of those which merely hold their own.

An excessive supply of shore drift over and above what the associated current and waves are competent to transport leads to deposition. This occurs where a stream of some magnitude adds its quota of debris. A moderate excess of this nature is disposed of by the formation of a wave-built terrace on the lee side of the mouth of the stream, that is, on the side toward which flows the littoral current accompanying the greatest waves. A great excess leads to the formation of a delta, in which the stream itself is the constructing agent and the influence of waves is subordinate.

On the other hand, there is a constant loss of shore drift by attrition, the particles in transit being gradually reduced in size until they are removed from the littoral zone by the undertow. As a result of the defect thus occasioned, a part of the energy of the waves is expended on the subjacent terrane, and the work of transportation is locally accompanied by a sufficient amount of erosion to replenish the wasting shore drift. For the maintenance of a continuous beach in a permanent position, it appears to be necessary that small streams shall contribute enough debris to compensate for the waste by attrition.

Theoretically, transportation must be exchanged for erosion wherever there is a local increase in the magnitude of waves, and for deposition where there is a local decrease of waves; but practically the proportions of waves are so closely associated with the velocities of the accompanying currents that their effects have not been distinguished.

The factor which most frequently, by its variation, disturbs the equilibrium of shore action is the littoral current. It has already been pointed out that wherever it leaves the shore, shore drift is deposited; and it is equally true that wherever it comes into existence by the impinging of an open-water current on the shore, shore drift is taken up and the terrane is eroded. It has been shown also that the retardation of the littoral current produces deposition, and it is equally true that its acceleration causes erosion. Every variation, therefore, in the direction or velocity of the current at the shore has a definite effect in the determination of the local shore process.

Reentrant angles of the coast are always, and reentrant curves are usually, places of deposition. The reason for this is twofold: first, currents which follow the shore move with diminished velocity in passing reentrants; second, currents directed toward the shore escape from reentrants only by undertow, and, as heretofore explained, build terraces at the heads of the embayments.

Salient angles are usually eroded, and salient curves nearly always, the reasons being, first, that a current following the shore is relatively swift opposite a salient, and, second, that a current directed toward the shore is apt to be divided by a salient, its halves being converted into littoral currents transporting shore drift in opposite directions *away* from the salient.

Some salient angles, on the contrary, grow by deposition. This occurs where the most important current approaches by following the shore and is thrown off to deep water by a salient. The most notable instances are found on the sides of narrow lakes or arms of lakes, in which case currents approaching from the direction of the length are accompanied by greater waves than those blown from the direction of the opposite shore, and therefore dominate in the determination of the local action.

It thus appears that there is a general tendency to the erosion of salients and the filling of embayments, or to the simplification of coast outlines. This tendency is illustrated not only by the shores of all lakes, but by the coasts of all oceans. In the latter case it is slightly diminished by the action of tides, which occasion currents tending to keep open the mouths of estuaries, but it is nevertheless the prevailing tendency. The idea which sometimes appears in popular writings that embayments of the coast are eaten out by the ocean is a survival of the antiquated theory that the sculpture of the land is a result of "marine denudation." It is now understood that the diversities of land topography are wrought by stream erosion.

Figure 8, representing about seven miles of the shore of Lake Ontario, illustrates the tendency toward simplification. Each bluff of the shore marks the truncation by the waves of a cape that was originally more salient. Each beach records the partial filling of an original bay. Each bar is a wave-built structure partitioning a deep reentrant from the open lake. The lagoons receive the detritus from the streams of the land and are filling; partly for this reason there is a local defect of shore drift, and the coast is receding by erosion; and by this double process the original reentrants are suffering complete effacement. For the original coast line—a sinuous contour on a surface modeled by glacial and fluvial agencies—will be substituted a relatively short line of simple curvature.

The simplification of a coast line is a work involving time, and the amount of work accomplished on a particular coast affords a relative measure of the time consumed. There are many modifying conditions—the fetch of waves, the off-shore depth, the material of the land, the original configuration, etc.—and these leave no hope of an absolute measure; but it is possible to distinguish the young coast from the mature. When a water level is newly established against land with sinuous contour, the first work of the waves is the production of the beach profile. On the gentlest slopes they do this by excavating the terrane at the point where they first break and throwing the material shoreward so as to build a barrier. On all other slopes they establish the profile by carving a terrace with its correlative cliff. The coarser products of terrace-cutting gather at the outer edge of the terrace, helping to increase its breadth; the finer fall in deeper water and help to equalize the off-shore depth. The terrace gradually increases by the double process of cutting and filling until it has attained a certain minimum width essential to the transportation of shore drift. This width is for each locality a function of the size of the greatest waves. Before it is reached, the fragments detached from the cliff linger but a short time on the face of the terrace; after a few excursions up and down the slope they come to rest at the edge of the deeper water. When it is reached—when the beach profile is complete—the excavated fragments torn from the cliff no longer escape from the zone of wave action, but are rolled to and fro by the waves of every storm, lose their angles by attrition, and are drifted along by the shore current. It may happen that the material of the cliff is a gravel, already rounded by some earlier and independent process, but when this is not the case, the cut-terraces of adolescent and mature coasts are distinguished by the angular forms on the one hand and the rounded forms on the other of the associated detritus. When the formation of shore drift has once been begun, its further development and the development of efficient shore currents are gradual and by reciprocation. The spanning of minor recesses of the coast-line by its beach helps to smooth the way for the shore current, and the current promotes the beach. Embankments come later, when ways have been straightened for the current and shore drift, and those first constructed usually attempt the partition of only small embayments. The more extended and powerful shore currents, competent to span the bays between the greater headlands, become possible only after minor rugosities of coast and bottom have disappeared.

Low but nearly continuous sea-cliffs mark the adolescent coast; simple contours and a cordon of sand, interspersed with high cliffs, mark the mature coast. As a result of the inconstancy of the relations of land and water, it is probable that all coasts fall under these heads, but Richthofen has sketched the features of the theoretic senile coast.[1] As sea-cliffs retreat and terraces grow broader the energy of the waves is distributed over a wider zone and its erosive work is diminished. The resulting defect of shore drift permits

[1] Führer für Forschungsreisende, p. 338.

the erosion of embankments, and the withdrawal of their protection extends the line of cliff; but eventually the whole line is driven back to its limit and erosion ceases. The cliffs, no longer sapped by the waves, yield to atmospheric agencies and blend with the general topography of the land. Shore drift is still supplied by the streams and is spread over the broad littoral shoal, where it lies until so comminuted by the waves that it can float away.

The length of the period of adolescence varies with local conditions. Where the waves are powerful, maturity comes sooner than where they are weak. It comes sooner, too, where the material to be moved by the waves is soft or incoherent than where it is hard and firm; and it comes early where the submerged contours and the contour at the water's edge have few irregularities. Different parts of the same coast accordingly illustrate different stages of development. The shores of Lake Bonneville are in general mature, but in small sheltered bays they are adolescent. The shore of Lake Ontario is in general mature, being traced on a surface of glacial drift, but near the outlet is a region of bare, hard rock disposed in promontories and islands, and there much of the coast is adolescent.

The classic "parallel roads" of Glen Roy in Scotland illustrate the adolescent type, and this although the local conditions favor rapid development. The smooth contours of the valley gave no obstruction to shore currents, depth and length of lake permitted the raising of large waves, and a mantle of glacial drift afforded material for shore drift; but the beach profile was not completed, the bowlders of the narrow terraces are still subangular, and there are no embankments. It is fairly inferred that the time represented by each shore-line was short.

STREAM WORK; THE DELTA.

The detritus brought to lakes by small streams is overwhelmed by shore drift and merges with it. The tribute of large streams, on the contrary, overwhelms the shore drift and accumulates in deltas. In the formation of a normal delta the stream is the active agent, the lake is the passive recipient, and waves play no essential part.

The process of delta formation depends almost wholly on the following law: *The capacity and competence of a stream for the transportation of detritus are increased and diminished by the increase and diminution of the velocity.* The capacity of a stream is measured by the total load of debris of a given fineness which it can carry. Its competence is measured by the maximum size of the particles it can move. A swift current is able to transport both more matter and coarser matter than a slow current. The competence depends on the velocity of the water at the bottom of the channel, for the largest particles the stream can move are merely rolled along the bottom. Finer particles are lifted from the bottom by threads of current tending more or less upward, and before they sink again are carried forward by the general flow. Their suspension is initiated by the bottom current, but the length and speed of their excursion depend on the general velocity of the current. Capacity is therefore a function of the velocity of the more superficial threads of current as well as of those which follow the bottom.

Suppose that a river freighted with the waste of the land is newly made tributary to a lake. Its water flows to the shore, and shoots out thence over[1] the relatively still lake water until its momentum has been communicated by friction to so large a body of water as to practically dissipate its velocity. From the shore outward the velocity at the bottom is the velocity of the lake water and not that of the river water, and is inconsiderable. The entire load consequently sinks to a final resting place and becomes a deposit. The coarse particles go down in immediate contiguity to the shore. The finest are carried far out before they escape from the superficial stratum of river water.

The sinking of the coarse material at the shore has the effect of building out a platform at the level of the bottom of the river channel. Postulate the construction of this platform for some distance from the shore without any modification of the longitudinal profile of the river, the river surface descending to the shore and then becoming horizontal. Evidently, the horizontal portion has no energy of descent to propel it, and yet is opposed by friction; its velocity is, therefore, retarded, its capacity and competence are

[1] It is said that some glacier-fed streams on entering lakes pass under instead of over the lake water and that peculiar delta features result, but these are not fully described.

consequently diminished, and it drops some of its load. The fall of detritus builds up the bottom at the point where it takes place, and causes a checking of the current immediately above (up stream). This in turn causes a deposit; and a reciprocation of retardation and deposition continues until the profile of the stream has acquired a continuous grade from its mouth at the extremity of the new platform backward to some steeper part of its channel—a continuous grade sufficient to give it a velocity adequate to its load. The postulate is, of course, ideal. The river does not in fact build a level bed and afterward change it to a slope, but carries forward the whole work at once, maintaining continuously an adjustment between its grade and its work. Moreover, since the deposition begins at some distance from the mouth, the lessening load does not require a uniform grade and does not produce it. The grade diminishes gradually lakeward to the foot of the deposit slope, so that the longitudinal profile is slightly concave upward. At the head of the deposit slope there is often an abrupt change of grade. At its foot, where the maximum deposit is made, there is an abrupt change of a double character; the incline of the river surface is exchanged for the horizontal plane of the lake surface; the incline of the river bottom is exchanged for the steeper incline of the delta front.

The river current is swifter in the middle than at the sides, and on a deposit slope, where velocity is nicely adjusted to load, the slight retardation at the sides leads to deposition of suspended matter. A bank is thus produced at either hand, so that the water flows down an elevated sluice of its own construction. The sides are built up pari passu with the bottom, but inasmuch as they can be increased only by overflow, they never quite reach the flood level of the water surface. A river thus contained, and a river channel thus constructed, constitute an unstable combination. So long as the bank approximates closely to the level of the surface at flood stage, the current across the bank is slower than the current of the stream, and deposits silt instead of excavating; but whenever an accidental cause so far lowers the bank at some point that the current across it during flood no longer makes a deposit, there begins an erosion of the bank which increases rapidly as the volume of escaping water is augmented. A side channel is thus produced, which eventually becomes deeper than the main or original channel and draws in the greater part or perhaps all of the water. The ability of the new channel to drain the old one depends on two things: first, the outer slope of the bank, from the circumstances of its construction, is steeper than the descent of the bottom of the channel; second, the first-made channel, although originally following the shortest route to the lake, has so far increased its length by the extension of its mouth that the water escaping over its bank may find a shorter route. The river channel is thus shifted, and its mouth is transferred to a new point on the lake shore.

Repetition of this process transfers the work of alluvial deposition from place to place, and causes the river to build a sloping plain instead of a simple dike. The lower edge of the plain is everywhere equidistant from the head of the deposit slope, and has therefore the form of a circular arc. The inclination is in all directions the same, varying only with the diminishing grade of the deposit slope, and the form of the plain is thus approximately conic. It is, in fact, identical with the product of land-shaping known as the alluvial cone or alluvial fan. The symmetry of the ideal form is never attained in fact, because the process of shifting implies inequality of surface, but the approximation is close in cases where the grade of the deposit slope is high, or where the area of the delta is large as compared with the size of the channel.

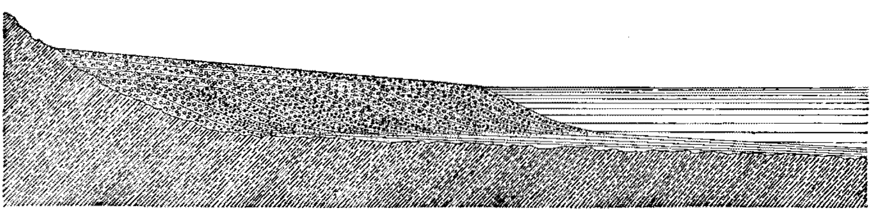


FIG. 14.—Section of a Delta.

At the lake shore the manner of deposition is different. The heavier and coarser part of the river's detrital load, that which it pushes and rolls along the bottom instead of carring by suspension, is emptied into the lake and slides down the face of the delta with no impulse but that given by its own weight. The slope of the delta face is the angle of repose of this coarse material, subject to such modification as may result from agitation by waves.

The finer part of the detritus, that which is transported by suspension, is carried beyond the delta face, and sinks more or less slowly to the bottom. Its distribution depends on its relative fineness, the extremely fine material being widely diffused, and the coarser falling near the foot of the delta face. The depth of the deposit formed from suspended material is greatest near the delta and diminishes gradually outward, so that the slope of the delta face merges by a curve with the slope of the bottom beyond.

As the delta is built lakeward, the steeply inclined layers of the delta face are superposed over the more level strata of the lake bottom, and in turn come to support the gently inclined layers of the delta plain, so that any vertical section of a normal delta exhibits at the top a zone of coarse material, bedded with a gentle lakeward inclination, then a zone of similar coarse material, the laminations of which incline at a high angle, and at bottom a zone of fine material, the laminations of which are gently inclined and unite by curves with those of the middle zone.

The characters of the fossil delta, or the delta as it exists after the desiccation of the lake concerned in its formation, are as follows: The upper surface is a terrace with the form of an alluvial fan. The lower slope or face is steep, ranging from 10° to 25°; it joins the upper slope by an angle and the plain below by a curve. The line separating the upper surface from the outer slope or face is horizontal, and, in common with all other horizontal contours of the structure, is approximately a circular arc. The upper or landward limit of the upper surface is a line horizontally uneven, depending on the contours of the antecedent topography The lower limit of the face is a vertically uneven line, depending on the antecedent topography as modified by lake sediments. The material is detrital and well rounded; it exhibits well-marked lines of deposition, rarely taking the character of bedding. The structure as seen in section is tripartite (Fig. 15). In the upper division the lines of deposition are parallel to the upper surface of the delta; in the middle division they are parallel to the steep outer face, and in the lower division they are gently inclined. The separation of the middle division from the lower is obscure. Its separation from the upper is definite and constitutes a horizontal plane. The fossil delta is invariably divided into two parts by a channel running from its apex to some part of its periphery and occupied by a stream, the agent of its construction becoming, under changed conditions of base level, the agent of demolition.

The fan-like outline of the normal delta is modified wherever wave action has an importance comparable with that of stream action. Among the great variety of forms resulting from the combination of the two agencies, there is one which repeats itself with sufficient frequency to deserve special mention. It occurs where the force of the waves is considerable and the amount of shore drift brought by them to the delta is inconsiderable. In such case the shore current from either direction is deflected by the mass of the delta, and wave action adjusts the contour of the delta to conformity with the deflected shore current. If the wave influences from opposite directions are equal, the delta takes the form of a symmetric triangle similar to that of the V-terrace.

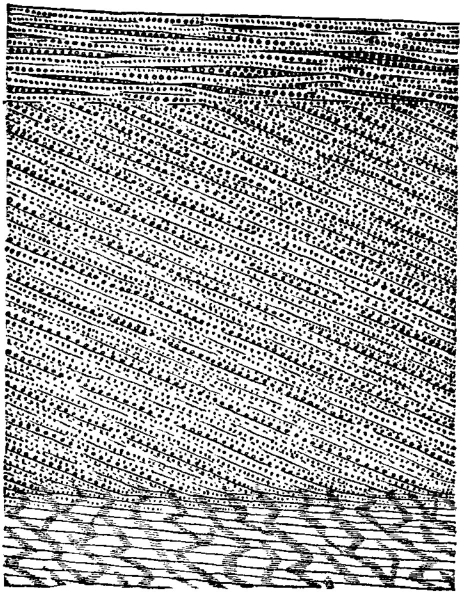


FIG. 15.—Vertical section in a Delta, showing the typical succession of strata.

Numerous illustrations are to be seen on the shores of Seneca and Cayuga Lakes, where the conditions are peculiarly favorable. The lake is long and narrow, so that all the efficient wave action is associated with strong shore currents, and these alternate in direction. The predominant rock of the sides is a soft shale, so easily triturated by the waves that the entire product of its erosion escapes with the undertow, and no shore drift remains. The sides are straight, and each tributary stream builds out a little promontory at its mouth, to which the waves give form. Some of these triangular deltas embody perfectly the Greek letter, but they turn the apex toward the water instead of toward the land.

ICE WORK; THE RAMPART.

This feature does not belong to lakes in general, but is of local and exceptional occurrence. It was named the "Lake Rampart" by Hitchcock, who gave the first satisfactory account of its origin.[1] Earlier observations, containing the germ of the explanation of the phenomenon, were made by Lee[2] and Adams.[3] A later and independent explanation was given by White.[4]

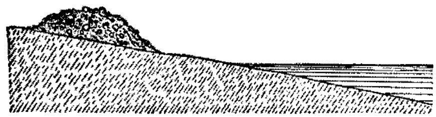


FIG. 16.—Section of a Rampart.

In ignorance of Hitchcock's description, I gave credit in the Fifth Annual Report of the U. S. Geological Survey to White, and myself proposed the name "Shore Wall." I now substitute Hitchcock's name, "Rampart", being moved thereto not only by the priority and the eminent fitness of the name, but by the consideration that "Shore Wall" is liable to be confounded with "Sea Wall", a term applied on some marine coasts to steep-faced embankments of shingle.

The ice on the surface of a lake expands while forming, so as to crowd its edge against the shore. A further lowering of temperature produces contraction, and this ordinarily results in the opening of vertical fissures. These admit the water from below, and by the freezing of that water they are filled, so that when expansion follows a subsequent rise of temperature the ice cannot assume its original position. It consequently increases its total area and exerts a second thrust upon the shore. Where the shore is abrupt, the ice itself yields, either by crushing at the margin or by the formation of anticlinals elsewhere; but if the shore is generally shelving, the margin of the ice is forced up the acclivity, and carries with it any bowlders or other loose material about which it may have frozen. A second lowering of temperature does not withdraw the protruded ice margin, but initiates other cracks and leads to a repetition of the shoreward thrust. The process is repeated from time to time during the winter, but ceases with the melting of

[1] Lake Ramparts in Vermont. By Chas. H. Hitchcock. In Proc. Am. Ass. Adv. Sci., vol. 13, 1860, p. 335.

[2] C. A. Lee. Am. Jour. Sci., vol. 5, 1822, pp. 34–37, and vol. 9, 1825, pp. 239–241.

[3] J. Adams. Am. Jour. Sci., vol. 9, 1825, pp. 136–144.

[4] C. A. White. Am. Naturalist, vol. 2, 1869, pp. 146–149.

the ice in the spring. The ice formed the ensuing winter extends only to the water margin, and by the winter's oscillations of temperature can be thrust landward only to a certain distance, determined by the size of the lake and the local climate. There is thus for each locality a definite limit, beyond which the projection of bowlders cannot be carried, so that all are deposited along a common line, where they constitute a wall or rampart.

The base of a rampart stands somewhat above and beyond the ordinary margin of the water. It is parallel to the water margin, following its inflections. Its size is probably determined in fact by the supply of material, but there must also be a limit dependent on the strength of the ice formed in the given locality. Its material is usually coarse, containing bowlders such as the waves generated on the same lake would be unable to move. These may be either smooth or angular, heavy or light, the process of accumulation involving no discrimination.

Ramparts are not found on the margins of large lakes, for whatever record the ice of winter may make is obliterated by the storm waves of summer. Neither do they occur on the shores of very deep lakes, for such do not admit of a heavy coating of ice; and for the same reason they are not found in warm climates. So far as the writ is aware, they have never been found in the fossil condition, except that in a single instance a series of them serves to record very recent changes of level.

SUBMERGENCE AND EMERGENCE.

In the preceding discussion the general relation of the water surface to the land has been assumed to be constant. In point of fact it is subject to almost continuous change, and its mutations modify the products of littoral shaping.

Lakes with outlet lower their water surfaces by corrading the channel of outflow. Lakes without outlet continually oscillate up and down with changes of climate; and finally, all large lakes, as well as the ocean, are affected by differential movements of the land. The series of displacements which in the geologic past has so many times revolutionized the distribution of land and water, has not ceased; and earth movements are so nearly universal at the present time that there are few coasts which betray no symptoms of recent elevation or subsidence. In this place it is unnecessary to consider whether the relation of water surface to land is affected by mutations of the one or of the other; and the terms emergence and submergence will be used with the understanding that they apply to changes in the relation without reference to causes of change.

The general effect of submergence or emergence is to change the horizon at which shore processes are carried on; and if a considerable change of level is effected abruptly, the nature of the processes and the character of their products are not materially modified. A submerged shore-line retains its configuration until it is gradually buried by sediments. An emerged shore-line is subjected to slow destruction by atmospheric agencies. Only the delta is rapidly attacked, and that is merely divided into two parts by the stream which formed it. In the case of submergence the new shore constructed at a higher horizon is essentially similar to the one submerged. In the case of emergence the new shore constructed at a lower horizon rests upon the smooth contours wrought by lacustrine sedimentation, and, finding in the configuration little that is incongruous with its shore currents, carves few cliffs and builds few embankments. The barrier is usually one of its characteristic elements.

A slow and gradual submergence modifies the products of littoral action. The erosion of sea-cliffs is exceptionally rapid, because the gradually deepening water upon the wave-cut terraces relieves the waves from the task of carving the terraces and enables them to spend their full force against the cliffs. The cliffs are thus beaten back before the advancing tide, and their precipitous character is maintained with constant change of position.

A rhythm is introduced in the construction of embankments. For each level of the water surface there is a set of positions appropriate to the initiation of embankments, and with an advancing tide these positions are successively nearer and nearer the land; but with the gradual advance of water the position of embankments is not correspondingly shifted. The embankment constructed at a low stage controls the local direction of the shore current, even when its crest is somewhat submerged, and by this control it determines the shore drift to follow its original course. It is only when the submergence is sufficiently rapid to produce a considerable depth of water over the crest of the embankment that a new embankment is initiated behind it. The new embankment in turn controls the shore current, and by a repetition of the process a series of embankments is produced whose crests differ in height by considerable intervals.

A slow and gradual emergence causes the waves, at points of excavation, to expend their energies upon the terraces rather than the cliffs. No great cliffs are produced, but a wave-cut terrace is carried downward with the receding tide. There is now no rhythm in the construction of embankments. At each successive lower level the shore drift takes a course a little farther lakeward, and is built into a lower embankment resting against the outer face of the one just formed.

The delta is very sensitive to emergence. As soon as the lake water falls from its edge, the formative stream, having now a lower point of discharge, ceases to throw down detritus and begins the corrasion of its channel. It ceases at the same time to shift its course over the surface of the original delta, but retains whatever position it happened to hold when the emergence was initiated. Coincidently it begins the construction of a new or secondary delta, the apex of which is at the outer margin of the original structure. With continuous emergence a series of new deltas are initiated at points successively farther lakeward, and there is produced a continuous descending ridge divided by the channel of the stream.

THE DISCRIMINATION OF SHORE FEATURES.

A shore is the common margin of dry land and a body of water. The elements of its peculiar topography are little liable to confusion so long as they are actually associated with land on one side and water on the other; but after the water has been withdrawn, their recognition is less easy. They consist merely of certain cliffs, terraces, and ridges; and cliffs, terraces, and ridges abound in the topography of land surfaces. In the following pages the topographic features characteristic of ancient shores will be compared and contrasted with other topographic elements likely to create confusion.

Such a discrimination as this has not before been attempted, although the principal distinctions upon which it is based have been the common property of geologists for many years. The contrast of stream terraces with shore terraces was clearly set forth by Dana in the American Journal of Science in 1849, and has been restated by Geikie in his Text-Book of Geology. It was less clearly enunciated by the elder Hitchcock in his Illustrations of Surface Geology.

CLIFFS.

A cliff is a topographic facet, in itself steep, and at the same time surrounded by facets of less inclination. The only variety belonging to the phenomena of shores is that to which the name "sea-cliff" has been applied. It will be compared with the cliff of differential degradation, the stream cliff, the coulée edge, the fault scarp, and the land-slip cliff.

The Cliff of Differential Degradation.—It is a familiar fact that certain rocks, mainly soft, yield more rapidly to the agents of erosion than certain other rocks, mainly hard. It results from this, that in the progressive degradation of a country by subaerial erosion the minor reliefs are generally occupied by hard rocks while the minor depressions mark the positions of soft rocks. Where a hard rock overlies one much softer, the erosion of the latter proceeds so rapidly that the former is sapped, and being deprived of its support falls away in blocks, and is thus wrought at its margin into a cliff. In regions undergoing rapid degradation such cliffs are exceedingly abundant.

It is the invariable mark of a cliff of differential degradation that the rock of the lower part of its face is so constituted as to yield more rapidly to erosion than the rock of the upper part of its face. It is strictly dependent on the constitution and structure of the terrane. It may have any form, but since the majority of rocks are stratified in broad, even sheets, and since the most abrupt alternations of texture occur in connection with such stratification, a majority of cliffs of differential degradation exhibit a certain uniformity and parallelism of parts. The crest of such a cliff is a line parallel to the base, and other associated cliffs run in lines approximately parallel. The most conspicuous of the cliffs of stratified rocks occur where the strata are approximately horizontal; and these more often than any others have been mistaken for sea-cliffs.

The Stream Cliff.—The most powerful agent of land erosion is the running stream, and, in regions undergoing rapid degradation, corrasion by streams so far exceeds the general waste of the surface that their channels are cut down vertically, forming cliffs on either hand. These cliffs are afterward maintained by lateral corrasion, which opens out the valley of the stream after the establishment of a base level has checked the vertical corrasion. Such cliffs are in a measure independent of the nature of the rock, and are closely associated with the stream. They stand as a rule in pairs facing each other and separated only by the stream and its flood plain. The base of each is a line inclined in the direction of the stream channel and in the same degree. The crest is not parallel thereto, but is an uneven line conforming to no simple law.

The Coulée Edge.—The viscosity of a lava stream is so great, and this viscosity is so augmented as its motion is checked by gradual cooling, that its margin after congelation is usually marked by a cliff of some height. The distinguishing characters of such a cliff are that the rock is volcanic, with the superficial features of a subaerial flow. It has probably never been mistaken for a sea-cliff, and receives mention here only for the sake of giving generality to the classification of cliffs.

The Fault Scarp.—The faulting of rocks consists in the relative displacement of two masses separated by a fissure. The plane of the fissure is usually more or less vertical, and by virtue of the displacement one mass is made to project somewhat above the other. The portion of the fissure wall thus brought to view constitutes a variety of cliff or escarpment, and has been called a fault scarp. In the Great Basin such scarps are associated with a great number of mountain ranges, appearing generally at their bases, just where the solid rock of the mountain mass is adjoined by the detrital foot slope. They occasionally encroach upon the latter, and it is in such case that they are most conspicuous as well as most likely to be mistaken for sea-cliffs. Although in following the mountain bases they do not vary greatly in altitude, yet they never describe exact contours, but ascend and descend the slopes of the foot hills. The crest of such a cliff is usually closely parallel to the base for long distances, but this parallelism is not absolute. The two lines gradually converge at either end of the displacement. In exceptional instances they converge rapidly, giving the cliff a somewhat abrupt termination, and in such case a new cliff appears en échelon, continuing the displacement with a slight offset. In Chapter VIII these cliffs are described at length and illustrated by views and diagrams.

The Land-Slip Cliff.—The land-slip differs from the fault chiefly in the fact that it is a purely superficial phenomenon, having its whole history upon a visible external slope. It occurs usually in unconsolidated material, masses of which break loose and move downward short distances. The cliffs produced by their separation from the general or parent mass, are never of great horizontal extent, and have no common element of form except that they are concave outward. They frequently occur in groups, and are apt to contain at their bases little basins due to the backward canting which forms part of the motion of the sliding mass.

Comparison.—The sea-cliff differs from all others, first, in that its base is horizontal, and, second, in that there is associated with it at one end or other a beach, a barrier, or an embankment. A third valuable diagnostic feature is its uniform association with the terrace at its base; but in this respect it is not unique, for the cliff of differential degradation often springs from a terrace. Often, too, the latter is nearly horizontal at base, and in such case the readiest comparative test is found in the fact that the sea-cliff is independent of the texture and structure of the rocks from which it is carved, while the other is closely dependent thereon.

The sea-cliff is distinguished from the stream-cliff by the fact that it faces an open valley broad enough and deep enough to permit the generation of efficient waves if occupied by a lake. It is distinguished from the coulée edge by its independence of rock structure and by its associated terrace. It differs from the fault scarp in all those peculiarities which result from the attitude of its antecedent; the water surface concerned in the formation of the sea-cliff is a horizontal plane; the fissure concerned in the formation of the fault scarp is a less regular but essentially vertical plane. The former crosses the inequalities of the preexistent topography as a contour, the latter as a traverse line.

The land-slip cliff is distinguished by the marked concavity of its face in horizontal contour. The sea-cliff is usually convex, or, if concave, its contours are long and sweeping. The former is distinguished also by its discontinuity.

TERRACES.

A terrace is a horizontal or nearly horizontal topographic facet interrupting a steeper slope. It is a limited plain, from one edge of which the ground rises more or less steeply, while from the opposite edge it descends more or less steeply. It is the "tread" of a topographic step.

Among the features peculiar to shores are three terraces: the wave-cut, the wave-built, and the delta. These will be compared with the terrace by differential degradation, the stream terrace, the moraine terrace, the fault terrace, and the land-slip terrace.

The Terrace by Differential Degradation.—The same general circumstances of rock texture which under erosion give rise to cliffs produce also terraces, but the terraces are of less frequent occurrence. The only case in which they are at all abundant, and the only case in which they need be discriminated from littoral terraces, is that in which a system of strata, heterogeneous in texture and lying nearly horizontal, is truncated, either by a fault or by some erosive action, and is afterwards subjected on the truncated section to atmospheric waste. The alternation of hard and soft strata gives rise under such circumstances to a series of alternating cliffs and terraces, the outcrop of each hard stratum appearing in a more or less vertical cliff, and the outcrop of each soft stratum being represented by a gently sloping terrace, united to the cliff above by a curve, and, in typical examples, separated from the cliff below by an angle.

The length of such terraces in the direction of the strike is usually great as compared with their width from cliff to cliff. They are never level in cross profile, but (1) rise with gradually increasing slope from the crest of one cliff to the base of the next, or (2) descend from the crest of one cliff to a medial depression, and thence rise with gradually increasing slope to the base of the next. The first case arises where the terrace is narrow or the dip of the strata is toward the lower cliff, the second case where the terrace is broad *and* the dip of the rocks is toward the upper cliff. In the first case the drainage is outward to the edge of the lower cliff; in the second it is toward the medial depression, whence it escapes by the narrow channels carved through the rock of the lower cliff.

The Stream Terrace.—The condition of rapid erosion in any region is uplift. In a tract which has recently been elevated, the rate of degradation is unequal, the waste of the water channels being more rapid than that of the surface in general, so that they are deeply incised. Eventually, however, the corrasion of the water channels so reduces their declivities that the velocities of current suffice merely for the transportation outward of the detritus disengaged by the general waste of surface. In other words, a base level is reached. Then the process of lateral corrasion, always carried on to a certain extent, assumes prominence, and its results are rendered conspicuous. Each stream wears its banks, swinging from side to side in its valley, always cutting at one side, and at the other building a shallow deposit of alluvium, which constitutes its flood plain. The valley, having before consisted of the river channel margined on either side by a cliff, now consists of a plain bounded at the sides by cliffs and traversed by the river channel.

If now the corrasion of the stream bed is accelerated by a new uplift or other cause, a smaller valley is excavated within the first and at a lower level. So much of the original flood plain as remains constitutes terraces flanking the sides of the new valley. Outwardly one of these terraces is bounded by the base of the old line of cliffs, which may by decay have lost their vertical habit. Inwardly it is bounded by the crest of the new line of cliffs produced by lateral corrasion.

Acceleration of downward corrasion is brought about in many ways. As already mentioned, it may be produced by a new uplift, and this stimulus is perhaps the most potent of all. It is sometimes produced by the downthrow of the tract to which the streams discharge, or, what is nearly the same thing, by the degradation of stream channels in that tract. It is also brought about, within a certain range of conditions, by increase of rainfall; and finally, it always ensues sooner or later from the defect of transported material. The general waste of the originally uplifted tract undergoes, after a long period, a diminution in rapidity. The streams have therefore less detritus to transport. Their channels are less clogged, and they are enabled to lower them by corrasion. Perhaps it would be better to say that after the immediate consequences of uplift have so far passed away that an equilibrium of erosive action is established, the degradation of the entire tract proceeds at a slow continuous rate, the slight variations of which are in a sense accidental. Lateral corrasion under such circumstances coexists in all stream channels with downward corrasion, and is the more important process; but the horizon of its action is continuously lowered by the downward corrasion. The terraces which result represent only the stages of a continuous process.

In a great number of stream valleys, not one but many ancient flood plains find record in terraces, so that the stream terrace is a familiar topographic feature.

When a stream meandering in a flood plain encroaches on a wall of the valley and corrades laterally, it carries its work of excavation down to the level of the bottom of its channel; and afterward, when its course is shifted to some other part of the valley, it leaves a deposit of alluvium, the upper surface of which is barely submerged at the flood stage of the stream. The depth of alluvium on the flood plain is therefore measured by the extreme depth of the current at high water It constitutes a practically even sheet, resting on the undisturbed terrane beneath. When the stream finally abandons it, and by carving a deeper channel, converts it into a terrace, the terrace is necessarily bipartite. Above, it consists of an even layer of alluvial material, fine at top and coarse at bottom; below, it consists of the preexistent formation, whatever that may be. Where the lower portion is so constituted as to resist erosion, it loses after a long period its alluvial blanket, and then the terrace consists simply of the floor of hard rock as pared away by the meandering stream. The coarse basal portion of the alluvium is the last to disappear; and if it contains hard bowlders some of these will survive as long as the form of the terrace is recognizable.

The elder Hitchcock enumerated and described four types of stream terrace: the lateral terrace, the delta terrace (grouped by the writer with shore terraces), the gorge terrace, and the glacis terrace;[1] and Miller, whose clear analysis of stream terracing is the most recent contribution to the subject,[2] adds the amphitheater terrace, the junction terrace, and the fan terrace. Such detail is not required in this connection, but it is proper to dis-

[1] Illustrations of Surface Geology. By Edward Hitchcock. p. 5.

[2] River-Terracing: its Methods and their results. By Hugh Miller. In Proc. Royal Physical Soc., vol. 7, 1883, pp. 263–306.

tinguish the fan terrace from the lateral terrace, to which the phraseology of the preceding paragraphs more particularly applies.

The fan terrace of Miller, as developed in a mountain country, has been admirably described and figured by Drew, who speaks of it as an "alluvial fan cut by a river", but gives no shorter title;[1] in the nomenclature of the present chapter[2] it is an alluvial-cone terrace.

Where a large stream flowing through an alluvial plain receives a small tributary from an upland bordering the plain, the tributary often builds an alluvial cone upon the margin of the plain. If afterward the large stream, shifting its course over the plain, encroaches on the alluvial cone, it converts it into a terrace. The small stream acquires in this manner a lower point of discharge and is induced to corrade a channel through its own alluvial cone, dividing it into two parts. With reference to the valley of the small stream, these parts are lateral terraces. With reference to the valley of the large stream, they constitute together an alluvial-cone terrace. The alluvial-cone terrace differs from the lateral terrace in that its surface does not incline uniformly in the direction of the current of the stream it overlooks, but inclines radially in all directions from a point at the side of the valley.

The Moraine Terrace.—When an alluvial plain or alluvial cone is built against the side or front of a glacier and the glacier is afterward melted away, the alluvial surface becomes a terrace overlooking the valley that contained the ice. The constructing stream may flow from the ice and gather its alluvium from the glacial debris, but it usually flows from the land. The slope of the alluvial plain is determined by the direction and other accidents of the stream. Where the plain adjoins the glacier, it receives whatever debris falls from the ice, and it may be said to coalesce initially with a morainic ridge. Its internal constitution is partly alluvial and partly morainic. If the morainic ridge is large, the plain does not become a moraine terrace. If it is small, it falls away when the removal of the ice permits the margin of the plain to assume the "angle of repose."

[1] Alluvial and lacustrine deposits and glacial records of the Upper-Indus Basin. By Frederic Drew. Quart. Jour. Geol. Soc. London, vol. 29, 1873, pp. 441–471,

[2] The *alluvial fan* of Drew is the *alluvial cone* of American geologists, and there would be some reasons for preferring *fan* to *cone* if it were necessary to employ a single term only. It is convenient to use them as synonyms, employing cone when the angle of slope is high, and fan when it is low.

Moraine terraces may be classified, after the manner of moraines, as lateral and frontal. The history of the lateral type is illustrated by Fig. 17, representing in cross section the side of a glacier in an open valley. The alluvium, *a*, is built up synchronously with the glacial debris, *d*, and the two interbed and mingle at their junction. When the ice melts, the face of the deposit assumes under gravity the profile indicated by the dotted line.

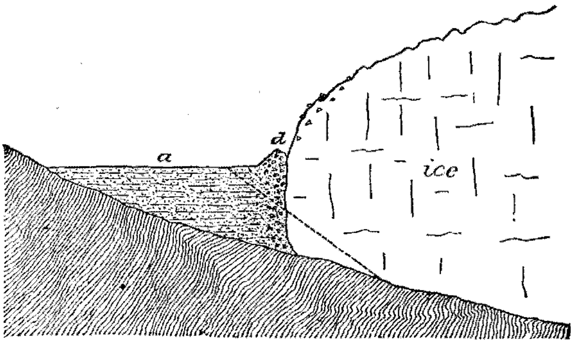


Fig. 17.—Ideal section, illustrating the formation of a Moraine Terrace at the Side of a Glacier.

If the glacier diminishes gradually, successive terraces are formed, and these frequently overlap. In Fig. 18 it is assumed that the ice profile had successively the positions of the dotted lines *x* and *y*. When it retreated to *y*, the accumulated deposit assumed the profile *abc*, and a new deposit began between the ice and the face *bc*. By subsequent ice retreat the second deposit assumed the profile *def*. As a result of this process the material of the terrace *de* overlies unconformably the material of the terrace *ab*.

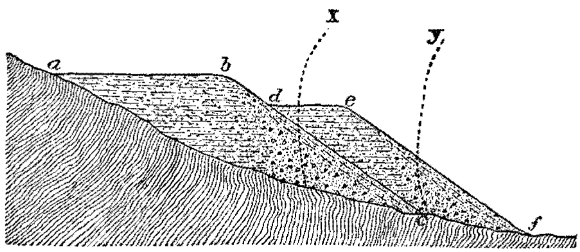


Fig. 18.—Ideal section, showing the internal structure of grouped Lateral Moraine Terraces.

An alluvial plain bordering the front of a glacier is apt to overlap the ice and to include near its outer margin not only morainic debris but blocks of ice. When the ice melts, the overlapping deposit cannot assume the simple earth-slope or angle of repose, but receives a hummocky, morainic surface (Fig. 20).

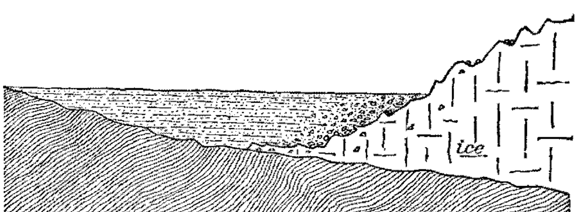


Fig. 19.—Ideal section of alluvial filling against Front Edge of Glacier.

So closely does the moraine terrace simulate the stream terrace that it is usually undistinguished.[1] The lateral type is identical in cross-profile and in longitudinal profile, and, unless portions of the morainic ridge remain, has but one formal difference: the contours of its outer face, being determined by the side of an ice stream, are smooth curves of gentle flexure.

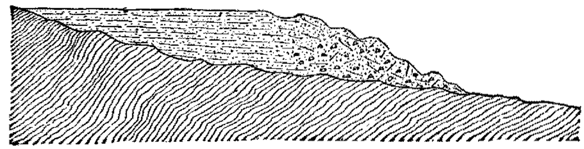


FIG. 20.—Ideal section of Frontal Moraine Terrace.

The Fault Terrace.—It sometimes occurs that two or more fault scarps with throw in the same direction, run parallel with each other on the same slope, thus dividing the surface into zones or tracts at various heights. Each of these tracts contained between two scarps is a terrace. It is a dissevered section of the once continuous general surface, divided by one fault from that which lies above on the slope and by another from that which lies below. It is the top of a diastrophic block, and its inclination depends upon the attitude of that block. Usually the block is tilted in a direction opposite at once to that of the throw of the limiting faults and to that of the general slope of the country. This has the effect of giving to the terrace an inclination less steep than that of neighboring plains, or (exceptionally) of inclining it in the opposite direction.

In the direction of its length, which always coincides with the strike of the faults, the terrace is not horizontal, but undulates in sympathy with the general surface from which it has been cut.

The Land-Slip Terrace.—This is closely related in cross-profile to the fault terrace, but is less regular and is of less longitudinal extent. Its length is frequently no greater than its width. The surface on which motion takes place has a cross section outwardly concave, so that the sliding mass moves on an arc, and its upper surface, constituting the terrace, has a less inclination than in its original position. Frequently this effect is carried so far as to incline the terrace toward the cliff which overlooks it, and occasionally the

[1] Its recognition was probably late. W. S. Green describes it in "The High Alps of New Zealand" (London, 1883), and Chamberlin describes and names it in the Third Annual Report of the U. S. Geological Survey, p. 304. The name "moraine terrace" was provisionally attached by E. Hitchcock (Surface Geology, pp. 6, 61) to a phenomenon not now regarded as a terrace.

edge of the terrace is connected with the cliff in such way as to form a small lake basin.

An even terrace of such origin is rarely observed. The surface is usually hummocky, and where slides occur in groups, as is their habit, the hillside is thrown into a billowy condition suggestive of the surface of a terminal moraine.

Comparison.—The only feature by which shore terraces are distinguished from all terraces of other origin, is the element of horizontality. The wave-cut terrace is bounded by a horizontal line at its upper edge; the delta is bounded by a horizontal line about its lower edge; and the wave-built terrace is a horizontal plain. But the application of this criterion is rendered difficult by the fact that the terrace of differential degradation is not infrequently margined by horizontal lines; while the inclinations of the stream terrace and the moraine terrace, though universal and essential characters, are often so small in amount as to be difficult of recognition. The fault terrace and land-slip terrace are normally so uneven that this character sufficiently contrasts them with all shore features.

The wave-cut terrace agrees with all the non-shore terraces in that it is overlooked by a cliff rising from its upper margin, and usually differs in that it merges at one end or both with a beach, barrier, or embankment. It is further distinguished from the terrace of differential degradation by the fact that its configuration is independent of the structure of the rocks from which it is carved, while the latter is closely dependent thereon. In freshly formed examples, a further distinction may be recognized in the mode of junction of terrace and cliff. As viewed in profile, the wave-cut terrace joins the associated sea-cliff by an angle, while in the profile wrought by differential degradation, the terrace curves upward to meet the overlooking cliff.

The wave-cut terrace is distinguished from the stream terrace by the fact that it appears only on the margin of an open basin broad enough for the propagation of efficient waves, whereas the latter usually margins a narrow or restricted basin. In the case of broad terraces a further distinction is found in the fact that the shore terrace descends gently from its cliff to its outer margin, whereas the stream terrace is normally level in cross section. In fresh examples the alluvial capping of the stream terrace affords additional means of discrimination.

The wave-cut terrace is distinguished from the moraine terrace by the fact that its floor consists of the preexistent terrane in situ, the moraine terrace being a work of construction. The wave-cut terrace occurs most frequently on salients of the topography; its inner margin is a simpler curve than its outer. The moraine terrace is found most frequently in reentrants; its outer margin is a simpler curve than its inner.

There are certain cases in which the wave-formed and stream terraces merge with each other and are difficult of separation. These occur in the estuaries of ancient lakes, where the terraces referable to wave action are confluent with those produced contemporaneously by the lateral corrasion of streams. The stream being then tributary to the lake, it could not carry its erosion to a lower level, and its zone of lateral corrasion was at its mouth continous with the zone of wave erosion in the lake.

The wave-built terrace may be distinguished from all others by the character of its surface, which is corrugated with parallel, curved ribs. It differs from all except stream and moraine terraces in its material, which is wave-rolled and wave-sorted. It differs from the stream terrace in that it stands on a slope facing an open basin suitable for the generation of waves.

The delta differs from all except the stream terrace and the moraine terrace in its material and in its constant relation to a water way. Its material is that known as stream drift. Its mass is always divided by a stream channel so as to lie partly on each bank; its terminal contour is a convex arc centering on some point of the channel; and it is usually confluent in the ascending direction with the normal stream terrace. Indeed, when considered with reference to the dividing channel, it is a stream terrace; and it is only with reference to the lakeward margin that it is a shore terrace. It is distinguished from the normal stream terrace by its internal structure. The high inclination of the lamination of its middle member—formed by the discharge of coarse detritus into standing water—is not shared by the stream terrace, while its horizontal alluvium does not, as in the case of the stream terrace, rest on the preexistent terrane. It is distinguished from simulating phases of the moraine terrace by its outer contour, which is outwardly convex and more or less irregular, while that of the moraine terrace is straight or simply curved. The frontal moraine terrace often affords a further distinction by the hummocky character of its outer face.

As the formation of the delta is independent of wave action, it may and does take place in sheltered estuaries and in small basins. A small lake interrupting the course of the stream may be completely filled by the extension of the delta built at its upper extremity; and when this has occurred, there is nothing in the superficial phenomena to distinguish the formation from the normal flood plain.

The terrace of differential degradation is further distinguished from all shore terraces by the fact that, without great variations in width, it follows the turnings of the associated cliff, conforming to it in all its salients and reentrants. Where the shore follows an irregular contour, wave-cut terraces appear only on the salients, and in the reentrants only wave-built terraces and deltas.

RIDGES.

Ridges are linear topographic reliefs. They may be broadly classed into (1) those produced by the erosion or dislocation of the earth's surface, and (2) those built upon it by superficial transfer of matter. In the first class, the substance of the ridge is continuous with that of the adjacent plain or valley; in the second, it is not; and this difference is so obvious that shore ridges, which fall within the second class, are not in the least liable to be confused with ridges of the first class. They will therefore be compared in this place only with other imposed ridges. Of shore phenomena, the barrier, the embankment, and the rampart are ridges. They will be contrasted with the moraine and the osar.

The Moraine.—The detritus deposited by glaciers at their lateral and terminal margins is usually built into ridges. The material of these is fragmental, heterogeneous, and unconsolidated. It includes large blocks, often many tons in weight, and these are angular or subangular in form. Sometimes their surfaces are striated. The crest of the moraine is not horizontal, but descends with the general descent of the land on which it rests.

Moraines are found associated with mountain valleys, and also upon open plains. In the first case their crests are narrow, and their contours are in general regular. The lateral moraines follow the sides of the valleys, often standing at a considerable height above their bottoms, and are united by the frontals or terminals, which cross from side to side with curved courses whose convexities are directed down stream. The moraines of plains have broad, billowy crests abounding in conical hills and in small basins.

The Osar or Kame.—These names are applied to an indirect product of glacial action. It is multifarious in form, being sometimes a hill, sometimes a ridge, and often of more complicated form. It doubtless embraces types that need to be separated; but it is here sufficient to consider only the linear form. As a ridge, its trend is usually in the direction of glacial motion. Its material is water-worn gravel, sand and silt, with occasional bowlders. Its contours are characteristically, but not invariably, irregular. Its crest is usually, but not invariably, uneven; when even, it is parallel to the base or to that upon which the base rests. In other words, the ridge tends to equality of height rather than to horizontality.

Comparison.—The shore ridges are primarily distinguished from the glacial ridges by the element of horizontality. The barrier and the embankment are level-topped, while the rampart has a level base and is so low that the inequality of its crest is inconsiderable. It is only in exceptional cases and for short distances that moraines and osars exhibit horizontality. Shore ridges are further distinguished by their regularity. Barriers and embankments are especially characterized by their smoothness, while smooth osars are rare, and the only moraine with even contours is the lateral moraine associated with a narrow valley.

Other means of discrimination are afforded by the component materials, and the moraine is thus clearly differentiated. The barrier and the embankment consist usually of sand or fine gravel, from which both clay and larger bowlders have been eliminated. Except in immediate proximity to the sea-cliff whose erosion affords the detritus, the pebbles and bowlders are well rounded. The material of the rampart has no special qualities, but is of local derivation, the ridge being formed simply by the scraping together of superficial debris. The moraine contains heterogeneous material ranging from fine clay to very large, angular blocks. The materials of the osar are normally less rounded than those of normal shore ridges.

Certain osars of great length, even figure, and uniform height are distinguished from barriers by the greater declivity of their flanks, and by the fact that they do not describe contours on the margins of basins.

THE RECOGNITION OF ANCIENT SHORES.

The facility and certainty with which the vestiges of ancient water margins are recognized and traced depend on local conditions. The small waves engendered in ponds and in sheltered estuaries are far less efficient in the carving of cliffs and the construction of embankments than are the great waves of larger water bodies; and the faint outlines they produce are afterward more difficult to trace than those strongly drawn.

The element of time, too, is an important factor, and this in a double sense. A water surface long maintained scores its shore mark more deeply than one of brief duration, and its history is by so much the more easily read. On the other hand, a system of shore topography from which the parent lake has receded, is immediately exposed to the obliterating influence of land erosion, and gradually, though very slowly, loses its character and definition. The strength of the record is directly proportioned to the duration of the lake and inversely to its antiquity.

It will be recalled that in the preceding description the character of horizontality has been ascribed to every shore feature. The base of the sea-cliff and the coincident margin of the wave-cut terrace are horizontal; and so is the crest of each beach, barrier, embankment, and wave-built terrace; and they not merely agree in the fact of horizontality, but fall essentially into a common plane—a plane intimately related to the horizon of the maximum force of breakers during storms. The outer margin of the delta is likewise horizontal, but at a slightly lower level—the level of the lake surface in repose. This difference is so small that for the purpose of identification it does not affect the practical coincidence of all the horizontal lines of the shore in a single contour. In a region where forests afford no obstruction, the observer has merely to bring his eye into the plane once occupied by the water surface, and all the horizontal elements of shore topography are projected in a single line. This line is exhibited to him, not merely by the distinctions of light and shade, but by distinctions of color, due to the fact that the changes of inclination and of soil at the line influence the distribution of many kinds of vegetation. In this manner it is often possible to obtain from the general view evidence of the existence of a faint shore tracing, which could be satisfactorily determined in no other way. The ensemble of a faintly scored shore mark is usually easier to recognize than any of its details.

It is proper to add that this consistent horizontality, which appeals so forcibly and effectually to the eye, can not usually be verified by instrumental test. The surface of the "solid earth" is in a state of change, whereby the vertical relations of all its parts are continually modified. Wherever the surveyor's level has been applied to a fossil shore, it has been found that the "horizon" of the latter departs notably from horizontality, being warped in company with the general surface on which it rests. The level, therefore, is of little service in the correlation of shore lines seen at different places and not continuously traced; but when an ancient shore-line has been faithfully traced through a basin, the determination by level of its variations in height discovers the nature of displacements occurring since its formation. It might appear that the value of horizontality as an aid to the recognition of shores is consequently vitiated, but such is not the case. It is, indeed, true that the accumulated warping and faulting of a long period of time will so incline and disjoint a system of shore features that they can no longer be traced; but it is also true that the processes of land erosion will in the same time obliterate the shore features themselves. The minute elements of orographic displacement are often paroxysmal, but so far as observation informs us, the general progress of such changes is slow and gradual, so that, during the period for which shore tracings can withstand atmospheric and pluvial waste, their deformation is not sufficient to interfere materially with their recognition.

CHAPTER III.

SHORES OF LAKE BONNEVILLE.

In the preceding chapter the features of a *single* desiccated shore-line are described; a shore-line, that is, with nothing above it on the sloping side of its basin except the varied topography characteristic of dry land, and nothing below it but the smooth monotony of a lake bottom. Proceeding now to the consideration of the Bonneville shores, we pass from the simple to the complex, for the Bonneville Basin is girt by many shore-lines, which form a continuous series. Only the highest of these is contiguous to land topography, and only the lowest encircles an area covered exclusively by lake sediments. The water has undergone changes of volume which have carried its surface and waves to every part of the basin from the bottom to an altitude of 1,000 feet. So much of the basin as lies below the highest shore-line has received lake sediments; and the geologic data comprised in these sediments are combined with the phenomena of the lower beaches in a manner that is at once instructive and complicated. The superpositions of shore-line upon lake sediment and lake sediment upon shore-line record a history of contracting and expanding lake area, the deciphering of which constitutes one of the chief subjects of our study. These will be discussed at length in the sequel. Here it is desired merely to state the fact that for a vertical space of 1,000 feet on the sides of the basin, the evidences of lacustrine waves and lacustrine sedimentation have been imposed on the preexistent configuration of the country.

Lake Bonneville lay in the district of the Basin Ranges, and the whole configuration of the land above the shore-lines is of the Basin Range type. As described in the introductory chapter, that district is studded with a great number of small mountain ranges, standing in irregular order, but with a nearly constant north-south trend. Between them are narrow valleys floored by detritus worn from their summits during the uncounted ages of their existence. At the foot of each range, and piled high against its sides, are great conical heaps of alluvium, each with its apex at a mountain gorge. At top these alluvial cones are separate, but lower down they adjoin, and their bases coalesce into a continuous scolloped slope, the visible footstool of the mountain. The cones, like the valley floors, are composed of detritus eroded from the mountains, but their material is coarser. At the margins of the undrained valleys the cones merge by gentle curvature with the valley floors. In the higher valleys, which drain to the closed basins, cones from the two sides meet along the medial line, giving to the cross profile the form of an obtuse ∨. Above the alluvial cones all is of solid rock, and the topographic forms are hard and angular. Every water-parting is a sharp ridge, and every water-way is an acutely V-shaped gorge.

The ridge and the gorge are characteristic features of land sculpture, being carved only where rain and running water serve for erosive tools. The alluvial cone is an equally characteristic land feature, being formed only where running water throws down detritus, without itself stopping. They are all the distinctive and exclusive products of land shaping, and could never originate beneath a lake or ocean.

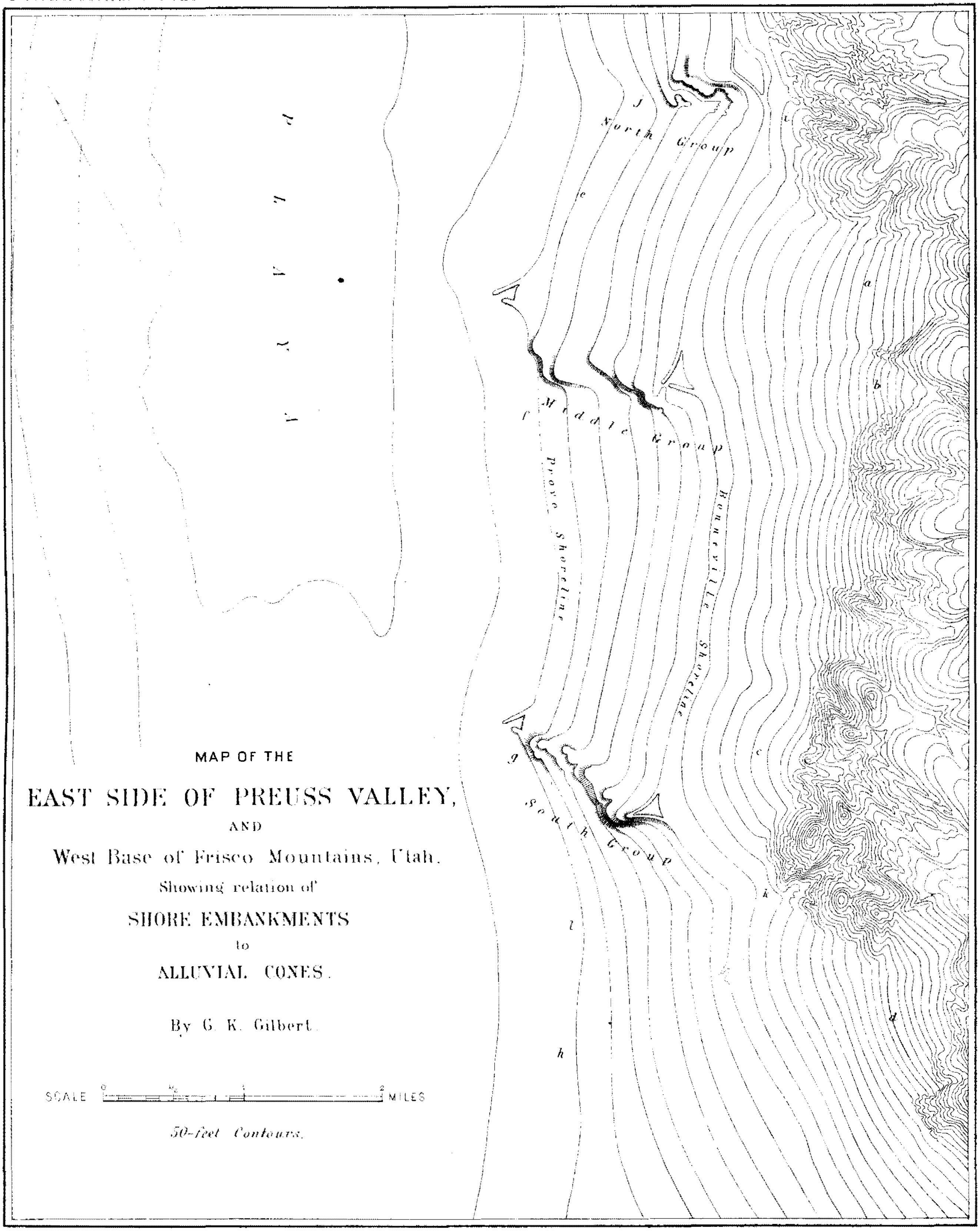
These are the features exhibited by the Bonneville Basin above the highest shore-line; and the same features can be traced continuously downward past the shore-line and to the bottoms of the once submerged valleys. If one stands at a distance and views the side of a valley, he will see that each of the great alluvial cones is traceable within the zone of submergence almost as distinctly and quite as surely as above it. Its curving contour formed a part of every individual shore of the series. So, too, of the mountain gorges and ridges; wherever they extend below the ancient water limit the shore-line can be seen to follow their contours in a manner demonstrating that they were already in existence when the lines were drawn.

The preexistent topography of the Bonneville Basin was therefore of terrestrial type and of subaerial origin. The sea-cliffs and embankments and sediments of the lake were carved from and built on and spread over a system of reliefs which originated at a time anterior to the lake, when the drainage of the mountains descended without obstruction to the bottoms of the valleys. In this respect, and in other respects to be developed further on, the pre-Bonneville conditions were identical with the post-Bonneville.

Illustrations of this general fact could be adduced almost without limit, for they are afforded by all the slopes of the basin, but a few will suffice.

In Plate VIII there appears at the right a portion of the western front of the Frisco Range. The crowded and uneven contour lines mark the position of steep-faced rock undergoing erosion. At the foot of the range is a system of alluvial cones, represented by contours with smooth curves and regular spaces. Still lower are the contours produced by wave action, and lowest of all is the outline of a playa. A moment's attention will show that the great alluvial cone at *a*, which, like a trunk glacier, is compounded at its head of a number of single cones, is represented at the base of the slope by the convexity at *e*. The cone *b* appears, though less plainly, at *f*; and the cone *d* appears at *h*. The cone *c* is greatly disguised at *g*, being loaded with a group of embankments; but it is probable that it has had something to do with the deflection of shore-currents whereby those embankments were originated. Conversely, the indentation at *j* represents the unbroken rock-face at *i*, where for a space of half a mile no debris-conveying gorge issues from the mountain; and the dearth of detritus in the region *k* is represented by the indentation at *l*. The map also suggests, what a study of the ground demonstrates, that the material built into embankments was derived by the paring away of the coast to the north of each locality of deposit. Considered by themselves, the monuments of the waves' activity are by no means inconsiderable; each group of embankments contains some hundreds of millions of cubic yards of gravel; but they sink into insignificance when compared with the stupendous monuments of alluvial activity on which they rest. They are mere appendages, and the erosion of their material from the adjacent slopes has by no means obliterated, though it has somewhat defaced, the alluvial forms.

Granite Rock, an isolated mountain of the Salt Lake Desert, has at its north end a gorge dividing the extremity into two narrow spurs. About these spurs the Bonneville waters rose to a height several hundred feet



Julius Bien & Co. lith

Drawn by G. Thompson

above any alluvial accumulation. All about the spurs there is a distinct terrace cut in the granite at the highest water level, and the same can be traced, less continuously but still unmistakably, along the sides of the gorge to its head. This relation could not subsist had not the gorge and the spurs been carved out in substantially their present form before the waves attacked them.

Bradley, speaking of the canyon of Ogden River, says:

> It is evident that, when this canyon was originally excavated, the Great Salt Lake was not far, if at all, above its present level; so that the rushing torrent which wore out this old rounded bottom met no check until it had passed entirely beyond the mouth of the canyon. There followed a time when the lake filled nearly or quite to its highest terrace; and, meanwhile, the Ogden River continued to bring down the sand and pebbles which it had before been accustomed to sweep out upon the lower terrace, but now, checked by the rising lake, deposited them in the lower parts of its old channel, until they accumulated to a very high level, not yet accurately located. Again, the lake retired, and the stream again cut down its channel, sometimes reaching its old level and sometimes not.[1]

In each of these localities the subaerial work antecedent to the lake epoch has greatly exceeded in amount the lacustrine work; and the last has in like manner exceeded the subaerial work subsequent to the lake epoch. Disregarding the rate at which the several processes are carried on, it is evident that the construction of the alluvial cones of Frisco Mountain is a greater work than the building of the embankments that ornament their flanks; while the preservation of the embankments shows that little alluvial accumulation has since been made. The carving of the spurs and gorge at Granite Rock implies the decay and removal of cubic miles of granite, while the production of the shore terrace involved the excavation of only a few thousand yards of the same rock.

THE BONNEVILLE SHORE-LINE.

The shore-lines of the series in the Bonneville Basin are not of uniform magnitude. The water rose and fell step by step, but not with equal pace, and at a few stages it lingered much longer than at others, giving its waves time to elaborate records of exceptional prominence. One of the exceptional records is that which holds the highest position on the slopes; and to

[1] U. S. Geol. Surv. of Terr., Ann. Rept. for 1872, p. 196.

this one, par excellence, the name Bonneville has been applied. It marks the greatest expanse of the ancient lake, and forms the boundary of the area of lacustrine phenomena.

Above the Bonneville shore-line the whole aspect is that of the dry land—here, an alternation of acutely cut water partings and water ways; there, huge, rounded piles of alluvium; the first stream-carved, the last stream-built; and each presenting to the eye a system of inclined profiles. Below the shore-line, the same oblique lines are to be found, but with them are an abundance of horizontal lines, wrought by the waves at lower levels—the terraces, beaches, barriers, and embankments of lower shore-lines.

Except in sheltered bays, where the waves had little force, and except on smooth, mural cliffs of rock, where a beach could not cling and where the waves were impotent for lack of erosive tools, the contrast between wave work and stream work is strong, and the line separating the two types of earth-shaping is easily traced. If the Bonneville shore-line were far less deeply engraved than it is, it would still be conspicuous by reason of its position. As it is, no geologic insight is necessary to discover it, for it is one of the pronounced features of the country. It confronts all beholders and insists on recognition. The tourist who visits Ogden and Salt Lake City by rail sees it on the Wasatch and on the islands of Great Salt Lake, and makes note of it as he rides. The farmer who tills the valley below is familiar with it and knows it was made by water; and even the cow-boy, finding an easy trail along its terrace as he "rides the range", relieves the monotony of his existence by hazarding a guess as to its origin.

The altitude of the Bonneville shore-line is about 1,000 feet above Great Salt Lake and about 5,200 feet above the ocean. In defining it as the highest shore of the basin, I have assumed the correctness of the more prevalent view of a mooted question; but before proceeding farther the opposing view should be considered.

THE QUESTION OF A HIGHER SHORE-LINE.

It has been announced by Peale[1] that there is evidence of a Pleistocene lake in the Bonneville Basin with a water level from 300 to 600 feet above the Bonneville shore-line, or from 5,500 to 5,800 feet above the sea. "On

[1] The Ancient Outlet of Great Salt Lake. By A. C. Peale, Am. Jour. Sci., 3d series, vol. 15, 1878, pp. 439–444.

both sides of the Portneuf where it comes into Marsh Creek Valley an upper terrace is seen, and in 1872 Prof. F. H. Bradley also readily identified an upper terrace in the Marsh Creek Valley at the level of about 1,000 feet above the stream. In Gentile Valley and in Cache Valley also, traces of this upper terrace exist." In the passage referred to,[1] Bradley mentions this terrace in connection with stream terraces, but does not speak definitely of its origin. Its interpretation as a shore feature therefore rests with Peale, who regards it as identical with the one observed by him "on both sides of the Portneuf." It has not been seen by me, but I am by no means sure that in seeking it I succeeded in following Bradley's route. With more confidence it may be asserted that Marsh Valley is not contoured by any well-marked shore-line. I was careful to study its slopes from stations at various levels and under favorable atmospheric conditions, and I failed to discover even the faintest trace of wave work. The same careful search was made for high-level shore traces in Cache Valley and Gentile Valley, but none were found. There are indeed terraces in Gentile Valley, and these are elsewhere mentioned by Peale, who found their altitudes 5,526, 5,242 and 5,186 feet;[2] but they are stream terraces, not shore terraces.

It is with reluctance that I record not only my inability to rediscover phenomena which another has reported, but also my opinion that his reported discovery was based on an error of observation; but the question here involved is of such importance in its relation to the Bonneville history that it can not well be ignored.

As set forth in the second chapter, there are various other types of terraces liable to be mistaken for shore terraces; and the ranging of shore terraces and other wave-wrought features in the same horizontal line, or plane, is a characteristic of great importance in their discrimination. To the observer who places himself in that plane and views the distant hillside at his own level, certain elements of the various shore features appear united in a horizontal line. If he selects for his observation an hour when the distribution of lights and shadows gives strong expression to the details of the configuration, he is able to detect a shore record so faint that he might cross and recross it repeatedly without suspecting its existence. Having searched

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[1] Rept. U. S. Geol. Survey Terr. for 1882, pp. 202–203.
[2] Rept. U. S. Geol. Survey Terr. for 1877, Washington, 1879, p. 601.

with distant view and selected light for the reported high-level shore traces in Marsh and Cache Valleys, and having failed to discover them, I am satisfied that Peale misinterpreted terraces formed in some other way.

The matter is not fully set forth by the recital of the conflicting observations. The Valley of Marsh Creek falls outside not only the Bonneville Basin but the Great Basin. It is drained to the great plain of the Snake River by a deep and rather broad canyon which bears the marks of antiquity. The sides of this canyon, though of crystalline and schistose rocks, are not steep, and at the most constricted point there is a flood-plain a thousand feet broad. If there was, as Peale supposes, a barrier at this point containing the ancient lake, then its cutting must have consumed a long period; and it is incredible that shore terraces have survived the contemporaneous general waste of the surface. If there was no barrier at this point, then the supposed lake was a great inland sea, flooding the plain of the Snake River, and its shore tracings on the margins of that plain should have been much more conspicuous (by reason of the greater magnitude of its waves) than any drawn in Marsh Valley,—but they have not been discovered.

Moreover, a body of water capable of forming the supposed shore terraces in Marsh Valley would have extended not only to Cache and Gentile Valleys but to the Great Salt Lake Desert, and the work of its waves should be visible, if anywhere, on the face of the Wasatch Range. In that region, the conditions for the generation of large waves are far more favorable than in the relatively narrow valley of Marsh Creek. Nevertheless, a higher line has not been observed on the margin of the greater basin. Not only has Peale failed to record it there, but Bradley, Howell, Emmons, Hague, and King have expressly noted the Bonneville as the highest shore-line.[1]

It may be objected that the failure of these numerous observers to detect an upper shore-line is negative evidence merely, and should be given little weight in comparison with a single positive observation. But the failure to detect is in this case something more than a negation. Subaerial land sculpture is as positive a fact as wave-wrought shore sculpture; and the as-

[1] F. H. Bradley, U. S. Geol. Surv. of Terr. Ann. Rept. 1872, p. 192 E. E. Howell, U. S. Geol. Surv. West of the 100th Meridian, vol. 3, Geology, p. 250. S. F. Emmons, U. S. Geol. Explor. 40th Parallel, vol. 2, Descriptive Geology, p. 441. Arnold Hague, Idem. pp. 421, 428. Clarence King, U. S. Geol. Explor. 40th Parallel, vol. 1. Systematic Geology, p. 491.

THE GREAT BAR AT STOCKTON. UTAH.

sertion that the Bonneville is the highest shore-line implies the assertion that above it the topography is of the ordinary dry land type. Every recognition of an ancient shore is based, consciously or unconsciously, on an acquaintance with the ordinary characteristics of the features of the land as well as with the peculiarities of shores; and ability to discriminate the presence of wave sculpture implies in the same degree ability to note its absence and its limits. The supremacy of the Bonneville shore has been recognized not only by many observers but in a great number of localities, and an induction resting on so broad a basis may justly demand of a conflicting observation the most rigorous verification.

If the reader will turn to Plate IX he will be able to realize the weight of this evidence. The view presents the Bonneville shore at the pass between Töoele and Rush Valleys. The observer stands on the west side of the pass and looks eastward toward the Oquirrh Mountains. At the left lies Tooele Valley, open to the main body of the old lake. At the right is Rush Valley, which held a sheltered bay. The greatest waves came from the north, and, beating on the southeast shore of Tooele Bay, carved out a long line of sea-cliffs. The debris was at the same time drifted southward, part of it being built into a free spit 7,000 feet long and 150 feet high at the extremity, and another part being accumulated during lower stages of the lake in an immense bay-bar, obstructing the pass. The spit appears in the picture at the right, following the base of the mountain. The bay-bar extends from the center of the view to the foreground. It will be observed that the line of sea-cliff at its most distant point impinges on a spur of the mountain; and at its southern end, near the middle of the picture, it touches another spur, while in the interval it crosses only the alluvial slope. There could scarcely be a greater contrast than between the sculpturing of the mountain-spurs above the line of sea-cliffs and the smooth contours of the slopes below that level. The cliffs are here of rather unusual height, and the shore embankments are of exceptional magnitude, so that the separation between subaqueous and subaerial topography is more than ordinarily distinct. This fact does not weaken the evidence that the Bonneville shore-line is the highest, but gives it greater strength. For, if the water had occupied a higher level in Pleistocene time, the waves would have been able to record it at this point by a shore-line of unmistakable definition. If shore traces of a greater lake are anywhere preserved they should be found at such a point as this, where the conditions for wave beating are exceptionally favorable. The same lesson may be learned from Figure 21, and from the views on

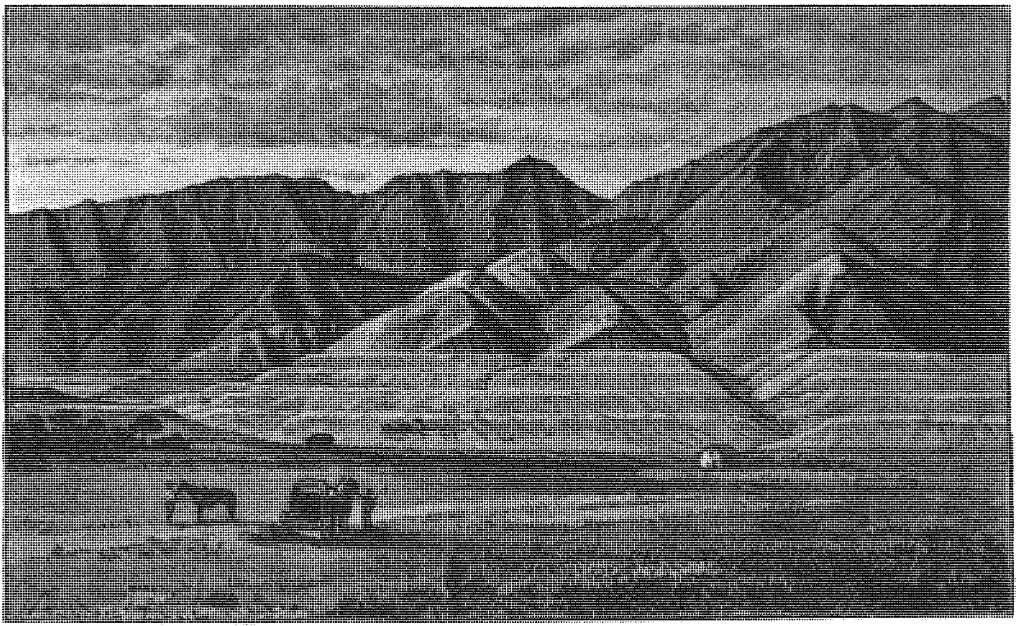


FIG. 21.—Bonneville and Intermediate embankments near Wellsville, Utah, showing contrast between Littoral and Subaerial Topography.

Plates XXI and XXII, representing the shore topography and mountain topography at Wellsville and Dove Creek.

MORE ANCIENT LAKES.

Although Peale's supposed discovery is unverified, and though it is believed that an exhaustive investigation would prove it to be illusory, it is nevertheless true that some or all of the mountains of the Bonneville Basin were girt by shore-lines long before the Bonneville epoch, and that if these shore-lines were extant they would, in some places at least, lie higher than the Bonneville. The mountains against which Lake Bonneville washed are relatively very old, so old that they were greatly eroded before Tertiary time. Ever since their first uplifting they have been wasted by erosion, and during at least a portion of the time the detritus worn from them has been received by the interjacent valleys. The degradation of their crests and the burial of their bases would long ago have obliterated them had they not been preserved by a series of supplementary upliftings, which, like the original, were differential, not being shared by the intervening valleys. In the region of the Great Salt Lake Desert, where a plain has been formed by the coalescence of many valleys and the local burial of the ranges, the depth of detritus must be several miles. Of the constitution of this deposited mass nothing is known by direct observation. It is smoothly covered by the sediments of Lake Bonneville, and no section is exposed. But indirectly we are shown that some part of the debris was spread under water, for the uprising mountain ranges have carried with them here and there, clinging to their flanks, small patches of lacustrine strata. It is believed that four separate groups of lake beds have been thus distinguished. The first of these occurs in the southeastern part of the basin, and probably touches the shore of the ancient lake only in the estuary of the Sevier River. No fossils have been found at that point, but there is little reason to doubt that the strata were once continuous with the Pink Cliff formation, which covers large areas farther east, and has been classed as early Eocene. The principal locality of the second is the eastern base of the Ombe Range, where an isolated outcrop of barren strata resting against the mountain dips abruptly beneath the later sediments of the desert. These strata have been correlated on lithologic grounds with fossiliferous beds farther west, and are regarded by the geologists of the Fortieth Parallel Survey as of Middle Eocene age. The third group, though yielding no fossils, is believed to be Neocene. It was first noted by Emmons in Rush Valley south of the Great Salt Lake Desert, and has since been found at the narrows of the Jordan River, at Salt Lake City, at the north edge of the desert near Matlin, and at the extreme northwest corner of the basin in Cache Valley, whence it extends across the rim of the basin into Marsh Creek Valley. The strata of the fourth group, known chiefly from the investigations of King and Hayden and their assistants, occur at a number of points along the northern margin of the plain, and are believed to appear also north of the divide in districts now draining to the Snake River. From Morgan Valley to Cache Valley they occupy a trough between two divisions of the Wasatch Range.

On the low northward continuation of the main Wasatch ridge, where it separates Cache and Malade Valleys, they are seen to be wrapped around a series of low crags of Paleozoic rocks; and it is evident that they have been raised to their present prominent position by the relifting of an ancient crest. On the east side of it they have been upturned by the displacement so as to dip at a high angle beneath the Bonneville lacustrine beds of Cache Valley. On the west they are separated from their original continuation beneath Malade Valley by a fault, the throw of which is probably more than 1,000 feet. Their relation to the third group has not been established, and it is possible that they constitute a part of the same series. The locality of the fifth group is just north of Salt Lake City, where an epaulette of Tertiary gravel and sand rests on a jutting shoulder of the Wasatch Range. This fragment is completely surrounded by faults, its eastern continuation having been lifted high in air and obliterated by erosion, and its prolongation in every other direction having been dropped so low that it is at once preserved and concealed by the deposits of the plain. This, too, is unfossiliferous; and it is here assigned to the upper Neocene merely on the strength of its structural relations. It is needless to enter upon these at this place; but it should be remarked that the same relations, considered from another point of view, led King to surmise its Eocene age.

Each of these lakes made its contribution to the filling of the basin, receiving, sorting, and spreading the debris from the wasting mountains; but neither can in strictness be called the predecessor of Lake Bonneville, for neither was confined to the area of the Pleistocene basin. So far as indicated by observed outcrops, the oldest Eocene lake lay almost entirely outside the Bonneville area; and it may have existed at a time when the greater part of that area was dry land. The second stretched westward far beyond the present drainage of the Salt Lake Desert, and may have overlapped the Bonneville Basin but slightly. The third and fourth encroached northward on the drainage of the Columbia River. Too little is known of the fifth to indicate its relation to the Bonneville Basin.

Their record is exceedingly fragmentary, but if it were full it would still give an imperfect history of the basin in Tertiary time, for there is no reason to believe that they represent more than a small part of that time

They tell us, however, that the physical mutations of the period included numerous local elevations and depressions, whereby the drainage of the country was repeatedly revolutionized; it was dry land at one time and and lake basin at another. It is quite possible that the lakes were exceptional phenomena, and that the prevailing condition was one in which the whole area drained to the ocean. It is equally possible that the Bonneville Basin continuously held a lake which, as the land rose and fell unequally, was expanded and contracted, now in one direction, now in another.

The character of the lake beds and their relations to the mountains, show in numerous localities that the ranges were not submerged. Waves must therefore have beaten on their flanks, and the cliffs, terraces, and embankments peculiar to shores must have been wrought, but of these there is no known vestige. When the structure of the mountains has been elaborately studied, so that those elements of their configuration which depend on the distribution of strata and on faults can be definitely indicated, it may be possible to point out dissected terraces and ruined sea-cliffs as remnants of Neocene shores; but for the present such vestiges are beyond recognition. A shore is of the most perishable of geologic phenomena. It is little more than a congeries of forms; and whether worn away by atmospheric agencies or buried by sedimentation, it ceases to be available as evidence of a water margin.

OUTLINE OF THE LAKE.

The outline of Lake Bonneville at its highest stage was intricate. Its shores presented a succession of promontories and deep bays, and it was beset with islands. Its longer diameter lay north and south, parallel to the trend of the mountain ranges of the district and to nearly all the lines of geologic structure. Its general outline was rudely pear-shaped, with the stem pointing southward. A straggling series of promontories and islands crossed it near the middle, dividing it into two principal bodies, of which the northern and larger covered the Great Salt Lake Desert, and the southern the Sevier Desert. The long southward bay representing the stem of the pear, occupied the Escalante Desert. The main body was joined to the Sevier body by three straits, of which the deepest and broadest lay between Simpson Mountain at the east and McDowell Mountain at the west, in the region now known as the Old River Bed. The Escalante Bay was connected with the Sevier body by a long strait, most constricted at Thermos Spring.

The following details are of local rather than general interest, but are essential to a full description of the lake. They will be more readily followed by the aid of the large map accompanying the volume.

The trend of the ranges gave character to all the major details of the coast, and the axes of the larger islands, peninsulas, and bays lay approximately north and south. Beginning at the north to describe them, we have first Cache Valley bay, an oblong sheet of water, tangent at one side to the main body and there joined to it by a broad strait interrupted by several islands. Inside the bay were three islands, whose positions are now marked by Franklin, Cache, and Battle Creek buttes. The butte near Smithfield was likewise an island at first, though finally connected with the land by a bar. The canyons of Bear, Cub, Logan, and Blacksmith rivers were occupied by inlets, and the Bear River inlet may have reached at first to Gentile valley. These were all gradually diminished by the deposits from the streams, and eventually the Bear River inlet was approximately, and the Logan completely, filled.

Malade Valley held a long bay running northward from the main body, and having an expansion where the towns of Malade and Samaria now stand. Parallel but smaller bays occupied the Pocatello and Blue Spring valleys and the valleys containing Hanzel Spring and the town of Snowsville. Park Valley was filled by a bay, exceptional in its east and west trend, and separated from the main body by a group of islands. The Promontory range was divided by a strait at the point where it is crossed by the Central Pacific Railroad, the north part being a peninsula and the south a narrow, rocky island.

Little Mountain, near the town of Corinne, was a small island, and the mountain from which Hanzel Spring issues made a group of islands. There were three small islands near the site of Kelton, and one just south of Terrace. The Ombe range, including Pilot Peak, was an island, sheltering behind it a bay or sound from which a narrow arm ran northward to

Thousand Spring Valley, the extreme limit of the water in a northwest direction.

Of the existing islands of Great Salt Lake, Stansbury and Antelope were islands then, and Fremont barely showed its apex above water. Of the "lost mountains" of Great Salt Lake Desert, nearly all overtopped the flood. Silver Islet, Newfoundland, Terrace Mountain, Lakeside Mountain, Granite Rock, and a half-dozen nameless buttes, were circled by rocky and inhospitable coasts, but the Cedar Range west of Skull Valley made a broad and low island, which, bleak and barren as it now is, we may picture as then mantled with verdure.

The eastern shore of the main body followed the steep base of the Wasatch Mountains, and had a simple outline except at three points, where it was diversified by the estuaries of Box Elder Creek, Ogden River, and Weber River. The Box Elder estuary extended nearly or quite to the little mountain valley where the Danish settlement of Mantua lies. Ogden Canyon was occupied by a long and narrow strait, communicating with a bay several miles broad, hemmed in by mountains. Through the canyon of the Weber a similar strait connected the main body of the lake with a small bay in Morgan valley,—a bay on which the Weber delta gradually encroached, but which was not completely obliterated before the final subsidence of the water.

The western shore of the main body followed the eastern base of the Gosiute range, and was characterized by an abundance of small islands. Its only estuary ran southward a short distance into Deep Creek Valley, stopping several miles north of the settlement.

Southward from the main body ran four long bays, two associated with the east shore and two with the west. The first of these, counting from the east, was divided by a close stricture into an outer bay and an inner, the outer covering the valley of the Jordan River and the inner spreading over Cedar, Utah, and Goshen valleys and a part of Juab Valley. In the inner bay the Goshen Hills made two islands, and the Pelican Hills constituted one large and several small islands. Small estuaries occupied Emigration and Little Cottonwood canyons, connecting with the outer bay, and the inner bay sent an estuary into Provo Canyon. The shallow arm in Juab

Valley was nearly closed by one of the Goshen islands. It connected by the canyon of Salt Creek with the division of the bay in Goshen Valley, and by the pass followed by the Utah Southern Railroad with the bay in Utah Valley.

The second of the southward stretching bays was similarly constricted, its outer and open portion covering Tooele Valley, and its inner, Rush Valley. The two were nearly dissevered by the formation of a wave-built bar at Stockton.

The third bay occupied White Valley, a barren plain between the Confusion Range and the high part of the House Range. Its entrance was obstructed by a rocky island consisting of the northern part of the House Range, and a long, crooked arm extending southward lacked little of communicating with a southerly division of the lake and converting the main part of the House Range into an island.

The fourth bay occupied Snake Valley and was long and shallow, turning eastward at its southern extremity.

The Confusion Range east of Snake Valley, and the House Range east of White Valley, were massive peninsulas, joined at their southern extremities to the western shore of the lake. A corresponding great peninsula on the east side was constituted by the Oquirrh, Aqui, Simpson, Cherry Creek, and Tintic mountains and their dependencies, and had a greater area than the State of Delaware. These peninsulas, together with the group of islands lying between them, separated the main body of the lake from the Sevier body. The group of islands comprised two of large size and about twenty of small size. The largest island was constituted by the Dugway Range and its southward prolongation, Drum Mountain; the second, by the McDowell Mountains.

With the Sevier body were connected two long bays running southward and a number of smaller ones indenting the eastern and northeastern coast. Of the northern bays, one received the water of Judd Creek and another that of Cherry Creek. A third, occupying Tintic valley, was more constricted at the mouth and contained islands. A land-locked bay received the water of the Sevier River and was partially filled by delta deposits. It was connected with the open lake by a narrow passage through the Canyon Range, comparable with the passage of the Hudson through the Highlands.

Of the southern bays, the shorter and more open occupied Sevier Lake Valley and Preuss Valley. The longer was narrow and irregular, filling the valley of Beaver Creek from George's ranch to Minersville, and extending thence southwestward into the Escalante Desert, where it was shallow. Its total length was about one hundred miles.

The largest island of the Sevier body was constituted by the Beaver Range, or Beaver Creek Range, which was separated by a narrow and tortuous strait from a peninsular tract bearing the Frisco and Picacho Mountains. There were two low islands a few miles broad close to the western shore, near Antelope Spring. The apex of Fumarole Butte was slightly emergent, and so was the highest point of the contiguous lava mesa. Small islands marked the sites of Pavant and Kanosh buttes, and there were four rocky islands near the mouth of Escalante Bay, one of which is now represented by the more northerly of the Twin Buttes. In Escalante Bay there were five or six islands.

EXTENT OF THE LAKE.

The area of the Bonneville water surface was 19,750 square miles, a magnitude ranking it with the Laurentian lakes. A fifth part of this belonged to the Sevier body with its dependencies, and the remainder to the main body. Its length, measured in a direct line from Cache Bay to the south end of Escalante Bay, was 346 miles, and its extreme width, from the mouth of Spanish Fork Canyon to a point on the Shoshone Range near Dondon Pass, was 145 miles. If its water surface were given a circular shape, its circumference would be 500 miles, but the actual length of coast, exclusive of islands, was 2,550 miles. Its maximum depth was about 1,050 feet. The following table will enable the reader to compare these dimensions with the corresponding dimensions of Great Salt Lake and the Laurentian lakes.[1]

[1] The area of Lake Bonneville was measured by I. C. Russell; the areas, lengths, and widths of the Laurentian lakes, by A. C. Lane. The length of a lake was, for this purpose, defined to be the length of the longest straight line terminated by two points of the lake shore; its width, the greatest distance between shores in a direction at right angle to the line of the length.

TABLE I. *Dimensions of Lakes.*

	Bonneville.	Great Salt.	Superior.	Huron.	Michigan.	Erie.	Ontario.
Area in square miles	19, 750	*2, 170	31, 500	23, 800	22, 300	9, 900	7, 250
Length in miles	346	83	377	247	330	246	197
Width in miles	145	51	170	215	106	58	67
Extreme depth in feet	1, 050	†49	1, 008	702	870	210	738

* In 1869; near high stage. † At high stage.

The greater part of the desiccated bed is an irreclaimable desert, but its eastern edge is the granary of the Great Basin. The Bear, the Weber, the Jordan, the Sevier, and other tributaries, fed by the snow-banks of a score of mountain ranges and plateaus at the east, carry their life-giving moisture to the genial climate of the lowlands, and a belt of oases is the result. If the water were to rise again to its old mark, more than one hundred towns and villages would be submerged and 120,000 persons would be driven from their homes. The Mormon temple at Salt Lake City would stand in 850 feet of water, and the temple at Logan, the metropolis of Cache Valley, would stand in 500 feet of water. Fort Douglas would be covered to a depth of 150 feet, Ogden 850, Provo 650, Kelton 1,000.

Seven hundred miles of railroad would be immersed, and trans-continental passengers would be transferred by boat either from Morgan City or from Spanish Fork to some point near Toano, Nevada,—a voyage of 145 miles for the northern route or 185 miles for the southern. The town of Fillmore would be half covered, the State House barely remaining on dry land, and Mantua, Paradise, Morgan, and Minersville would be lake ports. Heramon, Bingham, Ophir, Vernon, and Frisco would be peninsular towns; and the mining settlements of Drum and Buell would be stranded on islands.

SHORE DETAILS.

The sinuosity of the coast and its diversity of slope and material give to the shore phenomena the utmost variety. Every typical feature of non-tidal shores is well illustrated, and some of the combinations are perhaps unique.

The abundance of salients and reentrants, of promontories and inlets, has occasioned a large number of spits and bay bars, while long beaches and barriers are rare.

At an early stage of the investigation, the writer thought that the coasts facing in certain directions gave evidence of exceptional amounts of wave work, and imagined that he had discovered therein the record of prevalent westerly winds or westerly storms in ancient times. This belief was dissipated by further study; and he discovered, as students of modern shores long ago discovered, that there is a close sympathy between the magnitude of the shore features and the "fetch" of the efficient waves. The greater the distance through which waves travel to reach a given coast, the greater the work accomplished by them. The highest cliffs, the broadest terraces, and the largest embankments are those wrought by the unobstructed waves of the main body; and opposite coasts appear to have been equally affected.

The most interesting details of the upper shore-line are found at localities where similar details affect the lower shore-lines, and it will be convenient to describe them in discussing the order of succession of the shores; but certain features should be mentioned here. The greatest sea-cliffs are as a rule carved from headlands and from the islands of the main body, but the highest of all occurs in the Jordan Bay at a locality known as the Point of the Mountain. For a distance of half a mile the cliff there has an average height of one thousand feet, the eroded material having been swept to the southwestward and built into a magnificent spit, around the extremity of which the Utah Southern Railroad winds in passing from Draper to Lehi. Another notable cliff occurs on the south face of a butte east of Dove Creek, and is visible from the Central Pacific Railroad between Ombe and Matlin. The eroded material was in this case swept eastward and northward, being carried about the angle of the butte, then an island, and distributed in embankments on its eastern face.

The cut-terraces of the Bonneville shore are narrow as compared with those of one of the lower shore-lines. They rarely exceed a few rods in width. A good example can be found on the flank of the Wasatch Range just north of Big Cottonwood Canyon and others on the north end of the Oquirrh Range near Black Rock. These are mentioned as being easy of access, but they are less striking than some that are carved on islands at various points near the margin of the Great Salt Lake Desert.

Spits are exceedingly numerous, being attached to nearly all of the ancient islands and to many of the salients of the main coast. Of those having some magnitude, the most accessible are at Stockton (Pl. IX), near Grantsville, Tooele Valley (Pl. XV), at the Point of the Mountain between Draper and Lehi, on Kelton Butte near Ombe station, and on the extremities of the Terrace Mountains.

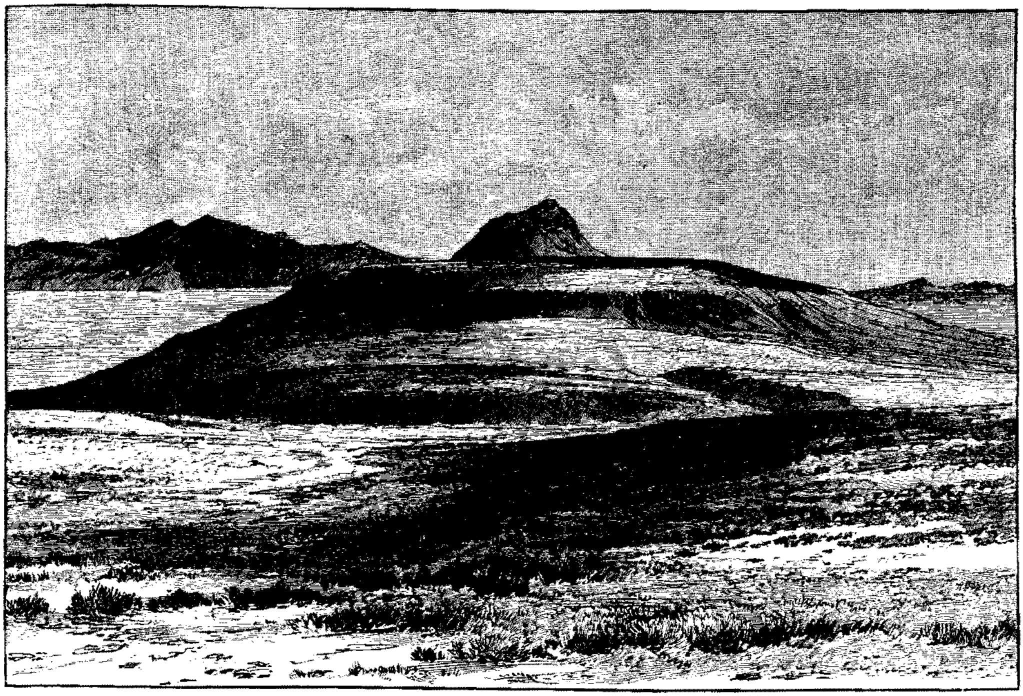


FIG. 22.—Butte near Kelton, Utah.

Embankments connecting islands with each other or with the mainland are to be seen at the west end of Park Valley, at Smithfield in Cache Valley, on Antelope Island in Great Salt Lake, a few miles east of George's Ranch south of Deseret, and at the eastern base of the Gosiute Range.

V-shaped embankments are most numerous in Snake Valley, where no less than ten occur. Four are attached to the Simpson Mountains opposite to the Old River Bed and others were seen in Preuss Valley and in Beaver Creek Valley.

Typical deltas are rare. Certain parts of the valleys of all the principal streams were occupied by inlets or estuaries, and the heads of these inlets received alluvial deposits of the nature of deltas; but the process of accumulation appears usually to have been arrested before the deposit had extended to the open lake; and afterward, when the lake receded and the streams resumed their work of excavation, all but scattered patches of the alluvium was removed. American Fork, Spanish Fork, and Rock Creek built free deltas in the Utah Bay, and Spring Creek furnished one to the shore of Cedar Bay, but these were exceptional and small. At lower levels great deltas were constructed by many streams, and the deltas of the Bonneville shore are described in connection with these in one of the later sections of this chapter

Plate VI exhibits a peculiar circular bar observed in a single locality only. The sketch is in part ideal, for there was no commanding point from which to obtain the bird's-eye view necessary for the best presentation of the subject. Near the Old River Bed there is a group of quartzite buttes which were surrounded by deep water and formed a cluster of rocky islands. To the north and northwest the deep lake stretched unbroken for more than one hundred miles, but in all other directions land was near at hand. Each island butte shows a weather side facing the open water and a lee side facing land. Each weather side is marked by a sea-cliff, which looks down on a broad terrace carved from the solid rock. The lee sides have no cliffs, but are embellished by embankments of various forms, built of the debris from the weather sides. In the case of the butte figured, the excavation of the platform was carried so far that only a small remnant of the original island survived, and a comparatively small additional amount of wave work would have sufficed to reduce it to a reef. From each margin of the surviving crest, an embankment streams to the leeward, and the two embankments, curving toward each other, unite so as to form a complete oval. At their point of junction they are a few feet lower than where they leave the butte. Their material is coarse, ranging up to a diameter of two feet, and is conspicuously angular, exhibiting none of the rounding characteristic of detritus that has been rolled long distances upon a beach. Within the oval rim is a cup 38 feet deep, its sides and lip consisting, on the north, of the rocky slope of the butte, and elsewhere of the wall of loosely heaped blocks of quartzite. If the material were volcanic, instead of sedimentary, it would be easy to imagine the cavity an extinct crater.

Reservoir Butte, another island of the cluster, is figured in Pl. XXIV, and further represented in Pl. XXV and in Fig. 3 of Pl. VII. It derives its name from a series of natural cups analogous to the one just described. These are attached to its steep slopes at various levels, the process of construction having been repeated at as many epochs in the history of the oscillating lake. In this connection, only the cups associated with the highest shore-line will be described. The longer diameter of the butte trends north and south. At its northern extremity and along its northwestern face it displays a bold sea-cliff, from 50 to 100 feet high, springing from a terrace at the Bonneville level several hundred feet broad. On the eastern side the cliff and terrace give place near the north end to a massive embankment, which first swings free from the side of the butte and then curves inward toward it, meeting it somewhat south of the middle. From the middle of the western side there starts a similar embankment, which, curving through an oval arc of 150°, joins the butte at its southern extremity. The interval between the termini of the two embankments, a space of 1,000 feet along the southeastern face of the butte, was almost unaffected by the waves, being neither abraded nor covered by debris. The material contained in the embankments was derived exclusively from the weather side of the butte, and though each looped embankment joined the shore at two points, the conveyance of shore-drift along its crest appears to have been in one direction only. It is difficult clearly to realize the process of this conveyance, but there is no question as to the fact. In one case it left the shore at a small salient, its course being there tangent to the contour, and, curving through an arc of 90°, finally assumed a course directly toward the coast, there almost precipitous. In the other case it left the shore at an obtuse salient, and before returning swung through so great an arc as nearly to reverse its direction.

The cups within these loops have been somewhat silted up in modern times, but still, except for their dryness, they deserve the name of reservoirs. The eastern was found to be 38 feet deep. The embankments were built in deep water and upon a foundation inclining steeply from the shore. Their forms are independent of the configuration of their foundation. They were not accumulated from the bottom upward, but were constructed by successive additions at the end, the boulders being rolled along the crest of the embankment by the breakers and then dropped in deep water at its extremity. The outer face of the eastern bar has a height above its base of four hundred feet.

EMBANKMENT SERIES.

It might be inferred from the preceding description that the Bonneville shore-line was the product and is the index of a single uniform and continuous water stage. Indeed, it has been so regarded by every observer who has published an account of it, and the impression is readily and properly derived from its ordinary phase. There are, however, a few localities where the shore mark is distinctly resolvable, and shown to be compounded of several similar elements at slightly different heights superposed on one another. One of the most striking localities, and at the same time the one which first demonstrated the compound nature of the phenomenon, is represented in Pl. X. A rocky cape projecting from the east shore of Snake Valley sheltered on one side a small bay opening to the south. Across this bay the waves built a series of bars, as represented in the map. The outermost of the series, that is, the one farthest from the land, is connected at its eastern end with a shore cliff labeled on the map "Bonneville Sea-cliff"; and this cliff runs for some miles southward along the slope of the valley.

A study of the locality demonstrated beyond question that the excavation occasioning the cliff and its terrace, furnished the material for the bar, and furthermore, that the same cliff line had previously been connected with each bar of the series.

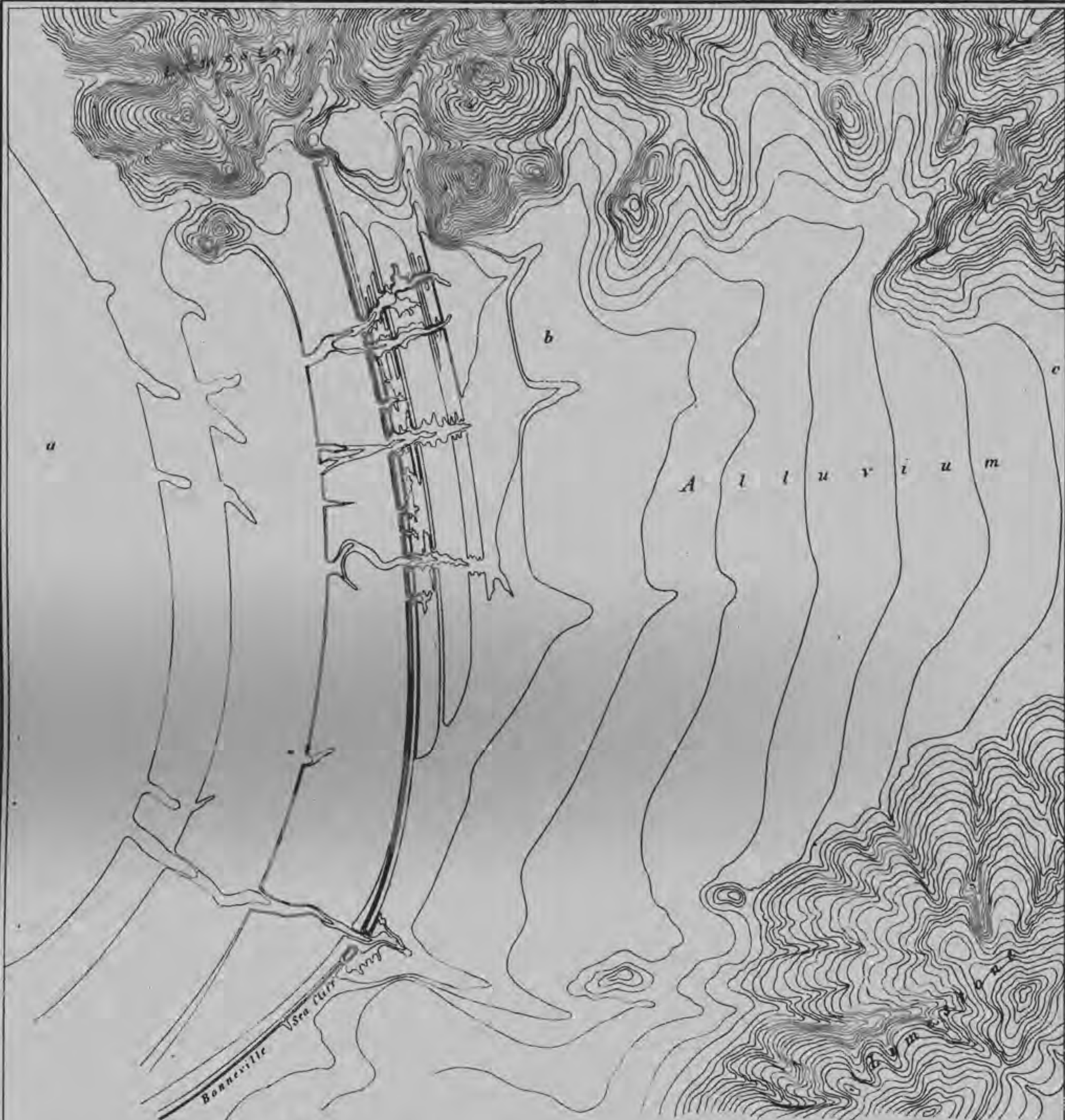
It will be readily understood that the inner bar was the first one to be built, and that the order of position is also the order of age. They stand so nearly at the same level that no one of them could have been formed in the rear of another. Their differences of level therefore record changes in the relation of the water to the land during the period of their formation. If we call the inner bar No. 1 and its altitude 11 feet, the series will be represented by the following list:

	Feet.		Feet.
No. 1	11	No. 6	$4\frac{1}{2}$
No. 2	12	No. 7	8
No. 3	13	No. 8	0
No. 4	$4\frac{1}{2}$	No. 9	0
No. 5	$4\frac{1}{2}$	No. 10	18

No importance is to be attached to the individuality of the bars. There is a rhythm of action in the process of their formation which would prevent the construction of a continuous and even-topped terrace under the most uniform conditions. If the bay had been so shallow that the same accumulation of shore drift would have abridged it twice as much, there might have been twenty bars instead of ten. The first three bars signify but a single epoch, during which the water stood at one level, or perhaps rose slowly. The next three, which in point of fact are but obscurely individualized, represent a succeeding water stage eight feet lower and possibly of somewhat greater duration. The seventh bar shows that the next movement consisted of a deepening of the water and was not long sustained. The eighth and ninth record the lowest stage of all, and the tenth the highest. The tenth contains so much more material than either of the others, being founded in deeper water and carried higher, that it must be considered as representing a longer time, and may be coordinated with either of the antecedent groups.

Outside the tenth bar the plain slopes gently lakeward, being interrupted within the area of the map only by a low bar, indicated in the profile. This bar lies so far below the others that, if older, it might not have interfered with the wave action necessary to their formation. Its relative age therefore does not appear.

The process of construction is clearly demonstrated by the local details. The sea-cliff was excavated from the alluvial foot slope of a mountain range. The derived material consisted primarily of boulders, large and small, sand, and a certain portion of clay. The finer part was immediately washed lakeward by the undertow. That of middle grade was carried along the shore to the bay, and the larger boulders remained in situ until sufficiently



MAP OF

BAY BARS OF THE BONNEVILLE SHORE

Near the Salt Marsh, in Snake Valley, Utah

By W. D Johnson

SCALE 0 ¼ ½ MILE

10-feet Contours

Fig. Profile, *Vertical Scale three times the Horizontal.*

reduced by attrition to be transported. In the bay the surface currents were concentrated by converging shores, and a powerful undertow was produced, whereby a further separation was effected, the shore drift being deprived of a coarser grade of debris than that previously eliminated, so that the matter actually deposited consisted of particles ranging from a half inch to four inches in diameter,—a clean shingle without admixture of sand. The sand and fine gravel thus eliminated by the undertow were deposited in large part near the head of the bay, causing the water to shoal rapidly, and ultimately determining the breaker line to a new position outside the first, and thus initiating the construction of a new bar. In this way the depth and length of the bay were at the same time progressively diminished.

For purposes of comparison the profile of the Snake Valley bars has been repeated in Pl. XI, where a series of similar phenomena are also drawn to the same scale. A brief description will be given of each locality.

At the head of Skull Valley, a few miles north of Government Creek, there is a low alluvial water-parting separating the valley from the open desert at the west. At the time of the Bonneville water stage this pass was reduced to an isthmus only a few rods in width, and the water was shallow on each side. On the Skull Valley side there were formed a series of bay bars, represented in profile in the plate. The winds under the influence of which they were formed, could have blown only from the northward.

The third profile represents in similar manner a group of bay bars observed a few miles east of Sevier Lake. The general trend of the old shoreline is there north and south, but at this particular spot there was a small cove lying on the north side of a rocky promontory. The bars were formed by northwesterly winds.

The fourth locality is a few miles east of the third, being on the opposite side of the Beaver Creek mountain range near George's Ranch. A small rocky hill was insulated at high-water stage by a narrow and shallow strait, and across this strait embankments were eventually built by the northeasterly winds. The first of the embankments, however, did not completely close the passage, and remains as a spit, while the others are completed bars. The topographic relations are shown by Fig. 23.

The locality of the fifth profile is the southwestern angle of Tooele Valley, the constructive winds blowing in this case also from the northeast.

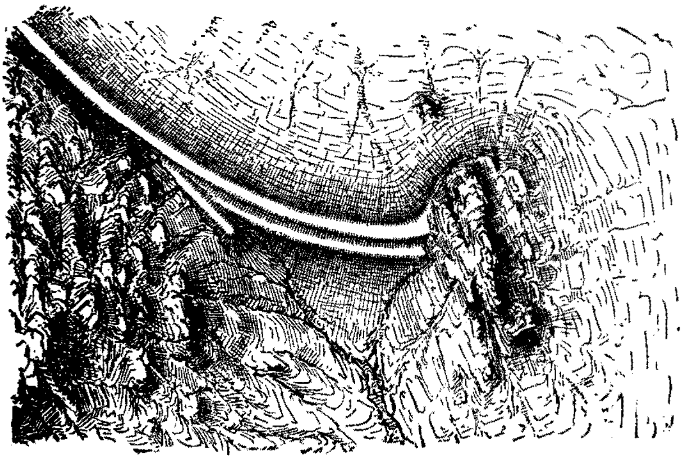


FIG. 23.—Bars near George's Ranch, Utah.

The Dove Creek locality is far to the north of the others, being on one of the ancient islands south of Park Valley. Trains of the Central Pacific Railway pass it midway between Ombe and Matlin; and it falls within the area represented by Pl. XXII. If the reader will turn to that plate, he will see that the Bonneville shore is represented on the southeastern face of the island by a sea-cliff and terrace, and on the northeastern by an embankment. The material for the embankment was derived from the sea-cliff and carried around the angle by shore action, doubtless by the alternating agency of winds from different directions. Below the Bonneville embankment there is a fine series of other embankments, which will be described in a later section of this chapter.

The surface of the island was eroded before the lake epoch, so that its slopes consist of a series of ridges radiating in all directions. On the southeast face these were pared away at the Bonneville level, reducing the shore to a straight cliff; but on the northeast face, where the action of the waves was constructive instead of destructive, the ridges retained their form, and the embankment was built across from one to another, enclosing a series of small basins occupied by lagoons. The first and second of these basins are now about twenty feet deep, and are undrained. The enclosing parapet is a simple bar not susceptible of subdivision, the formative currents appearing to have held a uniform course during its construction. The third basin is shallower, and a recently-formed drain reveals a section of its parapet, showing it to consist of the three bars indicated in the lowest profile of Pl. XI. The current at this point must have been thrown farther and farther from the land as accumulation proceeded. The fourth basin is similar to the third, but the fifth has no inner bar. The low-lying inner bars are obviously older than the high outer bar, and all the minor features of the locality tend to the conclusion that, during the period of their formation, the train of shore drift did not extend to the fifth basin. It is inferred by analogy that there was an antecedent time, within the epoch of the Bonneville shore, when the shore drift failed to reach the third basin, so that the series of bars there exhibted is incomplete.

Let us now consider the question why the successively formed bars in these several localities differ in height. At least three general answers are possible. The embankments were built upon the land by means of the water of the lake, thrown into motion by the wind, and their variations in height may have resulted from variations of the wind or of the water or of the land. It is conceivable that the highest bars were produced by storms of exceptional force, and the lower by less violent storms. It is conceivable that the water of the lake rose and fell from time to time, and that the bars marked successive stages. It is conceivable that the land rose and sank, so as to bring different horizons successively within reach of the waves; and finally, it is conceivable that two or more of these causes conspired to produce the phenomena.

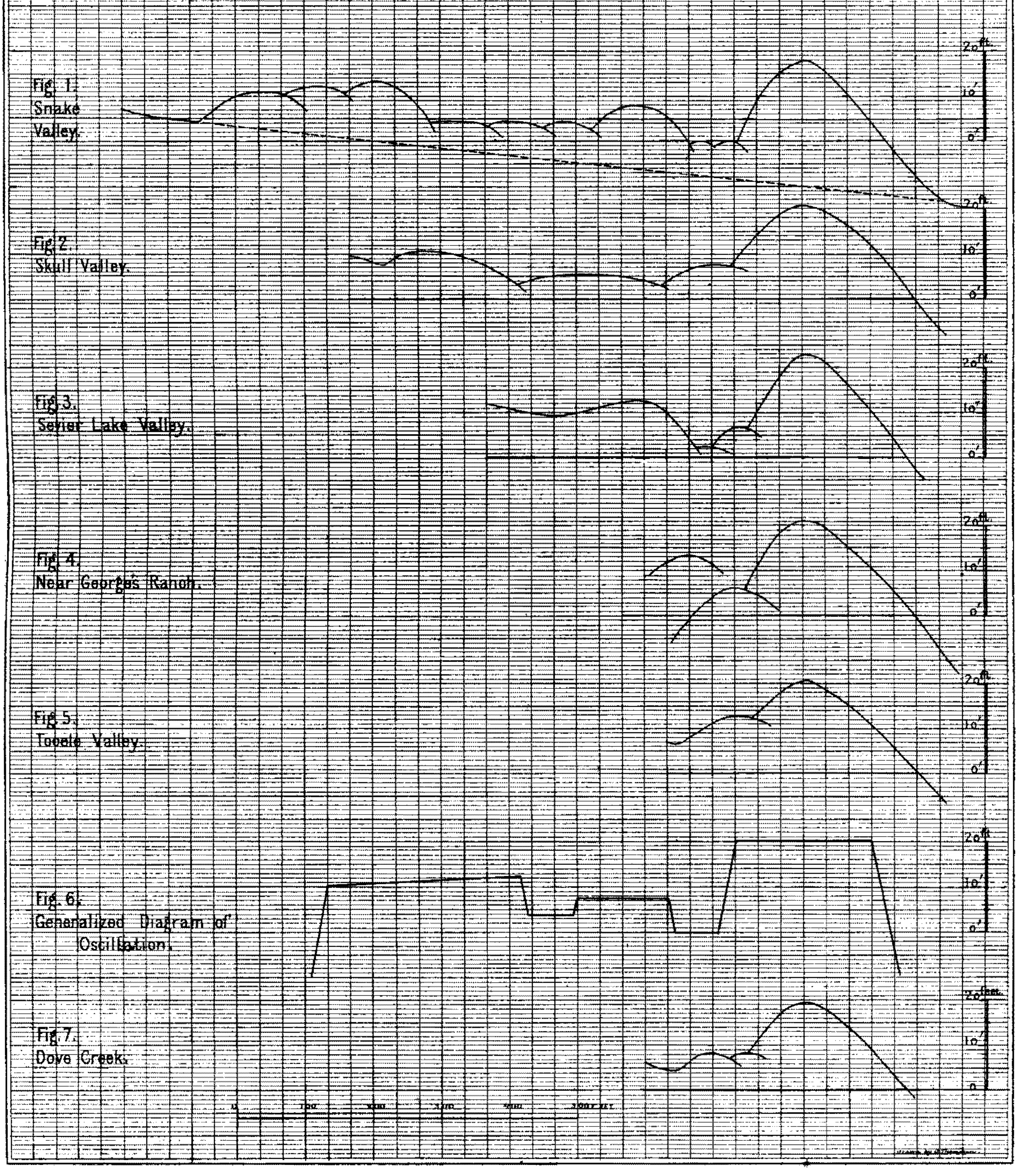
A movement of the land might have been general, involving the entire basin, or there might have been differential movements, changing the relative height at various points. In the first case the lake would be carried up and down with its basin, and there would be no change in the relation of shore and water. The only land movement therefore which could produce the phenomena, is one of a differential nature, and this would of necessity give rise to dissimilar results at widely separated places. If the several bar series are harmonious in their vertical relations, it is safe to say that they do not indicate oscillations of land.

A movement of the water surface would evidently produce changes of the same vertical amount at every point, so that the hypothesis of lake oscillation would be negatived if the several systems of differentiated bars were found to be inharmonious.

The remaining hypothesis of unequal storm force may take two forms. In the first place, it might be imagined that each individual embankment of exceptional height was the creature of a single storm, or of a limited series of storms; or, in the second place, it is conceivable that the general character of the weather underwent secular variations; so that from century to century there were notable changes in the maximum force of storm winds. Under the first view, we should anticipate that localities dominated by winds from different directions would not accord in the character of their bar systems; the approximate coincidence of exceptional storms from opposite directions, being only adventitious, could not be expected to recur with uniformity. Under the second view, on the contrary, there would be uniformity of result,—a general change of climate affecting all localities alike. The eolian hypothesis would therefore be disproved neither by the harmony nor by the lack of harmony of the observed results. It admits, however, of an independent test of crucial value. Great waves are unquestionably able to transfer coarser shore drift than small waves, so that where the supply of debris is heterogeneous, the character of that selected for the construction of embankments is an index of the power of the waves. If, therefore, in localities where the shore drift is derived from the unsorted alluvium, it be found that the higher bars contain coarser fragments than the lower, it is proper to infer that they owe their superior height to superiority of wave force; but if it be found that all the bars of a series are uniform in composition, their inequalities of size cannot be referred to variations of storm force, either local or general.

As a matter of fact, there is no correlation of coarse material with high bars. The Snake Valley series was scrutinized with reference to this point and found to be uniform in composition. We may then cease to consider the wind, at least so far as the more important variations are concerned, and limit attention to the hypotheses of land movement and lake movement. The theory of land movement would be sustained by a discordance among

PROFILES OF RAY BARS OF THE BONNEVILLE SHORELINE



the systems of bars. The theory of lake movement would be sustained by an accordance. An imperfect accordance might indicate a combination of the land and lake changes.

The facts are assembled in Pl. XI, to which the reader is again referred. Each of the profiles represents a section at right angles to the system of bars it illustrates, and all are drawn to the same scale, the vertical element being exaggerated three-fold. They are grouped on the page in such manner that the outer embankments of the several series appear at the right and fall in the same vertical column.

The first consideration affecting the comparison is that each series presumably represents the same period of time, so that, if a correlation is possible, the embankment drawn at the right in one series should correspond to that at the right in the others. That at the extreme left in one should correspond to that at the extreme left in the others, and the intermediate portions should be comparable. The only exception to that rule is in the case of the Dove Creek series, which, as already explained, may represent only the later portion of the time consumed in the formation of the others.

Restricting attention to the first five groups of bars, we note first that the right-hand member of each is higher than any other. The second conspicuous fact is that the member second in size stands at the extreme left. To this there is a single unimportant exception, which vanishes if we consider the three bars at the left of the upper profile to constitute a single member comparable with the individual bars of the other series. It is by no means improbable that a more careful study of the Skull Valley locality would resolve the left-hand maximum into such a series as was found in Snake Valley.

The most extended series exhibits a third maximum, lower than either of the others, but intermediate in position and standing somewhat to the right of the middle of the profile. No other profile shows a third maximum, but three of them exhibit bars of approximately the same height, which may be conceived to represent it, if the bars of the second minimum are assumed to have been covered and concealed by the great outer bar. It is easy to understand that a condensed or foreshortened series would exhibit superficially only the maxima of a fully extended series. It therefore seems proper to correlate the intermediate maximum of the upper profile with the bar appearing at the inner base of the outer maximum in the second, third, and fourth profiles. In the fifth profile, bars representing the first and third maxima stand in juxtaposition; and it is necessary to assume that the intervening maximum, as well as the two minima, is covered and concealed.

It thus appears that, in their most general features, the groups of bars are in accordance, with no greater variation than might readily be ascribed to local disparity of condition.

The difference between the altitude of the outer bar and that of the intermediate maximum was measured in four localities. In Snake Valley it is 10 feet, in Skull Valley 12 feet, in Sevier Lake Valley 15.3 feet, and at George's Ranch 15 feet. The range of these measurements is 5 feet, and this must be regarded as a real discrepancy, though not a great one.

The altitude of the outer bar above the inner maximum was measured at five points and found to be 5 feet, 10 feet, 10 feet, 7 feet, 8 feet,—the enumeration following the order of the diagrams. Here again the range is 5 feet.

If the inner bar be compared with the intermediate maximum instead of with the outer bar, the differences are found to be 5 ft., 2.7 ft., 5.3 ft., and 8 ft., showing again a range of 5 feet.

Finally, the low bars observed between the inner and intermediate maxima have approximately the same relation in the three localities where they were observed. Compared with the intermediate maximum, their measured differences are 3.5 ft., 2.3 ft. and 4.7 ft., the range being 2½ ft.

These comparisons exhaust the data, and they appear to establish the systematic harmony of the phenomena. It is inconceivable that such accord should be fortuitous. The most complete record (that in which the bar system was spread out most broadly, so as to resolve it most completely into its elements) exhibits three maxima with intermediate minima. The record second in extent shows the three maxima and one minimum,—the other minimum being overplaced and concealed. The Sevier Lake record shows the same four elements, but more compactly arranged. At George's Ranch the three maxima are so closely crowded that both minima are concealed. At the head of Tooele Valley, the outer and inner maxima are in juxtaposition and all the intermediate elements of the series are buried. The ordinary bay bar, in which all the elements are welded together and covered by the last and highest deposit, is logically the final term of the series of facts.

The hypothesis of water movement is therefore sustained. The changing relations of land and water during the formation of that complex record to which we have applied the title of the Bonneville shore-line, were brought about by the alternate rising and falling of the water surface. While the higher bars were being formed, there was more water in the basin; while the lower, less.

Having thus established the correlation of the series of profiles by a comparison of the unmodified facts of observation, it is now proper to adjust them to one another for the purpose of ascertaining the mean quantitative value of changes of water level. Applying the method of least squares, we obtain for the most probable values of the water stages, referred to the lowest of the series as zero and arranged in the order of time:[1]

	feet.	
First maximum	**12.3**	**± .2**
First minimum	**3.9**	**± .2**
Second maximum	**7.3**	**± .2**
Second minimum	**0.0**	
Third maximum	**20.1**	**± .2**

Adjusted to the same zero, the observations at the several localities exhibit the following relations:

TABLE II. *Embankment Series of the Bonneville Shore-line.*

Locality.	Altitude in feet.					Variation from adjusted mean.				
	1st Max.	1st Min.	2d Max.	2d Min.	3d Max.	1st Max	1st Min	2d Max	2d Min	3d Max
Snake Valley......	13.0	4.5	8.0	0.0	18.0	+.7	+.6	+.7	....	−2.1
Skull Valley......	10.3	5.3	7.6	....	20.3	−2.0	+1.4	+.3	....	+.2
Sevier Lake Valley.	12.2	2.2	6.9	....	22.2	−.1	−1.7	−.4	....	+2.1
George's Ranch....	13.6	....	5.6	....	20.6	+1.3	....	−1.7	....	+.5
Tooele Valley.....	12.2	....	....	....	20.2	−.1	....	....	....	+.1

[1] The computation included data from the Dove Creek profile and from the Preuss Valley bars. It was performed by Mr. A. L. Webster.

The residual discordance, as shown by the columns at the right, is not large, though it is somewhat greater than the range of variation found in the longitudinal profile of the crest of a single bar. A part of it is probably due to inaccuracies of measurement; no instruments of precision were employed, and the methods at more than one locality were improvised and crude. There will be no impropriety in referring the remaining part to exceptional storms combined with local conditions.

Reverting now to the Dove Creek series, which the field observations gave reason to suspect of incompleteness, we find by inspection that its two levels can readily be correlated with the second and third maxima of the generalized profile. It is highly probable, therefore, that the earlier water stages, including the first maximum and the first minimum, failed to make an independent record at that place.

To convert the data fully into terms of lake history it is necessary to compare the epochs of formation of the several bars in the matter of duration as well as in that of water stage. The amount of shore drift accumulated in the several bars has to be considered, and likewise the manner in which the varying water stage affected the rate of accumulation. A determination of absolute duration is manifestly out of the question, and any estimate of relative duration is largely a matter of individual judgment.

An attempt has been made in Fig. 6 of Pl. XI to represent the oscillations and their periods in a quantitative way, so far as they are deducible from the phenomena. If the facts permitted us to draw the full curve of oscillation with all its details it would unquestionably be far less simple. The number of minima concealed by the bars of even the most extended series may be very great; and it is even possible that these bars do not represent a continuous history. If, after the series had been partly formed, the lake shrank to much smaller dimensions, returning to the region of the Bonneville shore only after a long interval, there seems no way to determine this fact by the phenomena of the shore. Probably the only conclusions deducible from the profiles are; first, that, when the lake basin was full, the position of the water level was unstable; and, second, that of a series of high-water stages, the latest was the highest of all.

It will perhaps occur to the reader that the enumeration and discussion of these facts have been needlessly prolix; and this I am not prepared to deny. But it may be said in extenuation that the phenomena belong to a novel type, and that the method of investigation was so far new that the simple conclusions finally reached required for their establishment a full presentation of the alternative hypotheses eliminated by the investigation. In the sequel it will appear that even these simple conclusions afford a key to the understanding of some of the most important elements in the history of the lake, and through that history are brought into relation to the problem of the physical condition of the earth's interior.

One result of the discovery and interpretation of the groups of bay bars of the Bonneville shore-line was the explanation of certain features of the V-embankments which had previously been problematic. V-embankments have already been described as triangular terraces built against mountain slopes at the shore level, and margined toward the lake by even-topped parapets. In the light of the conclusions thus detailed it becomes evident that this conformation was occasioned by oscillations of the lake during the period of the formation of the terrace. The space within the parapet is usually occupied by a playa, the surface of which is from five to eight feet below the enclosing rim. This represents a certain amount of silting up of the basin. If there were no filling, it cannot be doubted that the interior of each enclosure would exhibit a series of bars parallel to one or both arms of the parapet, and corresponding in height and arrangement to the bay bars. In fact, this very phenomenon was finally observed at several localities. The most interesting are in Preuss Valley along the western base of the Frisco Mountains. In that valley the shore features of many different horizons afforded an instructive study, and were carefully mapped. Pl. VIII gives a general view of the phenomena on the east side of the valley, and it will be noted that the Bonneville shore-line includes three of these triangular terraces. The same appear on a somewhat larger scale in Pls. XVI, XVII, and XVIII. The parapet associated with the middle group of embankments (Pl. XVII) offers an exception to the general rule, in that it is broken through by the drainage, so that the interior contains no playa. It contains instead the eroded remnants of a system of bars parallel to the southern parapet. In this system it is easy to recognize the equivalents of first and second maxima of the Snake Valley bars, holding their proper relation to the parapet, which corresponds to the third or outer maximum. The V-embankment of the south group, Pl. XVIII, is undrained, but its filling has not progressed so far as to obliterate the inner maximum. Two elements of the bay-bar series are therefore represented; and the same were found in the north group of embankments.

In the case of the middle and southern of these Preuss Valley embankments, and in two or three other instances, the interior embankments are parallel to one parapet only, so as to constitute with that a series of parallel ridges connecting the remaining parapet with the shore. It seems evident that in these cases the growth of the triangular terrace was chiefly or entirely by additions to a single face; and it may not be improper to define the aggregate structure as a spit gradually projected into the lake by recurrent storms from a certain direction and buttressed by successively formed bay bars connecting its extremity at various stages with other points of the shore, the bay bars being the work of a series of storms from a different direction.

The variety of contour assumed by the parapets of the V-embankments, and by the crests of the hooks and loops with which they are more or less affiliated, is illustrated by Pl. VII.

DETERMINATION OF STILL WATER LEVEL.

One of the collateral results of the composite nature of the Bonneville shore-line is a discrepancy in the evidence afforded by different parts of the shore phenomena as to the altitude of the ancient water level. Those parts of the coast which were given their character by excavation indicate the water level by a line forming the angle between a cliff above and a terrace below, and this line often represents the lowest of the series of water levels recorded by the bay bars. The impression made by the waves at the last and highest level is usually, though not always, so faint that it has been obliterated by the falling down of the cliff. On the other hand, those parts of the shore formed by the accumulation of detritus appear as a rule at the highest water stage only. The localities in which embankments represent-


MAP OF
LAKE BONNEVILLE
showing
THE PRESENT HYDROGRAPHIC DIVISIONS
OF THE
BONNEVILLE BASIN
(in red)
and
The areas with altitude
greater than 7000 feet.
(in blue)
Note. The dotted lines indicate doubt
SCALE: 0 50 MILES.
I D A H O
W Y O M I N G
N E V A D A
U T A H
GREAT SALT LAKE
BASIN
DESERT
BASIN (?)
MAIN BODY
PILOT KNOB BASIN
POCATELLO
RUSH VAL.
CEDAR VAL.
SEVIER BODY
SEVIER BASIN
WHITE VAL.
SNAKE VALLEY
PRESSE VAL.
SAGE BRUSH VAL.
ESCALANTE BASIN
Little Salt Lake V.
Outlet
Red Rock
Franklin
Logan
Kelton
Willard
Ogden
Morgan
Salt Lake City
Black Rock
Weber R.
Provo R.
Grantsville
Utah Bay
Snake Bay
Willow Sp.
Deep Cr.
Fillmore
Frisco
Milford
Beaver Cr.
Sevier R.
Escalante
115°
114°
113°
112°
111°
42°
41°
40°
39°
38°

ing progressive action are differentiated, are exceptional; and in ordinary cases the latest additional material covers all the preceding. For an accurate determination of the height of the maximum water level, it is therefore necessary to consider the character of the record to which measurement is applied. The base of a sea-cliff is apt to give too low an indication, while the crest line of an embankment is not.

If this element were the only one to be taken into account, it would be a simple matter to ascertain in every region, by using embankments only, the precise height of the old water level; but there is unfortunately a complication. The crest of a completed embankment always stands somewhat higher than the still water level of the lake to which it pertains; and the amount of the difference depends on conditions which are not entirely simple. They include some elements of the configuration of the bottom, and especially the magnitude of the largest incident waves. The same elements of configuration affect also the record embodied in the base line of a cliff, but the magnitude of the waves does not. On a coast facing deep water the base of the sea-cliffs coincides very closely with the still water level. If, therefore, the surface of Lake Bonneville had not fluctuated while near its highest stage, the sea-cliffs would afford a more intelligible record of its precise horizon than the embankments.

As the case stands, the best indications are sometimes afforded by one class of facts and sometimes by the other. Wherever it is evident that the sea-cliffs associated with the maximum water stage survive, their base is assumed to give the most authentic record. Where these cannot be discriminated, embankments have been employed, an allowance being made for their height above the water line. This allowance is a matter of judgment in each individual case.

It will be instructive to illustrate the difficulties of the subject by a few examples.

If the reader will refer to the general map of the lake, he will see that the Jordan valley was occupied by a large bay receiving waves from the open lake, while the Utah Lake valley was occupied by a land-locked bay affected by no waves but those generated within its own borders. These two bays were joined by a narrow strait at the locality now known as the

Point of the Mountain, and from the coast east of this strait there was constructed an immense triangular terrace, receiving upon one side the detritus rolled by the great waves of the Jordan Bay, and on the other the shore drift moved by the smaller waves of the inner bay.

The parapets on the two margins of the V-shaped embankment give clear expression to this disparity of conditions. That facing Jordan Bay is the more massive and the longer, and the other is built against it as a sort of appendage. The general altitude of the larger bar is six feet greater than that of the less; and since the latter has all the features of a completed embankment rising above the water level, it follows that the northern or higher embankment was built more than six feet above the still water level of the lake.

Kelton Butte (Fig. 22) projected its apex as a small island above the water level and was surrounded by deep water. From one direction it received waves propagated through a distance of thirty miles, and by these a cliff and terrace were carved out and an embankment was constructed. The terrace is itself terraced in such way as to encourage the belief that the base of the cliff corresponds with the highest water stage; but this base is 7½ feet lower than the contiguous embankment.

At a locality in Preuss Valley, where the conditions did not admit of the generation of waves of great size, an embankment has been connected by leveling with a sea-cliff and terrace, and found to be 5 feet higher than the terrace. In this case part of the discrepancy is doubtless referable to the failure of the waves at the highest stage to score a durable record on the face of the sea-cliff carved at a lower level.

A similar measurement was made at Wellsville in Cache Valley, where also the waves were not of the greatest magnitude, and gave a difference of 19 feet. At the opposite end of Cache Valley, near the town of Franklin, there is a small indentation in the shore in which an isolated embankment has been preserved with a crest 12 feet above the base of the adjacent sea-cliff; and in a sheltered spot north of the town of Tecoma, in the northwestern portion of the basin, the measurement of similar details showed a difference of 20 feet.

The state of preservation of the embankments is all that could be desired for purposes of measurement. The majority of them are composed of gravel, and are exempted by their ridge-like form from the destructive action of cross-flowing drainage. A few inches at most would express the loss their crests have sustained from the wash of the rain. With the sea-cliffs and wave-cut terraces it is different. The decay of a cliff throws down a constantly increasing amount of debris, which falls to the base and forms a talus; and every little drainage channel by which a cliff is divided spreads a heap of alluvium upon the terrace below. The base of the cliff, therefore—the element of the profile which for purposes of measurement it is most desirable to recognize—has been almost universally covered by the rising alluvium, so that its precise position is a matter of estimation or indirect observation.

The discovery that the old water line is no longer of uniform height, and the fact that its variations of altitude afford a means of measuring the recent differential movements of the earth's crust within the basin, give occasion for great regret that the exact identification of the highest water stage is so difficult a matter. In a majority of instances the range of uncertainty, after all allowances have been made, amounts to five or six feet.

DEPTH.

The greatest depth of the lake was about 1,050 feet; and this depth obtained over all the western part of the present site of Great Salt Lake. The point west of Antelope Island, where the deepest water in Great Salt Lake is now found, did not sustain the same relation to Lake Bonneville, but was rivaled and perhaps surpassed by points between Promontory and the Terrace mountains. The Great Salt Lake Desert has now a remarkably flat floor, and the ancient depth of water above it did not vary greatly in different parts. The mean depth of the main body of Lake Bonneville was in the neighborhood of 800 feet. The Sevier body had a maximum depth of 650 feet, and Escalante bay of about 90 feet.

THE MAP.

The mapping of the Bonneville shore received careful attention; and it is probable that the extent and form of no modern lake in an unsettled country is more accurately known. The determination of certain questions with reference to overflow necessitated the inspection of a large part of the periphery; and the knowledge thus obtained of the position of the coast was afterwards systematically supplemented until a complete map became possible. The insular mountains standing on Great Salt Lake Desert were not visited, and the coast lines about their sides were for the most part deduced from the contours of the published maps of the Survey of the Fortieth Parallel; but with this exception all of the coast was seen by some member of the corps and sketched from actual observation. A large part of it was examined by more than one individual. The map is indebted to Mr. Gilbert Thompson for the details of the west coast between Deep Creek and Montello, and for the bays at the north ends of Pocatello and Malade Valleys. He delineated also the details west of Sevier Lake and in the southern extension of White Valley. The map is indebted to Mr. Thompson and Mr. Albert L. Webster for the outlines of the Escalante Bay. Mr. Willard D. Johnson delineated the shores of the White Valley Bay and the coasts on the Dugway, MacDowell, and Simpson Mountains. The outline in Tintic Valley was furnished by Mr. H. A. Wheeler. Mr. Israel C. Russell mapped the bay east of the Canyon Range, and is responsible for most of the coast between Fillmore and George's Ranch. He contributed also numerous details in all parts of the basin. The remaining portions of the shore were mapped by me. Some idea of the distribution of responsibility for the map, as well as of the thoroughness of the exploration, may be derived from an examination of Pl. III, where the routes of travel are exhibited.

THE PROVO SHORE-LINE.

Below the Bonneville shore-line are numerous other shore-lines, among which one is conspicuous. The name Provo was given to it on account of a great delta, which is at once a notable feature of the shore-line and a prominent element of the topography of Utah Valley in the vicinity of the town of Provo. The shore mark so far surpasses in strength all others of the series that this character serves for its identification; and it has been recognized in all parts of the basin without the necessity either of tracing its meander or of measuring its altitude. It has indeed been recognized with confidence despite conflicting determinations of altitude, for it is neither uniform in height nor uniform in its vertical relation to the Bonneville shore-line. In a general way it is 375 feet lower than the Bonneville shore and 625 feet higher than the water of Great Salt Lake.

The Provo record is more recent than the Bonneville. This appears, first, from its state of preservation; the Provo cliffs are the steeper and sharper and the smaller talus lies at their base. It appears, second, from the absence of lake sediments on the surfaces of the Provo terraces. During the formation of the Bonneville shore, the horizon of the Provo was sufficiently submerged to receive a layer of fine sediment; and a lake deposit commensurate in amount with the shore drift accumulated in the Bonneville embankments would not escape detection if it had rested on the terraces of the Provo shore. The relative age is shown also by the relation of the shores to the outlet of the lake, as will be explained in another chapter.

The duration of the water stage recorded by the Provo shore was greater than that of the Bonneville water stage. Although the Bonneville is the most conspicuous of all the shore-lines, it does not exhibit the greatest monuments of wave work, but owes its prominence largely to its position at the top of the series, where it is contrasted with topographic features of another type. There are several other shore-lines which rival it, and, although it probably outranks in magnitude all except the Provo, its discrimination would be a difficult matter were it an intermediate member of the series. The Provo, on the contrary, is rendered conspicuous chiefly by the magnitude of its phenomena. Its embankments are the most massive, and its wave-cut terraces are the broadest. Moreover, the Provo Lake was in every way inferior to the Bonneville as a field for the generation of powerful waves. It was narrower and shallower and obstructed by larger islands. To have constructed shores equal to those of the Bonneville, it must needs have existed a longer time; and still longer to have built its greater structures.

OUTLINE AND EXTENT.

The outline of the lower shore was the less tortuous. The sinuosity of the Bonneville shore is due to the fact that the water flooded a large number of the narrow troughs of the Great Basin and was partially divided by the mountain ridges. When the water retreated to the Provo level, it abandoned a considerable number of the valleys and retired on many parts of the coast from the uneven mountain faces to the smooth contours of the alluvial slopes. Two of the largest bays, the Escalante and the Snake Valley, were completely desiccated, and so was a third part of the Sevier Desert. The water was withdrawn from Thousand Spring and Buell Valleys, from Grouse Valley and Park Valley, from Ogden Valley and Morgan Valley, from Cedar Valley, Rush Valley, and Tintic Valley, and from both ends of Juab Valley. Of the three straits joining the Sevier body with the main body of the lake, only the eastern remained. The closing of the central and western straits joined to the western peninsula the islands which had been constituted by the MacDowell and Dugway Mountains. The islands formed by the Promontory, the Cedar, and the Beaver Creek Ranges, were converted into peninsulas, and so was Pilot Peak. The group of islands south of Park Valley and the group south of Curlew were joined to the mainland; and it is possible that the islands constituted by the Lakeside Mountains were united to the Cedar Mountain peninsula. Doubtless many other hills that had previously been submerged now appeared as islands; but none of these were of great extent, and the total number of islands must have been greatly diminished. Among the emergent islands were some of the volcanic buttes west of the town of Fillmore and a basaltic mesa southwest of the town of Deseret. The passage from Cache Valley to the main body was reduced to a narrow strait only a few hundred feet in width, and the entrances to the Utah Lake bay and the White Valley bay were greatly restricted.

SHORE CHARACTERS.

In several respects the newer shore-line has a different facies from the older. It has already been remarked that it is more freshly cut. It is characterized also by its broader terraces, by its deltas, by its tufas, and by a peculiar duplication in its profile.

While the Provo cut-terraces are far broader than the Bonneville, the associated sea-cliffs are not so high, the difference being occasioned, in part at least, by the relations of the two water surfaces to the general slope. If a

Julius Bien & Co, lith.

Drawn by G. Thompson

profile be drawn across any of the valleys occupied by the lake, it will be found to be broadly U-shaped. The floor of each valley is nearly flat; and the alluvial slopes at the sides, rising very gently at first, gradually increase their inclination until they join the acclivities of the mountains. The Bonneville and Provo shores are so related to the valleys that their difference of a few hundred feet of altitude corresponds to a general and notable difference in the slopes of the land at their margins. The Provo waves, attacking comparatively gentle slopes, produced terraces of great width, as the companions of cliffs with but moderate height. Floors 200 to 400 feet broad are of frequent occurrence; and in one place a cliff 75 feet high overlooks a terrace 750 feet wide.

FIG. 24.—Limestone butte near Redding Spring, Great Salt Lake Desert; an island at the Provo stage.

Deltas.—The abundance of deltas on the Provo coast requires for its explanation a considerable chapter of the history of the lake. It has already been remarked that the principal streams tributary to the basin rise at the east. In flowing westward each of them encounters one or more mountain ranges, across which it passes in a deep and narrow defile or canyon. The drainage system is older than the lake; and this series of canyons was completed by the streams before the Bonneville epoch, so as to form part of the system of valleys flooded by the lake. When the water first rose to the Bonneville level, it set back a number of miles into each of the canyons; and in some instances extended beyond the first mountain range, forming small bays on the eastern side. During the period represented by the Bonneville shore-line, the detritus brought by the rivers was thrown into these bays and inlets and gradually reduced their dimensions. A few of the smaller inlets were completely filled; and in three or four instances small deltas were projected into the lake; but the remainder of the canyons retained the character of inlets until the water fell. At the beginning of the Provo epoch it is probable that nearly all of the larger canyons admitted short estuaries, but of this there is no definite record. If such existed, they were quickly filled by alluvium,—the preexisting accumulations at the heads of the canyons affording an abundant supply ready at hand. The formation of a delta in the open lake must have begun at the mouth of each canyon soon after the establishment of the water stage; and it was continued until the close of the Provo epoch. The water surface then fell once more, and the lowering of the mouths of the streams caused them to begin the erosion of the deltas; but the broad terraces built on the open plain were not so easily effaced as the alluvial deposits within the narrow canyons, and the destructive activity of the streams has accomplished only the opening of terraced channels through them.

The channeling of the deltas was accompanied by the construction of other deltas at lower levels, so that each river course is margined by a series of deltas embodying a portion of the history of the progressive changes of the lake. In the discussion of these series in a later section, the several deltas of the Provo shore will receive separate mention and description.

Calcareous tufa has been found in association with many of the shore-lines and was probably deposited in some amount at all stages of the lake. It is exceptionally abundant at the Provo level, but it will be more convenient to describe its occurrence in a special section devoted to the subject of tufa.

The Underscore.—Where the Provo water mark is a work of excavation, its characteristic profile includes two sea-cliffs and two terraces. The upper cliff is the greater of the two, and the terrace at its foot is the broader terrace. The lower terrace is rarely more than a twentieth part as great as the upper, and in many places it could not be detected. The vertical space between the two shelves is estimated to range from five to twenty feet; at the sole point of measurement it is six feet. The main terrace is conspicuously distinguished by its flatness. At no other stage of the lake have the waves carved out so level a platform. In its broader examples the lakeward slope is barely perceptible to the eye; and at no point does the total descent from the foot of the upper cliff to the crest of the lower exceed five feet. The lower terrace has no idiosyncrasies aside from its association with the upper, but that peculiarity has caused it to be styled in the field notebooks "the underscore," and it will be convenient to retain the designation. Though not universally discernible, yet it is so persistent a feature as to be found serviceable in the identification of the Provo shore at doubtful points.

EMBANKMENT SERIES.

Where the water mark consists of works of construction its characters are less constant. As a rule, the bays of the Provo coast are spanned by single bars; and its spits, like those of the Bonneville shore, are apparently simple in structure; but in a few instances the accumulations in bays are observed to consist of two bars with the outer lower than the inner. The difference of height was never subjected to measurement; but was estimated to be about fifteen feet. At Dove Creek (see Pl. XXII) the shore exhibits two wave-built terraces, of which the outer and later formed is 14 feet lower than the inner.

On Tĕrrace Mountain, a few miles south of Ombe station, the Provo embankments in a small bay are separated after the manner of the Bonneville embankments in Snake Valley, and include six distinct bars with a faint suggestion of four others. A profile of these is given in Fig. 3 of Pl. XIV. Fig. 1 of the same plate exhibits the cut terrace with the underscore; Fig. 2, the double bay bar.

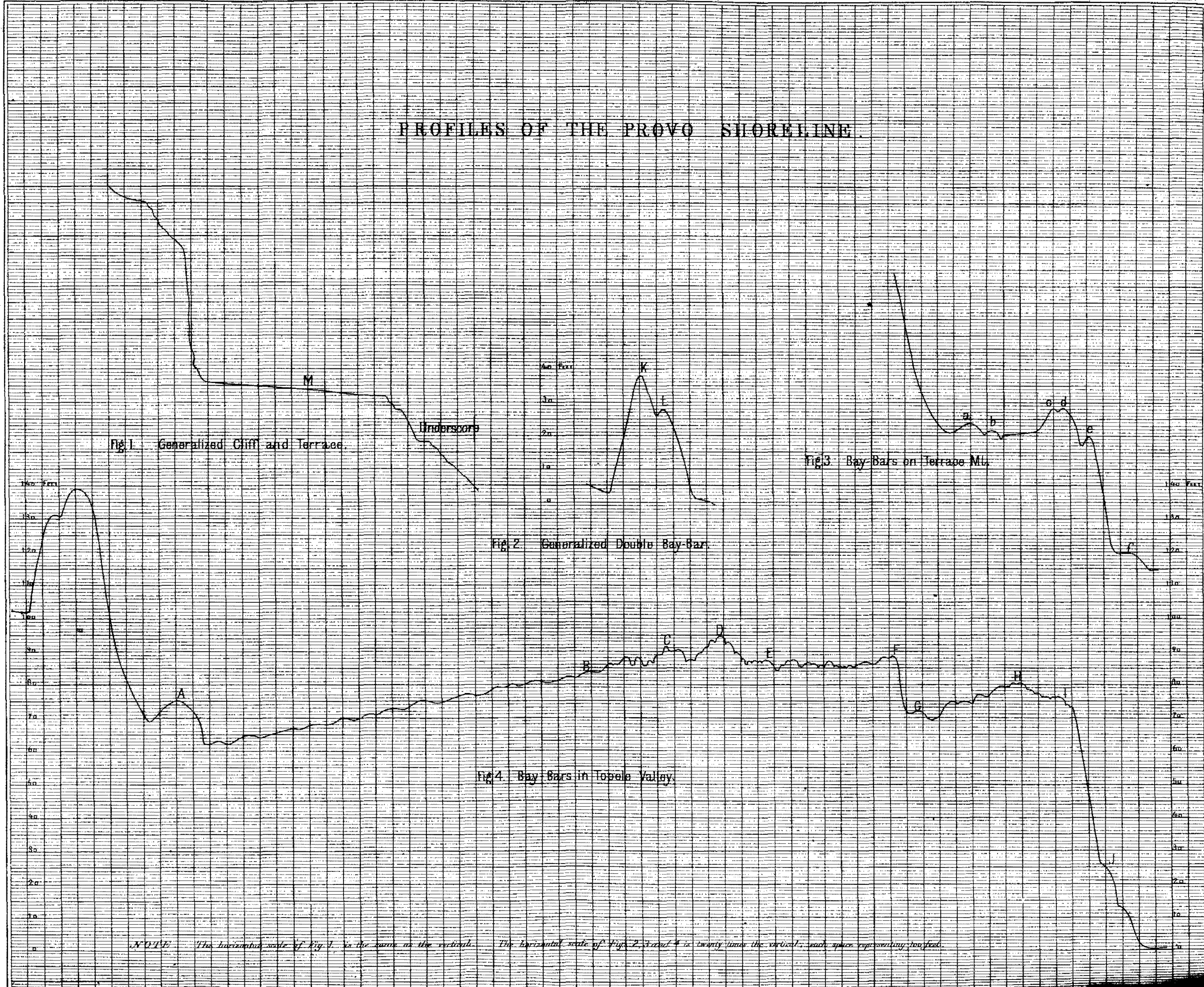
In Tooele Valley the Provo presents the most remarkable expansion of a shore record that has anywhere been preserved. During that epoch the valley contained an open bay receiving storm waves from the broadest portion of the lake. The principal excavation was from the alluvial slopes of the western base of the Oquirrh mountains, and the material was swept southward to the shallow head of the bay, where it was built into a series of bars stretching from shore to shore with sweeping curves. In this series 65 individual bars have been counted and their aggregate width is more than a mile. Their order of position is necessarily the order of their formation; and their profile (Pl. XIV, Fig. 4) exhibits in consecutive order the local variations of the relation of water to land during the Provo epoch.

The double terraces, the double bay bars, the bar series of Terrace Mountain, and the bar series of Tooele Valley, constitute the whole of our information with regard to the oscillations of the lake during the Provo epoch; and all effort to correlate them and deduce a consistent history has failed. In the discussion of the Bonneville profiles, it was found that the more extended series was represented in the less extended only by its highest members, the minima of the profiles disappearing as they were condensed. If the same relation subsists between the Provo profiles, then each member of the Terrace Mountain series should be found to correspond to some maximum of the Tooele Valley series. The comparison is necessarily begun by equating the highest member of one locality with the highest member of the other:—that is, by saying that the Terrace Mountain *c* and *d* are equivalent to the Tooele Valley C and D. Then *a* and *b* of the Terrace profile should be represented by maxima to the left of C in the Tooele profile; but the only maximum of this kind is at A, and is too low by nearly 30 feet. The terrace from E to F may be compared without great incongruity with the bar *e;* but the maximum at H is 20 feet too high to be represented by the bar *f.* Similar difficulties prevent the correlation of the Terrace profile with the double bar, Fig. 2; but they do not arise when the latter is compared with the Tooele profile. The higher bar of the pair may fairly be taken as the equivalent of the Tooele group from A to F, and the lower bar may represent the embankments from G to I.

The wave-cut terrace and underscore (Fig. 1) have no sympathy with any bar group except the simple pair. It is probable that the greater and higher bar K was in whole or part the contemporary of the terrace M; and it is possible that the minor bar L was the contemporary of the underscore.

Though the wave-cut terraces and the Tooele Valley bar series sever-

PROFILES OF THE PROVO SHORELINE.



NOTE. The horizontal scale of Fig. 1. is the same as the vertical. The horizontal scale of Figs. 2, 3 and 4 is twenty times the vertical; each space representing 100 feet.

ally accord with the double bars, they do not harmonize with each other. Upon the assumption that each records the oscillations of the water-surface, the deduced histories are different. The exceptional flatness and extreme breadth of the upper terrace seem to show that the waves were for a long time at a uniform horizon, or else that the latest work of excavation was at so low a level that all terraces of anterior production were undercut and obliterated; the underscore appears to represent a brief lingering after the main terrace had been finally dried. The Tooele Valley profile, on the other hand, indicates a gradual rise of 40 feet from the base of the bar A to the upper terrace B, followed, first, by a tolerably uniform high stage BF, and, second, by a stage GI ten or fifteen feet lower. If the breadth of the bars be taken as a time scale, the higher stage had twice the duration of the lower, but occupied somewhat less time than the gradual rise preceding it. If the production of an individual bar be taken as the unit for time-scale, the higher stage had two and one-half times the duration of the succeeding low stage and three times the duration of the antecedent rise. If, now, we correlate the central group of Tooele bars with the main wave-cut terrace, and correlate the outer group of bars with the underscore, we find two difficulties. In the first place, the underscore represents but a small fraction of the period of wave action under consideration, while the outer series of Tooele bars, upon any plausible basis of estimate, represents a relatively large fraction. In the second place, the progressive rise implied by the Tooele profile has no expression in the wave-cut terraces, where its effect would be to impair the definition of the outer edge of the main terrace and contravene its characteristic flatness. There appears then no way in which to reconcile the various analytic manifestations of the Provo shore on the hypothesis that the recorded oscillations are purely those of the water surface. The presumption is therefore in favor of the alternative hypothesis that there were differential movements of the earth's crust within the basin during this epoch. Unfortunately, the data are too meager for the discussion of this hypothesis.

THE MAP.

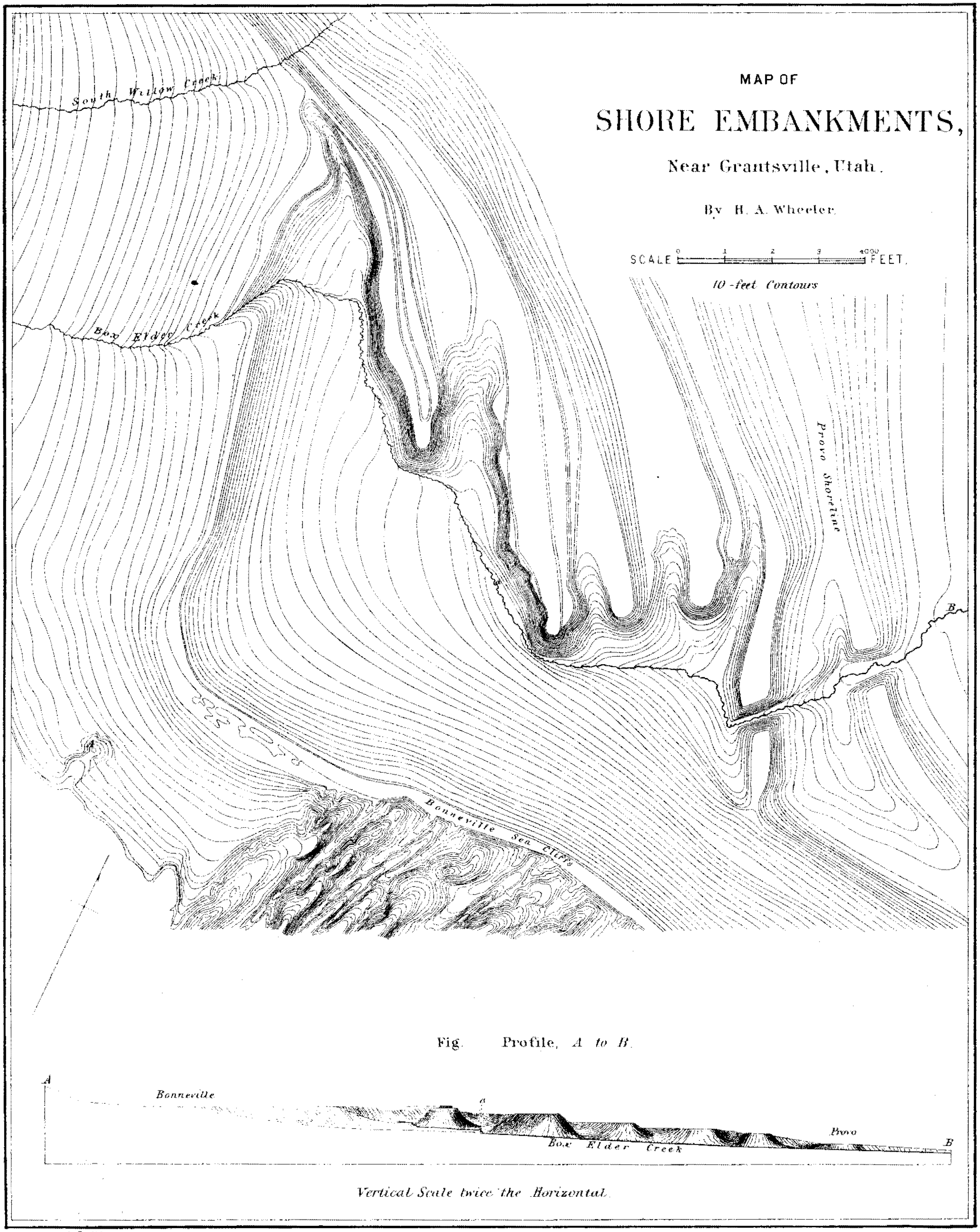
During the prosecution of the field work, no attempt was made to obtain the data necessary for mapping the Provo shore-line; but the notebooks contain so many incidental references to its position that it has been found possible to construct a map not grossly erroneous. The reader is warned that the outline delineated in Pl. XIII is approximate only. A similar qualification applies to estimates of area. The water surface at the Provo stage had an approximate extent of 13,000 square miles, 11,500 belonging to the main body and 1,500 to the Sevier body.

THE STANSBURY SHORE-LINE.

From the Provo water line to the margin of Great Salt Lake, the descent is more than 600 feet. From the same line to the Bonneville shore the ascent is less than 400 feet. In the upper space all the conspicuous lacustrine features are referable to shore action, but there are subordinate evidences of sedimentation. In the lower space lake sediments predominate, giving their peculiar smoothness to the surface, and the shore tracings are relatively unimportant. Upon any profile a considerable number of shores can be recognized below the Provo; and it is probable that a system of levelings would enable these to be correlated in a consistent system. This has not been done, and only a single one has been widely recognized. That one is distinguished merely by the greater magnitude of its cliffs and embankments, but is not sufficiently accented to be everywhere identified. It is called the Stansbury shore-line. Its strongest delineation is upon Stansbury Island, where owing to local conditions it rivals the Provo shore in definition and surpasses the Bonneville. In abundance of tufaceous deposit it probably ranks next to the Provo.

Its height was measured at two points only. On the west side of the Terrace Range it lies 310 feet below the Provo shore; and at the north end of the Aqui Range 346 feet. At the latter locality it was found to be 330 feet above the level of Great Salt Lake. It is thus seen to divide about equally the interspace betwen the Provo shore and the shore of Great Salt Lake.

At the time of its formation the maximum depth of the lake was only about half as great as at the Provo date; and the water surface was corre-



Julius Bien & Co. lith.

Drawn by G. Thompson

spondingly diminished. The constructive waves were therefore less powerful and the time necessary for the performance of an equal work was longer. There is good evidence, however, that the period of time represented by this shore is shorter than that represented by the Provo. The body of water covering the Sevier Desert during the Provo epoch was smaller than the body occupying the Great Salt Lake Desert at the Stansbury epoch; and yet the shore phenomena by which it is outlined are upon a far larger scale than any exhibited by the Stansbury.

The water was at this time withdrawn from the Sevier Desert, but covered the main portion of the Great Salt Lake Desert. It washed the foot of the Wasatch and extended within a few miles of the western line of the Bonneville shore, but was excluded from most of the bays at the north and south. Its total area was in the neighborhood of 7,000 square miles.

THE INTERMEDIATE SHORE-LINES.

In every locality where the Bonneville and Provo shores are marked by considerable accumulations of shore drift, the whole of the intermediate slope is similarly characterized. In every locality where the Bonneville and Provo shores give evidence of excavation, the intervening space is completely occupied by similar evidence, but the phenomena are in this case less conspicuous.

DESCRIPTION OF EMBANKMENTS.

Grantsville.—If the reader will turn to Pl. XV, which represents a tract of country a few miles south of the town of Grantsville, he will see that an angle of the valley, containing a bay of the ancient lake, occasioned the local accumulation of large embankments. By studying the contours of the map, or by referring to the accompanying profile, he will see that these embankments have their crests at various levels, the order of height being also the order of horizontal position. The Provo embankment was carried entirely across the bay, so as to complete a bar; and the same is true of the one next to it in the series. The development of the other embankments was arrested while they were yet spits. Box Elder Creek, which was tributary to the bay, has its modern course deflected by the spits, and has opened a passage through the bay bars. Each of these embankments is the product of essentially the same combination of local conditions. At each of the represented stages the shore drift derived from a long alluvial slope at the north, beyond the field of the map, was carried southward toward the edge of the bay and there accumulated in a long embankment, built in the deep water of the bay on a line tangent to the shore at the north. Between the Bonneville and the Provo there are four principal embankments; and it was a natural assumption, made at an early stage of the investigation, that each of these embankments recorded the work accomplished by the waves at a stage represented by the height of its crest. This assumption was for a time unquestioned, but later developments led to doubt of its validity; and, in order to test it, a systematic collection of shore data was undertaken. Localities were sought where the configuration of the lake bottom favored the construction of shore embankments at all levels from the Bonneville to the Provo, and at such localities contour maps were made and profiles were measured with the spirit-level. By means of these maps and profiles, taken in connection with the details of structure observed at the same locality, the general history of the Intermediate shore-lines was developed, but the original assumption was overthrown.

In order to present this history to the reader, with the evidence upon which it rests, it will be necessary to make him acquainted with a selected series of the maps, which series has been reproduced in the accompanying plates.

Preuss Valley.—Pl. VIII represents eight miles of the eastern side of Preuss Valley. At the right stand the rocky spurs of the Frisco Mountains, and against their base the stream drift from the canyons is piled in great alluvial cones. While the lake occupied the valley, the form of its shore was given by the contours of the alluvium, each great cone occasioning a rounded cape, and each interval between the cones, a bay, From three of the capes the currents were deflected in such way as to accumulate the shore drift in a system of embankments,—and this at all levels from the Bonneville to the Provo. Pls. XVI, XVII and XVIII show the details of the three localities of accumulation.

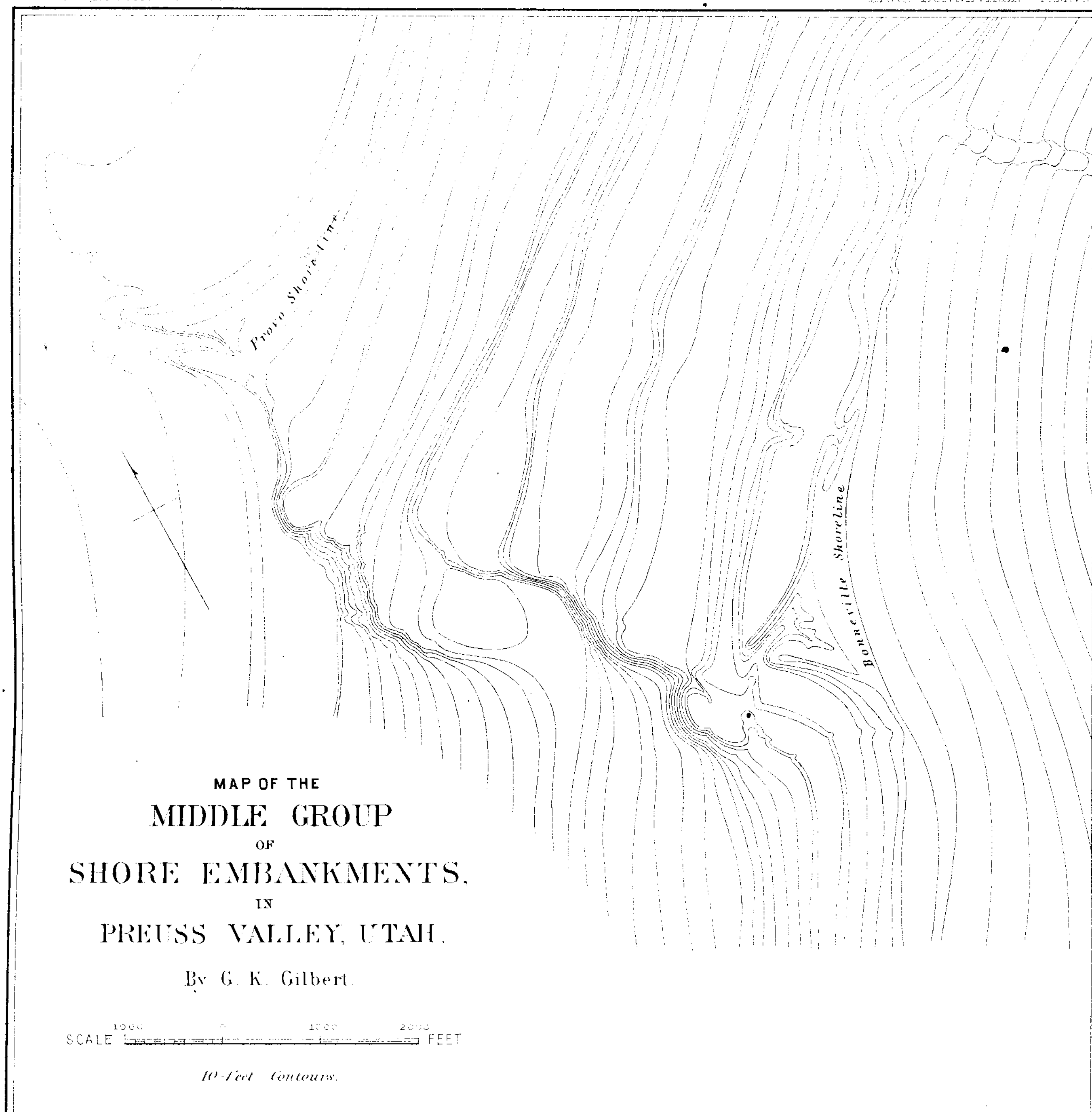
MAP OF THE
NORTH GROUP
OF
SHORE EMBANKMENTS
IN
PREUSS VALLEY, UTAH.

By G. K. Gilbert.

SCALE: 1000 0 1000 2000 FEET

10-feet Contours.

VIEW AS SEEN FROM THE SOUTH.



MAP OF THE

MIDDLE GROUP

OF

SHORE EMBANKMENTS,

IN

PREUSS VALLEY, UTAH.

By G. K. Gilbert.

SCALE 1000 0 1000 2000 FEET

10-Feet Contours.

Fig. 1. Profile as seen from the South.

Vertical Scale double the Horizontal.

Julius Bien & Co. lith.

Drawn by G. Thompson

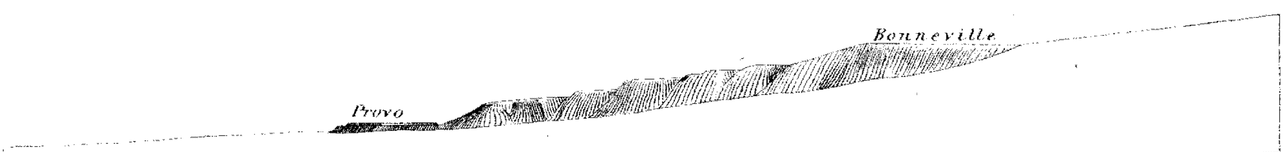
MAP OF THE

SOUTH GROUP
OF
SHORE EMBANKMENTS,
IN
PREUSS VALLEY, UTAH.

By G. K. Gilbert.

SCALE 1000 0 1000 2000 FEET.

10-feet Contours.



Profile as seen from the South.

Vertical Scale double the Horizontal.

The Snowplow.—A similar compound embankment, but on a grander scale, was formed at the southern opening of the strait joining the two principal bodies of the lake. Its general relations appear on Pl. XXXI and its details on Pl. XIX. The shore drift in this case came from the east, being derived from a great alluvial slope formed by the coalescence of many cones from the Simpson Mountains. The embankments into which it was built are characterized by the V-form, and are so piled one upon another as to have suggested the name Snowplow, by which the group was distinguished in the field notes.

Stockton and Wellsville.—The embankments at Stockton (Pl. XX) are of a different type, having been thrown across a strait and not merely projected from a shore. That of the Bonneville stage is, however, exceptional, running athwart the others in the form of a broad spit; and those of the Provo stage, which fall without the field of the map on the south side, are typical bay bars. A perspective view of the field of this map is given in Pl. IX, and a profile of the contiguous Provo bay bars in Pl. XIV. The embankments at Wellsville in Cache Valley (Pl. XXI) are of the same type as those near Grantsville, but are less perfectly preserved. A mountain stream flowing across them has opened a wide channel; and the extremities of two embankments have been truncated by land slides.

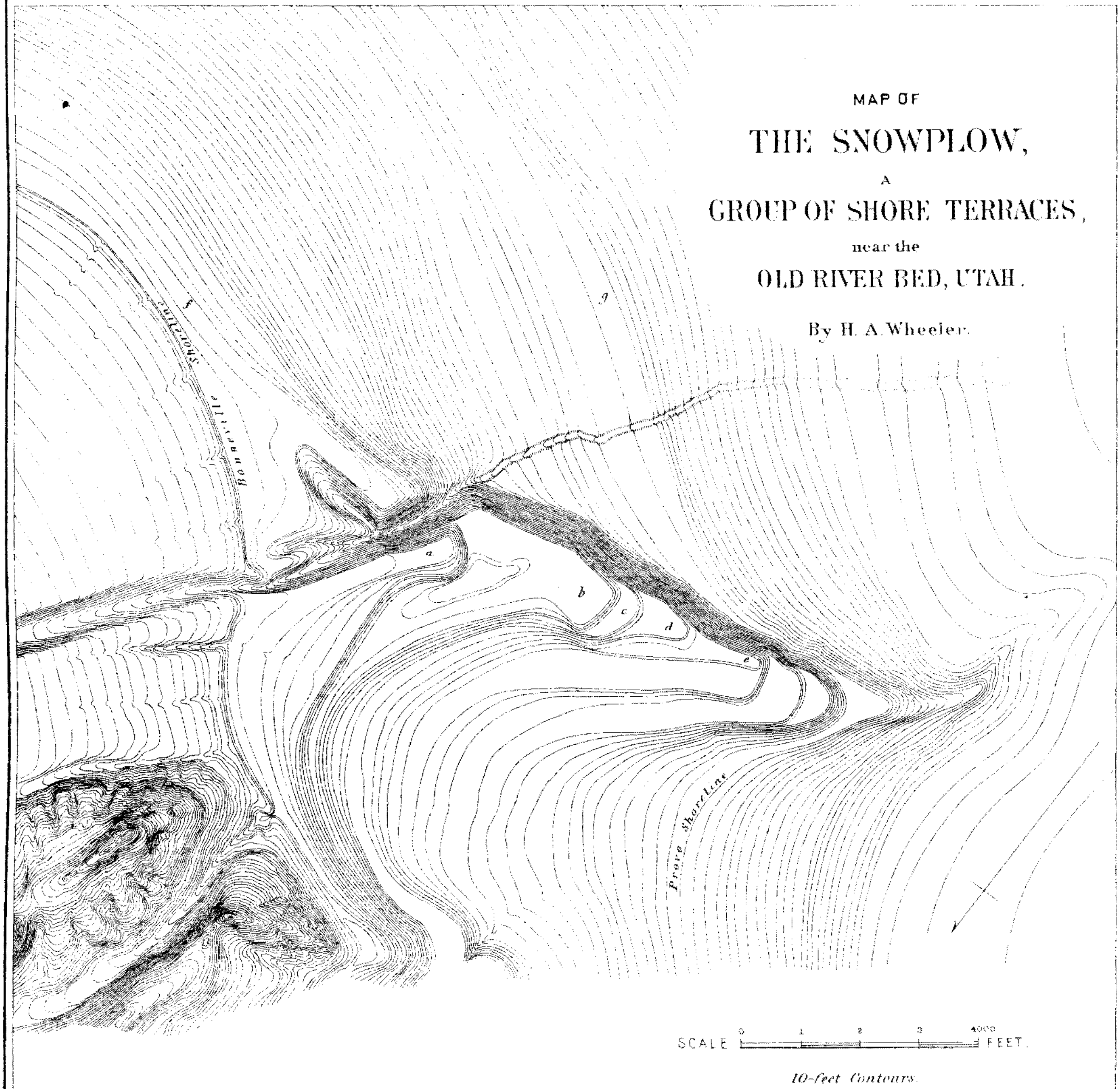
Dove Creek.—A group of embankments near Dove Creek, represented in Pl. XXII, is somewhat similar to the Snowplow, but the material was in large part torn by the waves from solid rock, and not merely dug from alluvium. It first traveled northward along the coast from which it was cut; and then turning abruptly to the northwest, was built into terraces upon another face of the same island.

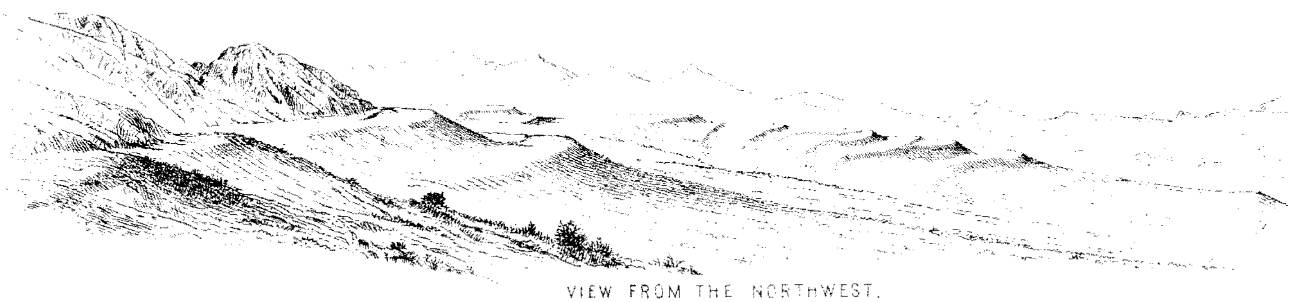
COMPARISON OF EMBANKMENTS.

For the purpose of comparison, the vertical elements of all these localities have been assembled on a single page in Pl. XXIII. The data are so diverse in character that they are not easily compared by means of profiles on a natural scale, and an attempt has therefore been made to eliminate all accessory features and represent merely altitudes and quantities of wave work. In each of the profiles of the plate, a straight line inclined at 45° is made to stand for the original surface upon which the embankments were built. The horizontal distance of each point of each profile from this base represents the total quantity of material added to the shore at that locality and level. In the case of the Stockton diagram, Fig. 6, it was impossible to represent comparative quantities of material, and only altitudes are expressed. At the north end of Preuss Valley the lower members were not mapped, because they lay at an inconvenient distance from the upper; and the profile, Fig. 3, is therefore incomplete. The profile is additionally exceptional in that it is doubled, to represent two series of embankments differing in date of formation. The earlier series is drawn at the left, and the later, which in part overlies it, at the right. Fig. 5 represents a profile measured at Cup Butte, five miles northwest of the Snowplow. In this case the vertical element only is valuable for comparison, because the upper and lower portions of the slope were not similarly disposed with reference to the waves. The lower received no deposit, but exhibits the rock of the butte carved in terraces and cliffs. Fig. 10 represents the great embankment at the Point of the Mountain south of Salt Lake City.

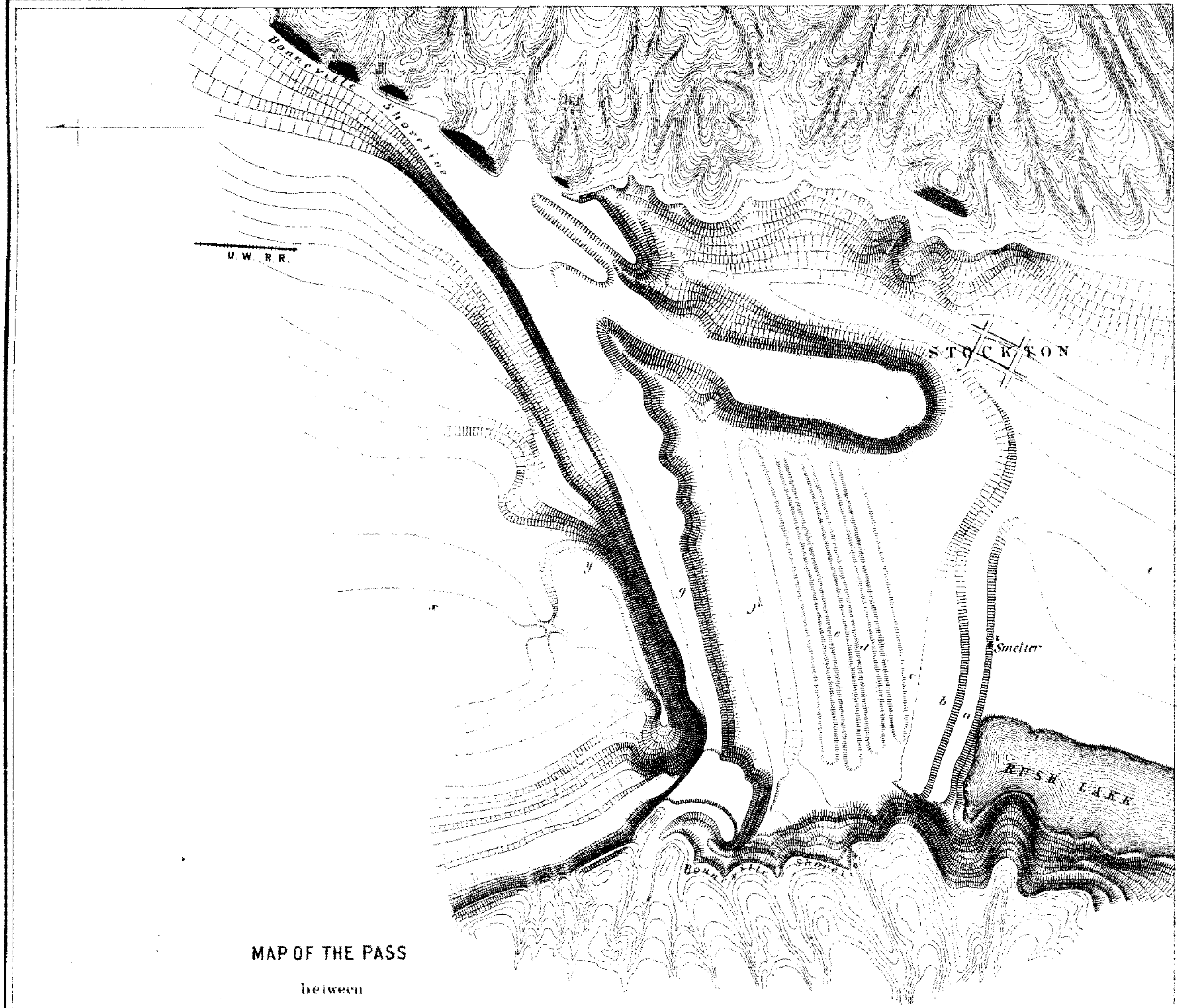
The vertical measurements for the profile in Fig. 7 were made by means of two mercurial barometers, one of which was read at short intervals at a station near by, while the other was carried from point to point. At Cup Butte, Fig. 5, the measurement was by means of a hand-level attached to a Jacob's staff, the unit of the instrument having been determined experimentally by comparison with the surveyor's level. The remaining profiles were measured with a spirit-level.

The profiles are arranged upon the page in the order of geographic position. The three groups in Preuss Valley fall within a radius of three miles. The Snowplow and Cup Butte groups are 100 miles farther north but are separated from each other by five miles only. The Grantsville and Stockton groups are 10 miles apart and are 45 miles north of the Snowplow. The Wellsville and Dove Creek groups are isolated. They are 80 miles apart and each is 90 miles distant from Grantsville, the nearest of the other localities. The Point of the Mountain is separated from the Stockton group by an interval of more than 20 miles, including a mountain range.





VIEW FROM THE NORTHWEST.



MAP OF THE PASS

between

RUSH AND TOOELE VALLEYS, UTAH.

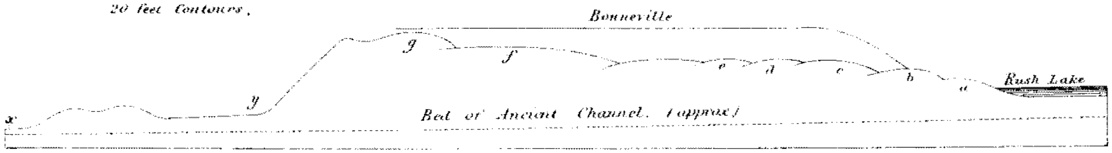
showing the

WAVE BUILT BARRIER.

By H. A. Wheeler.

SCALE 1000 0 1000 2000 FEET

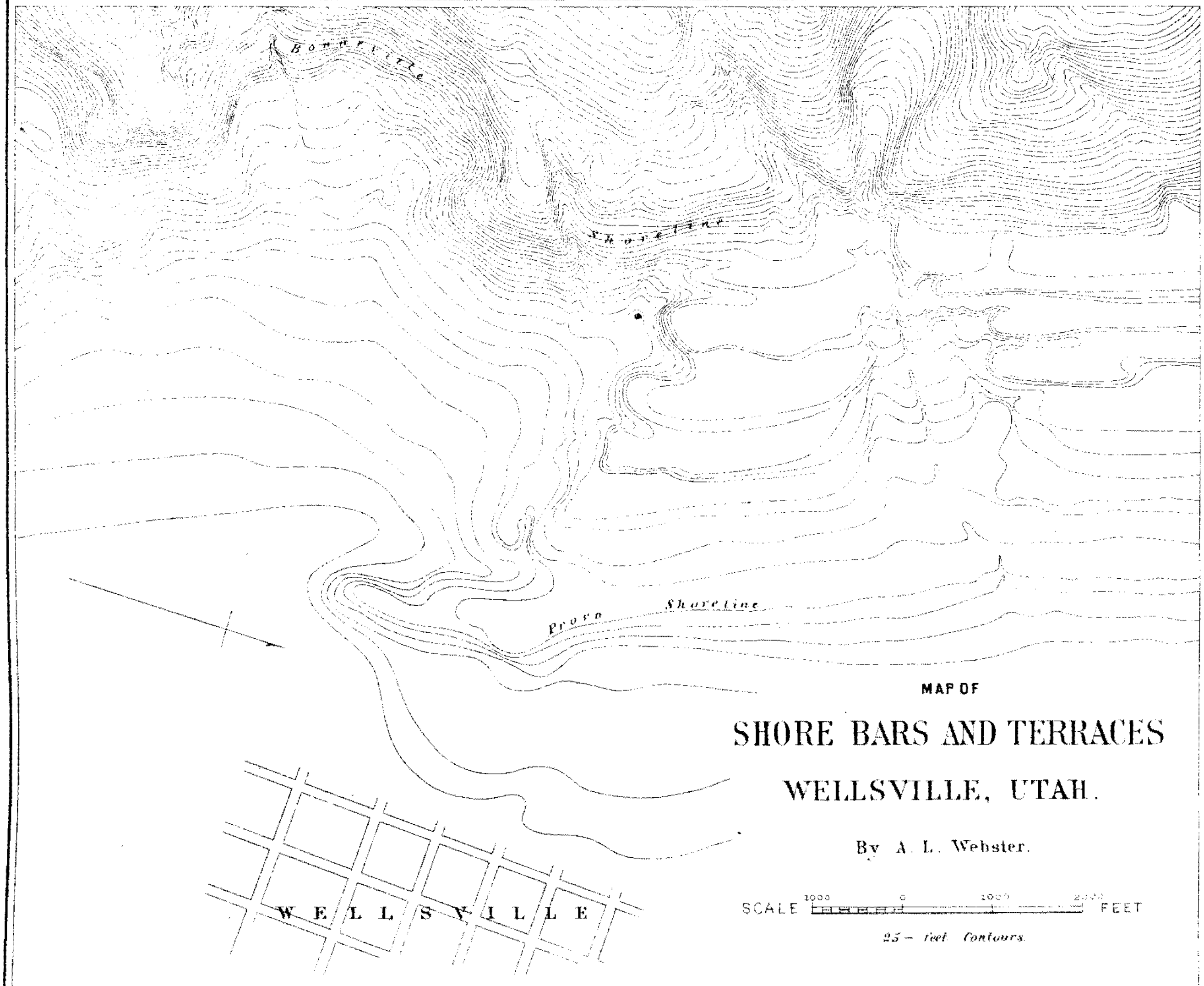
20 feet Contours,



Vertical Section from x to Rush Lake

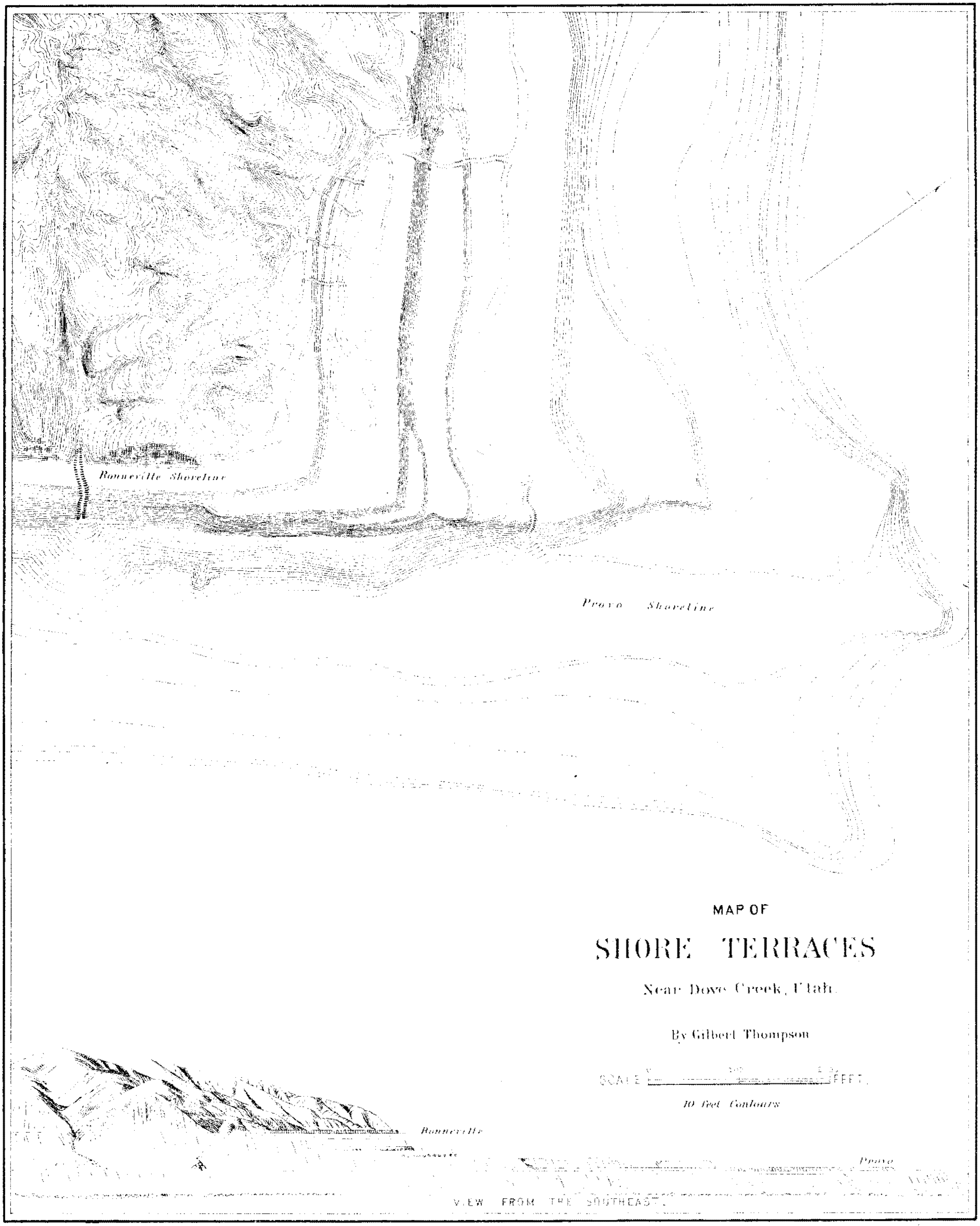
Vertical Scale double the Horizontal.

Julius Bien & Co. lith. Drawn by G. Thompson



VIEW FROM THE EAST.

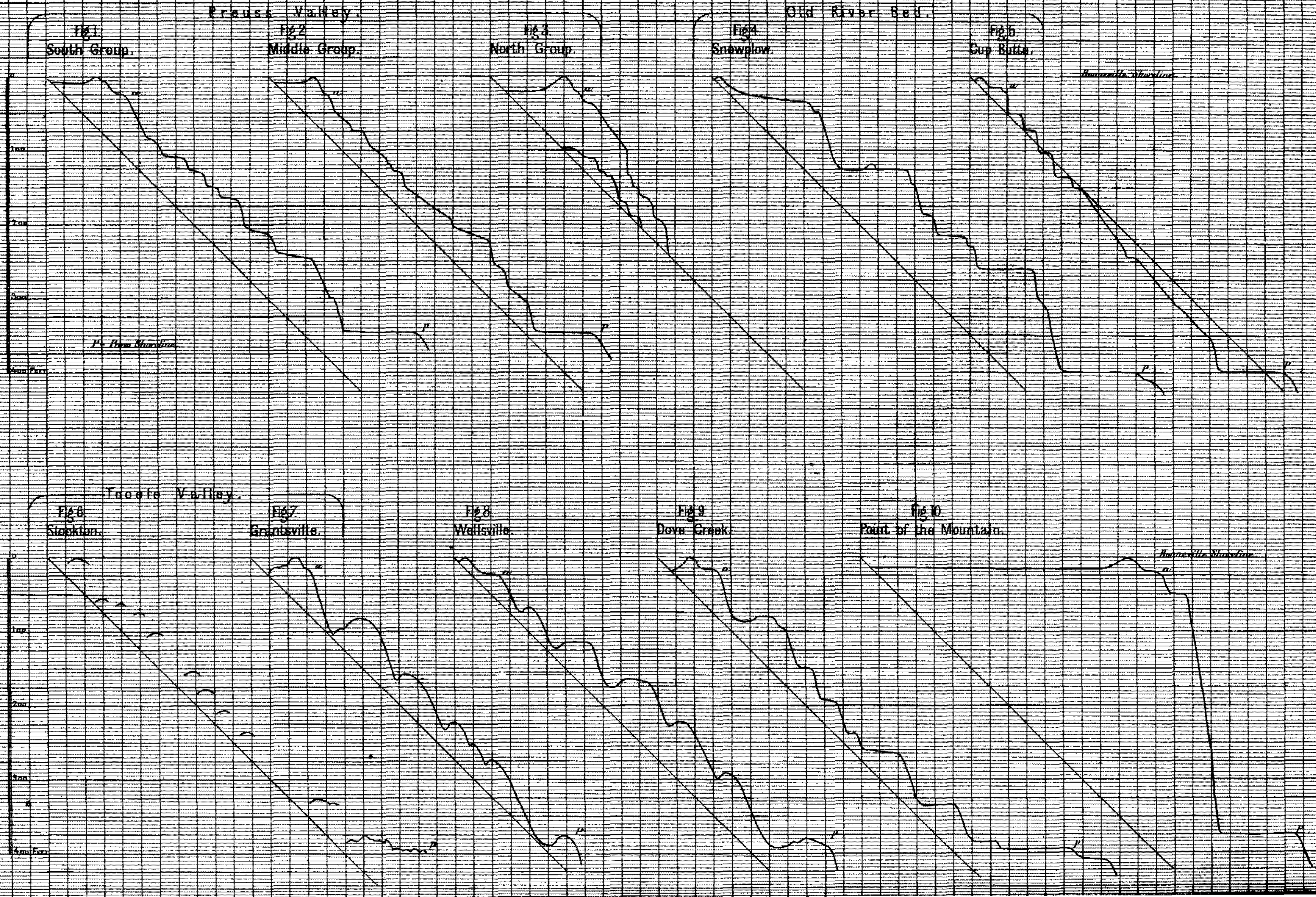
Julius Bien & Co. lith. Drawn by G. Thompson and W. H. Holmes



Julius Bien & Co. lith

Drawn by G. Thompson

COMPARATIVE PROFILES OF THE INTERMEDIATE SHORELINES OF LAKE BONNEVILLE.



Having thus assembled the data, let us now endeavor to obtain a clear conception of the questions to be answered by their comparison. At the Grantsville locality the shore drift is built into a small number of large, definite, individual embankments, differing in height. The analogy of the Bonneville and Provo shores suggests the hypothesis that each of these embankments was produced by, and therefore represents, a prolonged maintenance of the water surface at a corresponding height. Under this hypothesis there should have been accumulated at each of the other localities during this time a corresponding embankment; and if all the embankments remain undisturbed in their original position, a complete correlation should readily be made out. For each of the principal embankments at Grantsville there should be found a representative at the same height in each of the other localities. If such correspondence is not found, it is necessary either to abandon the hypothesis, or else to supplement it by the assumption that the relations of the embankments were deranged by differential movements of the earth's crust occurring during the general period of their formation.

Examining now another locality, as, for example, the Wellsville, Fig. 8, we find that, although it exhibits a small number of large individual embankments, the altitudes of these do not correspond each to each with the altitudes of the Grantsville embankments. However the comparison is made this disparity appears. In the plate the Bonneville horizon is assumed as the common zero for the vertical elements of the profiles. This assumption is purely arbitrary, and was not adhered to in making the comparisons. In order to test the matter fully, each group of embankments was represented on a sheet of transparent paper by a system of parallel lines whose intervals were drawn to a scale, so as to agree with the vertical intervals of the embankments. These transparent sheets were then superposed in pairs and other combinations, and were tentatively adjusted in numerous ways, in the hope of discovering occult correspondences.

Only one element of order was discovered. A horizon from 15 to 25 feet below the Bonneville (marked *a* on the plate) is discernible in eight of the ten localities. With this single exception, there are no correspondences which can not be referred to fortuitous coincidence. Not only is the series of altitudes different at each locality, but the number of embankments varies from place to place. It is evident, therefore, that the hypothesis of persistent water stages is tenable only with the addition of a hypothesis of contemporaneous displacement; and the question arises whether we have any means of subjecting this phase of it to test.

HYPOTHESIS OF DIFFERENTIAL DISPLACEMENT.

The supplementary hypothesis is not a priori a violent one. As will be set forth in a following chapter, our investigation has fully demonstrated that the Bonneville shore-line is no longer of equal altitude at all points, but varies within the region comprising these localities through a range of more than 100 feet. The same has been shown with reference to the Provo shore-line; and it has also been shown that a part of the Bonneville derangement occurred before the Provo epoch. In the series of localities represented by the profiles, the interval between the Bonneville and Provo shore-lines ranges from 345 feet to 400 feet, exhibiting a difference of 55 feet. It is therefore easy to believe that the localities may have undergone relative displacement after the construction of certain of the Intermediate embankments and prior to the construction of others, or even that local changes of water level may have been thus occasioned at one locality while the process of shore formation was continuous at another. The possibility of confusion thus introduced seems at first unlimited, and a rigorous test of the hypothesis would be difficult were it not for a fortunate circumstance. The surveyed localities include several pairs, the members of which are so closely associated geographically that there is a strong presumption against their having been affected discordantly by contemporaneous earth movements. The middle and southern localities of Preuss Valley, Figs. 1 and 2, are but two miles apart, and bear the same relation to the adjacent mountain range. The localities of the Old River Bed, Figs. 4 and 5, are five miles apart, and those of Tooele Valley, Figs. 6 and 7, about ten miles apart.

The principal recent displacements of the basin have been of the nature of broad, gentle undulations, not affecting the horizontality of the shore-lines, so far as that is distinguishable by the eye. The region including each group of localities may properly be assumed to have risen or fallen in consequence of such earth movements without important internal change;

and this circumstance leads us to anticipate that the members of each of these groups of embankment localities will be found to correspond with each other better than with the members of other groups or with isolated localities.

This expectation is realized in the relation of the Bonneville and Provo shores. In each of the two Preuss Valley localities the Bonneville-Provo interval is 345 feet. At the two localities of the Old River Bed it is 400 feet and 398 feet. At the two localities of Tooele Valley it is 375 feet and 378 feet. At the Point of the mountain, 20 miles east of Tooele Valley, it is 375 feet. When, however, the Intermediate shores are considered, no correlation is found.

The harmonious relations exhibited by the Bonneville and Provo shore-lines at contiguous localities confirm the postulate that a general correlation should be possible in these localities, despite the influence of contemporaneous displacement, and compels us to reject displacement as a sufficient explanation of the discordance of the Intermediate shore-lines.

By these considerations, and by others which it is unnecessary to detail, the writer was led to abandon the hypothesis of persistent water stages, even though a better was not immediately suggested. Eventually another was found, and this is believed to give a satisfactory explanation of the phenomena. It may be called the hypothesis of an oscillating water surface.

HYPOTHESIS OF OSCILLATING WATER SURFACE.

In order to set forth this hypothesis, it will be necessary to recur to the general theory of the construction of shore embankments, page 46, and imagine how the process would be modified by the contemporaneous oscillation of the water surface. Let us select some point of the coast where the local conditions determine the deposition of shore drift, and assume that a spit has been formed, its crest being slightly higher than the surface of the water when still. Suppose now that the height of the water surface is gradually increased. A portion or the whole of the shore drift contributed by the next storm is deposited upon the top of the embankment, tending to restore the profile to its normal relation with the still-water level. During this restoration the growth of the end of the spit is retarded, or perhaps altogether checked. If the general rise of the water is very slow, the construction of the embankment keeps pace with it, and the crest maintains its normal height, but if the rise of water is more rapid, the spit is sooner or later submerged, so that the storm waves sweep over it. With a slight submergence, the course of the shore current is unchanged, and the waves still break as they reach the line of the spit, so that the conditions of littoral transportation are not there abrogated. A portion of the force of the waves is expended on the land inside the spit, but the shore drift is not diverted or divided so long as the position of the shore current remains unchanged. The growth of the spit therefore continues in its submerged condition, and if the water level ceases to rise, the crest of the spit eventually emerges and acquires its normal height.

Assume now that the rise of the lake surface, being more rapid than the growth of the spit, does not cease, but continues indefinitely. A time must sooner or later be reached when the depth of water on the submerged spit permits the waves to pass over it almost unimpeded, and at the same time permits the shore current to be deflected inward. The formation of a new spit then begins in a position higher on the sloping side of the basin.

Now let the tendency of the water level be reversed, so that it gradually falls. Additions will continue to be made to the new spit by the accumulation of shore drift on its weather face and at its end; but sooner or later the water will reach a stage at which the shore current will be deflected by the lower-lying spit, and at which the waves in sweeping over that spit will be broken and diminished in force. Additions to the upper spit will then cease, and the growth of the lower spit will be renewed.

If this theory is well founded, there should be produced at the margin of an oscillating lake a series of embankments separated by vertical intervals bearing some relation to the magnitude of the waves, and each of these should grow in height every time the oscillating water surface passes its horizon, either in ascending or in descending. The rate of growth would naturally be different at different points on the margin of the lake; and the interval between embankments, being a function of wave magnitude, should vary in different regions, being greatest where circumstances are most favorable for the development of waves.

This relation between the embankment interval and the local conditions affecting wave magnitude is so evident a consequence of the theory that it may be used to test its applicability to the problem in question, and this may be further tested by considering the phenomena of littoral excavation in connection with those of littoral construction. The conditions which theoretically produce a rhythm in the process of littoral deposition have no similar effect upon the concomitant erosion. In the regions of littoral erosion, the shore currents are not deflected by circumstances associated with the rise and fall of the water level, and the zone subjected to the beating of the waves bears always the same relation to the still water level. An equable rise of the water should therefore pare away the coast in an equable manner; and upon the theory of rhythmic deposition, the Intermediate embankments should not be associated with sea-cliffs and cut-terraces of comparable magnitude.

Proceeding now to the application of the hypothesis to the problem in question, we may premise that the water level has twice risen above the Provo horizon and afterward descended, one rise extending to the Bonneville shore-line and the other being nearly as great. The space occupied by the Intermediate embankments has thus been subjected to wave action at least four times. These oscillations have been demonstrated by independent evidence; and it is probable that there were also numerous minor oscillations. The conditions were therefore favorable for the production of the rhythmic result.

The vertical interspaces between the Intermediate embankments yield evidence confirmatory of the hypothesis. Six of the localities represented in the profiles and maps are suitable for comparison. Among these the local conditions indicate the greatest waves at Grantsville and Dove Creek, and at these points the average interspaces between the principal embankments are 72 feet and 75 feet. The conditions are less favorable at Wellsville and the Snowplow, but it is doubtful which of these two localities should rank next. At Wellsville the average interspace is 60 feet. At the Snowplow it is either 71 feet or 61 feet, according as an embankment of doubtful rank is included or excluded. In Preuss Valley, where there was comparatively small scope for the formation of waves, the average interspace is 53 feet.

Equally harmonious is the evidence from the phenomena of littoral excavation. Take, for example, the Snowplow. The material there aggregated was derived from a broad alluvial slope, partly represented in the northern portion of the map (Pl. XIX). In this region there is a nearly continuous slope from the Provo terrace to the Bonneville terrace; and above the Bonneville cliff there is a continuous slope of undisturbed alluvium. This latter originally extended over the entire slope, including and beyond the Provo horizon, and it can be restored in imagination so as to realize the magnitude of the excavation. From ten to thirty feet appear to have been removed from the general surface, and this so evenly that there are only one or two points where the presence of sea-cliffs can be indicated; and even these can not readily be traced to corresponding embankments. The same is true in a general way of all localities. Not only are the Intermediate embankments nowhere connected with a system of differentiated cliffs and terraces, but it has been found impossible, (wherever the attempt has been made,) to trace their horizons fairly into the region of excavation. At the Snowplow locality, the excavated alluvium is of such nature as to be easily modified by the rain and it does not preserve the minor details of the configuration impressed on it by the waves; but elsewhere, on alluvial slopes of coarser material, the interspace between the Bonneville and Provo cut-terraces has been observed to be occupied by a continuous system of narrow terraces and cliffs, constituting a sort of horizontal striation of the surface. At one point, near Pilot Peak, thirty-three separate terraces were counted, the average interspace being less than ten feet.

The hypothesis receives additional support from the structure of the individual embankments. The spit built by the waves of a lake with a constant level should normally have a certain simplicity of structure, the principal additions to its mass being made at the distal end, and the deposits near the crest having no irregularity, except that referable to the disparity, in force and direction, of the constructive storms. A spit constructed by the waves of an oscillating water surface should theoretically be begun at a relatively low level and receive additions in the form of superposed spits of various altitudes and lengths, some extending to the end of the mole and others stopping short. The compound structure is characteristic of the

Intermediate embankments. Sectional exposures are indeed rarely to be seen; but from many of the embankments there project, either at the distal extremity or on the shoreward side, shelves or spurs indicating the horizons of the lower wave work and testifying to the composite structure of the mass.

Fig. 25 gives an illustration of this, observed near Willow Spring, west of the Great Salt Lake Desert. A broad spit is characterized by a hook at its extremity. A study of its details shows that the shore drift, under the

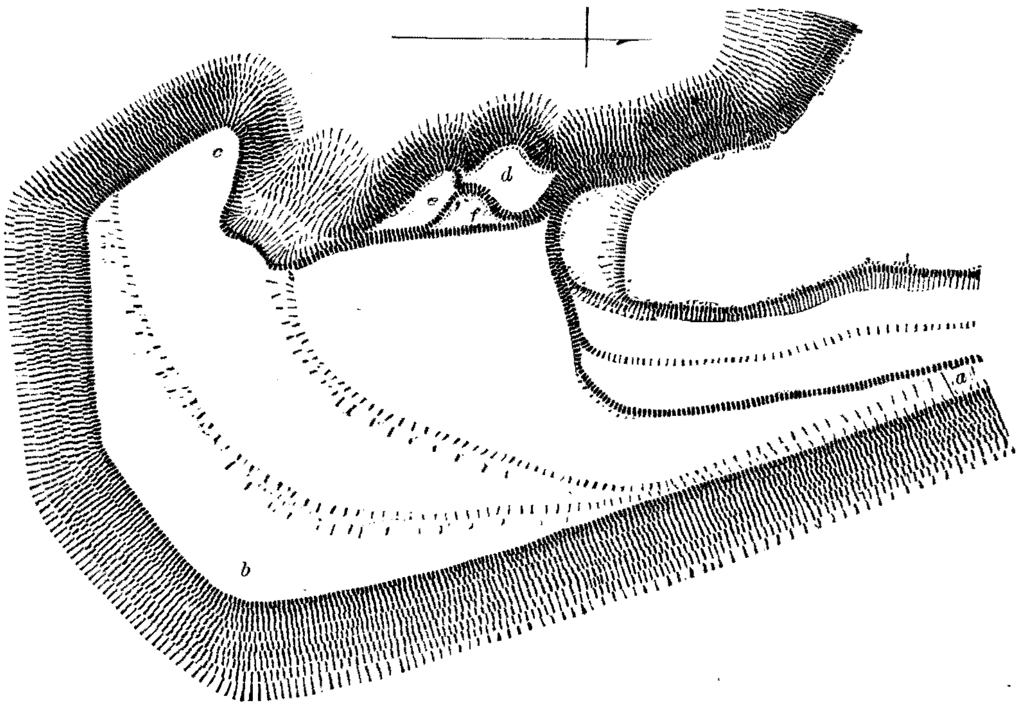


FIG. 25.—Compound Hook of an Intermediate Shore-line near Willow Spring, Great Salt Lake Desert.

influence of the dominant waves, here from the north and northeast, traveled from *a* to *b*. By less powerful waves from the east and south it was then carried about the end of the embankment to the recurved point *c*, a point with a peculiar and notable outline. On the lee side of the spit, at a point where the waves could have no force after its construction, there are three projecting tongues *d*, *e*, *f*, built of beach-rolled gravel and closely resembling the extremity of the point *c*. The highest is twenty feet below the spit; the others thirty and forty feet. They are evidently more ancient hooks, the appendages of similar but shorter and lower spits, which may fitly be regarded as progressive stages of the huge table ultimately constructed.

Finally, the single element of order detected in the accumulated profiles is by this hypothesis shown to be consistent with the general want of order. The terrace (*a*, Pl. XXIII) lying from 15 to 25 feet below the highest Bonneville embankment, was preserved because it was the penultimate deposit of the ascending series, and because the ultimate deposit was too meager to mask it. The differentiated series of Bonneville bars described in a preceding section shows that the penultimate water stage was about 20 feet below the ultimate. Wherever the penultimate contribution to an embankment was made upon its lakeward face, it escaped concealment by the final contribution, which was small in amount and was perched upon the top of the same embankment.

The second hypothesis is thus sustained at all points. The Intermediate embankments record the wave action of an oscillating water surface. Within this zone the water level did not long linger at any one horizon, or if it did, the record of that lingering was effaced by later action.

It follows as a corollary from this discussion that cut-terraces with their associated sea-cliffs afford a more trustworthy record of persistent water stages than do embankments. It is an additional mark of persistent stages that they afford coordinated terraces and embankments.

It is important to note, however, that neither the sea-cliff nor the cut terrace, if observed alone, affords satisfactory evidence of persistent wave action at one horizon. They must be found together. A slowly rising tide continually abandons the freshly cut terrace and attacks with its waves the freshly cut cliff above it. In this way a cliff is carried before the advancing water of an oscillating lake; and when the maximum is reached and recession follows, the cliff is stranded, so to speak, at the upper limit, even though the water margin was retained there a short time only. Similarly, it is conceivable that a falling lake surface may carry before it a cut terrace without leaving at any horizon a sea-cliff of comparable magnitude. The first of these conclusions has an application in the case of the Bonneville shore-line, which, as already remarked, is characterized by the great height of its sea-cliffs, but is inferior to the Provo shore-line in the width of its cut terraces. The considerations here adduced serve to complement the partial explanation of this contrast advanced on page 129.

As already intimated, the compilation of the Intermediate embankments was the result of a series of oscillations of the ancient lake, whereby a zone of wave action was carried alternately upward and downward over the slope. The basis for this statement does not lie in the embankments themselves so much as in the associated lacustrine and alluvial deposits. It is unquestionably true that the entire history of oscillation is embodied in the internal structures of the embankments, but these are not exposed for examination, and the external forms afford information for the most part only of the latest additions.

It is a curious fact that these forms of embankments appear to have been moulded by a gradually rising rather than by a falling tide. The last general movement of the water was of course a recession, for the slopes are now dry, but that recession has left so little trace above the Provo horizon that we are led to believe it was far more rapid than the preceding advance.

This conclusion is as interesting as it was unexpected; and it is proper that the evidence on which it rests be presented somewhat fully, especially as it has been assumed by several investigators, including myself, that the several shore marks of the series represent lingerings of the ancient lake during a gradual recession.

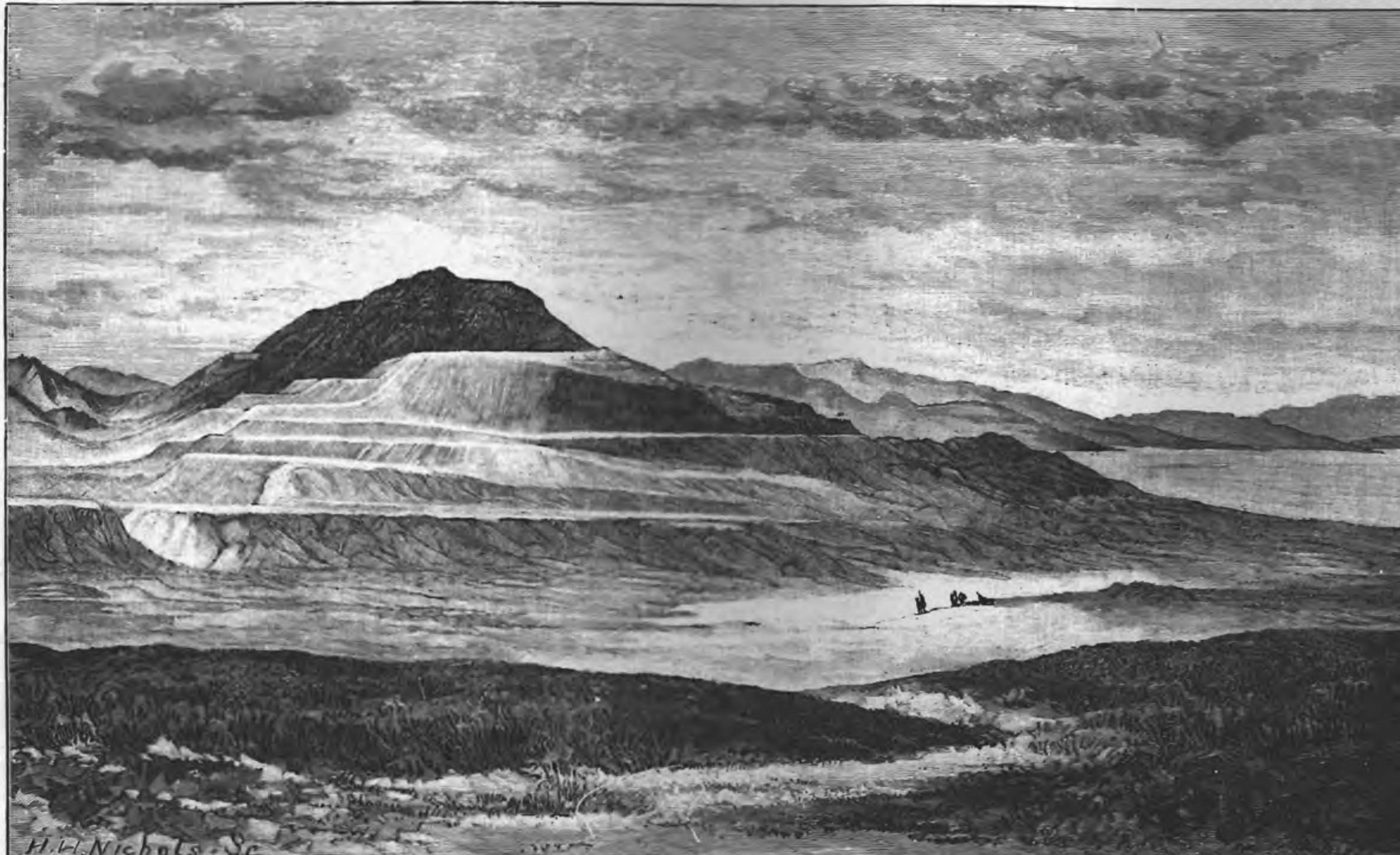
SUPERPOSITION OF EMBANKMENTS.

The Snowplow.—In the first place, there are many superficial indications of the overlapping of low embankments by high ones. If the reader will turn to the map of the Snowplow (Pl. XIX), he will see that the table lettered *a* is not entirely supported by the table *b*, but projects a little on the south side so as to rest partly upon the general slope which is the common foundation of both. (It is necessary to restore in imagination the contours interrupted by the drainage line southeast of the letter *a* and dividing the embankment it indicates.) As has already been explained, the material of the Snowplow was derived from the region *fg*, and was drifted along the shore from southeast to northwest. That which composes the upper surface of each embankment must have been carried along the southern edge of the

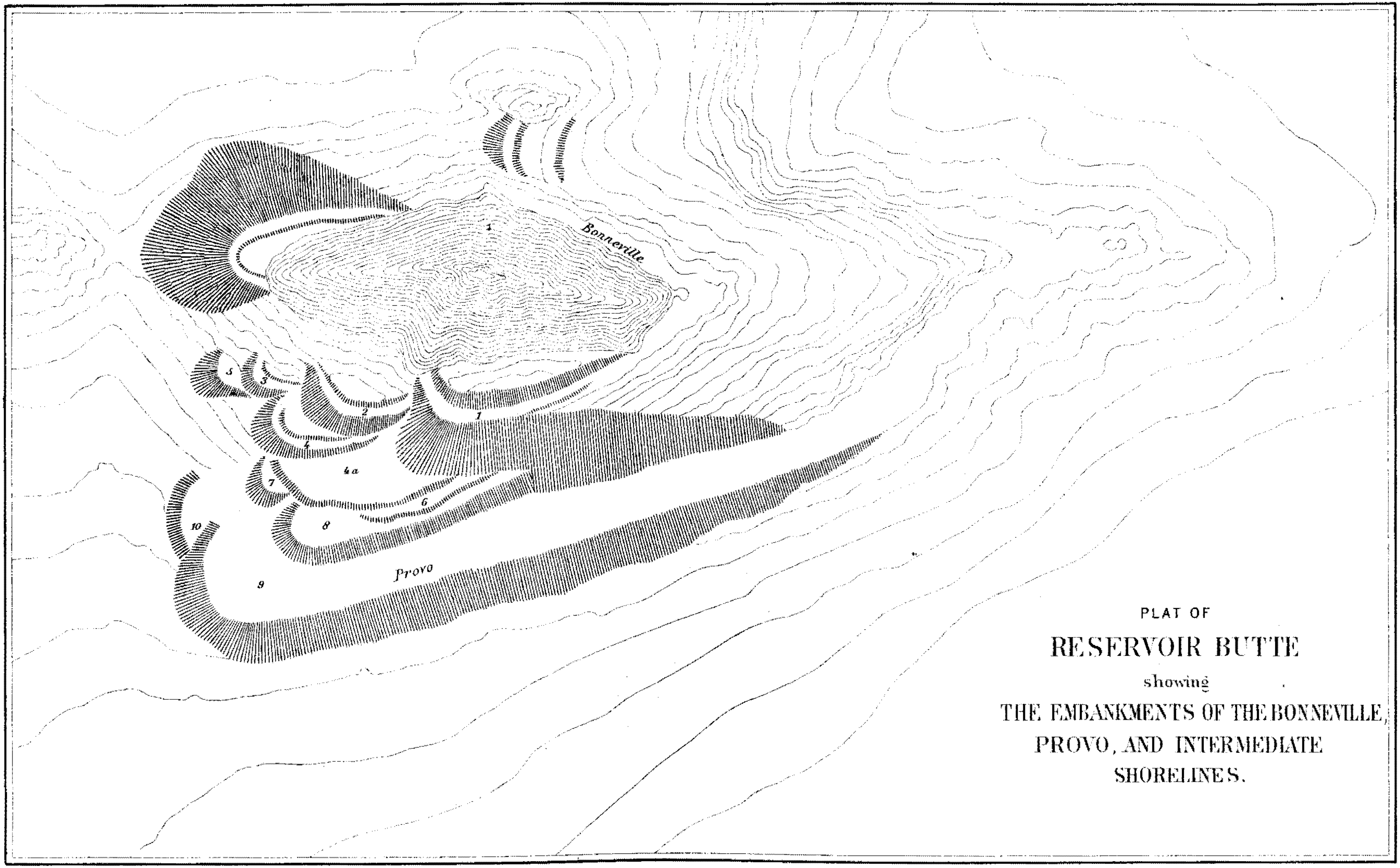
Snowplow by beach action, so that each embankment was, at the time of its completion, connected by a continuous beach with the source of supply. The embankment *b* is not so connected, for the evident reason that its southern edge has been overlapped by the latest addition to embankment *a*. If the waves during the recession of the water had made a contribution to the lower embankment, they must either have excavated the side of the upper embankment or else have built a platform around it, and in either case the slope from the crest of the upper to the foundation plain would not have the observed uniformity and steepness. A similar relation of parts shows that the embankment *b* was completed after the embankment *c*, so that at least three of the members of the series received their final moulding in ascending order.

Reservoir Butte.—At Reservoir Butte substantially the same story is told, but in different language. The face of the butte turned toward the open lake was rugged in the extreme, and the configuration of the neighboring bottom was irregular, so that, as the depth of the water changed, the conditions determining the transfer of shore drift and the construction of embankments were continually modified. The resulting embankments were not built into a symmetric system but were thrown together in an irregular and unique group. By referring to Pls. XXIV and XXV, where they are represented by vertical and horizontal sketches,[1] it will be seen that, of those above the Provo, the highest is the last formed, overlapping all the others. Number 2 (they are numbered in the order of height) has no visible connection by beach with the north or weather face of the butte, whence its material was derived; and its form and relations show that it could not have been constructed after the completion of Number 1. The third and part of the fourth are in a similar manner overplaced by the second, and were evidently earlier formed. The fourth is however separable into two parts, which may have been formed at different times; and the outer, marked 4*a* in the diagram, is not so related to No. 2 as to demonstrate the order of sequence. It is however overplaced by No. 1. The relative age of the third and fourth is not apparent; but the fifth, which lies in a bay completely sheltered by the fourth, is evidently of greater age. The sixth and eighth have no determined relation

[1] The plat of these embankments given in Pl. XXV cannot claim the accuracy of other maps of embankments. It was sketched in the field without the aid of instruments, and may be very inaccurate in matters unessential to the discussion above.



RESERVOIR BUTTE, FROM THE EAST, SHOWING BONNEVILLE EMBANKMENTS AND TERRACES.



Julius Bien & Co. lith.

Drawn by Anton Karl

to any other except the first, which they underlie; and the seventh, which projects from beneath the fourth, shows no direct relation with any other. The ninth is the Provo, and this proclaims its recency by its relation to the first. Its table extends to the north face of the butte, and not merely passes the face of the first or Bonneville embankment but is in part carved from it. The Provo waves encroached also upon the eighth embankment. These relations may be tabulated in the following form, in which the word "*ante*" should be construed to mean *completed at an earlier date than.*

$$\left.\begin{array}{r} \begin{array}{r} 3 \\ 5 \text{ ante } 4 \\ 7 \end{array}\begin{array}{l} \big\}\text{ ante } 2 \\ \big\}\text{ ante } 4a \end{array} \\ 6 \\ 8 \end{array}\right\}\text{ ante } 1 \text{ ante } 9$$

Stockton.—Another unique aggregate of embankments is equally instructive. Previous to the rise of the lake, the drainage of Rush Valley was tributary to that of Tooele Valley, the connecting parts having a continuous descent from south to north, and an ample channel, of which a portion is yet clearly to be seen. At the point of greatest constriction between the two valleys, where the Bonneville strait had a width of only 8,000 feet, the bottom of the channel ran about 350 feet below the level afterward marked by the Bonneville shore. At all high stages of the lake the strait received a large quantity of shore drift from the northeast, and a series of curved bars were thrown across it. These bars have a total width of 5,000 feet, and partially overlap each other, so as to constitute a single earthwork of colossal proportions. Whenever the water surface fell below the highest completed bar, the Rush Valley bay was completely severed from the main body, and became a lake by itself. This lake was so small that its waves were comparatively powerless; and, although traces of their work can be discovered, they did not materially influence the configuration of the earthwork. The locality is exhibited in the foreground of the view in Pl. IX and in the map and profile of Pl. XX. If the reader will refer to the latter plate and give attention to the profile in connection with the map, he will see that the bars rise in consecutive order from *a* to *g*, and that each has a curved axis with concavity toward the north. This curvature, which is characteristic of bay bars in general, shows that the waves concerned in their production came from the north. It is evident that after the bar *b* was constructed, the bar *a* was protected from all further wave action. *a* was therefore completed before *b* was built; and in general the order of construction could not have been other than the order of the letters,—the lowest bar *a* being the first, and the highest bar *g*, the last. The order of construction was therefore from low to high. It is to be noted that this order is demonstrated only for the visible or superficial portions of the earthwork. There may be beneath the bar *g*, for example, a deeply buried series of bars lower than *a*, and either younger or older; and so of any other of the higher bars. We have no reason to believe that the whole history is embodied in the visible phenomena.

The bar *g* differs from the others in that it is not uniform in height throughout its length. The lowest point of its crest is approximately in the position occupied by the letter; and from this there is an ascent of about 30 feet toward either shore. At the Bonneville stage the strait was not closed by a bar, but the shore drift was built into spits. That at the west is short and has the form of a hook. It is crested from end to end by a slender ridge, built at the culminating water stage. The eastern is straight and broad and 6,000 feet in length. Its proximal end bears two small spits, referable to the culminating stage of the water; and its distal end evidently overlaps the lower members of the compound earthwork. So far as outward appearance goes, this is purely the product of shore action at the Bonneville stage; but it is possible that similar spits were formed at lower stages, so as to constitute a foundation for the Bonneville spit.

One of the most striking features of the series of bars is the paucity of wave marks upon the northern face. There is a diminutive bar, characterized by an abundance of tufa, imposed on the face of the great bar *g* four feet below its crest; and twelve feet lower a wave-cut terrace is barely perceptible. These may record an oscillation of the water after the completion of the great bar and before it rose to the Bonneville shore; or they may have been produced by the receding water after the highest level had been touched. In any event, the final recession must have brought every foot of the northern slope of the earthwork within reach of the waves, and the surviving continuity of the slope testifies to the rapidity of the recession. The conditions for wave work were unchanged. The alluvial slopes which had furnished the gravel for the several embankments, still offered an inexhaustible supply, and the same currents and waves must have been set in motion by the storm winds; but the lake seems not to have tarried long enough at any one level to add a terrace to the structure.

Another evidence of the rapidity of the final descent of the waters is found in the failure of the waves at any of the Intermediate horizons to undercut the embankments constructed at the higher stages. If the water tarries long at one level, the changes it effects in the form of the shore finally modify the currents so as to shift slowly the districts of erosion and of construction. Spots that were at first excavated are afterward made to receive deposits, and portions of the original deposit are afterward removed. Instances are known in which the Provo waves have pushed their excavation to the heart of the Intermediate embankments, so as to undercut even the highest members; and there are few localities of great wave action which do not exhibit more or less encroachment; but there is no evidence that the waves of any Intermediate stage have seriously impaired any higher embankment. There is a narrow wave-cut terrace on the north face of the Stockton earthwork; two lines are engraved on the points of Intermediate terraces in the Snowplow; and there is possibly a similar occurrence in Preuss Valley; but no locality gives evidence of long-continued action.

Blacksmith Fork.—The undercutting of the Provo shore has in two places exposed instructive sections of the Intermediate embankments. At the south end of Cache Valley, close to the point where Blacksmith Fork issues from the mountain, there is a section, nearly 300 feet in height, showing a face of clean gravel, which has slidden down so as to cover the entire surface—if, indeed, it does not constitute the entire mass. At four horizons this is barred across by level lines of cemented gravel marking successive positions of the upper surface of the mass as it was piled.

Dove Creek.—A similar escarpment of gravel is exposed on the south face of the Dove Creek group of embankments (see profile diagram on Pl. XXII.), and a similar series of parallel lines can be traced across it. They are best seen from a distance, and on close examination prove to consist merely of a scattering growth of bushes. There is no visible variation in the character of the gravel, but the position of the bushes is doubtless determined by the existence beneath the surface of relatively impervious strata. Whatever the nature of these strata, they are elements of structure and demonstrate the growth of the series of embankments from the base upward. The feature especially interesting is the relation of the section to the unimpaired eastern face of the embankment group. Each line of division is the continuation of the upper plane of a terrace, so that the terraces are shown to be units of stratification. The evidence from external form is thus connected with that from internal structure; and the general conclusion in regard to the succession of the Intermediate terraces is strengthened.

Here, as in the other localities mentioned, it is necessary to guard against the impression that the entire history of the lake during the formation of the Intermediate shore-lines is revealed by what can be seen of the embankments. These structure lines do not extend through the entire mass, and no other lines replace them. Those portions of the general mass of detritus which lie next to the original hill slope may have been accumulated by rising or falling waters, or, for aught we know, by a surface subjected to many oscillations. In the case of the Snowplow, all that we can predicate is that the latest additions to the mass were made in ascending order. With reference to the Stockton earthwork, we know only that, of a certain series of visible bar crests, the order of height is also the order of date. It is not only possible but even probable that the series is discontinuous, having been interrupted by epochs when the water was too low to add to the accumulations at this point.

Double Series in Preuss Valley.—But, while it would have been impossible to gain a knowledge of the repetitive movements of the lake surface from shore phenomena alone, they nevertheless serve to supplement the information afforded by the lake sediments. Having learned from the sediments, as will be explained in another place, that the water rose at least twice from the lower to the higher parts of the basin, besides undergoing many minor oscillations, it was not difficult to see that certain of the shore embankments were referable to an earlier flood than certain others. The most important locality is illustrated by the map and sketch of Pl. XVI, and shows a series of curved bars *(b b b b)*, overlapped by a series of spit-like embankments massed together into a few sloping terraces *(t t t)*. The source of the shore drift was at the north, and the beaches which conveyed it to the curved bars are hidden by the later embankments. It would be impossible for the bars to originate under the lee of the spits. Moreover, the spits everywhere exhibit their gravelly constitution, but the curved bars are half buried by lake deposits.

DELTAS.

The earliest allusion to the deltas of the ancient lake is by Bradley, who remarks that the lake terraces "are much more numerous near the mouths of the streams, where the stream-currents have distributed their sediment, when the lake waters were at these higher levels";[1] but the first clear discrimination of the deltas from other terraces was by Howell, whose observations were made only a few months later. Speaking of the horizon of the Provo shore-line, he says:—"When the old lake stood at this level, the detritus brought down by the Provo River formed a delta, covering at least twenty thousand acres. Another delta was formed at this time at the mouth of Spanish Fork Canyon, in the same valley, which covered an area of eight thousand or ten thousand acres."[2]

It was the magnitude of the former of these deltas that led Howell to suggest the application of the local name Provo to the shore-line at that level. It is now known not only that all of the more notable deltas of the basin appertain to the same shore-line, but that the delta built by each stream at that level equals or exceeds in mass the aggregate of its deltas at all other levels. At higher levels such accumulations are exceedingly rare; and at lower they appear to have derived their material largely from the partial destruction of the Provo deltas.

In attempting to translate these facts into terms of geologic history, the first impression is that the lake surface was held at the Provo level during more than half the period of its existence, but a fuller consideration shows that this conclusion is not warranted. The degradation of the uplands and the offscouring of the rivers are doubtless sufficiently uniform in rate to

[1] Frank H. Bradley: Geol. Surv. of Terr., Ann. Rept. 1872, p. 192.
[2] Edwin E. Howell: Geol. Surv. West of 100th Meridian, vol. 3, p. 250.

afford the basis for a time scale, but there are important modifying conditions given by the relations of the oscillating lake surface to the configuration of the stream valleys.

In the discussion of shore processes, it was pointed out that the detritus brought to a lake by a small stream is absorbed by the shore drift, while that brought by a large one overwhelms the shore drift and records its accession by a delta. The codeterminants are, on the one hand, the magnitude of the lake and the consequent force of the waves, and on the other, the volume of the stream's load of detritus. In the case of Lake Bonneville, the number of streams competent to project deltas from the shores of the open lake or of the larger bays, was small; and it is believed that all of their ancient mouths have been examined. With very few exceptions, they enter the lake basin through mountain gorges so deeply eroded before the lake epoch that the rising water set back into them, forming narrow estuaries. Knowing as we do from the study of the Intermediate shore embankments that the water rose slowly as it approached the highest level, we can not doubt that the stream drift was contemporaneously accumulated into a series of deltas within the mountain gorges. Afterward, when the water fell rapidly to the Provo level and there rested, the streams attacked the deltas in the defiles and carried their substance farther lakeward to form new structures. These new structures began for the most part within the walls of the defiles, and were progressively built outward until they protruded into the open lake, where space permitted them to develop into typical fan-shaped deltas. The material furnished by the older deltas in the defiles was close at hand, and in a condition peculiarly favorable for removal. Not only was it uncemented, but it was confined to the very courses of the streams, so that it could not escape their action. It must have been rolled to its new position in an exceedingly short time; and we need not be surprised that the traces of its original forms are nearly obliterated. The rapidity with which delta alluvia are torn up and carried away by running water finds abundant illustration at the present time in the irrigation districts of Utah. Wherever the water of a canal breaks through its bank, or is neglected and suffered to discharge unguided down a delta slope, it quickly erodes a cañada of formidable proportions.

Deltas associated with the Provo shore are thus composed not merely of the contemporaneous outscour of the catchment basins of their several streams, but of the detritus antecedently accumulated in the estuaries during the higher water stages; and, so far as they afford a time ratio, they represent the entire period during which the water stood at and above the Provo horizon. There are, however, a few exceptional localities where the Bonneville estuaries were so small and shallow that the stream drift not merely filled them but threw out semicircular capes into the Bonneville lake; and in such cases it is possible to make a comparison between the magnitude of the structures pertaining severally to the Bonneville and Provo epochs.

American Fork Delta.—The best locality for such observation is on a tributary of Utah Lake known as the American Fork, and this was carefully examined for me by Mr. Russell. The Bonneville delta there displayed has a radius of nearly 5,000 feet, and a height at its outer margin of 120 feet. It is bisected by the creek, and is thus cut nearly or quite to its base. The walls of the channel exhibit a section of the deposit, showing it to consist chiefly of rounded gravel, with some intermingled sand. The gravel, being uncemented, will not hold an escarpment, but flows down in the form of a talus wherever it is excavated by the stream, thus masking the greater part of the structure. There is, however, some indication of horizontal bedding. The outer margin of the terrace is fortunately more communicative. Around three-fourths of its periphery there runs a narrow shelf half-way down the steep face; and the details of this shelf show that it is the protruding edge of an older and lower delta terrace, furnishing the foundation for the upper. At some points lake beds were found intercalated with the alluvial gravels, but they appear to be local deposits and not continuous sheets traversing the whole body. The most complete local section has been introduced into the accompanying diagram, and presents the following sequence:

6. Well rounded gravel, forming the top of the upper terrace; 20 feet.
5. Lake beds; laminated clays with *Amnicola;* 30 feet.
4. Well rounded gravel; 15 feet.
3. Well rounded gravel cemented at the top by calcareous tufa; constituting a bench on the face of the terrace; 20 feet.
2. Well rounded gravel; constituting locally a distinct bench; 25 feet.
1. Lake beds, to foot of slope, 10 feet.

The continuity of the gravels 3 and 6 throughout the whole mass is shown by their relations to the topography. Each marks a water stage during which a broad delta was built in the lake. The beds numbered 2 and 4 are identical in character, and may be salients of similar deltas, here locally brought to light and elsewhere completely buried; or they may be merely local masses of alluvium, marking the positions held by the creek during temporary fluctuations of the lake level.

At another point of the profile, a less complete section was observed, exhibiting a rapid alternation of gravels and clays in the lower part of the mass, and at a few other points short tongues of gravel were seen to project from the table at various levels.

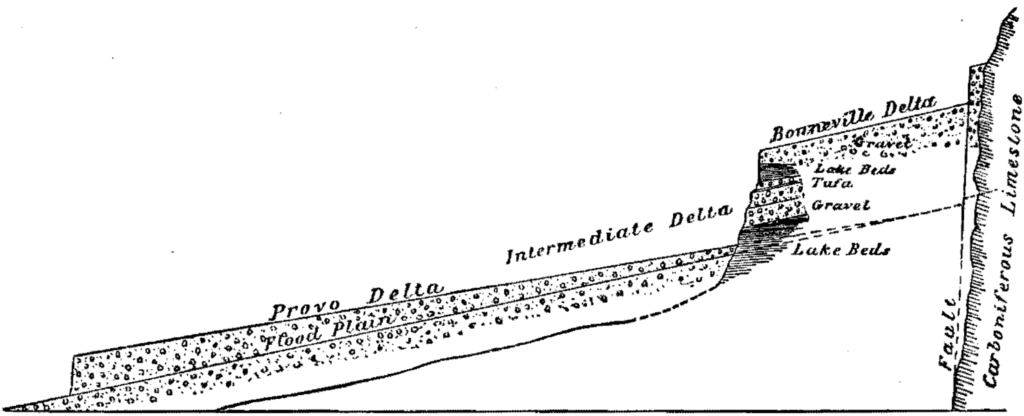


FIG. 26.—Generalized section of Deltas at the mouth of American Fork Canyon, Utah. By I. C. Russell. Horizontal scale, 4,500 feet = 1 inch. Vertical scale, 300 feet = 1 inch.

These indications of complexity of structure accord well with such conceptions of the oscillation of the lake at these stages as we have derived from the phenomena of the Intermediate embankments. If its surface was inconstant, rising and falling, like the surface of Great Salt Lake, with an irregular rhythm, all processes of deposition at the mouth of a stream would be successively interrupted, and any detailed section should show evidence of alternation. A rising tide would induce the formation of a delta far up the slope and give opportunity for the accumulation of lake beds farther down. A falling tide would cause the stream to deepen its channel by the partial erosion of the incipient delta, and perhaps of lake beds also, and would cause a local deposit of gravel at some lower level. A reascent would repair the breach in the delta, and a redescent might conduct the stream drift in some new direction. The same oscillations would carry the waves to all parts of the surface and enable them to work over the detritus, adding their tribute to the general confusion.

Assuming that the water did actually oscillate to and fro during the compilation of the delta, it is manifestly impossible to trace in detail and in true sequence the processes which make up its history. The most that can be affirmed is that a definite stage is marked at the horizon of Bed No. 3, where the water stood long enough to complete a well developed delta terrace, and that a similar definite stage is marked by Bed No. 6, which is a continuous delta sheet almost coincident in area with the one below. The lake level represented by this highest delta falls within the range to which the Bonneville shore-line pertains, but was not the absolute maximum. It is probable that the latter is represented by a shoal-water bar which crosses the south part of the delta with a crest about 20 feet higher than the delta margin.

The locality thus exhibits at least three ancient deltas, of which the order of position is:—

Bonneville delta; capped by Bed No. 6.
Intermediate delta; capped by Bed No. 3.
Provo delta.

In the order of time the Intermediate comes first and the Provo last. The Intermediate was built; the Bonneville was spread over its back, but failed to cover it completely; the lake fell, and the two were eroded by the creek, the Provo being formed at the same time. Finally the Provo shore also was abandoned by the lake water, which receded to its present position in Utah Lake. The creek has opened a broad passage through the Provo delta, cutting it at the outer margin to its base, and is engaged in building a modern delta in the modern lake. The apex of this delta lies within the channel through the Provo delta, and is continuous with the flood plain of the upper course of the stream.

The modern stream bed has a more rapid fall than the ancient, as will be seen by comparing the profiles of the modern flood plain and the Provo delta, as exhibited in the diagram. This is due chiefly to the lowering of the stream's mouth; but it is also due in part to the elevation of its point of issue from the mountain. A recent fault has lifted the mountain with reference to the valley through a space of 70 feet.

There is perhaps no locality more favorable than this for the estimation of the time ratios of the higher lake levels, but even here it is far from satisfactory. The Provo delta of American Fork coalesces with the contemporaneous delta formed by the next creek to the north in such way that it is impracticable to draw a line of separation; and there is no record of the tribute made by American Fork during the rising of the lake until it reached a level barely 100 feet below the Bonneville. Nevertheless, it is instructive to make such comparisons as the circumstances permit, and Mr. Russell's field notes have enabled him to compute approximately the volumes of alluvium accumulated at the different levels.

		Millions of cubic yards
Volume of Bonneville and Intermediate deltas before erosion by the creek		330
Volume of alluvium contemporaneously deposited in mouth of bed-rock canyon		5
Total volume of gravel furnished by American Fork while the lake level was within 100 feet of the highest stage		335
Volume of Provo delta of American Fork (the separation from delta of Dry Creek being arbitrarily made)		400
Deduct gravel derived from Bonneville and Intermediate deltas	28	
Deduct gravel derived from mouth of bed-rock canyon	5	
		33
Total volume of gravel furnished by American Fork while the lake stood at the Provo level		367

If these quantities were well ascertained, instead of being rudely estimated, they would show the gravel tribute of the stream to have been slightly greater during the Provo epoch than during the last 100 feet of the antecedent rising, and would warrant the inference that the time during which the lake level lingered within 100 feet of its highest mark was slightly exceeded by the duration of the Provo stage; and, after all allowance has been made for imperfection of data, there remains a presumption that the Provo epoch is comparable in duration with the epoch or epochs recorded by the upper deltas.

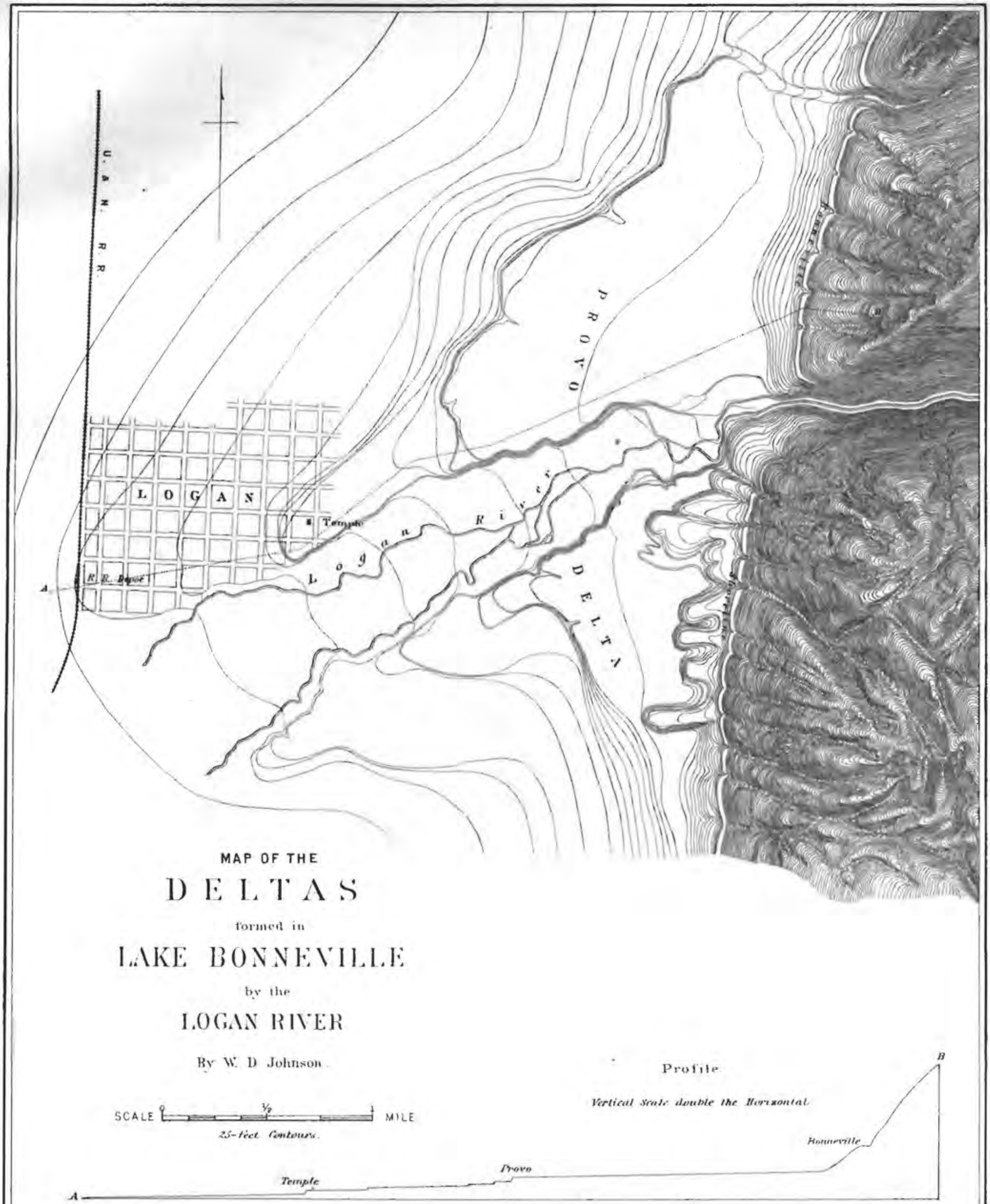
Mr. Russell has computed also the volume of gravel furnished by the creek after the completion of the Intermediate delta, finding it to be 153 million yards. This represents the tribute of the creek for all lake changes within 50 feet of the maximum, and includes the Bonneville tribute. Its ratio to the estimated Provo tribute is as 5 to 12. It is perhaps fair to assume that one-half of this mass pertains to the Bonneville shore proper; and on that assumption the indicated ratio of the epochs of the Bonneville and Provo shores is as 1 to 5. Quantitatively, this estimate has not a high value, but qualitatively it serves to confirm the impression derived from the wave work of the Bonneville and Provo shores.

It is worthy of note that the only halt of the lake surface which here finds record between the Provo and Bonneville horizons, was a halt of the advance and not of the retreat. The Intermediate delta is unmistakably older than the Bonneville; and there is none younger except the Provo. There was of course no cessation of stream action while the water of the lake was falling from the high mark to the low. The creek must have begun the erosion of the Bonneville delta as soon as its point of discharge was at all lowered by the recession of the lake; and the product of that erosion must have been deposited at the mouth of the creek in the form of a delta or group of deltas, but the eroded channel was so narrow and the resulting deposits were of so small bulk that later action destroyed them. While the Provo delta was being built the channel through the Bonneville was enlarged nearly to its present dimensions, and no stream terrace survives to mark the earlier stages of its excavation. In the same period the creek tore down and removed whatever deltas it may have built at the shore of the receding lake. If the lake had halted and lingered by the way, the creek would have been able to carve a broad flood plain and spread a broad delta, some vestiges of which would survive; and we can legitimately infer from their absence that the recession of the lake was rapid and without interruption until the Provo level was reached.

When the lake afterward shrank away from the Provo delta, its movement was less precipitate. The channel then opened by the creek has a maximum depth of only 70 feet, but five separate stream terraces, cut from its right wall, record the hesitation of the water as it fell.

Logan Delta.—One of the most beautiful and symmetrical of all the deltas is that constructed by Logan River at the Provo stage of the lake. The river enters Cache Valley from the east, débouching from a bold mountain front through which it has eroded a narrow V-form canyon. At the mouth of the canyon the Bonneville shore-line is engraved on the rock nearly five hundred feet above the river, and the grade of the river bed indicates that when the line was cut the lake water set back into the narrow way a distance of about four miles. There are are some slight traces of gravel accumulations within the canyon, but it probably was only partially filled, and certainly no delta was formed in the lake at the Bonneville level. If any estuary existed at the Provo stage it was small and quickly filled with alluvium. The apex of the Provo delta is at the mouth of the canyon, and about this point as a center the margin describes an arc of about 130 degrees with a radius of 8,000 feet (see map and profile of Pl. XXVI). The upper surface is visibly and distinctly conical, having a radial slope in all directions from the apex of 55 feet to the mile, or three-fifths of a degree from the horizontal. At the margin this gentle inclination is abruptly exchanged for a declivity of about 20 degrees. At the north the terrace joins and coalesces with a similar and contemporaneous but smaller terrace pertaining to what is now a small creek. The marginal height of the terrace is about 125 feet. During its construction the river occupied every part of its surface in turn, and when the construction work was brought to an end by the lowering of the lake, and the excavation of a channel was begun by the river, the position of that channel was determined by the chance position of the shifting stream. It is not medial, but bears so far to the south that the northern remnant of the delta is two or three times greater than the southern.

As soon as the erosion of the Provo delta commenced, the building of a new delta was begun at a lower level, and the apex of the new delta was at the mouth of the channel through the Provo. With the progressive lowering of the lake, yet other and lower deltas were built, the construction of each being accompanied by the partial or complete destruction of those above it; and this continued until the desiccation of the valley. For two miles below the Provo delta, each bank of the modern river is lined by the remnants of these old deposits, four or five lying on each side. One of the most conspicuous has been selected as the site of the Logan Temple, and two lower benches are occupied by the town of Logan. A glance at the



Julius Bien & Co, lith.

Drawn by G. Thompson

map will show their arrangement better than any description. The river has developed so broad a flood plain that half their mass has disappeared, and the dissevered remnants are too fragmentary to be readily correlated across the interval. No attempt has been made to restore their forms and compute their volumes, but it is evident by inspection that they included no rival of the great delta above. Their remnants do not exceed in total bulk the mass the river has dug from the upper terrace. They can have no value as a basis for time ratios, because it is impossible to tell how much they owe to the reworking of the material of the higher delta and how much to the annual tribute of gravel brought by the river from the mountains; but they serve to show, first, that the lake lingered by the way as it receded from the Provo shore, and second, that its lingerings were not long.

The same lingerings have left record within the Provo delta in the form of stream terraces, which abound near the mouth of the canyon. Mr. Russell has recognized ten independent benches on the north side of the stream and three on the south.

The view in Pl. XXVII was sketched from the wall of the Mormon temple standing on one of the lower terraces. It exhibits the Provo delta, divided by the alluvial valley and overlooked by the Bonneville shore mark, which happens to be strengthened immediately above the delta by an accumulation of shore drift.

The main delta, and probably all below it, rest upon a sloping floor of lacustrine sand and clay. The modern bed of the river runs below the bases of the deltas and within the zone of these sediments, but exposures are rare, by reason of the tendency of the uncemented delta gravel to slide down and overplace it. The best exhibition at the time of our examination was afforded by a fresh excavation for an irrigation canal along the bluff north of the river, and was sketched by Mr. Russell. The strata show many undulations beneath the Provo delta, but are relatively smooth beyond its margin. Mr. Russell suggests that the disturbance of the strata may have been an incident of the building of the delta. At every stage of the work there was a difference between the weights borne by the lake beds beneath the delta and by those beyond it, and the line of separation was sharply drawn at the edge of the deposit. The conditions were therefore favorable for the deformation of the freshly deposited sediments by differential pressure, some of the softer layers being made to flow out from beneath the gravel. The difference in weight between the water on one side and the saturated gravel on the other amounted to seventy-five pounds to the square inch. As the delta was progressively increased by additions at the outer margin, the zone of unequal pressure was correspondingly advanced, until the whole substructure of the delta had been subjected to the action and deformed as far as its constitution permitted.

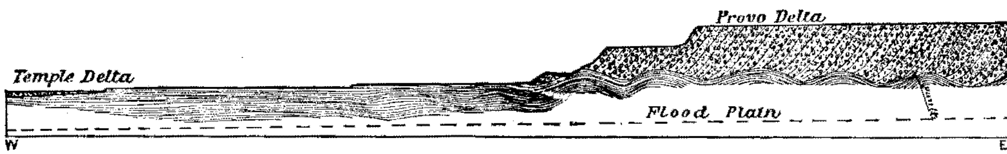
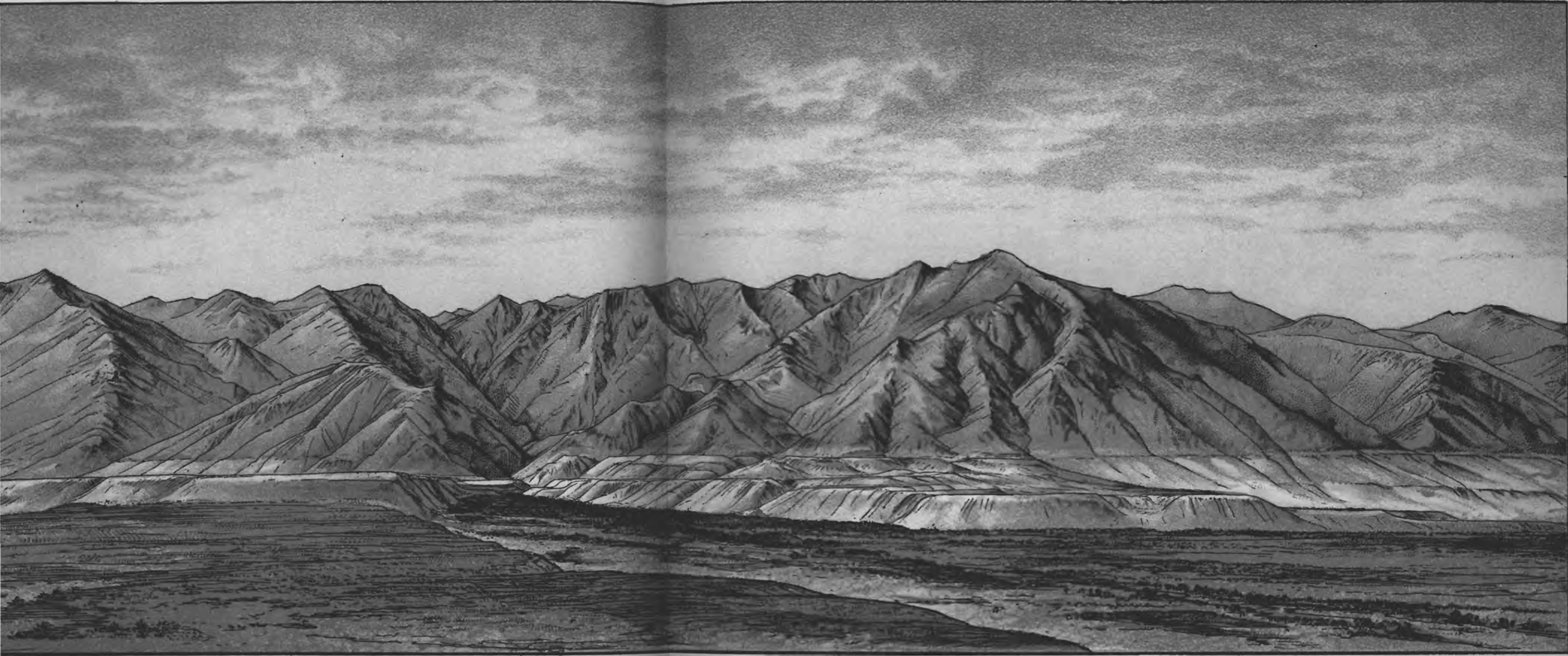


FIG. 27.—Partial section of Deltas at Logan, Utah. By I. C. Russell. Vertical scale greater than horizontal.

Wherever the body of the Provo delta is freshly exposed, it displays an oblique lamination inclining in the direction of the lakeward margin. The dip near the top of the deposit is 15 or 20 degrees, and diminishes downward, the layers being disposed in sweeping, parallel curves. Only a single locality exhibited (1880) the nearly horizontal beds which in a normal delta overlie the inclined—a point half a mile below the canyon's mouth, where the south bluff of the river had freshly fallen down, exposing ninety feet at the top of the face. The series consists of:

5. Fine sand, 5 feet.
4. Gravel, horizontally laminated, 10 feet.
3. Fine sand, 25 feet.
2. A line of small bowlders, unconformable to No. 1.
1. Gravel, coarse and fine intermingled; dipping 15° toward the SW. Exposed 50 feet.

Other Deltas.—Of the other streams of Cache Valley, as many as eight built Provo deltas, and one, Spring Creek, probably formed also a small Bonneville delta. The Cub Creek and High Creek deltas are small, and lie within the flaring mouths of the canyons. Smithfield and Bellville Creeks heaped their tribute just outside the canyons. Blacksmith and Muddy Forks debouched close together and built a confluent delta, larger perhaps than that of the Logan, but less symmetric. The original or ante-Bonneville canyon of Blacksmith Fork was so deeply cut that the modern stream has not yet removed all the débris gathered during the lake period. The mass of allu-



THE ANCIENT DELTAS OF LOGAN RIVER, AS SEEN FROM THE TEMPLE.

vium stored in it at the Provo epoch was great, and contributed to the formation at lower levels of a fine series of deltas, on which stands the village of Hyrum. Spring Creek issued from a canyon which was never cut down to the Provo level, and the apex of its Provo delta was quite outside the canyon. The modern stream is a mere rivulet that one may leap across; but its delta had a radius of two-thirds of a mile. The history of the Bear River deposits was not well made out. At the canyon mouth the river now flows at a level a few feet higher than before the lake period, and that level is four hundred feet below the highest lake shore; but the modern river outside the canyon is walled in by a great deposit, chiefly of sand, through which it has opened a passage. There was clearly no Bonneville delta at this point. The upper surface of the sand is a sloping plain, joining the mountain near the canyon only fifty feet below the Bonneville shore. Unfortunately the examination was made while snow lay on the ground, and the structure of the deposit could not be seen. If it is a delta it is probably of the Provo date, and its outer margin must be in the vicinity of Battle Creek Butte, ten miles away. Otherwise it must be regarded as a lake sediment, which owes its exceptionally great volume to the proximity of a silt-bearing river. In either case its source of material is the river drift; and in either case its accumulation was probably contemporaneous with that of the deposits which filled Gentile Valley, a small opening among the mountains at the head of the canyon.

Outside of Cache Valley all the notable deltas except that of the Sevier River lie at the western base of the Wasatch Range. The most northerly is near Brigham City, on Box Elder Creek,[1] a stream rising in a small valley just east of the main axis of the range, and cutting across it. In the upper valley there are remains of a detrital filling, which was probably coeval with Lake Bonneville, although not in visible continuity with delta formations. The canyon through the mountain has been swept clean of debris, except at the bottom; and at its mouth there is a small composite delta, of which the highest element has the Provo height.

The history of Ogden River is nearly the same, but its features are on a larger scale. The upper valley contained so large a bay that a discernible shore-line was carved therein; and it is probable that some of its sloping ter-

[1] Not to be confounded with the Box Elder Creek of Tooele Valley, mentioned in connection with the Grantsville embankments.

races are remnants of Bonneville deltas. The fall of the lake drained the upper valley and led to the building of a broad delta just outside the mouth of the canyon; but this delta is exceptional to the general rule in that it is somewhat below the Provo horizon. On the plain beyond it a series of terraces were afterwards formed similar to those at Logan. The city of Ogden stands at the end of the series, and its suburbs encroach on some of the lower benches.

Close to the Ogden deltas lie those of the Weber, less symmetric but far more massive. They extend from four to six miles in all directions from the mouth of the canyon. The channel cut through them by the modern river is several hundred feet deep, and is exceptionally indirect, curving through the fourth part of a circle. The broad flood plain within it supports three agricultural hamlets, and is traversed by the Union Pacific Railway. The westward-bound passenger issuing from the rock-bound defile of the Wasatch at Uinta Station finds himself enclosed by walls of delta sand, and does not fully emerge from the lowest terraces until he reaches Ogden Station, a ride of eight miles. The greater portion of the structure lies on the left or south bank of the river and is locally known as the Sand Ridge. It is the largest of all the deltas of the ancient lake built upon an open plain, but, owing to the lightness of its material, the details of its form are imperfectly preserved. Portions of the interior of the mass appear to be gravelly, but the upper parts are chiefly composed of sand, so fine as to be moved by the wind. The principal terrace is at the Provo level, and upon this there stands a hill more than 200 feet high, which may possibly be the remnant of a more ancient and more lofty delta, but is probably a dune accumulated during the Provo epoch. The lower terraces, marking the recession of the water, were built on the north side. The south face of the Provo delta has been superficially modified by subsequent wave action.

City Creek, the stream supplying Salt Lake City with water, rises in the Wasatch Range and flows through a long canyon before emerging on the plain. This canyon was capable of storing a large amount of alluvium; and it is probably due to this fact that the Provo delta is smaller than those at lower levels. The group of deltas constitute "the bench" on both sides of the creek, and are composed of coarse, well rounded gravel. While they were forming, a large amount of shore drift seems to have reached the locality from the southeast, and this modified the resulting topographic forms. The configuration of the bench owes nearly as much to the action of waves as to the deposition of stream drift.

The deltas formed by Little Cottonwood and Big Cottonwood Creeks coalesced with each other, and probably with one from the Dry Cottonwood; but their outlines are greatly obscured by subsequent stream erosion, and they have been further modified by a system of faults.

Following the base of the Wasatch southward, the next delta reached is that of American Fork, already described. Beyond it, is the delta of the Provo River, a broad low terrace of gravel spreading fan-wise from the mouth of the Provo canyon. The radius of the fan is about 4¼ miles, and the terrace has a marginal height of 70 feet. It is skirted rather than divided by the modern river, which turns abruptly southward from the mouth of its canyon. Lower deltas were only obscurely differentiated, but the form of the lake shore indicates that the river is now constructing one. The wagon road from Provo to Pleasant Grove crosses the main delta; the railroads pass around it.

Near Provo City a small stream named Rock Creek issues from a short, steep canyon in the mountain. It built a small delta during the Bonneville epoch, and another during the Provo; and these would afford an instructive study in chronology were it not for the injury they have suffered from the recent faulting. Hobble Creek, which irrigates the farms of Springville, built a well-marked delta at the Provo level, and probably a small one at the Bonneville. The subaerial alluvium here rests so high against the mountain that it constituted the coast at the Provo stage, and the Provo delta rests against it. Five miles southward Spanish Fork issues from the range, with a northwesterly course. In the Bonneville lake it built a delta with a radius of 4,000 feet, and in the Provo lake a larger delta coalescing with that of Hobble Creek. At Payson a small creek formed a delta at the Provo level. Salt Creek, the next stream issuing from the range, reached the ancient lake only after flowing for some distance across the plain. Its highest delta appears to be one at the Provo horizon, and lies at the south end of Goshen Valley.

Apart from the drainage system of the Wasatch, only three deltas were observed. A small one lies in an open canyon back of the town of Portage, in Malade Valley. A larger was probably formed by Beaver Creek at the Provo level near George's Ranch; but it is difficult in this case to distinguish stream drift from shore drift.

The deltas of the Sevier River are more important. At the Bonneville epoch alluvial terraces were built where the river enters Juab Valley, but the topography did not permit the formation of a broad fan. At the Provo epoch a broad, low delta fan was built by the river on the plain between Lemington and Deseret.

Summary.—The contributions made by the phenomena of the deltas to the history of the oscillations of the lake may be summarized as follows:

First, the Bonneville shore-line antedates the Provo.

Second, the Provo epoch was several times longer than the Bonneville.

Third, in falling from the Bonneville shore to the Provo the water lingered very little, if at all.

Fourth, in falling from the Provo level to the bottom of the basin the water occasionally lingered, but its lingerings were brief as compared to the halt at the Provo level.

Fifth, the water lingered during its advance antecedent to the Bonneville epoch, not standing long at one level, but oscillating up and down.

A certain significance attaches likewise to the absence of deltas from the greater portion of the coast of the old lake. All of the old deltas are associated with modern streams; and all the modern streams of importance built deltas. It would appear, then, that the ancient climate did not create important streams in regions where the outflow is now small. In the western portion of the basin, there are catchment districts of considerable extent which furnish little or no water to the lowlands by reason of the scantiness of rainfall. If the rainfall in Bonneville times was very great, as compared to the modern, these catchment districts should have furnished tributary streams; and such streams, flowing over tracts of alluvium, the accumulation of ages, should have transported large quantities of it to the margin of the lake and constructed deltas of it. We seem thus to have an intimation that the climatic change, whatever its nature, did not affect the rainfall in a degree commensurate with the difference in area of lake surface.

TUFA.

Calcareous tufa was deposited by many and perhaps all of the Pleistocene lakes. In Lake Lahontan and the other lakes of the western portion of the Great Basin, great masses were accumulated, and their study has resulted in an important contribution to the Pleistocene history. In Lake Bonneville very little tufa was formed, and its bearing upon the history of the lake seems to be unimportant. It is associated exclusively with the shores; and its amount upon individual shore-lines is in a general way proportional to the magnitude of the other shore features. At least this rule applies to the Bonneville, Intermediate, and Provo shore-lines. The Provo carries most of all; the Bonneville and Intermediate have an equable distribution.

Next to the Provo the Stansbury is most generously supplied; but this shore is not characterized by embankments and cliffs of great magnitude. The extent of the lake was so greatly reduced at this stage that the power of the waves was materially lessened; and it is perhaps legitimate to infer that the tufa records a protracted lingering of the falling water which does not find adequate expression in other shore features.

In embankments the position occupied by the tufa is on the weather face a few feet lower than the crest. It lies just beneath the surface, and has the function of a cement, binding the gravel together into a conglomerate. The association is far from being invariable; and indeed the majority of the embankments are uncemented. In regions of excavation the tufa occurs just outside the edge of the cut-terrace, coating the lower slope for a space of 20 or 30 feet. Its zone of maximum deposition was probably from 10 to 20 feet beneath the water surface.

Where the deposit is thin, it consists merely of a uniform film, but wherever it acquires a thickness of an inch or more, there is manifested a tendency to assume dendroid forms. These are not uniform in character, but generally consist of branching stems, an eighth or a fourth of an inch in diameter, frequently dividing and again joining, so as to constitute a reticulated mass in which the interspaces are not large.

The composition is shown by the following analysis, copied from the report of the Fortieth Parallel Survey, Vol. 1, page 502:

Analysis of Tufa[1] *from Main Terrace, Redding Spring, Salt Lake Desert, by R. W. Woodward.*

[Specific gravity, 2.4, 2.3, 2.4.]

	Percentages.	
	First sample.	Second sample.
Silicic acid (chiefly included sand)	8.40	8.22
Alumina	1.31	[illegible].20
Sesquioxide of iron	Tr.	Tr.
Lime	46.38	[illegible].50
Magnesia	3.54	3.52
Soda	0.48	0.54
Potassa	0.22	0.22
Lithia	Tr.	Tr.
Phosphoric acid	Tr.	Tr.
Water	1.71	1.62
Carbonic acid	38.20	38.33
Total	100.24	100.14

On pages 495 and 496 of the same volume, the microscopic characters of the tufa are described by King.

The distribution of the tufa along each shore is independent of the nature of the subjacent terrane. The heaviest observed deposits are upon quartzite and granite at a considerable distance from calcareous rocks. The most conspicuous accumulations are upon rock in place, but this difference probably depends upon the fact that deposits upon unconsolidated material are largely interstitial. A more important peculiarity of the distribution is its relation to wave action. No deposit is found in sheltered bays; and on the open coast those points least protected from the fury of the waves seem to have received the most generous coating. These characters indicate, first, that the material did not have a local origin at the shore but was derived from the normal lake-water; second, that the surf afforded a determining condition of deposition. It will appear in a later chapter that calcareous

[1] The analysis is headed "Thinolite (pseudo Gay-Lussite)"—probably through inadvertence, for the reference to the analysis in the text (p. 495) uses the designation tufa only; and the theory in regard to the origin of the Lahontan tufa which is embodied in the term "pseudo Gay-Lussite," appears from the context not to have been applied to the Bonneville basin.

matter constitutes an important part of the fine sediment of the lake bottom, and that this was chiefly or wholly precipitated from solution. It is not easy to see why this deposition should consist of discrete particles in the open lake and be welded into a continuous mass upon the shore; but a partial explanation appears to be afforded by the hypothesis that the separation was promoted by the aeration of the water. All precipitation being initiated at the surface during storms, coalescence at the shore may have resulted from contact at the instant of separation. The suggestion finds a certain amount of support in the part played by nuclei as determinants of precipitation.

The thickest deposit anywhere observed is on the outer verge of the Provo terrace at the north end of Reservoir Butte, where there is a maximum of four feet. The tufa there coats a knob of solid quartzite so situated that while it was fully exposed to the surf, whatever the direction of the wind, it was exempt from attack by shore drift. The locality is exceptional; in most places where the tufa is so abundant as readily to attract attention, its depth is measured by inches.

An allied deposit may be mentioned in this connection, namely, oolitic sand. This was first observed on the Bonneville shores by Miss Susan Coolidge, of Grantsville, Utah, and was afterward found by Messrs. W. J. McGee and George M. Wright on several shore terraces at the north end of the Oquirrh Range. It is now forming in Great Salt Lake along the coast between the delta of the Jordan and Black Rock, where it constitutes the material of a beach, and is drifted shoreward in dunes. Like the tufa, it is exclusively a shore formation, but the circumstances connected with its occurrence on the modern shores of Great Salt Lake and Pyramid Lake warrant the suspicion that it is not equally independent of local sources of supply. The locality mentioned on the shore of Great Salt Lake is near the mouth of a stream whose annual tribute of carbonate of lime can not be small, and the only known locality on Pyramid Lake is associated with hot calcareous springs.

RÉSUMÉ.

The highest of the shore-lines preserved on the slopes of the basin, namely, the Bonneville shore-line, has an altitude of 1,000 feet above Great

Salt Lake. By reason of its position at the top of the series, it is the most conspicuous of all; but the one most deeply carved is the Provo, 375 feet lower. Between the Bonneville and Provo are the Intermediate shore-lines, characterized by embankments of great size, but without correspondingly great sea-cliffs and terraces. Below the Provo the slopes exhibit lake sediments, with occasional shore-lines superposed. Of these latter the Stansbury is the most prominent.

The area of the lake at the Bonneville stage was 19,750 square miles; at the Provo stage, about 13,000 square miles; at the Stansbury stage, about 7,000 square miles.

The order of sequence of the shores to which names have been given is: first, Intermediate; second, Bonneville; third, Provo; fourth, Stansbury. During the period of the formation of the Intermediate embankments, there were no persistent water stages; but the water surface oscillated up and down. The last additions to the embankments were made during a general advance of the water. The oscillation of the water surface continued through the Bonneville epoch, the Bonneville shore representing the combined results of wave action at a series of water levels having a vertical range of 20 feet. The last stage of this series was the highest, and immediately afterward the surface fell rapidly to the Provo horizon, where it remained a long time. The water margin afterward receded from the Provo shore to its present position, halting occasionally by the way, and longest at the Stansbury shore.

CHAPTER IV.

THE OUTLET.

Thirteen years ago I had the temerity to predict,[1] first, that the position of the Bonneville shore-line would eventually be shown to have been determined by an overflow of the lake, and second, that the Provo shore-line would be found to have been similarly determined. The first of these predictions has been verified in its letter, but not in its spirit; the second has proved to have full warrant. My anticipation was based on the following consideration: A lake without overflow has its extent determined by the ratio of precipitation to evaporation within its basin; and since this ratio is inconstant, fluctuating from year to year and from decade to decade, it is highly improbable that the water level will remain constant long enough to permit its waves to carve a deep record. I failed to take account of the fact that the highest shore-mark of the series is conspicuous by reason of the contrast there exhibited between land sculpture and littoral sculpture. We now know that the height of the Bonneville shore-line was determined in a certain sense by overflow, since a discharge limited the rise of the water; but the carving of the shore was essentially completed before the discharge; and as soon as that began, the water level fell. At the Provo horizon, on the contrary, a constant or nearly constant water-level was maintained by discharge for a very long time.

The outlet of a lake is necessarily across the lowest point of the rim of its basin; and it is essential that this point be somewhat lower than the water level of the lake. The search for an outlet to Lake Bonneville was therefore a search for a pass in the rim of the basin lower than the neigh-

[1] Expl. West of the 100th Mer., vol. 3, pp. 90, 91.

boring shore-lines. It is equally necessary that the basin on the opposite side of the pass be competent to receive the discharged water. It must either drain to the ocean or else be sufficiently large and sufficiently arid to dispose of the affluent water by evaporation. The conditions of outlet having been satisfied, and a discharge having been produced, it is equally evident that the process of that discharge would modify the topography in a peculiar manner. A channel would be produced at the pass, and this would descend in one direction only, its sides and bottom merging at the pass into other topographic features. The site of the ancient outlet of Lake Bonneville should therefore exhibit a channel, the bed of which is lower than the contiguous shore-line, and the descent of which is toward some basin competent to receive and dispose of the water.

It is quite conceivable that a basin like the Bonneville, known to be subject to deformation through hypogene agencies, should discharge its surplus water at one time over one pass and afterward over another; and this possibility was one of the considerations leading to an examination of its entire coast line. By that examination it was ascertained that all the lower passes of the basin's rim are at the north, separating the basin from the drainage system of the Columbia River. These passes were systematically visited by competent observers; and it was ascertained that the Bonneville waters discharged at one point only.

The trend of the mountain ranges in that region is generally north and south and the passes are simply culminating points in the intervening valleys. As a rule they are not rocky, but consist of alluvium, the profiles of which rise gently toward the mountains on either side. South of each such pass the minor drainage lines from each mountain unite and produce a main drainage channel descending toward the basin of Great Salt Lake. At the north a similar confluence produces a drainage channel descending toward the tributaries of the Columbia. On the pass the alluvial profiles from the mountains unite with gentle curvature; and there is no channel of drainage.

It is a curious fact that in a region characterized by great reliefs of surface, a number of passes were so nearly at the same level that a difference of only a few feet determined the actual point of discharge. The water of the lake rose within 75 feet of the pass north of Kelton, where the Boisé stage-road crosses from the Salt Lake basin to the head-waters of Raft River; and it rose within 100 feet and 200 feet, respectively, of the passes north of Snowsville and Curlew.

Red Rock Pass.—The actual point of discharge was at the north end of Cache Valley, at a point known as Red Rock Pass; the outflowing river entered Marsh Creek valley, and being there joined by the Portneuf, flowed through Portneuf Pass to the valley of the Snake River. The first suggestion of its position was by Bradley, who crossed the old channel some miles below the pass in 1872; and it was independently demonstrated by Mr. Gilbert Thompson and by the writer, who separately visited the locality some years later.[1]

The ascent to Red Rock Pass from Cache Valley is so gentle as to be scarcely noticeable, and the descent on the opposite side, while perceptible to the eye, affords an easy grade to the Utah and Northern Railroad. A few miles west of the pass, there rises a lofty mountain ridge separating Cache Valley and Marsh Valley from Malade Valley. On the east are lower mountains, separating Cache Valley and Marsh Valley from Gentile Valley and Basalt Valley. From the base of the range on either side, an alluvial slope descends to the pass, but this is not continuous. Knobs of indurated rock, similar to those constituting the mountain, project through it, testifying to the existence a short distance beneath the alluvium of a rocky spur connecting the two ranges. At a few points there are exposures of less indurated rocks, supposed to be of Tertiary age, but these form no hills by themselves, being buried under the alluvium except where laid bare by recent erosion. The alluvium is further interrupted by the channel of the ancient outlet, which is one of the most notable features of the landscape. It has been excavated to a depth of several hundred feet, and has a general

[1] It was maintained by Peale that the original point of discharge was at Portneuf Pass instead of Red Rock Pass; and the discussion of this view gave to the subject of the outlet and its discovery a more voluminous literature than perhaps it deserved. The writer's dissent from Peale's determination has already been recorded in discussing the supremacy of the Bonneville shoreline (p. 94). Readers who care to pursue the subject further will find the following references useful:—G. K. Gilbert, in Surveys West of the 100th Meridian, vol. 3, Geology, p. 91; E. E. Howell, idem, p. 251; F. H. Bradley, Geol. Survey of Terr., Ann Rept. for 1872, pp. 202, 203; Gilbert, Bull. Phil. Soc. Washington, vol. 2, p. 103; A. C. Peale, Geol. Survey of Terrs., Ann. Rept. for 1877, pp. 565, 642; Am. Jour. Sci., 3d series, vol. 15, 1878, p. 65; Gilbert, idem, 3d Series, vol. 15, 1878, p. 256; Peale, idem, vol. 15, 1878, p. 439; Gilbert, idem, vol. 19, 1880, p. 342; Lieut. Willard Young, Surveys West 100th Meridian, Ann. Rept. for 1878, p. 121.

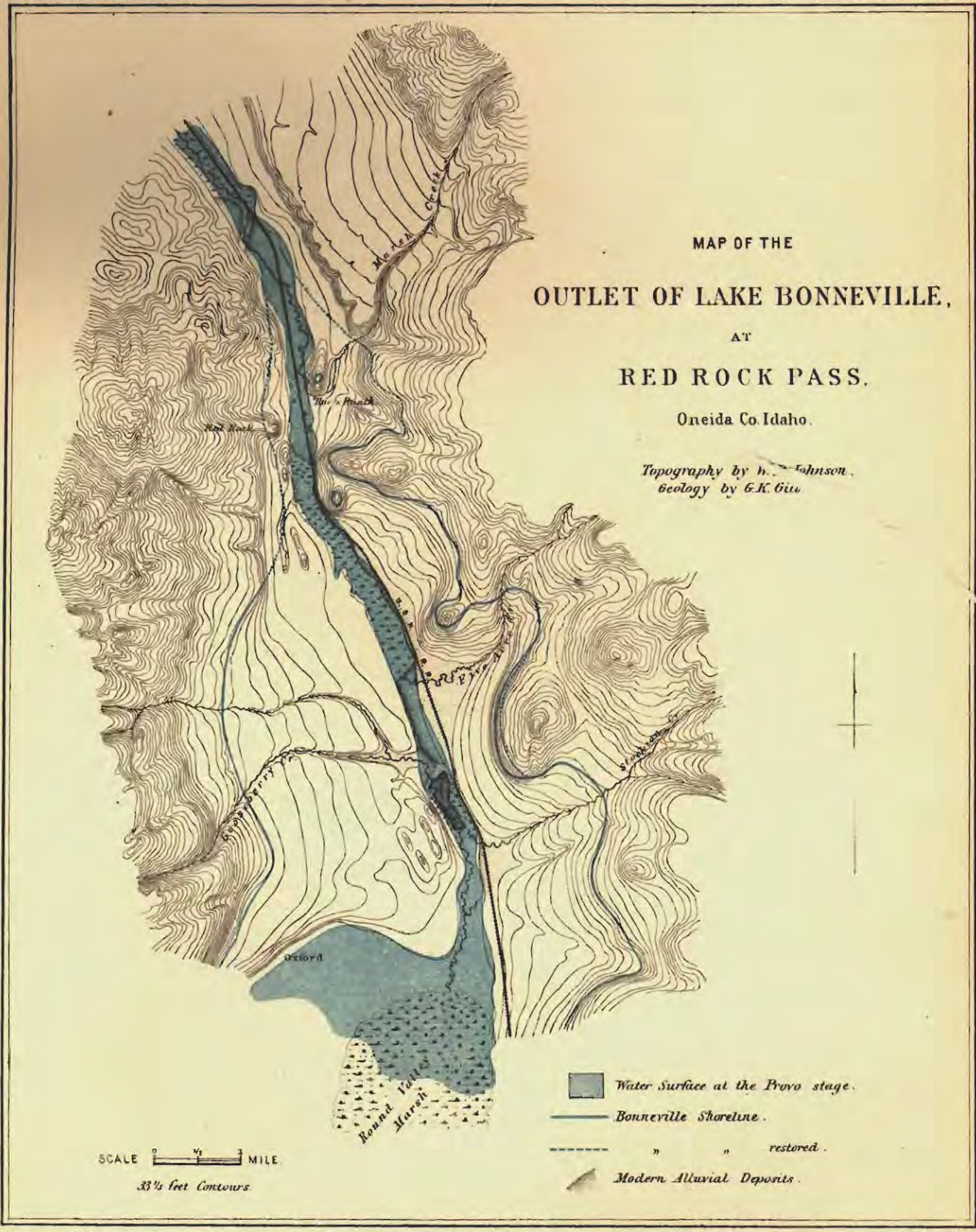
width of about one-third of a mile. Five small streams flow from the mountains to the ancient channel, and each of these has carved a deep trench in the alluvium, casting the eroded material into the channel. The greatest of the streams is Marsh Creek, débouching at Hunt's Ranch; and its freshly formed deposit occupies the old channel for a distance of nearly three miles. Three or four miles farther south Five Acre Creek makes a similar tribute, filling the old channel with alluvium for the space of a mile; and the same thing is repeated on a smaller scale by Stockton Creek, two miles farther south. The alluvial fan built by Marsh Creek is a few feet higher than the others, so that the actual water parting is at Hunt's Ranch.

Between the Marsh Creek and Five-Acre Creek alluvia, the old channel is occupied by a marsh three miles in length with an average width of twelve hundred feet; and within this there is a small pond. Between the alluvia of Five-Acre Creek and Stockton Creek there is a larger pond, known as Swan Lake. These marshes and ponds, whenever they accumulate water enough to overflow, drain southward to Cache Valley; and all the streams of the pass except Marsh Creek are tributary to them. Marsh Creek turns abruptly north on entering the channel and flows toward Marsh Valley. Its volume is so small that during the dry season it does not maintain a superficial flow through the valley, but repeatedly sinks beneath the surface and reappears below in springs.

The knobs of indurated rock, which in the immediate vicinity of the pass consist of arenaceous limestone, both adjoin and interrupt the channel. Near Hunt's Ranch there are two buttes, each several hundred feet in height, overlooking the channel from opposite sides, and between them are a number of low reefs projecting through the flood-plain of Marsh Creek Constricted by these reefs, the channel has a minimum superficial width of only 600 feet.

The relations of these various features will be better understood by reference to the map in Pl. XXVIII.

The Bonneville shore-line is traceable continuously about Cache Valley to the vicinity of the pass. On the east side its most northerly vestige is upon a butte a mile south of Hunt's Ranch. On the west side it is lost on the alluvial slope two miles from Hunt's Ranch. Its height above the marsh



Julius Bien & Co. lith.

Drawn by G. Thompson

between Marsh and Five-Acre creeks is 340 feet. The nearest point at which the Provo shore-line was observed is about eight miles farther south, in the vicinity of the town of Oxford.

Marsh Creek issues from its canyon in the mountains about two and one-half miles east of the old channel. The intervening space is occupied by a sloping alluvial plain terminating in a bluff. It is evident that this is an alluvial fan or alluvial cone constructed by the creek before the excavation of the Bonneville outlet. It was afterward partially eroded by the outflowing river, and also by Marsh Creek, which has excavated a passage several hundred feet in depth.

Where this old alluvial plain approaches nearest to the Bonneville channel, its edge is fifty feet higher than the nearest terrace of the Bonneville shore, and a restoration of its profile indicates that it coalesced with slopes from the opposite mountain range at about the level of the Bonneville shore. A careful study of the ground has satisfied the writer that the base or outer margin of the alluvial cone was part of the ancient water-parting, and was the point at which the outflow was initiated.

The fact that the Bonneville water discharged at first over a barrier of alluvium instead of solid rock had much to do with the subsequent history of the lake. Uncemented alluvium is easily and rapidly torn up and removed, and as soon as a current began to flow across the divide, it must have commenced the excavation of a channel. As the channel increased, the volume of the escaping water became greater, and this increase of volume reacted on the power of erosion. In a short time a mighty river was formed, and the lowering of the lake surface resulted. For a time the outpouring was a veritable débâcle, and it could not have assumed the phase of an ordinary river commensurate with the inflow of the lake until the alluvial barrier was completely demolished and the resistance of the limestone reef was called into play. When the corrasion of the channel had proceeded so far as to give the river a bed of limestone, the process of excavation was changed from the mere transportation of loose detritus to the corrasion of solid rock, and the rate of excavation was greatly diminished. We have here the explanation of the rapidity of the final recession of the lake from the Bonneville level to the Provo.

Marsh Valley.—Marsh Valley, like Cache Valley, is enclosed between mountain ranges, and has a north and south trend. Its length is about thirty-five miles, and its greatest width is eight or ten miles. Twenty miles from Red Rock Pass, the Portneuf River breaks through the eastern mountain chain and enters the valley, turning northward and running parallel with Marsh Creek to the end of the valley. There it receives the creek and then turns abruptly westward and escapes from the valley through a deep but open canyon. The upper canyon of the Portneuf has at some time admitted lava as well as water. A succession of basaltic coulées have poured through it into Marsh Valley and have followed the slope of the valley to the lower canyon. The Portneuf River follows the western margin of the lava beds, and Marsh Creek the eastern, each occupying a narrow valley sunk from 30 to 100 feet below the level of the lava table. A comparison of these valleys illustrates the disparity between Marsh Creek and its channel. Portneuf River is several times larger than Marsh Creek; but the immediate valley by which it is contained is smaller. Indeed, there is every evidence that the valley of Marsh Creek, having been formed by the ancient Bonneville river, is now in process of filling. It abounds in meadows and marshes, and at one point contains a lakelet.

The River.—It appears, however, that the Bonneville river was not contained during its entire existence in the channel now occupied by Marsh Creek. The whole upper surface of the lava tongue, where it has a width of more than a mile, is fluted and polished, and pitted with pot-holes after the manner of a river bed; and there seems no escape from the conclusion that it was swept by a broad and rapid current. The trenches at the side of the lava may or may not then have existed; but even if they did not, we have to contemplate, as the agent of corrasion, a river comparable with Niagara. Indeed it is even possible that Niagara might suffer by comparison.

Let us assume that at the time the Bonneville river traversed the lava-bed the lower channel at the side had not been eroded; and let us further assume that its width was somewhat less than that of the lava,—say one mile. When the river came into being, the total descent of its bed, from one end of Marsh Valley to the other, was at the rate of 13 feet to the mile.

RED ROCK PASS, THE OUTLET OF LAKE BONNEVILLE, AS SEEN FROM THE NORTH.

In the last stages of its existence its average grade in the same space was 7 feet to the mile. At all stages the declivity was greater near the pass than in the lower end of Marsh Valley. Let us assume that the slope of the water surface in flowing over the lava was $2\frac{1}{2}$ feet to the mile, or one foot in 2,000. If now we assume in addition that the discharge equaled that of the Niagara River, we have all the data necessary for computing the mean depth; and we obtain for that depth 9 feet. To one who stands upon the lava bed and notes the scale of the carvings which ornament its surface, this determination appears far too small. Twenty feet would better accord with the phenomena, and twenty feet would discharge the flood volume of the Missouri.

Another evidence of the magnitude of the outflow is found at the pass. West of the swamp there is an irregular terrace, extending from Swan Lake to Red Rock, the upper surface of which is corrugated with parallel furrows and ridges trending in the general direction of the current. These consist partly of limestone crags and partly of alluvium. Comparing them with similar flutings in other stream beds, they appear to be explicable only as details of channel-bottom wrought by a torrent of great volume.

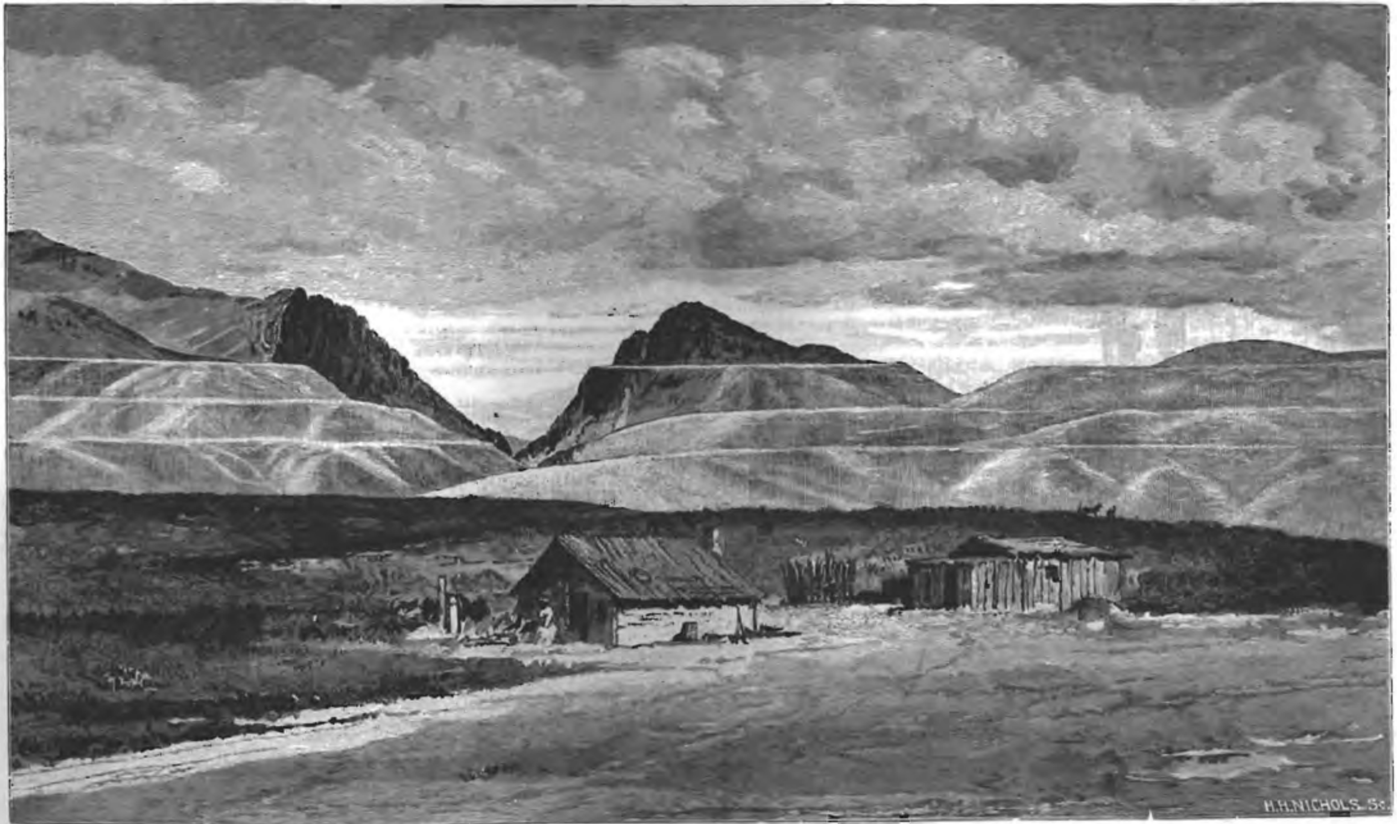
How long the discharging river maintained its colossal dimensions can not be learned, but the period certainly was not great. The entire prism of water between the Bonneville and Provo planes would be discharged by the Niagara channel in less than 25 years; and if the Bonneville river reached a greater size, it could have maintained it only for a shorter time.

It is evident that the channel at the pass has been partly filled since the desiccation of its river; but the precise amount of filling is not so evident. A crude estimate was based upon the configuration of certain small drainage lines tributary to it. Before the filling began, these drainage lines (as, for example, that of Gooseberry Creek; see Pl. XXVIII) found their base of erosion in the main channel, and adjusted their profiles thereto. As the filling of the channel progressed they were likewise partially filled near their mouths; and a study of their configuration yields a crude estimate of the amount of deposition. It is judged to be about thirty feet; and if this estimate is correct, the bottom of the channel is 370 feet lower than the Bonneville shore. This is approximately equal to the difference in level of the Bonneville and Provo shores and it serves to connect the testimony of the outlet with that of the shore-lines.

It is not easy to estimate the cross section of the channel of outflow at any stage of its existence. Undoubtedly it was broader and deeper while its walls and bed consisted of alluvium than afterward when solid rock was reached. The trough now occupied by the marshes and Swan Lake probably represents its width after rapid corrasion had ceased and before the final desiccation of the lake was begun; but this is a mere surmise. We need not doubt that it had a greater width at an earlier stage and a less width at a later.

As the degradation of the channel proceeded, the position of its head was continually transferred southward. The discharge was initiated on the Marsh Creek alluvial fan two miles north of Hunt's Ranch; but during its final stages the outflowing river headed seven miles farther south, between Swan Lake and the Round Valley marsh. When the outflow ceased, the water parting between the Bonneville and Snake River basins was at this latter point, Gooseberry and Five Acre creeks being tributary to the Snake River. In the course of time, however, the alluvium deposited by Marsh Creek effectually dammed their channel and turned their drainage southward. Marsh Creek itself must normally alternate in its affiliation. As its alluvial fan has gradually increased, its débouchure must have been shifted from Marsh Valley to Cache Valley and vice versa many times. Even now, in the irrigation of farming land at Hunt's Ranch, a portion of its water is sometimes artificially turned toward the Great Basin.

The Gate of Bear River.—Cache Valley is separated from the open basin of Great Salt Lake by a mountain range which at one place is low. Through this the Bear River escapes from the valley by a narrow passage between precipitous walls of limestone. During the Bonneville epoch the dividing ridge was submerged at several places, so that the waters of the Cache Valley bay communicated freely with those of the open lake. During the Provo epoch the connection was restricted to the passage now occupied by the river, a strait only a few hundred feet broad and a mile and a half in length. One-half of the present water supply of Great Salt Lake is derived from Bear River, and that river during the Provo epoch was a tributary of



THE GATE OF BEAR RIVER, FROM THE EAST.

Cache Bay. Cache Bay therefore presumably received half of the inflow of the Provo lake; and it is from Cache Bay that the outflow discharged. If the volume of outflow was greater than the tribute brought by Bear River, the difference was supplied by a current from the main lake through the narrow strait into Cache Bay. If the volume of Bear River was greater than the outflow, then the excess was discharged through the strait into the lake. Doubtless in either case the flow through the strait was regularly reversed by reason of the annual inequality of the Bear River tribute, and still more frequently by the effect of storm winds, but if the volume of Bear River greatly exceeded that of the outflow, it is conceivable that the fact of outflow did not imply the perfect freshness of the lake.

This speculation was suggested by a curious piece of negative evidence. The calcareous tufa which abounds upon the Provo shore has not been found associated with it in Cache Valley. If it be really absent, and not merely undetected, its distribution would seem to indicate that, during at least a large portion of the Provo epoch, the outflow was less than, or did not greatly exceed, the Bear River inflow. Under such circumstances the main body may have accumulated carbonate of lime to the point of saturation, while Cache Bay did not.

The lowering of the lake level by the wear of the outlet diminished the area of the lake surface about one-third, and it must have diminished the annual evaporation from the lake surface by about the same amount. Up to the moment of outflow the entire tribute of the lake was disposed of by evaporation; and if the change of climate which brought about the outflow went no farther, the amount of the discharge during the Provo epoch should have been one-third of the inflow. It is thus seen to be quite within the range of possibility that Cache Bay, receiving one-half the total inflow, was a fresher body of water than the main lake through the entire Provo epoch. It is certainly most remarkable that a concurrence of geographic and climatic conditions should enable a lake to maintain a higher degree of salinity than the water of the outlet limiting its size.

On the other hand, it is not supposable that the main body of Lake Bonneville was saline, or even brackish, as those terms are ordinarily used, during the maintenance of the Provo level by outflow. The strait at the entrance of Cache Bay was several hundred feet deep, and any sensible difference in density between the bay and the open lake would have produced an interchange of gravity currents, the light water flowing from the bay at the surface, and the dense water entering beneath. Adding to this regulative action the interchange of currents to and fro during storms and during floods, it is evident that only a small difference in the average constitution of the bay water and the lake water could be maintained. The very minute difference competent to produce the precipitation of carbonate of lime in the open lake would not affect the practical freshness of the water.

It may be remarked in passing that the deposition of tufa during the Provo epoch is not inconsistent with a contemporaneous discharge by the lake, even though Cache Valley did not operate as a distributing reservoir for the water of Bear River. In a broad way, it is true that salt lakes have no discharge, while fresh lakes have, and that lakes are freshened by discharge; but so long as the volume of outflow is less than the inflow, the freshening is a matter of degree. The inflowing streams bring a certain amount of mineral matter; the outlet carries away a certain amount; and as soon as equilibrium of action is established, these two quantities are equal. If the volume of the outflow is only a small fraction of the inflow, its salinity must be greater in inverse ratio: and, since the salinity of the discharge is normally identical with that of the lake, the latter can not be so pure as its affluents. Carbonate of lime is peculiarly sensitive to the effect of such conditions. On the one hand, it is dissolved from the rocks by rain and stream in greater quantity than most other minerals, and on the other, its point of saturation is quickly reached. It might be precipitated in a lake even while there was free discharge of a third part of the inflowing water.

The Question of an Earlier Discharge.—It has been suggested by Davis[1] that anterior to the Bonneville epoch, the altitude of the rim of the basin may have been such that its drainage was discharged to the ocean without the formation of a lake, or at least without the formation of a large lake. The more general problem on which his suggestion bears will be deferred to another chapter; but it is proper to inquire here whether there is any indication in the rim of the basin of a pre-Bonneville outflow. The possibility of such an outflow was

[1] Lake Bonneville [a review], by W. M. Davis: Science, vol. 1, 1883, p. 570.

fully recognized by the writer during his investigations in the field; and several of the lower passes were visited with special reference to this question. It was not considered important to examine the higher passes, because displacement of the earth's crust, while paroxysmal in detail, appears in a broad way to be slowly progressive, so that the time presumably necessary for lifting a barrier to a considerable height—say one thousand feet—would suffice for the obliteration by the processes of land sculpture of all traces of a preexistent channel. The results of the search were purely negative, no evidence of a pre-Bonneville channel being found. The only point where the indication is not so clear as could be desired is Red Rock Pass. A pre-Bonneville outlet, occupying the same position as the Bonneville outlet, would be very difficult to discover, especially if the intervening period were sufficient for the accumulation of large bodies of alluvium. Suppose, for illustration, that Red Rock Pass were to remain subject to the existing conditions until Marsh Creek was enabled to restore the original contours of its alluvial cone. While the Bonneville channel would be locally filled and concealed, other portions of it would be likely to remain visible; and its presence would be betrayed by some such phenomenon as Swan Lake. But if the valley were reflooded and another river traversed the pass, the washing out of the alluvium would leave a channel practically identical with the present, and the earlier history would be masked.

If, however, the interval between two discharges sufficed only for the partial restoration of the alluvial contours, the duplication of the history of outflow would be recorded by terraces, and its decipherment would not be hopeless. No such terraces were observed at Red Rock Pass.

These observations manifestly do not warrant the conclusion that the Bonneville basin never had free drainage. They indicate merely that the last epoch of outflow antecedent to the Bonneville was separated from the latter by so long an interval that the channel of discharge can not now be discovered.

THE OLD RIVER BED.

The overland stage road which, before the day of Pacific railroads, carried the mail across the Great Basin, skirted the southern margin of the Great Salt Lake Desert. From Salt Lake City to Canyon Station, at the eastern base of the Deep Creek Mountains, its route lay almost entirely upon the bed of Lake Bonneville. Midway it crossed a broad channel, which every one recognized as an ancient river bed. Here a stage station was established and a change of horses was kept. The horses were not watered by the river, nor even by a diminutive modern representative of it, but by means of a well sunk to a depth of 100 feet. Now that the road has fallen into disuse and earth has clogged the neglected well, the chance traveller finds nothing to quench his thirst from Simpson spring to Fish Spring, a distance of 40 miles. One who stands here in the midst of a desert, where the only vegetation is a scattering growth of low bushes, and looks on an ancient river course 2,000 feet broad and more than 100 feet deep, can not fail to be deeply impressed.

Naturally this old water trace was associated in the minds of observers with the shore traces on the flanks of the mountains; and it is not surprising that popular theory located here the outlet of the lake.[1] Nevertheless, the Bonneville shore-line, which is visible upon the adjacent mountains and buttes, is 700 feet higher than the highest part of the old channel; and our exploration demonstrated that the entire site of the channel was submerged during both Bonneville and Provo epochs.

Neither end of the channel is visible from the crossing of the stage road, but both are commanded by neighboring peaks. It is about 45 miles in length, and holds a direct course from the heart of the Sevier Desert to the edge of the Great Salt Lake Desert, passing between the McDowell and Simpson Ranges. Throughout its extent it is cut from the clays deposited by the ancient lake. Near the extremities these only are exhibited in its banks; but in the middle course, where it follows the base of the McDowell Mountains and associated buttes, it lays bare the older rocks at several points. Its general width is about half a mile, but it expands in places to nearly a mile, and is elsewhere constricted to about 1,000 feet. At the south its depth is small, and its southern end is ill defined, the channel features gradually losing themselves in the plain of the Sevier Desert. Its northern end is more definite, being bordered by low bluffs; and thence

[1] See A. S. Packard in Bull. U. S. Geol. Surv. Terr., 2nd series, vol. 1, p. 413 (No. 5); and G. K. Gilbert, Amer. Jour. Sci., 3d ser., vol. 10, 1876, p. 228.

Julius Bien & Co. lith. Drawn by G. Thompson

to the River Bed Station its depth increases to 130 feet. In the pass between the mountains its banks coalesce with the steep faces of buttes; and its general depth may be several hundred feet.

This description applies merely to its present condition. There is good reason to believe that, at the time of its desiccation, it was deeper, especially in the southern part. Everywhere it is margined by easily eroded lake sediments; and near the mountains the surface of these lies at such an angle that every rain washes down an abundance of mud into the old channel. On the Salt Lake Desert the plain is so nearly level that superficial waters have little power of erosion, and the silting of the channel has been less. In the vicinity of the pass the recent deposit has a probable depth of 100 to 200 feet.

The general descent of the channel is from south to north, but this is interrupted at one point in the pass by an alluvial dam, over which the water seems to find its way rarely. The direction of the original descent, or the direction of drainage through the channel, is not demonstrated by the existing levels; but fortunately there is other evidence in the shape of a terrace, marking a flood-plain of the ancient stream when its channel was half excavated. This appears on the banks of the channel north of the River Bed Station, and is capped by a deposit of fine gravel, the pebbles of which are evidently derived from the McDowell and Simpson Mountains.

From the head of the channel the plain of the Sevier Desert descends southward for many miles; and it is evident that, when the channel was occupied by a river, the desert was covered by a lake. In a word, the channel was opened at a time, during the final desiccation of the lake, when the level of the water in the main body fell below the bottom of the strait. The inflow of the Sevier body was for a time greater than its restricted lake surface could discharge by evaporation, and the surplus flowed over the pass to the main body, opening a channel as it flowed. The upper lake thus preserved on the Sevier Desert was both small and shallow, and its shore marks have not been identified. The lower lake was large, and may have left a well marked shore record; but this has not been discriminated from others on the margin of the desert. A rough estimate, based on a general knowledge of the contours of the country, indicates that the upper lake had one-eleventh the area of the lower. The lake system had also another member, for the Bonneville shore had then receded from Utah Valley, and the outlet of Utah Lake was, as now, an affluent of the Great Salt Lake basin. The continuance of the climatic decadence finally lowered Sevier Lake below the level of outflow and dried the river bed.

It has already been remarked that even in the pass between the mountains the river bed was carved from the lacustrine strata deposited by Lake Bonneville. The Bonneville strata there rest against steep faces of the rocky buttes; and the relation of these faces to each other, and to the general course of the channel, indicates that they are the walls of an older channel whose course the post-Bonneville river followed. The history of this older channel is unknown; and its discovery only tells us that, at some unknown period before the lake, there was free drainage from one desert to the other. There seems no way to determine in which direction this drainage led, nor whether either plain was covered by a lake.

OTHER ANCIENT RIVERS.

Three other long abandoned stream courses have been observed within the basin. One of these has already been mentioned. The pass between Rush and Tooele valleys is now dammed across by a great system of wave-built bars, which prevent the drainage of Rush Valley from passing through Tooele Valley to Great Salt Lake. Against this dam the water of Rush Valley sometimes accumulates in a lakelet known as Rush Lake, and this lakelet occupies a portion of the ancient drainage channel. It has a width of 1,000 feet, and is shallow. Doubtless the depth of the channel has been considerably diminished by recent deposits; and if these were cleared away the width of its bed would be found smaller than the indication given by the lake.

This channel is interpreted as showing, not that there was anciently in Rush Valley a water supply competent to override and remove such a barrier as now restrains it, but merely that, before the creation of the Bonneville lake, the valley had free drainage northward.

A larger channel, whose habit indicates a stream comparable with the smaller rivers of the basin, enters Snake Valley from the south at a point just east of Wheeler Peak known as the Snake Valley Settlement. The channel ends at the margin of the old lake, and appears to have contained a stream tributary to the lake, which disappeared at the same time. It is now occupied near the settlement by a streamlet from the adjacent mountain known as Lake Creek, but this enters the channel at its side, and played no important part in its formation. Above its confluence the channel has essentially the same dimensions, and these continue as far as it was traced, about twenty miles from its mouth. Circumstances did not permit its further exploration.

Near its mouth the ancient stream cut across the base of an immense alluvial fan, poured out from Wheeler Peak, opening a channel 1,000 feet broad, which retains a depth of 50 feet. A secondary alluvial fan, formed by the same mountain stream, and from the material amassed in the first, was afterwards thrown across the channel, damming it and causing a small lake. Still more recently this dam was broken through and a smaller channel was opened, whereby the lake was nearly drained, and Lake Creek escaped to Snake Valley. The closing chapter of the history has been contributed by man. The denizens of the little hamlet have built another dam within the small channel (a puny and insignificant affair compared with those of Nature's construction), whereby they have created a pond for the storage of water for irrigation.

A third stream course of some magnitude enters the basin in Idaho at the north end of Snowsville Valley, débouching, from a mountain at the west, almost precisely at the divide between the drainage of the Basin and that of the Snake River. It was not traced toward its source, but the grade of its bed indicates that it drains a valley of some size within the mountains. Its flood-plain has a breadth, just before it reaches the Bonneville horizon, of 2,000 feet, and below that horizon is covered by the lake sediments. Within the lake area it can be traced for several miles, although lined throughout by the lacustrine deposits. Through this channel water rarely finds its way at the present time. The flood-plain is covered by soil and vegetation, which give no evidence of recent disturbance except along a narrow meandering trench that one may leap across. There is here no delta associated with the Bonneville shore, and the implication seems to be that the locality was characterized at some very ancient date by a climate more humid than either the Bonneville or the present.

With these exceptions the water courses of the drier coasts are not known to give evidence of modification. All of them are larger than the ordinary streams within them require; but the extraordinary requirements in an arid region are so great that the channels do not seem abnormal.

OUTLETS AND SHORE-LINES.

The harmony between the conclusions based on the phenomena of the shore-lines and those derived from the features associated with the outlet has a double bearing. On the one hand, it serves to establish the elements of the lake's history thus far set forth; and on the other it defines the influence of outflow on shore topography. Without outflow the level of a lake is inconstant and oscillatory, and unless the water stands long at the same level the waves will not excavate cliffs and terraces comparable in magnitude with the embankments constructed.

It follows that the Stansbury shore, which gives evidence of a permanent water stage, not merely by its cliffs and terraces but by its accumulation of tufa, was determined by an outflow or its equivalent. At one time I supposed that the problem of its existence would be solved by the Old River Bed—that its level would be found to have been determined by a discharge from the main body to the Sevier body; but this hypothesis was was overthrown by the study of the river bed, which showed the discharge to have been northward instead of southward. The precise relation of the Stansbury shore to the river bed has not been ascertained, for the shore has not been recognized in that vicinity, but they do not differ greatly in altitude. It is probable that during the Stansbury epoch the main lake did not extend to the Sevier Desert. There is one other valley which might have served as a reservoir for surplus water at the Stansbury stage, but the connecting strait has not been critically examined. White Valley contained a large bay during both the Bonneville and Provo epochs, and was deep enough to have received a considerable discharge at the Stansbury stage, if the strait was adjusted to its delivery. Its area is indeed small as compared to the main lake at that level, but it might none the less have served as a regulator, causing the oscillating lake to linger at a particular level each time it rose.

The nature of the problem embodied in the Stansbury shore was not realized until the field examinations were so nearly complete that the opportunity had passed for visiting the localities important for its discussion. It therefore remains as one of the unanswered questions developed by the investigation.

CHAPTER V.

THE BONNEVILLE BEDS.

A certain series of lacustrine strata have been designated the Bonneville beds. Their relation to the old shore-lines was first pointed out by Hayden,[1] and afterward by the geologists of the Fortieth Parallel Survey and the Wheeler Survey. The grounds for the correlation have not been distinctly enunciated, probably because they are so patent to each observer that their statement seems surperfluous. In the present work, however, it is proposed to combine the history derived from the sediments with the history derived from the shore record; and there is a logical necessity for establishing the general synchronism of the two.

A brief account has already been given of the Tertiary lacustrine strata observed in the Bonneville basin. While these exhibit considerable variety in texture, they are in general so distinct lithologically from the Bonneville beds that their discrimination has been easy and unembarrassed by doubt. The Bonneville beds occupy the lowlands, constituting nearly the entire surface, and retain the attitude of deposition, lying flat on the open plain or gently inclining at the bases of the mountains. Wherever the outcrops of the Tertiary beds are associated with these, they exhibit dips referable to displacement, and they are overlain unconformably by the Bonneville. The Bonneville beds are thus seen to be the latest lacustrine deposit of the basin, and this fact indicates their synchronism with the latest littoral evidence of a lacustrine condition.

Again, the distribution of the Bonneville beds is strictly limited by the Bonneville shore-line; and none of the other groups are so limited. The latter are thus shown to be older than the shore-lines. The Bonneville

[1] Sun-pictures of Rocky Mountain Scenery, by F. V. Hayden, New York, 1870, p. 132; Ann. Rept. Geol. Survey Terr. for 1870, p. 170.

beds are not traceable outward from the center of the basin to all parts of the Bonneville shore-lines, or at least they do not to that limit hold their familiar characters; but they bear to the shore-line certain definite relations, which may be stated. Where the margin of the basin is steep and the shore-line is high, the lake beds reach to the foot of the slope; where the basin margin is gently inclined, as in the shallow bays, they extend nearly to the outer limit of wave work.

Finally, as has been fully set forth by King,[1] the Bonneville beds are in places interstratified with alluvial deposits; they rest upon the principal mass of alluvium from the mountains and support alluvium of recent transportation. This relation is strictly paralleled by the shore-lines, which rest upon the alluvial cones of the mountain bases and are themselves overplaced by recent alluvium.

Adding to these facts the *a priori* consideration that the deltas contain only the coarser material brought by streams, the finer having been carried in suspension to the lake, and that the shore embankments represent only the coarser part of the product of littoral erosion, the finer having been carried lakeward by the undertow, so that there must have been fine lake sediments contemporaneous with the deltas and embankments of the shore, the general correspondence of the Bonneville beds with the Bonneville shore-lines is clearly established.

It is only in regard to details that the correlation is less clear than could be desired. One result of the deposition of the sediments was the raising of the base level of erosion of all streams tributary to the basin, so as to make them agents of deposition along their lower courses in post-Bonneville time. The localities are therefore exceedingly rare where even partial sections of the Bonneville beds can be observed; and it is only at their extreme outer limits, where they rise toward the shore, that their base is ever seen.

LOWER RIVER BED SECTION.

The deepest section of the lake beds, or more strictly the section representing the largest fraction of the Bonneville Period, is exposed in the walls of the Old River Bed near the point where it is crossed by the Overland

[1] Geol. 40th Par., vol. 1, p. 493.

Stage-road. It has some title to be regarded as the typical section, and exhibits the following members:

1. (At base.) The Yellow Clay, a fine argillaceous deposit, laminated throughout, olive gray on its fresh exposure, but weathering to a pale yellow. In this are occasional passages of sand, but these are local and discontinuous. Nodules of selenite, consisting of grouped arrow-head crystals, are abundant; and jointage cracks sometimes contain rosettes of recrystallized gypsum. Bivalve shells of several species are included. The base is not seen; a thickness of 90 feet is exposed.

2. The White Marl, a fine calcareous clay or argillaceous marl, light gray or cream-colored on fresh exposure, nearly white on weathered surface. Contains some gypsum, but less than No. 1. Overlies No. 1 with unconformity by erosion, and is at its base crowded with shells representing nearly the same fauna. Thickness, 10 feet.

3. The marl passes upward into a fine sand, the transition being gradual and the continuity perfect. The sand contains also the same species of shells. Thickness, about 10 feet, the upper limit being obscured by a recent eolian deposit of similar texture.

The distribution of the Yellow Clay and White Marl is universal throughout the lower parts of the basin, and they ascend in the shallower bays toward the upper shore-lines. At low levels their physical characters undergo little change, and they are readily discriminated by their difference in color. At very low levels a yellow clay appears over the White Marl, blending with it as though continuously deposited. This may be the equivalent of the sandy member in the typical section, which is not everywhere found. The unconformity between the Clay and the Marl does not include any observed difference in inclination, and is not always detectable, but it was observed at localities so widely distributed as to indicate that it is not a mere local phenomenon. Against the steeper coasts the beds appear to terminate somewhat abruptly at low levels; but on gentle slopes they continue with a change of character, acquiring sand both by admixture and by intercalation. By these changes their distinctive characters are lost, and at high levels their separation is for the most part impossible.

The exposures of the Yellow Clay are so rare and so small that its special mutations can not be characterized, but abundant opportunity is afforded for observation of the White Marl. As the shore is approached, the arenaceous capping increases in relative thickness, encroaching on the marl below. The base is the last to change, holding its white color on many parts of the coast to levels above the Provo shore.

At numerous points between the Bonneville and Provo horizons, sedimentary deposits are seen to alternate with littoral, the former consisting of marls, clays, and sands, and the latter of shore drift in the form of spits and bars. We have not succeeded in correlating these sublittoral deposits either with each other or with the lacustrine sediments of the center of the basin; and the phenomena, although numerous, are so fragmentary that there seems no advantage in placing their details on record. Their only contribution to the deduced history of the lake is the confirmation they afford of the conclusion independently reached that the surface of the lake, when not limited by outflow, was subject to many minor oscillations.

At a few localities there was observed an abnormal development of the lacustrine section, a result of what may be called redeposition. A single illustration will suffice. Snowsville Valley contained at the Bonneville stage a bay eight miles broad and running twenty miles inland. At the Provo stage its linear dimensions were reduced one-half, and it became shallow. At a later and lower stage, possibly the Stansbury, the water barely reached to the entrance of the bay; and at this time the freshly deposited muds of the bay appear to have been washed lakeward in great volume, accumulating at the mouth of the bay in a series of sheets inclined at an angle of 3 or 4 degrees toward the lake. This may perhaps be called a delta deposit, but it differs from typical deltas in the fineness of its material and the consequent low angle of cross lamination. The last addition to the deposit constitutes the face of a perceptible terrace, ascended by the road from Curlew to Snowsville. Through this terrace Deep Creek or Deseret Creek, the drain of the valley, has excavated a channel from twenty to thirty feet in depth, exposing the structure of the mass. The deposit has a general resemblance to the normal lake beds, but exhibits four or five alternations of the typical yellow and white colors.

LEMINGTON SECTION.

The unconformity of the White Marl upon the Yellow Clay indicates discontinuity of lacustrine conditions; and at two localities this evidence is supplemented by the occurrence of subaerial deposits at the horizon of unconformity. One of these localities is at Lemington, where the Sevier River, issuing from its narrow valley in the Canyon Range, enters the Sevier Desert. During the highest water stages, no delta was formed at this point, because the land-locked bay on the east side of the range received and retained all the coarser alluvium; but a great amount of fine matter was washed into the lake, and this was deposited with exceptional rapidity about the mouth of the estuary. The total local deposit must have amounted to several hundred feet, and recent erosion by the river has exposed 150 feet of this to view. The point of special interest is just outside the canyon mouth, where the lacustrine strata are seen to abut against the steep face of

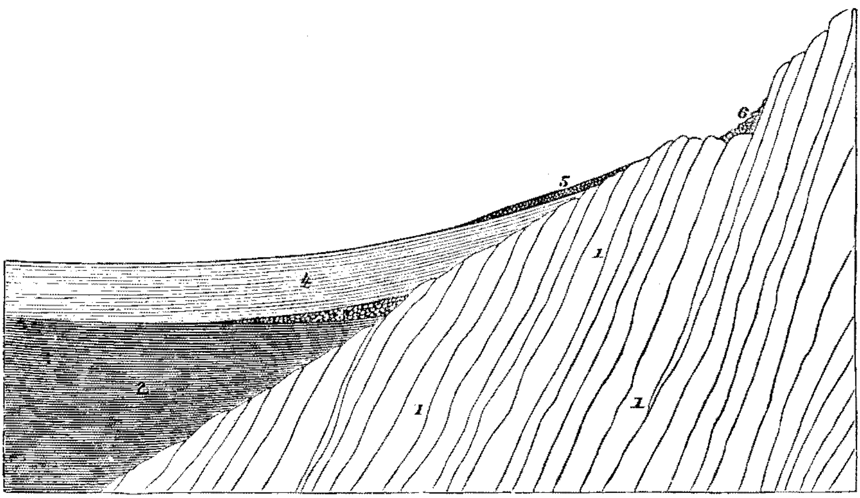


FIG. 28.—Section showing succession of Lacustrine and Alluvial Deposits at Lemington, Utah. 1. Paleozoic sandstone. 2. The Yellow Clay (Lower Bonneville). 3. Wedge of alluvial gravel. 4. The White Marl (Upper Bonneville). 5. Recent alluvial gravel. 6. Bonneville shore notch, with recent talus.

quartzite constituting the mountain front. The material of the lake beds is here coarser than in the typical section, and the contrast in color between the upper and lower series is barely discernible. The Yellow Clay includes through nearly its whole depth a considerable percentage of fine sand, and the White Marl has a fine texture only at its base, consisting above of coarse and fine sands.

Associated with the lake beds are two wedges of alluvium, the thicker ends of which abut against the quartzite of the mountain. The upper of these is a modern deposit, receiving additions at every storm; the lower, which otherwise is similar in all its characters, is inserted between the White Marl and the Yellow Clay.

The Marl and its associated sand have here a joint thickness of 50 feet, and the Yellow Clay a visible thickness of 100 feet, the base being concealed. The Bonneville shore-line, here taking the form of a terrace and cliff, runs 50 feet above the upper limit of the White Marl and 120 feet above the upper limit of the Yellow Clay.

The series of events by which these relations were produced can not be mistaken. While the lake stood at a high level the Yellow Clay was deposited against the base of the mountain; and as the deposit extends to within 120 feet of the Bonneville shore, the lake level must have approached this maximum very nearly. Then the water receded so far as to bring subaerial agencies locally into play. The waste from the mountain face was washed by the rain into the margin of the lacustrine deposit, and accumulated there in a talus or alluvial slope of low inclination. Afterward the water returned, and remained at a high level during the deposition of the White Marl; and at the same time the Bonneville shore terrace was cut by the waves.

The locality was carefully studied for the purpose of discovering other intercalary alluvial wedges, but none were found; and the exposures were sufficiently complete to warrant the confident assertion that none exist within the range of the section. Their absence indicates that during the deposition of the visible portion of the lower sedimentary formation the water did not fall more than 200 feet below the Bonneville horizon, and that during the period represented by the upper deposit the water did not fall more than 150 feet below the Bonneville horizon; that is to say, the locality records two high stages of the lake separated by an epoch of lower water, and precludes the hypothesis of a larger number of great oscillations of water surface within the limits indicated by the local deposits.

UPPER RIVER BED SECTION.

The second locality at which the clay and marl are separated by subaerial deposits is at the Old River Bed, about five miles south of the point at which the typical section of the lake deposits was observed. The sediments here lie about seventy feet higher, rising gradually toward the mountains and buttes between which the River Bed passes. The number of distinct members in the series is greater than in the northern part of the River Bed, and the relations are complicated by at least one other uncomformity. They are exhibited in the map on Pl. XXXII and in the sectional diagram, Fig. 29. The letters designating formations are made to correspond in the two illustrations.

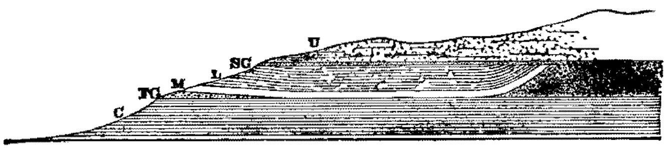
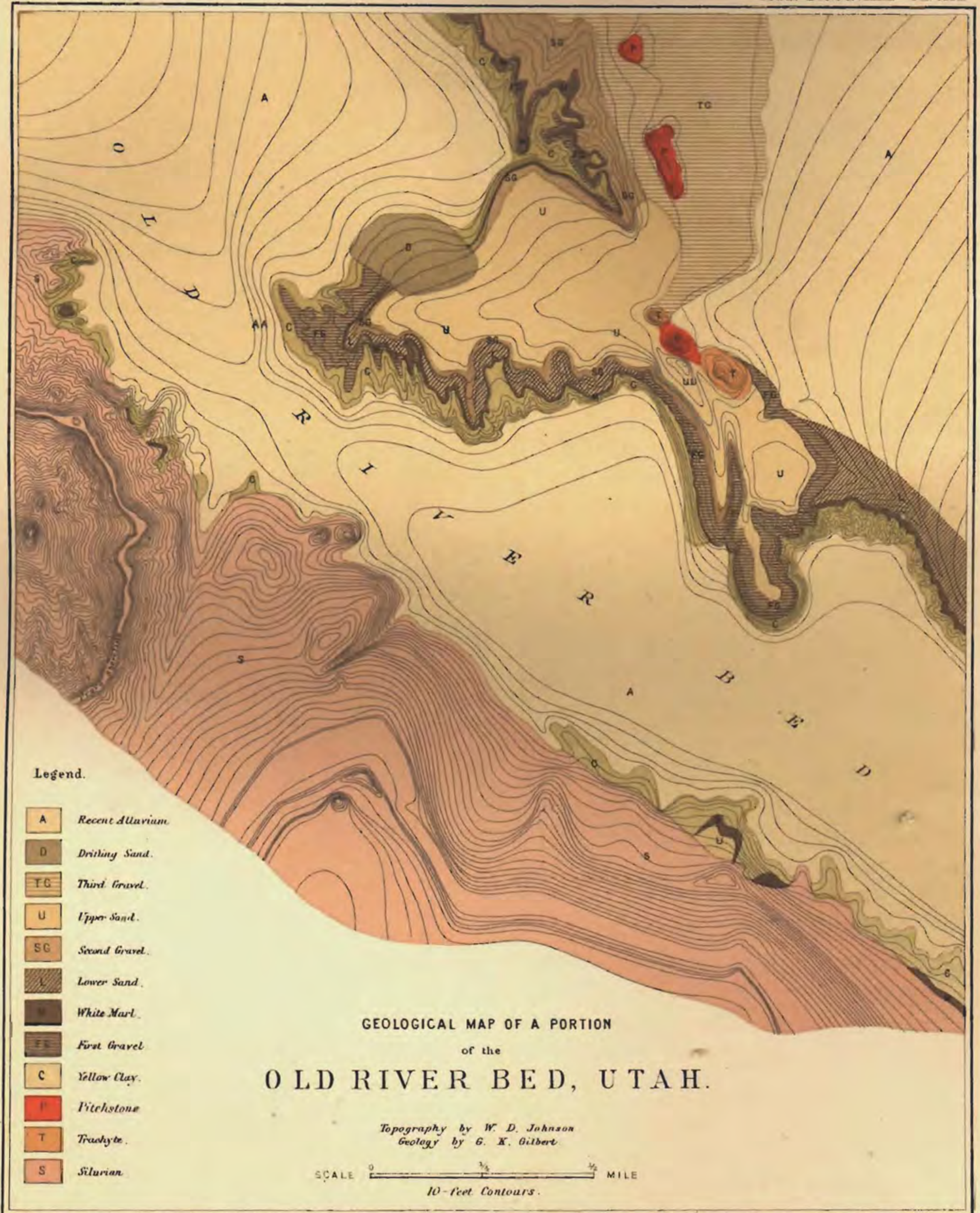


FIG. 29.—The Upper River Bed Section; running from *AA* to *UU* on Plate XXXII.
U. = Upper Sand. *SG* = Second Gravel. *L* = Lower Sand. *M* = White Marl. *FG* = First Gravel. *C* = Yellow Clay. Vertical scale greater than horizontal.

On the left or southwest bank of the River Bed, the paleozoic terrane is largely exposed, consisting of limestones and sandstones or quartzites, believed to be of Silurian age, though not yielding fossils at this precise point. The structure of the mass is not essential to the Pleistocene history. On the opposite side of the River Bed are five small buttes of trachyte and pitchstone, nearly buried by the later deposits. These are so ancient and worn that their forms convey no information as to the original extent of the masses from which they have been carved.

Yellow Clay.—The lowest member of the later series of formations is a fine laminated clay, which rests against the Silurian wall on the side of the River Bed, and presumably surrounds the bases of the buttes, although its contact is not seen. This is olive on fracture and yellow on weathered surfaces, and is visibly continuous with the Yellow Clay of the type section.

First Gravel.—Resting on the clay, with a slight unconformity by erosion, are several masses of gravel. The largest runs southward from the more southerly buttes, and has protected the underlying clay from erosion. It is


OLD RIVER BED
A
U
D
SG
TG
FG
C
L
M
P
T
S
Legend.
A Recent Alluvium.
D Drifting Sand.
TG Third Gravel.
U Upper Sand.
SG Second Gravel.
L Lower Sand.
M White Marl.
FG First Gravel.
C Yellow Clay.
P Pitchstone.
T Trachyte.
S Silurian.
GEOLOGICAL MAP OF A PORTION
of the
OLD RIVER BED, UTAH.
Topography by W. D. Johnson
Geology by G. K. Gilbert
SCALE 0 1/4 1/2 MILE
10-feet Contours.

lenticular in cross-section, and has a maximum thickness of fifty feet. Its pebbles are well rounded, and are relatively small at bottom, but at top include boulders six inches in diameter. Near the surface there is in places a calcareous cement, binding the pebbles together; and there are also rosettes or mushroom-like masses of calcareous tufa. The majority of the pebbles are of pitchstone and trachyte, similar to the material of the adjacent buttes, but there are also examples of other volcanic rocks not known to occur in situ within several miles, and also, limestone and quartzite, such as constitute the mountain ranges on both sides and are distributed through all the large alluvial cones of the neighborhood. At the west margin the mass can be seen to terminate in a wedge separating the Yellow Clay from the next member of the series, and beyond the limit of the mass there is a ribbon of sand, with occasional pebbles, marking its horizon. Half a mile farther west this ribbon expands into a bed of coarse sand and gravel, four or five feet in thickness, and half a mile north there is an independent outcrop of similar material at the same horizon. These masses are not of subaqueous deposition. The form of the one first described, the associated tufa, and the preponderance of boulders of local derivation, indicate shore action, but it is possible that an interlacustrine river was the agent of transportation. Whatever their origin, the gravels mark a period when the lake level was much lower than during the deposition either of the Yellow Clay or of the succeeding deposit.

White Marl.—Next in order is a bed of white marl, eight feet in thickness, deposited uniformly over the undulating surface of the gravel and clay This is in visible continuity with the White Marl of the type section

Lower Sand.—The marl graduates upward into a bed of sand, fine below and coarse above, with a total depth of 45 feet. The sand and marl are conformable throughout, but were both eroded before the deposition of the next bed.

Second Gravel.—Above the sand is a second gravel, which rests unconformably on the marl as well as the sand, and probably on the first gravel, from which it could not be separated at the point of contact Its pebbles are small and are mingled with a coarse sand, the whole having a thickness of about two feet.

Upper Sand.—Above the second gravel is an upper bed of sand, conformable with it so far as could be ascertained, but exhibiting little structure. This has an observed thickness of 32 feet, but may have gained or lost by the action of the wind, which throws its surface into waves, and has caused it to bury at the north the exposure of the lower formations.

Upper Gravel.—Finally, there appears about the bases of the more northerly buttes a fine gravel of alluvial habit. It rests on the second gravel; but its relation to the upper sand was not seen.

On the opposite side of the River Bed there are a few remnants of the White Marl capping the Yellow Clay; and at one point a small tract of sand appears, which may belong either to the lower or upper series.

In terms of lake oscillation, this section bears the following interpretation; first, an epoch of deep submergence, during which the Yellow Clay was deposited; second, an epoch of emergence, during which the surface of the Yellow Clay was slightly eroded and the first gravel was deposited, either by wave action or by running water; third, a second epoch of deep submergence, during which the White Marl was thrown down; fourth, a continuance of submergence, but with a less depth, during the deposition of the lower sand; fifth, a second epoch of emergence, during which the lower sand and White Marl were eroded and the second gravel was deposited; sixth, a third submergence, permitting the accumulation of the upper sand as a shallow-water deposit; seventh, the final emergence and the erosion of the River Bed. The locality has thus been three times submerged and as many times laid bare and subjected to atmospheric erosion.

It will be convenient to refer to this locality as the Upper River Bed. It is connected by continuous outcrop with the Lower River Bed, where the type section of the lake sediments is exhibited; but there is no such connection with Lemington, forty miles away. It is about seventy feet higher than the Lower River Bed, and about 450 feet lower than Lemington.

OSCILLATIONS OF WATER LEVEL.

At the Lower River Bed locality two emergences are recorded; at the Upper River Bed, three; at Lemington, two; and it is important to the determination of the history of the oscillation that the relations of these several emergences be ascertained.

There can be no error in referring the latest of the indicated emergences at each of the three localities to the final subsidence of the lake and desiccation of the basin. There were, of course, intervals between the appearances of the several localities, the highest being first exposed by the receding water, but the existence of these intervals does not contravene the general fact. We may therefore restrict our attention to the temporary emergences, of which the Upper River Bed witnessed two and the other localities one each. Continuity of outcrop demonstrates the identity of the first emergence at the Upper River Bed with the emergence recorded at the Lower River Bed; and there is stratigraphic evidence of a cumulative nature in favor of correlating the Lemington emergence with these two. Since this is not direct and positive, it is necessary to state it somewhat fully, in order to exhibit the weakness of the argument as well as its strength.

The temporary emergence is recorded at the Lower River Bed by an unconformity—by the erosion of the surface of the Yellow Clay before the deposition of the White Marl. The section includes in descending order: (1.) White Marl, crowded with shells at the base; (2.) Unconformity; (3.) Yellow Clay. All the elements of this section are traceable continuously to the Upper River Bed locality, and they are repeated at several other localities low down in the basin. A few of these are higher on the slopes of the basin than the Upper River Bed, and one attains an altitude of 250 feet above the latter locality, falling only 200 feet short of the Lemington locality. The unconformity may therefore be said to have been traced by a harmonious series of observations within 200 feet of the level of the Lemington locality. At Lemington the stratigraphic series is comparable, but not identical. It contains all the enumerated elements except the White Marl, and this is replaced by a white clay. On the other hand, the second emergence recorded at the Upper River Bed has not been recognized elsewhere, so that there is some warrant for the belief that the oscillation of lake surface causing it had not a great amplitude. Finally, the sediment recording the latest submergence at the Upper River Bed is a sand merely, indicating that the depth of the water was not great; and if this submergence did not include the Lemington locality, the preceding emergence, as recorded at the River Bed, could in no manner be separated, at Lemington, from the final emergence.

The accompanying diagram, Fig. 30, expresses graphically the conclusions reached from the joint consideration of the three localities. The vertical scale represents height of water surface, ranging from the level of Great Salt Lake to that of the Bonneville shore. The horizontal scale represents (from left to right) the order of sequence, but without any attempt to express the relative duration of the several elements of the

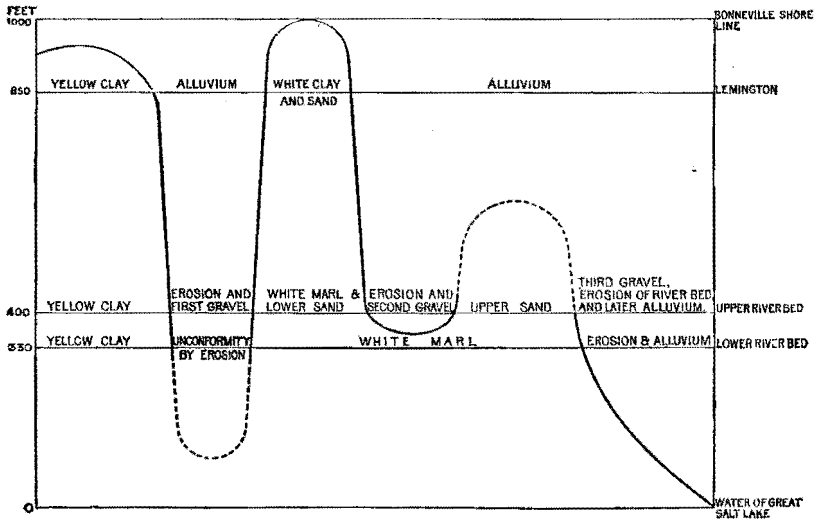


FIG. 30.—Diagram of Lake Oscillations inferred from Deposits and Erosions.

history. The curve exhibits the progressive rise and fall of the lake. Beginning at the left, we have high water represented by the Yellow Clay at all three localities, then an epoch of low water represented by the alluvium at Lemington, by the first gravel at the Upper River Bed, and by unconformity at the Lower River Bed. How low the water fell, does not appear. So far as this evidence goes, it may have fallen only to the bottom of the Old River Bed, or it may have descended to the level of Great Salt Lake, or even lower. Then came a second and shorter epoch of deep water, represented at Lemington by white clay and sand, at the Upper River Bed locality by the White Marl and the lower sand, and at the Lower River Bed by the White Marl. The final emergence is recorded at Lemington by the superficial alluvium and by the erosion of the modern channel of the Sevier River. It is recorded at the Lower River Bed by the erosion of the River Bed and by its partial filling with alluvium. At the Upper River Bed the second and third gravels, with the intervening sand, record a general descent of the water, interrupted by an upward movement of small extent.

It is not to be understood that this curve exhibits any more of the history of oscillation than is derivable from the deposits and unconformities at these three localities. The additional elements derived from the study of the shore-lines are purposely ignored, and innumerable minor oscillations are perforce omitted. If sections of all the alluvial, littoral, and lacustrine deposits of the basin were accessible; and if these were elaborately studied, it can not be doubted that the simple curves here drawn to represent the two great submergences of the basin would have to be replaced by lines with innumerable small inflections, similar to that deduced from the upper deposits at the Upper River Bed. In the sequel the data embodied in this curve will be combined with other data in our possession, including that from the shore-lines and outlet, and a more accurate curve will be drawn.

HEIGHT OF THE FIRST MAXIMUM.

If the first submergence had been carried so far as to produce outflow, the corrasion of the channel of outflow would have made it impossible for the second submergence to extend higher than the Provo level. Knowing, as we do from the phenomena of the shores and the features of Red Rock Pass, that the second submergence was characterized by outflow, we are warranted in concluding that the first rise was somewhat less than the second. The amount of the difference appears to be indicated by the embankments of Preuss valley, to which allusion has already been made. At the north group of embankments, figured in Pl. XVI, there is an older series partly buried by a newer; and the highest member of this lies 90 feet below the Bonneville horizon. It is probable that this represents the extreme advance of the earlier flood.

At the Lemington locality the Bonneville shore-line is the only one represented by a sea-cliff and terrace; but at lower levels there are lines of tufa adhering to the quartzite and apparently marking temporary positions of the water level. Probably the relation of the waves to the contiguous slopes enabled them to employ shore drift in attacking the mountain face at the Bonneville horizon, but did not afford them that aid at lower levels.

The unarmed waves not only were unable to tear down the cliff, but were compelled by their peculiar chemical constitution to add a mineral coating to its face. These lines of tufa are all covered by the lacustrine deposits except where exposed by recent denudation; and it is assumed that certain of them now buried by the White Marl beds were formed during the deposition of some portion of the Yellow Clay. The highest of these is separated from the Bonneville shore-line by an interspace of 90 feet (aneroid measurement).

THE WHITENESS OF THE WHITE MARL.

As soon as the wide distribution of the White Marl and the Yellow Clay and the constancy of their contrast came to be appreciated, attention was directed to the determination of the cause of their difference. It is easy to understand a gradation in texture and composition of strata as one passes from the margin of a basin toward its center, or from the vicinity of sea-cliffs and river mouths, where the supply of detritus is great, to quieter and remoter places, reached only by sediment long held in suspension; but it is not so easy to understand why there should be an abrupt change in the sedimentary sequence throughout an entire basin. If the true explanation of the difference between these strata can be reached, it should contribute something to the history of the lake. For the purpose of seeking such an explanation, the character of the two deposits has been examined both chemically and microscopically. Two samples each of the White Marl and Yellow Clay were analyzed by Prof. O. D. Allen of New Haven, with the results exhibited in Table III.

TABLE III.—*Analyses of Bonneville Sediments.*

I. White Marl from the Old River Bed.
II. White Marl from near Willow Spring, at the eastern base of the Deep Creek Mountains.
III. Upper part of Yellow Clay, Old River Bed.
IV. Lower part of Yellow Clay, Old River Bed.

	I.	II.	III.	IV.
Insoluble; percentage	98.2	96.84	99.29	95.57
Soluble; percentage	1.8	3.16	0.71	4.43
100 parts of the Insoluble portion contain—				
Silica	45.03	23.05	43.84	41.74
Alumina	8.63	3.26	13.85	12.00
Ferric oxide	2.85	1.16	4.04	3.61
Potassa	1.76	.70	2.46	1.87
Soda	.68	.54	.44	.70
Lime	19.08	31.08	12.43	16.01
Magnesia	2.71	2.87	4.54	4.96
Carbon dioxide	16.25	31.49	11.88	15.78
Water	2.33	1.23	2.84* 4.11†	3.78
	99.32	100.38	100.43	100.45
100 parts of the determined‡ Soluble constituents contain—				
Sulphuric oxide	23.539	20.204	8.806	2.045
Lime	.916	8.906	2.341	4.322
Magnesium	1.148	.721	5.986	1.897
Potash	.534	1.363	1.792	.370
Soda	47.639	39.295	50.742	50.637
Sodium oxide**	....	....	....	....
Chlorine	33.857	38.029	39.169	52.594
Nitric acid**	trace	trace	present	present
Boric acid	trace	....	....	....
Carbonic acid	trace	trace	....	trace
Lithium	....	....	trace	....
	107.633	108.578	108.836	111.865
Oxygen equivalent to chlorine	7.633	8.578	8.836	11.865
	100.000	100.000	100.000	100.000
Probable combination of soluble constituents—				
Calcium sulphate	2.225	21.775	5.685	3.477
Magnesium sulphate	3.444	2.163	8.193	....
Potassium sulphate	.987	2.521	....	....
Sodium sulphate	36.079	8.511	....	....
Calcium chloride	....		....	5.727
Magnesium chloride	....	....	7.729	3.759
Potassium chloride	....	....	2.835	.586
Sodium chloride	55.789	62.659	52.830	76.336
Sodium oxide**	1.476	2.371	22.728	10.115
	100.000	100.000	100.000	100.000

* Water lost at 100° C.

† Water lost by ignition.

‡ The total weight of the soluble portion could not be obtained by evaporating to dryness, because the magnesium chloride would be thus decomposed with loss of hydrochloric acid. The constituents were determined from separate portions of the solution, and their sum was assumed in the computation to represent the total soluble matter. If all the constituents were determined, the deduced ratios would be slightly modified.

** The sodium oxide reported among the constituents is not assumed to be free, but to exist as sodium nitrate. A trace of nitric acid was found in each instance; and in the case of the third and fourth samples its amount is considerable. A single determination from the fourth sample gave 14.63 parts N_2O_5—which is equivalent to 23.069 of $NaNO_3$, leaving only 1,716 of Na_2O unsatisfied.

The soluble constituents need not concern us at present, for they do not materially affect the color of the beds. Indeed the characteristic colors are everywhere recognized by the weathered surfaces, from which the soluble materials are nearly or completely leached. The carbonic acid in each of the samples is nearly sufficient to satisfy the lime and magnesia; and it may be assumed to have been all combined with those bases. The alumina, iron, soda, and the remaining lime and magnesia, undoubtedly exist in the form of silicates, while the unsatisfied silica is free. The microscopic characters indicate that the silicates are chiefly feldspars; and if we assume orthoclase to be predominate, the bases are barely satisfied in the case of one sample and there is an excess of silica in each of the others. It is probable that the following table represents the constitution of the earths nearly enough for the purposes of the present discussion.

TABLE IV.—*Condensed Results of Analyses in Table III.*

	Sample I.	Sample II.	Sample III.	Sample IV.	White Marl: Mean of I and II.	Yellow Clay: Mean of III and IV.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Carbonates of lime and magnesia	36	70	26	34	53	30
Silicates	54	18	74	62	36	68
Free Silica	10	12	0	4	11	2
Totals	100	100	100	100	100	100

Under the microscope the White Marl is seen to contain, first, numerous minute crystals exhibiting double refraction; second, minute particles, apparently clastic, likewise doubly refracting; third, siliceous organisms. The crystals are too small for measurement. They appear in general to be tapering pyramids whose longer diameters are three or four times their shorter. They undoubtedly represent the carbonates. The clastic matter is conceived to represent, in like manner, the silicates, and possibly a portion of the free silica. The remainder of the silica, or possibly the whole of it, is contained in the microscopic organisms. These are partly diatomaceous, but include also numerous slender tubes with punctate or papillate walls which may be spiculae of sponges.

Unfortunately, a majority of the samples of Yellow Clay which should have been examined for comparative purposes, were lost in transportation before the microscope was applied to them. The only two preserved are from a sublittoral deposit at Lemington and from the type section in the Old River Bed. These exhibit only rounded grains of crystalline matter, for the most part clear, uncolored, and doubly refracting. Neither diatoms nor crystals were discovered.

In brief, the White Marl and Yellow Clay resemble each other in composition, but the former is characterized by a relatively great amount of earthy carbonates and by free silica, while in the latter the argillaceous element predominates. In the former the carbonates were largely thrown down as a chemical precipitate, and at least a portion of the silica is an organic precipitate. The whiteness of the marl appears to be largely due to its precipitated elements.

These differences in the characters of the two deposits were unquestionably determined by some event in the history of the lake; during the intervening epoch of low water the conditions of sedimentation underwent some change. A double interest attaches to the determination of the nature of this change; on the one hand its discovery would add an element to the history of the lake; and on the other it might lead to the establishment of some law of sedimentation hitherto unrecognized. Much thought has therefore been given to the subject, hypotheses have been framed and many experiments have been made, but the results of the experiments are unfortunately negative, and the problem can not be regarded as solved. It is necessary, however, to give some consideration in this place to certain of the hypotheses for the purpose of showing the grounds upon which one of them was so seriously entertained as to receive a provisional publication.

SOURCE OF MATERIAL.

The simplest explanation of the change in sedimentation is that the nature of the material supplied to the lake by tributary streams was for some reason different. In the interval of time between the two epochs of deposition, the deformation of the earth's crust may have wrought changes in the area of the basin, either cutting off some important element of the detrital contribution or making some equally important addition. The prime difficulty with this hypothesis is that the configuration of the region offers no way of rendering it local and concrete. The calcareous tribute of the basin must flow chiefly from the limestones of the Wasatch and associated ranges, and the drainage system by which it is conveyed seems to have been established before the Pleistocene. The possibility of an ancient modification in the drainage system of the Bear River will be discussed in the next chapter; but such modification, if it occurred, can not have had so late a date as the epoch of the White Marl.

COMPOSITION OF LAKE WATER.

A second explanation is that the conditions of sedimentation and precipitation in the basin were modified after the epoch of the Yellow Clay by a change in the mineral contents of the water of the lake. It is well known that the precipitation of certain substances from solution is favored by the presence of certain other substances, and by yet others is retarded. It is equally well known that the fall of minute suspended particles is similarly accelerated by the presence of various substances; and their fall is probably retarded by other substances. Is there any ground for postulating a change in the mineral contents of the lake which would account for the observed change in the nature of the deposit?

There are three different changes of this sort readily conceived. First, the water having been relatively pure during the deposition of the Yellow Clay, it may have acquired, during the interval of recession, a large amount of mineral matter, so as to be a brine at the time of its second flooding. Second, the water of the first great lake, having been a feeble brine, may have become so concentrated during the epoch of low water as to precipitate its less hygroscopic minerals, with the result that, when the second flood came, a mother liquor was diluted instead of the normal brine. Third, the water of the first great lake, having been a feeble brine, may have been in the interval not merely concentrated but completely evaporated, the desiccation product being mingled with and buried by mechanical sediments, so as not to be redissolved at the time of the second flood. On the first supposition, the White Marl epoch was characterized by a stronger brine than the Yellow Clay epoch. On the second, it was characterized by the minerals pecular to mother liquors. On the third, it was characterized by purer water.

Each of these postulated changes may be supposed to have acted in either of two ways; first, the peculiar properties of the menstruum of the second flood may have caused the precipitation of an exceptionally large proportion of the calcareous matter in the center of the basin, and may have determined the assumption of the crystalline form; second, its properties may have determined the precipitation of argillaceous sediment near the shore, thereby diminishing its importance in the center of the basin and thus increasing the relative percentage of calcareous matter. No attempt has been made to test the first of these assumptions experimentally, for the reason that the natural reactions could not be fairly represented by the necessarily rapid processes of the laboratory. It may be said, also, that the assumption is less accordant with what is known of the distribution of calcareous matter in the basin. From the second point of view a series of experiments was instituted, the investigation being conducted by my assistant, Mr. I. C. Russell.

Experiments.—In the conduct of these experiments no attempt was made to discuss the general problem of the properties of dissolved substances as the precipitants of sediments, but attention was confined to the specific problem presented by the lake sediments. With the exception of distilled water, the only materials used were those which occur in the basin and are concerned with the practical problem. The brine of Great Salt Lake in various stages of dilution was assumed to represent the water of Lake Bonneville, the diluent being in each case the approximately fresh water of some stream now tributary to Great Salt Lake and anciently tributary to Lake Bonneville. The fine sediment employed was a sample of the Yellow Clay. The water of the selected stream was mixed in various proportions with the brine, and equal quantities of the mixtures were arranged in a series of similar vessels, the pure stream water and pure brine constituting the first and last terms of the series. Equal portions of the finely divided clay were then added to each vessel and mingled with the water by shaking or stirring, after which the vessels were allowed to stand for several days and notes were made of the relative rates of precipitation.

The first stream water employed was that of City Creek, the sample being gathered at Salt Lake City. The stream is not large, but its sources lie among rocks typical of the region from which the water supply of the basin is derived. The results were pronounced and apparently unequivocal. The clay fell rapidly in the water of the creek and its deposition was indefinitely delayed[1] in the brine, and the various mixtures gave a graded series of rates of sedimentation. It seemed evident that a relatively fresh condition of the ancient lake would favor the rapid precipitation of mechanical sediment, would thus accumulate it close to the shore, and would leave the calcareous or chemical precipitates in relative preponderance near the center of the basin. The provisional conclusion followed that the epoch of the White Marl was characterized by relatively fresh water, and this was published in a preliminary presentation of the investigation.[2]

It was afterwards learned that the experiments of Ramsey, Brewer, and others had demonstrated the potency of minute traces of certain substances as precipitants of sediment; and it became evident that in order to verify the results of the experiments with the water of City Creek, it would be necessary to employ waters representative of a larger share of the supply of the basin. Samples were accordingly obtained from Utah Lake, the principal source of the Jordan River, and from the Bear River at Evanston. Each of these samples represents about one-third of the supply of Great Salt Lake; and they may fairly be assumed to typify the fresh-water streams of the basin. Each was subjected to a series of experiments similar to those arranged for City Creek water. The sample from Utah Lake yielded identical results. With the sample from Bear River the results were different; it was found that the clay was precipitated with equal rapidity from Bear River water, from the brine of Great Salt Lake, and from all mixtures of the two. It is evident, therefore, that City Creek water is not in this respect a true representative of the entire fresh-water tribute of the basin;

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[1] It is not to be supposed that the sodium chloride and other mineral constituents of the Salt Lake brine *retard* the precipitation of sediments. The experiments show merely that they promote it less than the mineral constituents of the City Creek water. That they actually promote it, was demonstrated by comparative experiments with distilled water. Salt Lake brine and distilled water agree in retaining a residuary milkiness for an indefinite period, but the approximate clearing of the brine is by far the more rapid.

[2] Second Ann. Rept. U. S. Geol. Survey, pp. 177–180

and while the experiments with Bear River water do not negative the theory broached in the preliminary publication, they seriously weaken its support.

It is a curious fact that the City Creek and Utah Lake waters, having similar properties as precipitants, yet differ widely in their mineral constituents; and that the water of Bear River, while behaving very differently as a precipitant, yet closely resembles in constitution that of City Creek. The accompanying table of analyses (Table V.) shows that the water of Utah Lake is characterized by the sulphate of lime, while the waters of City Creek and Bear River are characterized by the carbonate.

TABLE V. *Mineral Contents of Fresh Waters in the Salt Lake Basin.*

I. Water of City Creek, taken at head of Main Street, Salt Lake City, December 3d, 1883.
II. Water of Bear River, taken at Evanston, Wyoming.
III. Water of Utah Lake, taken December, 1883.

[I, analyzed by T. M. Chatard; II and III, by F. W. Clarke.]

	Grams to the litre.			Per cent. of total solids.		
	I.	II.	III.	I.	II.	III.
Calcium	.0589	.0432	.0558	24.19	23.41	18.24
Magnesium	.0174	.0125	.0186	7.15	6.78	6.08
Sodium	.0091	.0082	.0178	3.74	4.44	5.81
Carbonic Acid	.1280	.0982*	.0608*	52.57	53.24*	19.88*
Sulphuric Acid	.0070	.0105	.1306	2.87	5.69	42.68
Chlorine	.0131	.0049	.0124	5.38	2.65	4.04
Alumina	.0010	....	....	0.41	....	....
Silica	.0090	.0070	.0100	3.69	3.79	3.27
	.2435	.1845	.3060	100.00	100.00	100.00

PROBABLE COMBINATION.

Calcium Carbonate	.1400	.1080	.0038	57.49	59.20	1.25
Magnesium Carbonate	.0606	.0438	.0644	24.88	24.01	21.19
Sodium Carbonate	.0014	....	.0204	0.57	....	6.71
Calcium Sulphate	.0099	....	.1849	4.07	....	60.84
Sodium Sulphate	....	.0155	....	....	8.48	....
Sodium Chloride	.0216	.0081	.0204	8.87	4.49	6.71
Alumina	.0010	....	....	0.42	....	....
Silica	.0090	.0070	.0100	3.70	3.82	3.30
	.2435	.1824	.3039	100.00	100.00	100.00

* Estimated by difference.

The postulate that the second flood diluted a brine which by fractional precipitation had acquired the character of a mother liquor, was tested in the following manner: Samples of the brine of Great Salt Lake were evaporated until various portions of the saline contents had been precipitated, and the residuary liquors were then diluted with distilled water and compared with similar dilutions of the Salt Lake brine. It was found that sediment separated with equal rapidity from the brine and the mother liquors; and parallel results were obtained from their corresponding derivatives.

The only one, then, of the alternative hypotheses suggested above which finds any support in the experimental results is the one of which publication has been already made, and the support accorded it is insufficient to inspire confidence. If the water of Bear River instead of City Creek had been first subjected to experiment, the theory would have been at once abandoned. Nevertheless, since it is not controverted by the experiments, and since it has practically no competitor, it is proper that its relation to the general question of lake history be fully set forth.

DEPOSITION BY DESICCATION.

Fully stated, it takes the following form. During the first rise of the lake, or at least during that part of it represented by the visible portion of the Yellow Clay, the saline matter was held in solution in such proportion that the precipitation of mechanical sediment was slow. The clay introduced by the streams and by the undertow remained in suspension a long time, and was therefore widely distributed, covering the whole bottom of the basin. At the close of the Yellow Clay epoch the basin was completely desiccated, the saline matter being gathered in the lowest depression and there precipitated. The rainfall of the basin, however, did not diminish to absolute zero, and occasional floods washed detritus into the depression containing the salt, until the latter was either covered or intermingled with mechanical sediment, and in either case effectually buried. It was never redissolved, and when the increase of the streams caused the basin to be reflooded, the water of the new lake was almost as fresh as the streams. It had the property of throwing down suspended clay with great rapidity, so that the greater part of the mud brought to it by the streams was deposited near the shore, and chemical and organic precipitates acquired relative importance in the center of the basin.

It is proper to add that the process of burial by desiccation, here invoked to account for the disappearance of saline matter, is not hypothetic, except as regards the particular application. It has been fully demonstrated, especially by the investigations of Russell,[1] that it is an actual process, all stages of which are exhibited in the modern history of the small basins of Utah and Nevada. Not only are soluble salts found mingled with the earths of the playas in all proportions, but crystalline layers have been discovered beneath earthy playa deposits; and there are numerous modern lakes of feeble salinity occupying closed basins whose upper slopes are covered by saliferous lacustrine deposits of earlier origin, and whose salts have never been discharged by means of a lake outlet.

It is an essential part of the hypothesis that the lake was evaporated to dryness after the deposition of the Yellow Clay; and the establishment of the hypothesis would demonstrate an element of the curve of oscillation for which there is no other evidence.

ORGANIC REMAINS.

The fossil remains yielded most abundantly by the Bonneville beds are tests of fresh-water univalve mollusks. These are found at all horizons in the lacustrine deposits, and are likewise imbedded in the tufa. They are best preserved in the White Marl, and are especially abundant at the base and the summit of that member. The specimens preserved in the Yellow Clay are fragile, usually crumbling on exposure to the air, and only in rare instances washing out so as to be found entire on the surface. Those at the base of the White Marl are firm, but of light weight and lusterless, as though completely despoiled of their organic matter. Those at the top of the Marl, lying free upon the surface of the desert, are still dense and brilliant, though completely bleached. They evidently belong to the epoch in which the lake was finally shrinking.

The first announcement of these mollusca was by Hayden, who made a small collection in 1870, publishing an account of it in his annual report for that year.[2] An earlier observation was made by Engelmann in 1859, but his report remained unpublished until 1876.[3]

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[1] Geological History of Lake Lahontan, pp. 81–86, 224–230.

[2] U. S. Geol. Survey of Wyoming, 1870, p. 170.

[3] Explorations across the Great Basin of Utah in 1859. Appendix I: Geological Report by Henry Engelmann, p. 313.

The list of species was somewhat increased by the collections afterward made by Howell and the writer, and still further additions have been made by the present Geological Survey. The last and largest collection has been studied by Call.[1] The following list is based chiefly on his determinations.

List of Molluscan Fossils.

Conchifers:
- Anodonta nuttalliana, Lea.
- Sphærium dentatum, Hald.

Aquatic gasteropods.
- Helisoma trivolvis, Say.
- Gyraulus parvus, Say.
- Limnophysa palustris, Müll.
  - sumassi, Baird.
  - bonnevillensis, Call.
  - desidiosa, Say.
- Limnæa stagnalis, Linn.
- Physa gyrina, Say.

Aquatic gasteropods—*Continued.*
- Physa heterostropha, Say.
  - lordi, Baird.
- Amnicola porata, Hald.
  - cincinnatensis, Anth.
- Fluminicola fusca, Hald
- Valvata virens, Tryon.
  - sincera, var. utahensis, Call.
- Pomatiopsis lustrica, Say.

Terrestrial gasteropod.
- Succinea lineata, W. G. B.

This list includes but one extinct form, *Amnicola bonnevillensis.* The genus *Anodonta* is represented only by flaky fragments, but the abundance of *A. nuttalliana* in the existing waters of the Great Basin, and its occurrence in Pleistocene strata in other parts of the Great Basin, render the specific reference highly probable. *Sphærium*, *Gyraulus*, *Limnæa*, *Physa*, *Valvata*, and *Succinea* were found only on the surface of the desert, but their distribution connects them unmistakably with the ancient lake. The Ostracoda are represented by a species of *Cypris*, which has been found at various horizons in the White Marl and Yellow Clay. Its occurrence is sporadic, but in a few localities its valves are so abundant as to constitute the entire mass of certain thin layers. Diatoms abound in certain portions of the White Marl, but have not been found in the Yellow Clay. Only a single occurrence of vegetal matter has been noted; at Lemington, close to the ancient shore, a stratum of the Yellow Clay contains numerous stems and roots of a rush, identified by Dr. George Vasey as belonging to the genus *Scirpus.*

No mammalian remains of any sort have been obtained from the lake beds proper, but the alluvium of the deltas has yielded bones at several

[1] On the Quaternary and Recent Mollusca of the Great Basin, by R. Ellsworth Call: Bull. U. S. Geol. Survey No. 11, 1884.

points. Such as have fallen under the writer's observation are so poorly preserved and so fragmentary as to convey no information with regard to the species or even genera represented. A skull supposed to have been obtained from Bonneville gravels at Salt Lake City, was identified by P. A. Chadbourne as belonging to the Musk ox;[1] but the writer has been unable to satisfy himself as to the precise locality, and the close juxtaposition of Tertiary, Pleistocene, and recent strata makes the reference to the Pleistocene doubtful. King reports the discovery in post-Bonneville gravels of *Bison latifrons* and bones of reindeer (?);[2] and elephantine bones and ivory were taken from a post-Bonneville marsh at Springville, near the eastern shore of Utah Lake.

The meagerness of this record is somewhat remarkable when we consider that the Bonneville beds constitute the surface of the country throughout nearly the extent of the old lake bottom, and that they have been traversed in all directions by persons interested in the discovery of fossils and accustomed to searching for them. It is evident that the conditions under which the lake beds proper were deposited were not favorable for the preservation of vertebrates or plants or naiads. We can not believe that such organisms failed to be received by the lake. The animals which deposited their bones in the deltas must occasionally have been washed into deeper water. Driftwood must have found its way to the lake bottom, and fishes and Anodons, which abound in all the rivers and larger creeks of the basin, must have inhabited the old lake while it was fresh. The fact that they are not preserved illustrates the fallibility of negative evidence in paleontology.

JOINT STRUCTURE.

The lower course of the Old River Bed is trenched through beds of White Marl and Yellow Clay, descending northward with the gentle slope of their deposition. A few rods back from its edge lies the unfurrowed plain, but the immediate wall is sculptured by short gullies alternating with crested ridges of "bad-land" type. From a commanding peak it was observed that the trends of the gullies and their branches exhibit parallelism, and the

[1] Am. Naturalist, vol. 5, p. 315. (Cited from Salt Lake Tribune, May 16, 1871.)
[2] Geol. Expl. Fortieth Parallel, vol. 1, p. 494.

cause of this was sought and found by Mr. Russell. They are controlled by a compound and extensive system of joints.

The principal series trend almost precisely north and south, and a subordinate series east and west. They all are vertical and straight, and (within each series) closely parallel. They are readily traced from top to bottom of the walls of the lateral ravines, and not infrequently a wall exhibits a broad, flat, sheer face, caused by the removal of the clay from one side of a plane of jointing. Elsewhere the faces of the bluffs are buttressed by square pilasters, or ornamented by outstanding rectangular columns, the forms of which have been determined by the two systems of joints. The main arroyos leading up from the river bed are controlled by the main system of joints, but at a short distance back from the bluff there is a tributary drainage at right angles to the primary, and controlled by the cross joints. The edge of the desert plain is thus marked out in a series of rudely rectangular blocks, which may be regarded as the incipient stages of the pilasters of the bluff.

The lamination of the clays and marls in which the joints occur is traceable across them, showing that there have been no faults upon their planes; and the absence of faults is also attested by the perfect continuity of the even surface of the plain at a little distance from the river bed.

Mr. Russell's observations showed that the joints are not restricted to the spot where they were first detected, but are discernible generally along the margin of the river bed. It is impossible to trace them upon the adjacent plain, but there can be little doubt that they extend beneath it. The surface is converted by every shower into a plastic mud, and in that condition is welded into continuity, obliterating all trace of structure. For aught that is known to the contrary, they may exist in the lake beds beneath the surface of the entire desert.

Through the pages of the American Journal of Science,[1] I called the attention of geologists to these joints, pointing out that they were not explicable on any existing theory for the origin of such structures. They are not faults. Their parallelism shows they are not shrinkage cracks. Traversing Pleistocene beds that lie unindurated and undisturbed in the attitude of

[1] Am. Jour. Sci., 3d series, vol. 23, 1882, pp. 25–27; vol. 24, 1882, pp. 50–53.

deposition, they can not have resulted from horizontal pressure and compression. I had no explanation to offer, but my inquiry led to the publication of one so accordant with the phenomena that it at once takes rank as the working hypothesis for the origin of all parallel jointing except slaty cleavage. It was offered independently by Crosby[1] and Walling,[2] and the force appealed to is the earthquake. During the passage of an earthquake wave the earth material traversed is subjected to momentary strains of compression and tension in the direction of wave transmission, and to shearing strains, instantly reversed, in a direction normal to that of wave transmission. At each instant the similar elements of the wave constitute a surface approximately spherical or ellipsoidal, with the locus of wave origin at its center, and at any locality remote from the locus of origin such surface is sensibly a vertical plane. Assuming the competence of the strains to create a rock structure, their directions and arrangement show that the structure should ordinarily exhibit vertical parallel planes.

Under this theory the two series of joints at the Old River Bed indicate two earthquake directions and at least two efficient earthquakes. As the joints extend as simple regular planes to the very margin of the old channel, and as they determine the directions of arroyos initiated immediately after the excavation of the channel, it is probable that they were formed while the lake sediments were yet continuous and unchanneled. We are thus told of earthquakes occurring just before the retreat of the lake laid bare the White Marl.

That the Bonneville Basin was subject in Bonneville and post-Bonneville time to numerous earthquakes of the type of the great Californian earthquake of 1872, is abundantly shown by the phenomena of fault scarps described in Chapter VIII; and the distribution of the fault scarps, so far as it is known, accords well with the strike of the principal system of joints.

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[1] On the classification and origin of joint-structure. By W. O. Crosby. Proc. Boston Soc. Nat. Hist. vol. 22, 1882, pp. 72–85.

[2] On the origin of joint cracks. By H. F. Walling. Am. Ass. Adv. Sci. vol. 31, Montreal meeting, 1882, p. 417.

CHAPTER VI.

THE HISTORY OF THE BONNEVILLE BASIN.

THE PRE-BONNEVILLE HISTORY.

The latest Tertiary series outcropping within the Bonneville basin has a distribution quite independent of the basin. Not only do its strata occur in the mountains above the shore-lines, but they override some of the passes on the rim of the hydrographic basin and extend continuously to the drainage of the Snake River, and possibly to that of the Humboldt. On the other hand, the Neocene strata have not been found in the southern third of the Bonneville area. It is probable, therefore, that the hydrography of the Neocene and that of the Pleistocene corresponded to configurations of the surface essentially different. The Bonneville Basin was not in existence during the period when the Neocene sediments were deposited; its history began at some later date, after the deformation of the earth's crust which elevated the Neocene strata upon the mountain flanks had wrought important changes in the face of the land.

The area formerly covered by the main body of Lake Bonneville is now a plain, conspicuous for its flatness. Great Salt Lake, resting on its surface, has a mean depth of but fifteen feet; and a rise of a few feet only, as pointed out by Stansbury, would extend it westward over the greater portion of what is known as the Great Salt Lake Desert. The occurrence of such a plain at an elevation of 4000 feet above the sea, and in the midst of a region characterized by mountains, admits of but one explanation, namely, lacustrine sedimentation. The narrow ridges that in places interrupt the continuity of the plain show that the district did not escape the general process of orogenic corrugation to which the Great Basin was subjected, and there seems no reason to believe that the displacements were here less profound than elsewhere. Certainly the degradation of the summits has been sufficient to lay bare in places Cambrian and even Archean rocks. Moreover, the habit of these ridges is peculiar, and itself indicates burial. The normal mountain ridge of the Great Basin is acutely serrate along its crest, and displays naked rock, deeply carved into gorges and amphitheaters down to a certain line. Below that line the slopes are gentler, the contours are smooth, and the material is alluvial, the waste from the sculpture above. The gorges above and the alluvial cones below are to a certain extent correlative, but the mass of the latter is derived from the general degradation of the mountain summit as well as the excavation of the canyons. The mountains and buttes of the Salt Lake Desert conform to the Great Basin type in the characters of their summits, but are almost devoid of alluvial cones. They spring from the plain so abruptly that the frontiersman as well as the geologist has recognized them as incomplete, or rather, as partially submerged, and has named them accordingly. One of them is known as Newfoundland, another as Silver Islet, a third, which towers 3,000 feet above its base, as Granite Rock; and generically they are spoken of as "lost mountains". How deep beneath the lacustrine plain their bases lie, it is impossible to say, but 2,000 feet is certainly a moderate estimate.

Not all of this lacustrine filling can be ascribed to the Pleistocene, and not all of it belongs to the history of the Bonneville Basin as such. The Neocene lake, and possibly earlier lakes, have contributed a share, and this before the hydrographic basin of Lake Bonneville was established. Since the establishment of the basin, sedimentation has been practically continuous in its lowest depression. If we conceive the local climate to have undergone a rhythmic series of changes, the area of lacustrine sedimentation has alternately expanded and contracted, and has always included the lowest depression; and even with a climate so dry as to maintain no perennial lake, the temporary floods occasioned by exceptional storms must still have continued the process of accumulation. The situation of the lowest depression may have varied from time to time, as local displacements of the earth's crust modified the configuration, but wherever it was, it was the scene of sedimentation, and the constant tendency of the lacustrine process was to fill the minor depressions and reduce the floor of the basin to a level surface. The evenness of the desert plain testifies to its lacustrine origin.

The process of filling might have been modified, but would not have been interrupted, by an overflow of the water of the basin such as occurred in the Bonneville epoch. As long as the basin was not drained to its lowest depths, those depths would continue to receive detrital deposits, and the outflowing water would carry with it only the soluble products of the degradation of the surface of the basin. Whether such an overflow ever took place is not apparent; but if it did, we may be sure that its date was remote as compared to the Bonneville epoch. The lower passes of the basin's rim show no traces of an ancient channel, and the time necessary for the effacement of such traces must be reckoned as long in comparison to the antiquity of the Bonneville shore-lines. Upon most of the passes the process would include the growth of great alluvial fans; and at Red Rock Pass, where the Bonneville discharge took place, the record of an earlier discharge could have been obliterated only by the restoration of the Marsh Creek alluvial fan, and its extension so as to fill the channel of outflow for many miles in Marsh Creek Valley. When we consider that no stream so small as Marsh Creek is known to have built a delta on either the Bonneville or the Provo shore, it becomes evident that such obliteration implies a period vastly longer than that consumed by the Bonneville oscillations. As far back, then, as we may hope to obtain a consecutive view of the history of the basin, its waters had no period of discharge save that of the Bonneville epoch. It was a closed basin, and the area of its lake surface was determined by the relation between its water supply and the rate of evaporation. The lake area was, therefore, a function of climate, provided the extent of the hydrographic basin remained unchanged. To avoid any possible misinterpretation of the climatic history it is important that the possibility of variation in the hydrographic basin receive full attention.

The general altitude of the country to the east of the basin is several thousand feet greater than that to the west, north and south, and at least 95 per cent. of all the water flowing into the modern lakes is furnished by the eastern highlands. These include the Wasatch Mountains, a portion of the

High Plateaus lying to the south, a portion of the Uinta Mountains lying to the east, and a mountainous tract lying to the northeast in western Wyoming and southeastern Idaho. The low country to the west of the basin is divided by mountain ranges into numerous independent drainage districts, and these have not been so thoroughly studied as to determine what would be their hydrographic combinations in the event of a more generous rainfall. We know, however, that they contribute nothing now to the water supply of the basin, and that in Bonneville times their tribute was small; and we are thus assured that in pre-Bonneville times the supply from that side was not less than at present. It will be shown hereafter that the possibility of a greater contribution from this region does not materially affect the conclusions in regard to climate. The same remarks apply to the region south of the Escalante Desert. North of the Bonneville Basin the configuration of the country about the water parting does not suggest any possible change in its position during the period under consideration.

The water supply from the east reaches the lower portions of the basin by four rivers: the Sevier, the Jordan, the Weber, and the Bear; and its drainage system is correspondingly divided into four parts. The Sevier River rises in what Dutton has called the High Plateaus, and is separated by high divides from the drainage of the Fremont, the Escalante, the Paria, and the Virgen, branches of the Colorado of the West. The Paunsagunt and the Markagunt plateaus, which constitute the most southerly elements of its drainage, are slowly diminishing in area through the sapping and recession of cliffs, and the hydrographic basins of the Paria and Virgen are thus growing at the expense of the Sevier. A less considerable change of the opposite tendency is in progress at the head of Moraine Valley, where a plateau draining to the Fremont River is encroached on by the recession of cliffs draining to the Sevier. The effect of these slow changes upon the water supply of the Bonneville Basin can not have been important, and there is no evidence that any considerable tracts have bodily transferred their allegiance.

The Jordan includes among its branches the American Fork, the Provo, the Spanish Fork, and Salt Creek.

It is quite possible that Salt Creek has changed its course within the basin, and that it was at one time connected with the Sevier and not permanently with the Jordan, but such a change is of no moment in this connection. American Fork and Spanish Fork head against high divides, whose position must have been permanent for a long period. The same remark applies to the Provo River, but there is one point in its course where its channel is not contained by solid rock and its water could easily be diverted. Kamas Prairie is a small valley lying athwart the western end of the Uinta Range. The Provo River crosses the southern end of the valley, entering by one canyon and leaving by another; and the Weber River in like manner crosses its northern end. The configuration of the plain shows that the streams have not always been separate; at one time the Provo turned northward in the valley and was tributary to the Weber. Here, however, as in the case of Salt Creek, the modifications of the drainage do not affect the water supply of the Bonneville Basin.

The drainage district of the Weber is so nearly embraced at the east by the basins of the Bear and the Jordan, that the only portion of its boundary coincident with that of the Bonneville drainage district is a high crest in the Uinta Mountains two or three miles in length. Variations in its course and drainage area are therefore unimportant to the present discussion; and the same remark applies to the American Fork and to the series of creeks issuing from the west face of the Wasatch Mountains.

The Bear is the most important of all the rivers, and has many tributaries. Its main branch heads in the Uinta Mountains, and, so far as may be judged from the maps of the Fortieth Parallel Survey, is surrounded by high divides, affording little opportunity for transmutations of drainage. Smith Fork and Thomas Fork, which join it in midcourse, occupy basins contiguous to those of Salt River and John Day River, tributaries to the Snake. These basins have been mapped by the Geological Survey of the Territories, and the testimony of the contours is sustained by that of Mr. Henry Gannett, who performed the topographic work and who states that the conformation indicates permanence of drainage. In its lower course (in Cache Valley) the river receives a large number of tributaries, but none of their drainage districts extend to the rim of the Bonneville Basin. The sources of the river appear thus to offer no suggestion of an ancient variation of the drainage area; but there is one point in its course of which the same can not be said. After receiving the waters of Smith Fork and Thomas Fork, and before entering Cache Valley, the river swings far to the north, approaching very near to the rim of the Bonneville Basin. At Soda Springs it is separated from the south fork of the Blackfoot River, a branch of the Snake, by a divide rising four or five hundred feet above the Bear, but only slightly elevated above the Blackfoot. A few miles lower down it crosses the southern end of a broad open valley (Basalt Valley), the northern end of which is traversed by the Portneuf River, likewise a branch of the Snake. The Portneuf is here the lower stream, and the water parting between the two rivers runs close to the course of the Bear. It is probably not more than one or two hundred feet above the bed of the Bear. In the Soda Springs pass, the summit is formed by basalt, lying in horizontal sheets and associated with cinder cones and other evidence of recent eruption. The principal masses are probably more ancient than the Bonneville epoch, but they have not suffered those dislocations which are apt to be observed in this region in the case of rocks dating far back in the Tertiary. It is believed by Mr. Gannett and by Mr. Gilbert Thompson that their eruption has affected the drainage system of the region in ways that are yet discernible, and it is possible that they have wrought a separation of the Blackfoot and the Bear. If the two streams were anciently united, it is most probable that the Blackfoot was tributary to the Bear; but the reverse is possible.

At the Basalt Valley pass the phenomena are essentially the same. The broad valley extending from the channel of the Bear to that of the Portneuf is covered throughout by basaltic lava, and portions of this lava are so recent that associated scoriaceous craters are still preserved. Before the epoch of eruption, the Bear and Portneuf Rivers may have been joined, and their united water may have flowed either to the Snake River or to the Bonneville Basin.

If the south fork of the Blackfoot were now to be diverted to the valley of the Bear River, as, according to Mr. Thompson, it readily might be, the Salt Lake drainage basin would be increased by 350 square miles of upland. If the canyon of the Portneuf below Basalt Valley were dammed, so as to turn its water toward Bear River, 500 square miles would be added to the basin. If another eruption were to dam Bear River above Gentile Valley and divert it to the valley of the Portneuf, the Bonneville Basin would lose about one-fourth of its water supply. All speculation in regard to the pre-Bonneville climate of the basin is therefore subject to the possibility that the catchment basin may on the one hand have been slightly greater or may on the other have been very materially less.

ALLUVIAL CONES AND ARIDITY.

The principal evidence bearing on the pre-Bonneville history of the basin is embodied in the alluvial cones. These extend nearly to the bottom of the basin, and since they could not have been shaped in the presence of a large lake, it is concluded that the epoch of their formation was an epoch of low water. The dependent conclusion that the pre-Bonneville epoch was characterized by aridity is of such importance that a little space will be devoted to the amplification of these propositions.

The drainage of a mountain mass, starting in innumerable rills, gathers into a smaller number of rivulets, and is finally aggregated into a very few main streams before issuing from its self-carved gorges. The outward borne detritus is therefore delivered to the adjacent valley at a limited number of points separated by interspaces. Each point of issue becomes the apex of a sloping mass of alluvium whose surface inclines equably in all directions. A series of such alluvial cones is usually to be found along the base of each mountain range, constituting a foot slope, the contours of which are scalloped. The topographic configuration which thus arises is peculiar and not liable to be confounded with any other.

It has already been stated that the alluvial bases of the insular mountains of the Bonneville Basin are buried by lacustrine sediments. Those of the peripheral mountains are not so buried, or at least are not so deeply buried, and the forms of their cones can at many localities be traced downward to the lower levels of the basin. The shore-lines are locally marked upon the cones, cliffs and terraces being excavated from them and embankments built against them; but where the cones are large, these modifications are relatively small and do not materially impair the general configuration. Good illustrations are to be found in Preuss Valley, in White Valley, at the eastern base of the Deep Creek and Gosiute Mountains, and on both sides of Pilot Creek. There are fine examples also in Tooele Valley, Skull Valley and Blue Creek Valley.

The phenomena of the Bonneville shores illustrate the fact that the building of alluvial cones is arrested by lacustrine conditions. Either the stream constructs a delta, which is an alluvial fan above the water but terminates in a submerged cliff at the water edge; or else, the stream being small, its load of detritus is absorbed by the shore drift. In the latter case, some point of the alluvial cone is usually trenched on by the waves, a cliff and terrace being produced; and whenever the stream, which had previously shifted its course over the whole surface of the cone, assumes a direction leading to this cliff, it is enabled by the lowering of its base level to excavate a more permanent channel, from which it does not quickly escape.

It is therefore legitimate to regard the formation of alluvial cones as a strictly subaerial process, and to conclude that the Bonneville Basin contained no large lake during the pre-Bonneville period when its alluvial cones were formed.

I do not overlook the possibility that traces of an epoch when the waves held sway may have been obliterated by the alluviation of a later epoch, but in my judgment such considerations do not impair the general conclusion. Within the masses of the alluvial cones there may be buried shore cliffs, shore embankments, and lacustrine sediments, but the time necessary for the obliteration in this manner of a record similar to that of the Bonneville lake is as long as the time necessary for the obliteration of a channel of outflow, and is certainly very long as compared to the duration of the Bonneville epoch.

Let us call this relatively long epoch antecedent to the Bonneville, the pre-Bonneville epoch. We have found reason to believe, first, that the basin had then no outlet, and, second, that the basin did not then contain a large lake. The size of an inclosed lake being determined by the ratio of water supply to rate of evaporation, it follows that that ratio was small. If the hydrographic area remained unchanged, the water supply as well as the rate of evaporation depended upon climate, and the climate must have been arid. If the main branch of Bear River was then tributary to the Portneuf Basin instead of the Bonneville, a greater climatic change would have been necessary to flood the basin, and the indicated aridity of climate is correspondingly less.

THE POST-BONNEVILLE HISTORY.

The closing event of the Bonneville history was the desiccation of the basin. A few stages in the retirement of the water are recorded by the Stansbury and lower shore-lines, but very little information is obtainable in regard to the oscillations which may have interrupted the retirement, for the reason that no natural sections of the deposits exist. If oscillations took place they must have wrought the superposition of littoral and subaqueous deposits, but the record of such superposition can be read only when new general conditions shall have exposed the lower reaches of the basin to stream erosion.

SUBDIVISION OF THE BASIN.

One effect of the desiccation was the subdivision of the Bonneville Basin. Not merely was the Sevier Desert set off from the basin of Great Salt Lake, but a number of smaller basins became equally distinct. The list of independent drainage districts includes at the present time the Escalante Desert, the Sevier Desert, Preuss Valley, White Valley, Snake Valley from the Salt Marsh southward, Rush Valley, Cedar Valley, the upper portion of Pocatello Valley, the Pilot Peak basin, and the basin of Great Salt Lake. It is possible that Snake Valley contains two drainage basins instead of one, and there is some reason also to suppose that the broad expanse of the Great Salt Lake Desert west of the Cedar Range is a distinct basin. The mutual relations and the relative size of these basins are shown in Pl. XII.

Three of them contain, or are known to have contained, perennial lakes; the others have playas in their lowest depressions, where water gathers after every storm but does not persist throughout the year. On the Great Salt Lake Desert the earth constituting the playa is exceedingly fine and affords in dry weather a hard surface of a pale yellow color. In places, and especially toward the margins of the area, it is less compact, and is superficially covered with saline efflorescence. A little rain renders the surface soft and adhesive, and the depth to which this change may extend seems limited only by the supply of moisture. The same description applies to Preuss Valley, White Valley, and the Escalante Desert, except that the playas of the last two are less compact. The Pilot Peak Basin lies southeast of that mountain, and is separated from the Great Salt Lake Desert by the range known as the Desert Hills. The surface of its playa was found by Stansbury to be covered by one or two inches of salt. In the southeastern angle of the Sevier Desert there is a tract partially partitioned from the general plain by a series of coulées of basaltic lava, extravasated during the Bonneville epoch. This contains several playas, marking localities where the drainage is checked but not completely imprisoned. The highest and most southerly of these differs from all the others in that its material is gypsum. It is probable that the deposit is independent of any special chemical reaction, and is due simply to the discharge by evaporation of a mineral dissolved from the rocks. The streams whose waters occasionally flood the playa rise among strata of Jurassic and Triassic age, and such strata in a neighboring mountain range are known to be highly gypsiferous. The heads of the streams were not examined. It was ascertained by digging in the playa that a portion of the deposit is amorphous and another portion crystalline. One phase of the precipitation results in the formation of small free crystals, which the wind sweeps from the surface of the playa and gathers in dunes. The dunes do not travel to a great distance, but are arrested by a low rhyolitic butte near by, to which they have given the name of White Mountain. Perhaps no gypsum deposit in the world is so easily exploited as this; it needs merely to be shoveled into wagons and hauled away. Mr. Russell estimates that the dunes contain about 450,000 tons, and a much larger amount can be obtained from the playa. The depth of the playa deposit was not ascertained, but its area is indicated on Pl. XXXV.

SNAKE VALLEY SALT MARSH.

The lowest depression in the Snake Valley Basin contains what is locally known as a salt marsh; but the term as here used denotes something very different from the salt marsh of the seashore. There is no vegetation, but simply a shallow lake, which nearly or quite disappears in summer. In winter it has a depth of about two feet, being then limpid and resting on a bed of soft mud. Near the lake are perennial fresh springs which replenish the water lost by evaporation. In winter, when evaporation is slow, the volume of the lake increases, and salts previously precipitated are redissolved. In summer a more rapid evaporation diminishes the volume, precipitating sodium chloride and sodium sulphate and reducing the brine to a mother liquor. The precipitate has a depth of about 1½ inches, and a portion of it is each year removed, to be employed as a reagent in the reduction of silver ore. This removal has not been found to affect materially the strength of the brine, which is in some way resupplied with salt.[1] It is believed by Mr. W. C. Barry, one of the owners of the marsh, that the supply is brought by percolating water from the saliferous mud beneath the lake, and this theory of its origin finds support in the phenomena of a series of salt marshes in Nevada examined by Mr. Russell.

SEVIER LAKE.

The lowest depression of the Sevier Desert has probably been occupied by a lake from the date of the earliest exploration nearly to the present time, but precise information in regard to it dates from 1872. Escalante in 1776 crossed the Sevier river sixty or seventy miles from the lake, and learned by report of its existence. Fremont did the same in 1845. In 1853 Gunnison was killed by Indians within a few miles of the lake while on his way to explore it.[2] Beckwith and Simpson, who conducted explorations in contiguous portions of the Great Basin in 1853 and 1859, were aware of its existence, but saw it only from a distance.[3] In 1869 Wheeler, approaching from the west, visited the south end of the lake and determined its true position. He was unaware of its identity, however, and, following an error prevalent at that time, called it Preuss Lake.[4] It was reserved for

[1] The statements regarding this marsh are chiefly based on observations made in the winter of 1879–'80.

[2] Report by Lieut. E. G. Beckwith, upon the route near the 38th and 39th parallels, explored by Capt. J. W. Gunnison: Pacific Railroad Explorations, vol. 2, pp. 72–74.

[3] Capt. J. H. Simpson, Explorations across the Great Basin, etc., p. 125; Lieut. E. G. Beckwith, Ibid., pp. 72, 76.

[4] See pages 3 and 4 of the Preliminary Report of the General Features of the Military Reconnaisance through Southern Nevada [1869] under Lieut. George M. Wheeler. 8°. [No imprint nor date, but probably San Francisco, 1870.] This report was reprinted in quarto form with some changes in 1875. The map prepared to accompany it marks "Preuss Lake" in the geographic position of Sevier Lake. The edition of the U. S. Engineer map of the Western Territories dated 1868 gives Sevier and Preuss as separate lakes, and most privately published maps follow it, but a map of Colton's dated 1864 gives Sevier Lake only, running into it the river with which imagination had furnished Preuss Lake.

Lieut. R. L. Hoxie, having charge in 1872 of one of the field parties of the Wheeler Survey, to demonstrate the full hydrography of the lake, determining its form and extent and its relation to the tributary stream. The map prepared by his topographer, Mr. Louis Nell, is copied in all modern compilations. The writer had the pleasure to accompany Lieut. Hoxie, and has since revisited the locality. In 1872 the lake was about 28 miles in length and had a water surface of 188 square miles. It has since been ascertained that its maximum depth was about 15 feet, the northern portion being deeper than the southern. Its only affluent was the Sevier River, which entered at the north. Its brine contained 8.64 per cent of saline matter, consisting chiefly of sodium chloride and sodium sulphate.

Salt Bed.—In January, 1880, the bed of the lake was nearly dry, and was explored by Mr. Willard D. Johnson, who was able to travel on foot across a bed of salt where the water had before been deepest. In places this bed was covered by a thin sheet of bitter water, but elsewhere its surface was dry. It was reported by persons resident in the vicinity that in the fall of the year the entire area had been dry, and that this condition had been attained by the lake basin during one or two preceding seasons. On the 20th of August, the same year, Mr. Russell and I visited the locality, but the condition of the crust of salt did not permit us to cross it. It had probably, in the interval, been partially or wholly redissolved and redeposited; and its new state of aggregation was less compact.

Mr. Johnson cut through the salt layer at several points, finding a general thickness of four or five inches; and he collected samples near the center of the area. Another series of samples was collected by Mr. Russell at the margin of the area; and at each point the underlying sediments were explored to a depth of a few feet. The following are the recorded sections:

Section at center of Sevier Lake salt bed, January, 1880.

1. (Top). Sodium sulphate, 2 inches.
2. Sodium sulphate with some sodium chloride; coherent to No. 1: 1 inch.
3. Sodium sulphate, tinged with pink, 2 inches.
4. Gray clay containing woody fibre, 2 inches.
5. Fine sand containing fresh water shells, 6 inches.
6. Gray clay.

Section at margin of Sevier Lake salt bed, August 20, 1880.

1. (Top). Sodium chloride, forming a coherent crust: ½ inch.
2. Sodium chloride, with sodium sulphate and magnesium sulphate; free crystals mingled with water: 1¼ inches.
3. Sodium sulphate, with sodium chloride; a crust of coherent crystals: ½ inch.
4. Sodium chloride, with magnesium sulphate; incoherent crystals mingled with water: 1¼ inches.
5. Sodium chloride, with sodium sulphate, chemically identical with No. 2 but fine-grained and with the consistence of an ooze; color white above with occasional passages of pink, green beneath: ½ inch.
6. Dark gray mud: 2 feet.

The subjoined table of analyses exhibits in detail the constitution of the saline deposits in each section, and the composition of the original brine is added for comparison. The conspicuous fact is that the sodium sulphate is concentrated in the middle of the basin, while the sodium chloride is chiefly deposited at the margin. The sulphates of magnesium and potassium likewise occur exclusively at the margin. It is noteworthy also that magnesium is reported in larger proportion in the brine of the lake than in any layer of the desiccation products at either point of determination. The magnesium chloride reported in the brine implies three per cent. of magnesium. The magnesium sulphate in the richest layer of the desiccation product implies only 1.7 per cent. of magnesium.

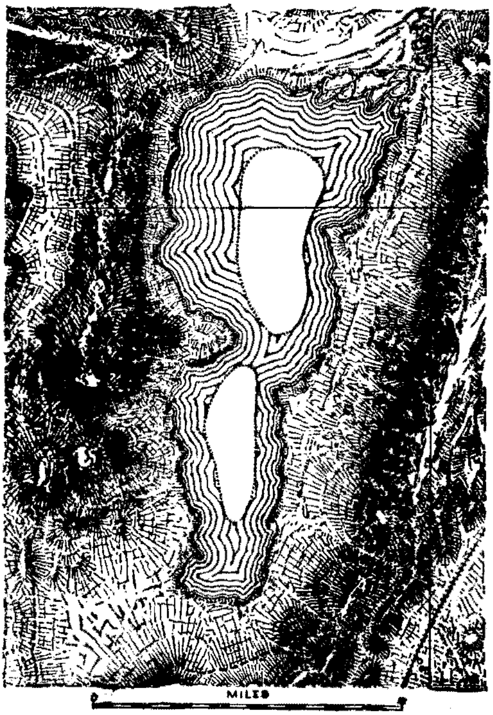


FIG. 31.—Sevier Lake in 1872 (Nell). The white areas with dotted boundaries show salt beds in 1880 (Johnson).

The brine of the lake was analyzed by Dr. Oscar Loew; the desiccation products from the center of the area by Prof. S. A. Lattimore; those from the margin by Prof. O. D. Allen. The brine contained 8.64 per cent. of saline matter; the constituents are here reported in percentages of total solid matter. The constituents of the desiccation products are likewise reported in percentages. The figures for the total deposit are obtained by combining those of the separate layers, making allowance for relative thickness.

A few weeks after our observation of the salt bed, Mr. Russell and I separately visited the southern portion of the lake bottom, where the water had been comparatively shallow. Near the old shore, and especially at the extreme southern end, the bottom had the ordinary playa character, a fine earth, highly charged with salt, for the most part firmly compacted, but in places softened by efflorescence. Farther from shore a thin crust of salt rested on a saline mud, and at the outermost point reached by Mr. Russell the superficial salt deposit had a thickness of 1½ inches, consisting chiefly of a moist, incoherent aggregation of crystals. Beneath this were greenish mud and sand.

TABLE VI. *Analyses of Sevier Lake Desiccation Products and Brine.*

Constituents.	Desiccation Products at Center.				Desiccation Products at Margin.						Solid contents of Brine.
	Upper layer.	Second layer.	Third layer.	Total.	Upper layer.	Second layer.	Third layer.	Fourth layer.	Fifth layer.	Total.	
Sodium Sulphate	87.65	71.23	89.10	84.6	4.78	5.51	83.79	2.71	5.04	14.3	15.5
Sodium Carbonate	1.08	......	......	.4	......	......	......	......	......	......	......
Sodium Chloride	2.34	23.85	2.65	7.0	91.39	79.86	13.84	88.49	80.62	75.8	72.1
Calcium Sulphate	trace	trace	......	......	trace	......	trace	......	.39	......	.5
Magnesium Sulphate	trace	trace	......	......	1.83	7.83	1.33	5.29	8.32	5.5	......
Magnesium Chloride	......	......	......	......	......	......	......	......	......	......	11.9
Potassium Sulphate	......	......	......	......	trace	.34	.26	.11	4.03	.7	......
Lithium	......	......	......	......	......	......	......	......	trace	......	......
Boric Acid	......	......	......	......	......	......	......	......	trace	......	......
Water	8.90	4.90	8.20	8.0	2.00	6.46	.78	3.40	.92	3.6	......
Insoluble	trace	trace	trace	......	......	......	......	......	.68	.1	......
Total	99.97	99.08	99.95	100.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00

The desiccation of this lake is to be ascribed to human agency. The water of its sole tributary flows for nearly 200 miles through valleys containing more or less arable land, and has gradually been monopolized by the agriculturist for the purpose of irrigation. The supply is however not completely cut off. It is reported that during the spring freshets, caused by the melting of the snow on the plateaus and mountains, the lake bottom receives considerable inflow, and that the desiccated condition obtains during only a portion of the year.

The principal salt deposit was estimated to extend eight miles north and south and to have an extreme width of about five miles. The accompanying sketch shows the form and area of the lake in 1872 and the approximate extent and position of the salt beds in 1880.

RUSH LAKE.

The lowest depression of Rush Valley contains a pond or lakelet which has been observed to undergo considerable fluctuation. It will be recalled that Rush Valley in pre-Bonneville time drained freely to Tooele Valley and that this drainage was cut off by an embankment built by the Bonneville waves. The lake occupies a portion of the old drainage channel close to the embankment. It is partially delineated in the map on Pl. XX. The earliest record of it appears on Stansbury's map (1850),[1] but it is not mentioned in his text. It is there assigned a length of about 1¼ miles, but there is circumstantial evidence that no measurement was made. In 1855 it was included in a military reservation laid out by Lieut. Col. E. J. Steptoe for the purpose of securing to the military post at Camp Floyd the meadow and pasturage about the lake shore. The map made for the purpose of defining the reservation, assigned to the lake a length of 2⅝ miles, and indicated that the water was shallow and marshy. The land surveys in the valley in 1856 did not include the military reservation, but showed the existence upon it of a lake. According to Gen. P. E. Connor, who succeeded Col. Steptoe in 1862, there was then only a small pond, the remainder of the lake bed being occupied by meadow land. In 1865 the water began to increase, the greatest height being attained in 1876 or 1877, since which time it has subsided. The rise of the water submerged the meadow land and rendered the reservation useless for its original purpose. It was therefore officially relinquished by the War Department in 1869.

In 1872, the water being near its highest stage, the lake was surveyed in connection with the surrounding country by one of the parties of the Wheeler Survey, and the length was determined to be 4¼ miles.

In 1880, when the lake was visited by the writer, it was said by residents to have shrunken to half its maximum size. The position of the highest

[1] Expl. and Surv. Valley of the Great Salt Lake of Utah. By Howard Stansbury, Capt. Corps Topog. Eng., U. S. A. Philadelphia, 1852.

shore-line was not pointed out, but it is believed to be represented at the north end by a fresh looking beach, not yet covered by vegetation. This beach had a height above the water surface of 10 feet. The greatest depth of the water was ascertained to be 5½ feet.

At no time does the lake appear to have been strongly saline. During its highest stage it was so fresh as to serve not only for the watering of stock but for domestic use; and in 1880 it was far from being undrinkable, though too brackish to be palatable. Its mineral contents, judged by the taste, did not exceed one-half of one per cent. This freshness stands in strong contrast to the salinity of the Snake Valley salt marsh and Sevier Lake, yet the conditions are in most respects nearly identical. Each of the three lakes is the evaporating pan for a closed basin; and each basin includes a valley plain sheeted with Bonneville sediments, everywhere more or less saliferous. The salinity of Sevier Lake and the salt marsh is thus easily accounted for, and only the freshness of Rush Lake is problematic. I conceive that the true explanation lies in the hypothesis of burial by desiccation, already advanced to account for an element of the Bonneville history. At some period, or at several different periods, the lake has evaporated to dryness; and its saline matter being thus precipitated has become buried beneath mechanical sediment. The last period of this kind was so recent that the subsequent accumulation of saline matter has not given a briny character to the water.

If this hypothesis is true, then Sevier Lake, having by the settlement of the Sevier Valley been changed from a perennial lake to an occasional lake or playa lake, should in the course of time lose its saline character. Every freshet of the Sevier River which carries mechanical sediment to the lake but does not pour into it a sufficient body of water to redissolve the precipitated salt, must mingle with that salt a certain amount of silt, and the continuance of the process will have the effect of obstructing and finally of preventing the access of the water to the salt. The lake bottom will then be reduced to the condition of an ordinary playa, and should some political or industrial revolution afterward stop the work of irrigation in the valley of the Sevier and permit the lake to be restored, the water of the lake will at first be fresh.

GREAT SALT LAKE.

The present investigation has added little to our knowledge of Great Salt Lake. It was part of the original plan to give to it a somewhat elaborate study, ascertaining the distribution of high and low salinity within its area, the nature of the deposits formed in various parts of its bed, and the economic properties of its brine. It was proposed also to make a thorough survey of its bottom, so as to ascertain the presence or absence of submerged shore-lines and playas. These inquiries, having been deferred until the end of the Bonneville investigation proper, were necessarily abandoned when it was decided to bring that work to an immediate close. Fortunately, the lake received careful attention at the hands of earlier expeditions and surveys, and its history is already as well known as that of any other inland lake, with the possible exception of the Dead Sea and the Caspian.

Surveys.—It was surveyed and mapped by Stansbury in the years 1849 and 1850. It was again mapped by the Fortieth Parallel Survey in 1868, and the data for a third map have since been gathered by the Survey West of the 100th Meridian. In connection with the first and second of these surveys analyses were made of the brine, and the first and third ran numerous lines of sounding. Additional data of value were gathered by Fremont in 1843 and by various parties of the Wheeler, Hayden, and Powell surveys. As a member of the Powell Survey, the writer made a study of the recent oscillations of the lake; and a system of records by means of gauges, instituted at that time, has been continued by the U. S. Geological Survey.

Depth.—The most striking feature of the hydrography of the lake is its shallowness. The soundings taken by Stansbury indicate a mean depth, in 1850, of about thirteen feet; and although the height of the water surface afterward rose fully ten feet, the rise was accompanied by the addition of such large areas of shallow water that the mean depth was increased less than 5 feet. The maximum depth reported by Stansbury is 36 feet, and at the highest stage, 49 feet of water was found near the same place.

Gauging.—In 1875 the first definite determination of the lake level was made, and since that time a nearly continuous record of its oscillations has been kept. A less accurate knowledge of the change of level, based in part on tradition, extends back to 1845. In the following account of the oscillations, the direct observations will be first described, and afterward the indirect determinations.

In the year 1875, Dr. John R. Park, of Salt Lake City, at the suggestion of Prof. Joseph Henry of the Smithsonian Institution and with the co-operation of other citizens, instituted a series of observations. There was erected at the water's edge at Black Rock a granite block cut in the form of an obelisk and engraved on one side with a scale of feet and inches; and Mr. John T. Mitchell was engaged to observe the water-height at intervals of a few days. In 1877 Mr. Jacob Miller of Farmington, at the instance of the writer, erected near that place, in a slough communicating with the lake, a post of wood graduated to inches. Upon this gauge a record was begun in November, 1877. In the course of time the lake fell so low that its water-level could not be determined by either of these gauges, and in 1879 a third was set up by Mr. E. Garn at the bathing resort known as Lake Shore. The Lake Shore gauge consisted of a wooden pile driven into the clay bed of the lake and engraved with a scale of feet and inches. The continued recession of the water rendering it apparent that this gauge also would eventually become useless, the U. S. Geological Survey in 1881 established a fourth gauge at Garfield Landing, a short distance west of Black Rock. It consisted of a red-wood plank, with a scale of feet engraved and painted, spiked to a pile of the steamboat wharf at that point. The Survey also ascertained th relative height of the zeros of all the gauges; and as none of them were of a permanent nature, it connected them by leveling with a durable bench-mark set out of the reach of the waves of the lake.

The Black Rock bench, as it will be convenient to call it, consists of a granite post about three feet in length, sunk in the earth all but a few inches, on the northern slope of a small limestone knoll just south of the railroad track at Black Rock. Its top is dressed square, about 10 by 10 inches, and is marked with a +. A sketch-map (Pl. LI) was made of the locality in 1877, at the time of the establishment of the bench, and it is hoped that this will serve for its identification at any future time.

Observations of lake level were made on the Black Rock gauge from September, 1875, to October, 1876, and single observations were made in July and October, 1877. The Farmington gauge was used from November, 1877, to November, 1879; the Lake Shore gauge from November, 1879, to September, 1881; the Garfield Landing gauge from April, 1881, to June, 1886.

The Garfield Landing gauge was inspected by members of the corps from time to time until 1884, when Salt Lake City ceased to be a base for field operations. In 1886 Prof. Marcus E. Jones of that city ascertained and reported that the gauge had suffered accidents whereby its zero had been raised three or four inches, but the dates of change were not learned. In June of the same year it was destroyed by a storm. Prof. Jones then began observations of the water height, and eventually prepared and installed a new gauge, placing it near the position of the old one at Garfield Landing, and fixing its zero at the same height. This gauge, which will be called the New Garfield, is still in use.

All of the gauges except the New Garfield have by various accidents become displaced, so that the authenticity and coherence of the records depend wholly on the leveling and other observations conducted to determine the relative heights of the gauge zeros. Connection between the Farmington and Lake Shore gauges was established by the writer by spirit-level at the time of the institution of the latter gauge. The Lake Shore and Garfield Landing gauges, which are separated by a space of more than 20 miles, were observed simultaneously for a period of five days in March, 1881, the lake being at the time little disturbed by wind. In 1877 the late Mr. Jesse W. Fox and the writer ran levels from the Black Rock gauge to the Black Rock bench; and in 1881 Mr. Russell, by the aid of the spirit-level and the level afforded by the calm lake surface, connected the Garfield gauge in like manner with the Black Rock bench.

These various determinations, together with others, have been compiled and reduced to a system by Mr. Webster, whose report on the hypsometric work performed in connection with the Bonneville investigation will be found in Appendix A. He has selected the zero of the Lake Shore gauge as the datum or reference point for all heights within the basin. I insert a table of gauge heights based on his compilation.

TABLE VII. *Datum Points connected with the gauging of Great Salt Lake.*

	Feet.
Black Rock Bench	+41.8
Farmington Bench	+16.7
Black Rock Gauge Zero	+ 5.3
Farmington Gauge Zero	+ 3.8
Lake Shore Gauge Zero	0.0
Garfield Gauge Zero	− 4.6
New Garfield Gauge Zero	− 4.6

Oscillations since 1875.—The following table shows all the trustworthy observations recorded by the observers at these several stations. It does not cover the entire period from 1875, but the breaks are unimportant.

TABLE VIII. *Record of Oscillations of Great Salt Lake.*

Gauge.	Observer.	Year.	Day.	Reading. Ft.	Reading. In.	Referred to Lake Shore Zero. Feet.
Black Rock	J. T. Mitchell	1875	Sept. 14	0	6	5.8
			22	0	5½	5.7
			25	0	5	5.7
			Oct. 6	0	4½	5.6
			12	0	4	5.6
			18	0	3½	5.6
			26	0	3	5.5
			Nov. 9	0	2	5.4
			16	0	1½	5.4
			23	0	4	5.6
			29	0	5½	5.7
			Dec. 7	0	5	5.7
			14	0	5½	5.7
			21	0	6	5.8
		1876	Jan. 5	0	8	5.9
			11	0	8½	6.0
			29	0	9	6.0
			Feb. 1	0	9	6.0
			15	0	9½	6.1
			22	0	9½	6.1
			Mar. 15	0	11	6.2
			22	1	0	6.3
			28	1	0½	6.3
			Apl. 17	1	2	6.4
			25	1	3	6.5
			May 2	1	4	6.6
			22	1	9	7.0
			June 2	1	11	7.2
			8	2	0	7.3
			13	2	2	7.4
			23	2	4	7.6

TABLE VIII. *Record of Oscillations of Great Salt Lake*—Continued.

Gauge.	Observer.	Year.	Day.	Reading.	Referred to Lake Shore Zero.
				Ft. In.	*Feet.*
Black Rock	J. T. Mitchell	1876	June 30	2 6	7.8
			July 18	2 3	7.5
			25	2 4	7.6
			Aug. 1	2 3	7.5
			10	2 2	7.4
			22	1 9	7.0
			29	1 8	6.9
			30	1 8	6.9
			Sept. 14	1 7	6.9
			19	1 6½	6.8
			26	1 6	6.8
			Oct. 9	1 5½	6.7
	G. K. Gilbert	1877	July 12	2 0	7.3
			Oct. 19	0 10	6.1
			Nov. 24	2 1	5.8
Farmington	J. Miller	1878	Jan. 21	2 1½	5.9
			Mch. 28	2 2½	6.0
			May	2 5	6.2
			June 30	2 6	6.3
			July 18	2 3½	6.1
			Nov. 1	1 0	4.8
			Dec. 11	0 11	4.7
		1879	May 2	1 4	5.0
Lake shore	E. Garn		Nov. 19	2 6	2.5
			Dec. 2	2 6	2.5
			16	2 7½	2.6
			31	2 9	2.7
		1880	Jan. 14	2 9½	2.8
			29	2 7½	2.6
			Feb. 23	2 7½	2.6
			Mar. 10	2 9½	2.8
			30	2 10	2.8
			Apr. 15	2 10½	2.9
			28	2 11½	3.0
			May 12	3 1	3.1
			26	3 3½	3.3
			June 10	3 4	3.3
			28	3 4½	3.4
			July 13	3 3½	3.3
			30	3 1	3.1
			Aug. 14	2 11	2.9
			29	2 8	2.7
			Sept. 14	2 5	2.4
			29	2 2	2.2
			Oct. 15	1 11½	2.0
			29	1 10½	1.9
			Nov. 12	1 9	1.7
			29	1 8½	1.7
			Dec. 11	1 8½	1.7
			14	1 9	1.7

TABLE VIII. *Record of Oscillations of Great Salt Lake*—Continued.

Gauge.	Observer.	Year.	Day.	Reading.		Referred to Lake Shore Zero.
				Ft.	*In.*	*Feet.*
Lake shore	E. Garn.........	1880	27	1	10	1.8
		1881	Jan. 14	1	10	1.8
			28	2	2	2.2
			Feb. 14	2	6	2.5
			28	2	6½	2.5
			Mar. 14	2	7½	2.6
Garfield Landing ...	T. Douris.......	... .	Apr. 1	7	3	2.6
			16	7	4½	2.7
			May 1	7	8	3.0
			16	7	11	3.3
			June 1	8	0	3.4
			16	8	0½	3.4
			July 1	7	10½	3.2
			16	7	10	3.2
			23	7	9	3.1
			Aug. 2	7	6	2.9
			19	7	4	2.7
			Sept. 8	7	0	2.4
			16	6	11	2.3
			Oct. 2	6	9	2.1
			16	6	9	2.1
			Nov. 2	6	8	2.0
			16	6	8	2.0
			Dec. 1	6	8	2.0
			15	6	9	2.1
		1882	Jan. 2	6	9	2.1
			16	6	10	2.2
			Feb. 2	6	10½	2.2
			16	6	11	2.3
			Mar. 2	6	11½	2.3
			21	7	0½	2.4
			Apr. 1	7	1½	2.6
			16	7	3	2.6
			May 2	7	5	2.8
			16	7	6	2.9
			June 2	7	6½	2.9
			16	7	6	2.9
			July 2	7	4	2.7
			17	7	2½	2.6
			Aug. 2	7	0	2.4
			15	6	10	2.2
			Sept. 2	6	5	1.8
			16	6	3	1.6
			Oct. 2	6	1½	1.5
			15	6	0	1.4
			Dec. 15	6	0	1.4
			30	6	0	1.4
		1883	Jan. 15	6	0	1.4
			30	6	0	1.4

TABLE VIII. *Record of Oscillations of Great Salt Lake*—Continued.

Gauge.	Observer.	Year.	Day.	Reading.	Referred to Lake Shore Zero.
				Ft. In.	*Feet.*
Garfield Landing	T. Douris......	1883	Feb. 15	6 1	1.5
			30	6 1½	1.5
			Mar. 15	6 2	1.5
			Apr. 2	6 4	1.7
			Sept. 3	6 6	1.9
			16	6 2	1.5
			Oct. 3	5 8	1.0
			15	5 5	0.8
			Nov. 1	5 3	0.6
			15	5 0	0.4
			Dec. 2	5 0	0.4
			15	5 0	0.4
		1884	Jan. 2	5 0	0.4
			15	5 0¼	0.4
			Feb. 2	5 0½	0.4
			15	5 1½	0.5
			Mar. 1	5 2½	0.6
			15	5 6	0.9
			Apr. 1	5 8	1.0
			15	5 11	1.3
			May 2	6 2	1.6
			15	6 5	1.9
			June 1	7 0	2.4
			15	7 3	2.6
			July 1	7 5½	2.8
			15	7 5½	2.8
			Aug. 2	7 2½	2.6
			15	7 0½	2.4
			Sept. 1	7 0	2.4
			15	7 0	2.4
			Oct. 2	7 0	2.4
			15	6 11	2.3
			Nov. 1	6 11	2.3
			15	6 10	2.2
			Dec. 2	6 10	2.2
			15	6 11	2.3
		1885	Jan. 2	7 1	2.5
			15	7 2½	2.6
			Feb. 2	7 3½	2.7
			16	7 5	2.8
			Mar. 2	7 6	2.9
			16	7 8½	3.1
			Apr. 3	7 10	3.2
			16	7 11	3.3
			May 2	8 1	3.5
			15	8 3	3.6
			June 1	8 6	3.9
			16	8 9	4.1
			July 2	8 10	4.2
			15	8 9½	4.2

TABLE VIII. *Record of Oscillations of Great Salt Lake*—Continued.

Gauge.	Observer.	Year.	Day.	Reading. Ft.	Reading. In.	Referred to Lake Shore Zero. Feet.
Garfield Landing	T. Douris	1885	Aug. 2	8	8	4.0
			15	8	7	4.0
			Sept. 2	8	3	3.6
			15	8	0	3.4
			Oct. 2	8	0	3.4
			15	7	11½	3.3
			Nov. 1	7	11	3.3
			15	7	9	3.1
			Dec. 2	7	9	3.1
			15	7	11	3.3
		1886	Jan. 2	8	0	3.4
			15	8	1	3.5
			Feb. 2	8	3½	3.7
			15	8	5	3.8
			Mar. 2	8	7	4.0
			15	8	9	4.1
			Apr. 1	8	10	4.2
			15	8	11	4.3
			May 2	9	0½	4.4
			15	9	1	4.5
			June 2	9	2½	4.6
New Garfield	M. E. Jones	......	July 29	8	10⅛	4.2
			Oct. 2	8	2	3.6
			Nov. 6	8	0	3.4
			Dec. 28	8	2¼	3.6
		1887	Feb. 5	8	1½	3.5
			Mar. 5	8	4	3.7
			19	8	5½	3.8
			Apr. 2	8	4¾	3.8
			16	8	6½	3.9
			May 7	8	5¾	3.8
			22	8	8¼	4.1
			30	8	8¼	4.1
			June 10	8	8¼	4.1
			June 22	8	7⅞	4.0
			July 4	8	6¾	3.9
			14	8	5⅜	3.8
			Aug. 6	8	1¾	3.5
			Sept. 5	7	8¼	3.1
			20	7	4½	2.7
			Oct. 4	7	3¾	2.7
			25	7	1½	2.5
			Nov. 11	7	1	2.5
		1888	Jan. 1	7	1	2.5
			10	7	2½	2.6
			Feb. 1	7	3	2.6
			24	7	4	2.7
			Mar. 3	7	4	2.7
			23	7	6½	2.9
			Apr. 6	7	7	3.0

TABLE VIII. *Record of Oscillations of Great Salt Lake*—Continued.

Gauge.	Observer.	Year.	Day.	Reading.	Referred to Lake Shore Zero.
				Ft. In.	*Feet.*
New Garfield	M. E. Jones.....	1888	May 8	7 5	2.8
			30	7 5¾	2.9
			June 22	7 3½	2.7
			July 3	7 1¼	2.5
			23	6 9	2.2
			Aug. 1	6 8	2.1
			16	6 6	1.9
			Sept. 1	6 4	1.7
			15	6 1½	1.5
			Oct. 1	5 11	1.3
			Nov. 1	5 5	0.8
			10	5 7	1.0
			Dec. 10	5 7	1.0
		1889	Jan. 1	5 7	1.0
			15	5 7	1.0
			Feb. 1	5 8	1.1
			15	5 9	1.2
			Mar. 1	6 0	1.4
			25	6 1	1.5
			Apr. 15	5 9	1.2
			May 1	5 11	1.3
			20	5 9	1.2
			June 1	5 8	1.1
			25	5 5	0.8
			July 12	4 11	0.3
			Aug. 10	4 6	−0.1
			30	4 1½	−0.5
			Sept. 23	3 7	−1.0
			Oct. 12	3 7½	−1.0
			Dec. 14	3 8	−0.9
		1890	Jan. 4	3 9	−0.8

An examination of these observations, or of the curve plotted from them, shows that the oscillations fall readily into two classes; the one periodic, completing its cycle in 12 months; the other non-periodic. The curve in Figure 32 shows the nature of the annual oscillation, being derived from the records of eight complete, though not consecutive, years. Three periods were used: October 1, 1875, to October 1, 1876; January 1, 1880, to January 1, 1883; and November 1, 1883, to November 1, 1887. The curve has a single maximum, falling near the summer solstice, and a single minimum, falling five months later. The maximum is more acute than the minimum. The range is 16 inches. The rise occupies seven months and the fall only five, but the most rapid change is that portion of the rise occurring in May.

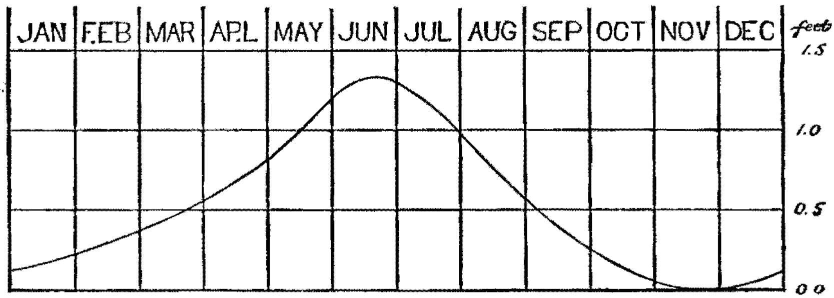


FIG. 32—Annual Rise and Fall of the water surface of Great Salt Lake.

The cause of this annual variation is at once apparent. The chief accessions of water to the lake are from the melting of snow on the mountains, and this occurs in the spring, occasioning the rise of the water from March to June. Water escapes from the lake only by evaporation, and evaporation is most rapid in summer. Before the influx from melting snow has ceased, it is antagonized by the rapidly increasing evaporation; and as soon as it ceases, the surface is quickly lowered. In the autumn the rate of evaporation gradually diminishes; in November it barely equals the tribute of the spring-fed streams; and in winter it is overpowered by such aqueous product of mountain storms as is not stored up in snow banks.

It cannot be doubted that the nature of the annual oscillation is modified by the diversion of water for irrigation, but an attempt to discover the modification failed. As the irrigation area steadily increased during the time covered by the gauge records, it was conceived that the influence of irrigation might become apparent if curves were separately derived from the earlier records and the later, but it was found that neither the curve deduced from four years of record between 1875 and 1883 nor the curve deduced from four years of record from 1883 to 1887 differed materially from the curve based on the whole eight years.

Observations prior to 1875.—Turning now to the indirect determination of oscillations prior to 1875, we have a collection of circumstantial and traditionary data which sufficiently indicate the general nature of the non-periodic oscillations since the year 1845.

From 1847 to the present time the islands of the lake have been used as herd grounds. Fremont and Carrington islands have been reached by boat, and Antelope and Stansbury islands partly by boat, partly by fording, and partly by land communication. A large share of the navigation has been performed by citizens of Farmington, and the shore in that neighborhood is so flat that changes of water height have necessitated frequent changes of landing place. The pursuits of the boatmen were so greatly affected that all of the more important fluctuations were impressed upon their memories; and most of the changes were so associated with features of the topography that some estimate of their quantitative values could be made. The data which thus became available were collated for the late Professor Henry by Mr. Jacob Miller, a resident of Farmington, who took part in the navigation. His results agree very closely with those derived from an independent investigation of my own, which has already been recorded in an essay on the water supply of Great Salt Lake, constituting Chapter IV of Powell's "Lands of the Arid Region." The following paragraphs are transcribed with little change from that volume.

Antelope Island is connected with the delta of the Jordan River by a broad, flat sand bar that has been usually submerged but occasionally exposed. It slopes very gently towards the island, and just where it joins it, is interrupted by a narrow channel a few inches in depth. For a number of years this bar afforded the means of access to the island, and many persons traversed it. By combining the evidence of such persons, the condition of the ford has been ascertained up to the time of its final abandonment. From 1847 to 1850 the bar was dry during the low stage of each winter, and in summer covered by not more than 20 inches of water. Then began a rise, which continued until 1855 or 1856. At that time a horseman could with difficulty ford in winter, but all communication was by boat in summer. Then the water fell for a series of years, until in 1860 and 1861 the bar was again dry in winter. The spring of 1862 was marked by an unusual fall of rain and snow, whereby the streams were greatly flooded and the lake surface was raised several feet. In subsequent years the rise continued, until in 1865 the ford became impassable. According to Mr.

Hiller, the rise was somewhat rapid until 1868, from which date until the establishment of the gauges, there occurred only minor fluctuations.

Since these paragraphs were written the publication of Fremont's "Memoirs of My Life" has afforded a still earlier observation. On the 13th of August 1845 he rode across the shallows to Antelope Island, the water nowhere reaching above the saddle girths.[1]

For the purpose of connecting the traditional history as derived from the ford with the systematic record afterward inaugurated, I visited the bar in company with Mr. Miller on the 19th of October 1877, and made careful soundings. The features of the ford had been minutely described, and there was no uncertainty as to the identification of the locality. We found 9 feet of water on the sand flat, and 9 feet 6 inches in the little channel at its edge. The examination was completed at 11 a. m.; at 5 p. m. the water stood at 10 inches on the Black Rock gauge.

The Antelope Island bar thus affords a tolerably complete record from 1845 to 1865, but fails to give any later details. It happens, however, that the hiatus is filled at another locality. Stansbury Island is joined to the mainland by a similar bar, which was entirely above water at the time of Capt. Stansbury's survey, and so continued for many years. In 1866, the year following that in which the Antelope bar became unfordable, the water for the first time covered the Stansbury bar, and its subsequent advance and recession have so affected the pursuits of the citizens of Grantsville who used the island for a winter herd ground, that it will not be difficult to obtain a full record by compiling their incidental observations. While making the inquiry I had no opportunity to visit that town, but elicited the following facts by correspondence. Since the first flooding of the bar the depth of water has never been less than a foot, and it has never been so great as to prevent fording in winter. But in the summers of 1872, 1873 and 1874, during the flood stage of the annual tide, there was no access except by boat, and in those years the lake level attained its greatest height. In the spring of 1869 the depth was $4\frac{1}{2}$ feet, and in the autumn of 1877, $2\frac{1}{2}$ feet.

[1] Vol. 1, p. 431.

The last item shows that the Stansbury bar is 7 feet higher than the Antelope, and serves to connect the two series of observations.

Further inquiries may render the record more complete and exact, but as it now stands all the general features of the fluctuations are indicated as far back as 1845. Beyond that time there is no tradition, but there is a single item of circumstantial evidence worthy of mention. All about the lake shore there is a storm line marking the extreme advance of the water during gales in the summers of 1872, 1873 and 1874. It is indicated by driftwood and other shore debris and is especially distinguished by the fact that it marks a change in vegetation. In some places vegetation ceases at this line, but usually there is a straggling growth of herbaceous plants able to live on a saline soil. Above the line, on all the steeper slopes not subjected to cultivation, the sage and other bushes flourish, but below the line they are represented only by their dead stumps. The height of this storm line above the contemporaneous still-water surface varies with the locality, being much greater on a shelving coast, over which the water is forced to a considerable distance by the winds, and especially small upon the islands. On the east side of Antelope Island it was found by measurement to be three feet above the summer stage of the lake in 1877, or about one foot above the winter stage in 1873.

A lower storm line was observed by Stansbury in 1850, and has been described to me by a number of citizens of Utah who were acquainted with it at that time and subsequently. The lake was then at its lowest observed stage; and the storm line was so little above it that it was submerged soon after the rise of the lake began. Like the line now visible, it was marked by driftwood, and a growth of bushes, including the sage, extended down to it; but below it no stumps were seen.

The relations in time and space of these two storm lines contribute a page to the history of the lake. The fact that the belt of land between them supported sage bushes shows that previous to its present submergence it had been dry for many years. Lands washed by the brine of the lake become saturated with salt to such an extent that even salt-loving plants can not live upon them; and it is a familiar fact that the sage never grows in Utah upon soil so saline as to be unfavorable for grain. The rains of many years, and perhaps even of centuries, would be needed to cleanse land abandoned by the lake so that it could sustain the salt-hating bushes; and we cannot avoid the conclusion that the ancient storm line had been for a long period the limit of the fluctuations of the lake surface.

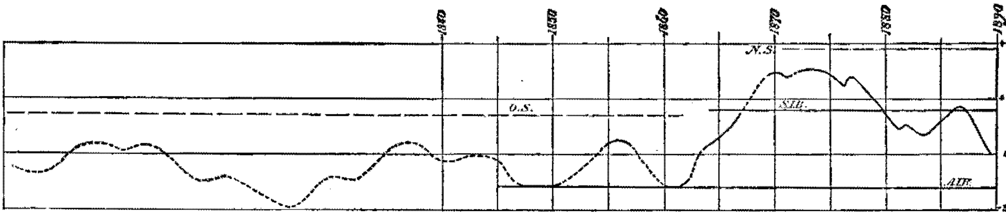


FIG. 33.—Non-Periodic Rise and Fall of Great Salt Lake.

A. I. B. = Antelope Island Bar. *S. I. B.* = Stansbury Island Bar. *O. S.* = Old Storm line. *N. S.* = New Storm line. The horizontal scale represents time. The vertical scale of feet is referred to the zero of the Lake Shore Gauge as a datum.

The curve in Fig. 33 embodies the results of direct observation and of traditional evidence as well as the inference from the phenomena of the ancient shore-line. It is drawn as a full line where based upon definite information, and as a broken line where the data are less precise. That to the left of the ordinate representing 1845 is intended to express merely the postulate that there were then, as afterward, oscillations, and the conclusion that those oscillations did not exceed the level of the ancient storm-line. The annual oscillation is omitted; the non-periodic only is represented.

The principal facts illustrated by this curve are, that during the historic period in Utah the lake has twice risen and twice fallen, the second fall being now in progress; that the second rise was carried five feet above a line which had not been submerged for several decades; and that the total observed range of fluctuation is about eleven feet.

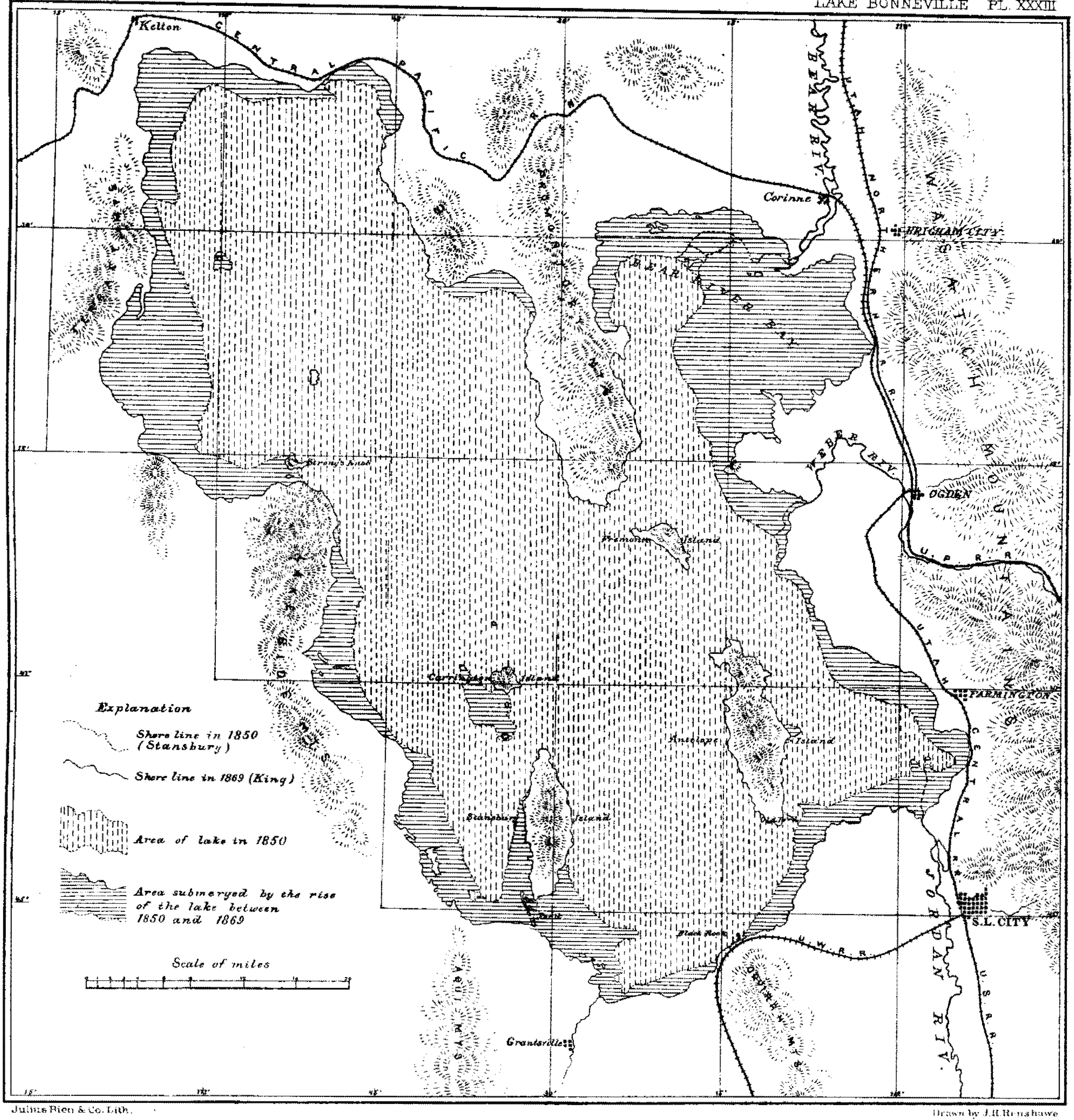
Changes in area.—The inclination of the shores is in many directions so gradual that this oscillation of eleven feet has been accompanied by very notable changes in the extent of the water surface. Fortunately, the two maps of the lake that have been published are based upon surveys made at such times as to illustrate this change. Stansbury performed his field work in the years 1849 and 1850, when the lake was at its lowest observed level, and the topographers of the Fortieth Parallel Survey delineated the lake margin in 1869, when the water was within a few inches of its highest stage. Pl.

XXXIII is compiled from the two maps conjointly, so as to exhibit the position and extent of the belt of land submerged by the rise of the lake. Upon the Stansbury map the water surface has an area of 1750 miles; upon the King, or Fortieth Parallel map, an area of 2170 miles, the increment being 24 per cent. of the smaller area.

The ability of the lake to dilate rapidly the water surface exposed to evaporation must ordinarily prevent any great fluctuation in its height. The effect of each temporary increment or decrement to either water supply or rate of evaporation is by this means quickly obliterated, and cumulative results are prevented. The lake level must be conceived to fluctuate normally within narrow limits, and the last high stage, in which the water was not merely carried above the old storm line, but maintained at a greater altitude for a period of eight or nine years, may be assumed to indicate some powerful and unusual cause.

Causes of change.—The fact that the exceptional lake maximum has occurred during the occupation of the region by the white man suggests that it may have been occasioned in some way by human agency; otherwise its cause is natural, and is almost of necessity climatic. Let us first consider the possible climatic causes. The height of the lake is stationary only when the gain from inflow and from rainfall on the water surface is precisely balanced by the loss from evaporation. Whenever in any year the total access of water exceeds the evaporation, the surface rises; when the evaporation exceeds, the surface falls. The elements of climate to be considered are therefore those which affect the water supply and the evaporation. The rate of evaporation is a function of the local temperature and humidity of the air and of the velocity of the wind. The water supply depends primarily on the rainfall and secondarily on the rate of evaporation, since a portion of the water falling on the land is evaporated, and it is only the unevaporated part which finds its way to the lake. Other things being equal, the lake surface should rise during those years in which the precipitation in rain and snow is great, the temperature low, the relative humidity high, or the wind velocity small.

Our climatic record in the Cordilleras is imperfect, but such as it is, it extends back nearly as far as the record of lake oscillation. The account



Julius Bien & Co. Lith.

Drawn by J.H. Renshawe

COMPARATIVE MAP OF

GREAT SALT LAKE, UTAH

COMPILED TO SHOW

ITS INCREASE OF AREA.

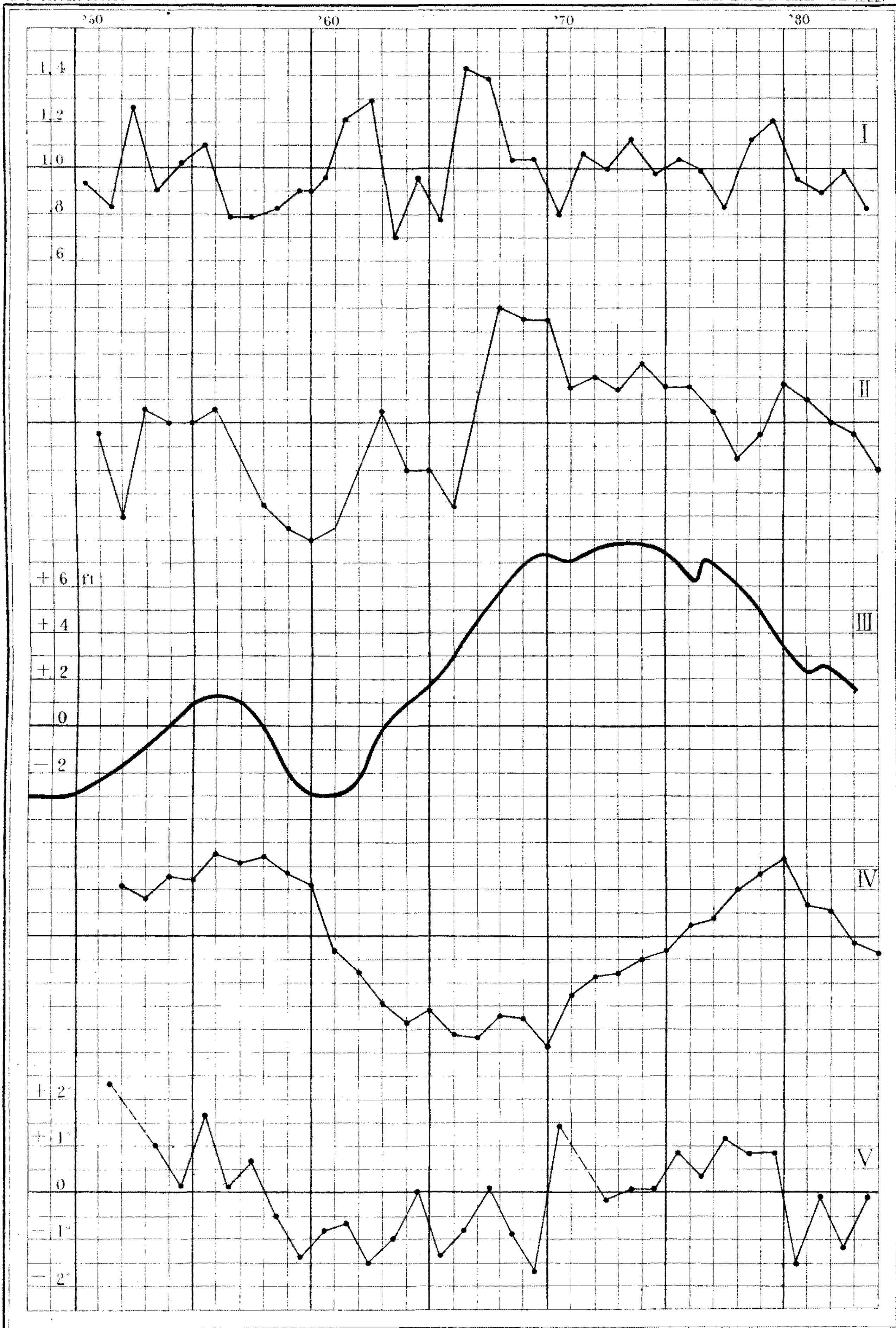
The Topography and later shore-line are taken from the Survey of Clarence King, U.S. Geologist; the earlier shore-line from the Survey of Capt. Howard Stansbury U.S.A.

it affords of the wind velocity and the relative humidity is not sufficiently definite to be of value in this connection; but the records of rainfall and temperature may profitably be compared. For this purpose I have availed myself of the statistics gathered by the Smithsonian Institution and discussed by Mr. Charles A. Schott in his papers on the precipitation and atmospheric temperature of the United States, and those gathered and published by the U. S. Signal Corps.

Aqueous precipitation is so capricious in its distribution that the record kept at a single station affords no valuable indication of secular changes. It is only by the combination of a system of observations made at a group of stations, that any trustworthy indication can be obtained. For the present purpose the stations of the Great Basin and of the adjacent portions of the Pacific Coast have been used, choice being restricted to those at which records have been kept for terms of years. These are: Astoria and Portland, Oregon; Fort Point, Sacramento, San Francisco and San Diego, California; Boisé City and Fort Boisé, Idaho; Salt Lake City and Camp Douglas, Utah. In the reduction of the observations the precipitation for each year and station has been divided by the mean annual precipitation for that station, and the several quotients have been arranged under their appropriate years. The mean of all the quotients for each year has then been found, and these means have been assumed to express the relative precipitation for the several years in the indicated districts. The curve representing these means is reproduced in No. 1 of Pl. XXXIV.

A brief consideration will show that this curve is not directly comparable with the curve of lake oscillation, III. Assuming for the moment that the oscillations of the lake are determined purely by variations of precipitation, then each year of excessive precipitation should correspond to a rise of the lake, and each year of small precipitation to a fall. A maximum of lake level would occur at the end of a series of years of great rainfall, but would not, except by accident, correspond in time with a year of maximum rainfall. If the area of the lake and the rate of evaporation were constant, the height of the lake level at any time could be determined by the summation of all the precedent precipitation factors up to that time; but the fact that the lake expands as it rises causes the annual loss by evaporation to be a function of the lake's height. The exceptionally great rainfall of an individual year, by increasing the area of the lake, initiates an excess of evaporation which eventually eliminates its influence from the curve of lake oscillation; the exceptionally small rainfall of an individual year, by diminishing the area of the lake, initiates a defect of evaporation which likewise eventually eliminates its influence from the curve of lake oscillation. The height of the lake at any time, as dependent on precipitation, is therefore to be derived by such an integration of the precipitation of antecedent years as will give the greatest weight to the years just passed and a progressively smaller weight to those more remote. An integration of this sort has been made, and is expressed in the curve marked II. It was arbitrarily assumed that the influence upon the lake level of the precipitation of a given year diminished in arithmetic ratio so as to disappear in ten years, and the integration was based on this assumption. For example, the factor for 1870 was multiplied by ten, that for 1869 by nine, that for 1868 by eight, etc., the factor for 1861 being the last included and being multiplied by unity. The sum of these several products was divided by the sum of the multipliers, 55, and the quotient was assumed to represent the integrated precipitation factor at the end of the year 1870.

The temperature was treated in a similar manner. Prior to the institution of the meteorologic observations of the Signal Corps, temperature was observed at a number of military posts and a few cities, and the records have been compiled and discussed by Mr. Schott. These observations have doubtless been continued at most points up to the present time, but they are less accessible than those of the Signal Service, and the latter have been employed for the period from 1872 to 1883. The Signal Service stations in the region already indicated include Portland, Ore., and San Francisco, and San Diego, Cal., occupied for the entire period; and Umatilla, Ore., Visalia, Cal., Boisé City, Idaho, Salt Lake City, Utah, Pioche, Nev., and Prescott, Ariz., occupied for terms varying from five to eight years. For each of these stations the mean of the annual means of temperature was subtracted from each of the annual means, and the residuals were arranged in columns according to years. The mean of the residuals for each year was then deduced, and the successive mean residuals were plotted in a curve.



Julius Bien & Co. lith.

CLIMATE CURVES.

This curve was found to be almost identical with that derived from the San Francisco observations alone and to be closely simulated by the curves of the other individual stations. It was therefore deemed legitimate to employ the San Francisco curve as representative of the district for the period antecedent to the institution of the Signal Service observations.

The San Francisco observations, however, were not employed alone. Mr. Schott has combined with them data from Alcatraz Island, Angel Island, Fort Point and Presidio, all of which stations were in the immediate vicinity. His results are published in the form of mean annual temperatures, and these have been prepared for the present purpose by subtracting from each the mean of the series. The residuals thus obtained and the residuals derived from the Signal Service observations are plotted in curve V of Pl. XXXIV. This curve may be considered to represent, with a fair degree of approximation, the non-periodic oscillations of temperature within the indicated period in the district of the Great Basin and Pacific Coast.

Here, too, it is evident that a direct comparison with the curve of lake oscillation should not be made; whatever the influence of temperature upon the volume of the lake, whether through rainfall or evaporation, it would be semi-cumulative. The temperature determinations have therefore been submitted to the same process of special integration as the precipitation determinations; it was again assumed that the influence of each year's temperature would diminish in arithmetic ratio so as to disappear in ten years. The deduced curve, IV, is far more regular than that derived from precipitation, and presumably represents the slow secular oscillation.

In comparing the integrated temperature curve with the curve of lake oscillation the question arises whether the maxima of the former should be compared with the maxima or the minima of the latter. If temperature affects the lake chiefly through rate of evaporation, the maxima of one curve should coincide with the minima of the other. If its chief influence is exerted through precipitation, the correspondence should probably be found in the same way; but about this there is difference of opinion. Fortunately, it is unnecessary to discuss the subject in this connection, for whether the comparison be made directly or by inversion, it is equally evident that the curves are inharmonious.

The integrated precipitation, curve II, resembles the curve of oscillation in several particulars. Its maximum from 1852 to 1855 is comparable with the lake maximum in 1855 and 1856. Its minimum from 1858 to 1860 is comparable with the lake minimum in 1860 and 1861; and during the great maximum of the lake from 1867 to 1879 the precipitation curve is for the most part above its mean line. The only great disparity occurs in the years 1863 to 1865, when the precipitation curve shows a minimum unrepresented in the curve of lake oscillation. The precipitation curve is therefore on the whole similar, and indeed its correspondence is quite as close as could be expected by one who realizes how imperfectly the average precipitation of a region is represented by the observed precipitation at a small number of stations. There is, therefore, some support for the hypothesis entertained by many persons that the exceptional rise of Great Salt Lake which culminated in 1873 was due to an increase of precipitation.[1]

Turning now to the consideration of the influences exerted upon the lake by man, we find them separable into two classes; first, those which cause a greater proportion of the precipitation falling on the land to be gathered by the streams and carried to the lake; second, those which cause a smaller proportion of the precipitation to reach the lake. The supposed influence of deforesting on the rainfall itself need not be discussed, because in this region no considerable body of forest has been destroyed.

The chief influence of man in increasing the inflow of the lake is through the grazing industry. In their virgin condition many of the lowland valleys and all the upland or mountain valleys were covered by grass and other herbaceous vegetation. These have been eaten off by the herds of the white man, and in their place has sprung up a sparse growth of low bushes between which the ground is bare. From this bare surface it is believed that the water falling as rain or freed by the melting of snow, runs off more readily than from the original grassy surface, so that a smaller share of it is evaporated in situ and a larger share flows through the water courses to the lake. This change has affected a large total area; and if its influence upon

[1] The observational data discussed close with the year 1883. As the manuscript goes to press they are available to 1889. The later data have not been systematically treated, but their inspection shows that the general conclusion is sustained by them.

water supply is here correctly interpreted, it is a factor of importance. Another factor of the same tendency is the draining of marshes and beaver ponds. Many of the small streams of the basin were clogged by beaver dams, and the courses of some of these have been opened by the white man for the purpose of increasing the supply of water for irrigation. The increased supply has been utilized for irrigation during a portion only of the year, and at other times has joined the streams flowing to the lake.

Plowing and irrigation have the contrary effect. Land broken up for cultivation is thereby rendered more porous, so as to retain a larger portion of the rain falling upon it. This retained portion is chiefly returned to the atmosphere by evaporation and is thus lost to the lake. The effect of irrigation is precisely similar. The water diverted from the streams and spread out on the land for the purpose of nourishing crops is restored to the atmosphere by evaporation from the surface of the soil and from the leaves of plants. In 1877 the writer estimated that the inflow of Great Salt Lake was diminished six per cent by this cause.

With the exception of irrigation, it is impossible to give quantitative expression to these factors. Those which tend to increase the lake probably culminated fifteen or twenty years ago, and have since remained constant. Those which tend to diminish the lake have increased continuously for the last 35 years. The time is probably past when the net tendency toward lake increment was at a maximum, but it is not entirely clear whether the present sum of human agencies tends toward lake expansion or lake contraction. In any case the consideration of the qualitative relation of the several factors suffices to show that a curve representative of the influence of human agencies could have but a single maximum, and could not correspond in detail with the determined curve of oscillation.

Ten years ago I discussed at some length the comparative merits of the climatic theory and the theory of human agencies,[1] concluding that neither was inconsistent with the facts and that the truth might include both. I pointed out that the former appealed to a cause that may be adequate but is not independently known to exist, while the latter appealed to causes known to exist but quantitatively undetermined. Since that time

[1] Lands of the Arid Region, pp. 68-77.

the publication of the second edition of Mr. Schott's discussion of rainfall and the progress of the work of the U. S. Signal Corps have rendered it possible to construct the most important comparative climatic curves, and the subject is here resumed for the purpose of exhibiting the relation of these curves to the curve of oscillation. The correspondence of the integrated precipitation curve to the curve of lake oscillation is sufficiently close to indicate a causal relation, especially in view of the fact that rainfall is the climatic factor to which hypothesis most naturally appeals.

In the present aspect of the problem, precipitation seems entitled to rank as the dominant factor, the results of its variation being only slightly modified by the variations of temperature and the changes introduced by grazing and agriculture.

Future Changes.—Those human agencies which tend to increase the water supply of the lake, namely, grazing and draining, have acquired a status that is practically permanent, but those which tend to diminish the supply, namely, plowing and irrigation, have not yet ceased to increase. In 1877, when the consumption of water by irrigation was estimated at six per cent. of the inflow of the lake, the intervention of the irrigator was restricted to the minor streams of the basin. The main bodies of the Bear and of the Jordan, the largest of all the streams, flowed unimpeded to the lake. Since that time, the diversion of the water of the Jordan has been undertaken on a large scale; and the time can not be distant when its entire volume will be utilized. The Bear River presents greater engineering difficulties, and has not yet been brought under control; but sooner or later a large district will be redeemed by means of its water, and the lake will be correspondingly deprived of tribute. Human agency is thus destined to play an important part in the determination of the future history of the lake. The next ten years will witness its shrinkage, for lack of affluent water, to a size smaller than has before been observed. It is not to be expected that it will ever share the fate of Sevier Lake, because the conservation of all the stream water for irrigation is not economically practicable, but it will probably be so reduced in volume as to precipitate a portion of its salt.

The final system of irrigation will include the storage in artificial reservoirs of the flood water of all the minor streams, and will cause the lake to be deprived of all inflow except from saline creeks and from the unused share of Bear River, but this system is not likely to be established by the present generation. The expansion of the methods now in vogue to a limit dependent on the extent of the readily available arable land, together with the construction of reservoirs on the most available sites, will employ about two-thirds of the water supply, and will proportionately reduce the area of the lake.

One effect of such a contraction of the lake will be to simplify its outline. Antelope, Stansbury, Carrington, Hat, and Dolphin islands will be permanently united to the land. Bear River Bay will be drained nearly to the southern extremity of Promontory, and the bay east of Antelope Island will be drained nearly to the northern end of that island. The Jordan, the Weber, and the Bear will unite their deltas in the vicinity of Fremont Island, and will eventually fill up all of the sound east of that island, reducing the lake to a linear body lying east of Stansbury Island and the Promontory. With a lowering of the lake surface the projection of deltas will be a rapid process. During the recent high stage of the lake the channels of the three principal rivers have been converted, in their lower portions, into estuaries whose sluggish current has permitted the accumulation of silt. The volume of this silt has been at the same time increased by the cultivation of the soil, an industry which always augments the detrital loads of the streams. The lowering of base-level incident to the falling of the lake surface will cause the streams to erode this detritus and transport it to the shore of the lake.

Saline Contents.—Another effect will be the concentration of the brine. The lake is so shallow that its volume is greatly affected by small changes of level, and since the total amount of contained salts undergoes no appreciable change, the strength of the solution is affected. Variations of salinity have been observed by persons engaged in the manufacture of salt from the brine, and quantitative expression has been given to the same facts by the analyses made from samples gathered at different dates. With the lake at its lowest observed stage, 1850, Stansbury collected a sample of the brine containing 22.4 per cent. of solid matter. From a sample gathered in 1873, when the lake was at its highest stage, Bassett obtained 13.7 per cent. of solid matter. At an intermediate stage King collected in 1869 a sample containing 14.8 per cent. and Talmage in 1885 and 1889 obtained samples yielding 16.7 and 19.6 per cent. It would appear from a comparison of the extreme results that with a rise of the lake surface of 10½ feet the salinity was decreased by 39 per cent. of its amount; and, assuming that the quantity of saline matter in solution remained unchanged, the volume of water in the lake was at the same time increased 73 per cent.

While these results are approximately true, they should not pass without qualification. Careful comparisons of the several determinations of salinity with the several determinations of density and with the corresponding determinations of height of water surface, reveal numerous discrepancies. The comparison of salinities with densities shows that there are errors in determinations of salinities or densities. Discrepancies between determined salinities or densities on the one hand, and heights of water surface on the other, suggest several sources of error. No collector of water samples has placed on record the spot where the collection was made; one may have stopped near the mouth of a stream and obtained too low a salinity; another may have visited a lagoon of the shore with abnormally high salinity. Stansbury and King neglected to record the dates of sampling; and of the five samples analyzed three were collected before the establishment of gauges; there is thus some uncertainty in determinations of the height of the lake when its brine was sampled.

The accompanying analyses embody all our knowledge of the nature of the brine and they accord so poorly with one another that they warrant our speaking with confidence only of the most striking characteristics. The principal base is sodium, and this exists chiefly in the form of chloride, but also as sulphate; next in rank is potassium, and then follow magnesium and calcium. Despite the fact that calcium carbonate is precipitated on the shore in the form of an oolitic sand, none of the analysts have succeeded in finding it in the brine; and it is probable that the weighable calcium found in two of the samples exists in the form of sulphate. The theoretic combination of acids and bases given in the lower division of the table is in the main tentative only; but the readiness with which sodium sulphate is obtained from the brine warrants the belief that it is one of the actual constituents.

When in winter the temperature of the water falls below 20° F., the precipitation of this salt begins, and it sometimes accumulates in such quantity as to be readily gathered from the bottom, or is even thrown upon the shore by the waves.

The sodium chloride has become the basis of a large industry, being manufactured for table and dairy use as well as for metallurgic purposes. This industry has so expanded since the close of my work in Utah that a statement of its condition at that time would have historical value only. It is reported that the output in 1886 was 23,000 tons; in 1887, 40,000 tons; in 1888, 21,000 tons. For several years sodium sulphate cast on the shore by the waves in winter has been gathered, and its utilization for the production of various sodium salts of commercial importance is already undertaken.[1] The quantity of sodium chloride contained in the lake is about 400 millions tons; of sodium sulphate, 30 millions tons.

TABLE IX. *Analyses of Water of Great Salt Lake.*

I. Sample taken in 1850; analysis by L. D. Gale.
II. Sample taken in summer of 1869; analysis by O. D. Allen.
III. Sample taken in August, 1873; analysis by H. Bassett.
IV. Sample taken in December, 1885; analysis by J. E. Talmage.
V. Sample taken in August, 1889; analysis by J. E. Talmage.

	I.	II.	III.	IV.	V.
Total solids in 1000 parts of water	224.2	148.2	136.7	167.2	195.5
Specific gravity	1.170	[1.111]	1.102	1.122	1.157

First arrangement of results; by acids and bases.

	Parts in 1000 of water.					Per cent. of total solids.				
	I.	II.	III.	IV.	V.	I.	II.	III.	IV.	V.
Chlorine	124.5	84.0	73.6	90.7	110.5	55.8	56.0	54.9	54.3	56.5
Sulphuric acid (SO_4)	12.4	9.9	8.8	13.1	11.7	5.6	6.6	6.6	7.8	6.0
Sodium	85.3	49.6	38.3	58.2	65.3	38.3	33.1	28.5	34.8	33.4
Potassium	......	2.4	9.9	1.9	2.1	......	1.6	7.4	1.1	1.1
Calcium	Trace	.2	.6	.4	.8	......	.2	.4	.3	.4
Magnesium	.6	3.8	3.0	2.9	5.1	.3	2.5	2.2	1.7	2.6
Boric acid	......	Trace	......	......	......	......	......	......	......	......
Phosphoric acid	......	Trace	......	......	......	......	......	......	......	......
Total	222.8	149.9	134.2	167.2	195.5	100.0	100.0	100.0	100.0	100.0

[1] The waters of Great Salt Lake. By James E. Talmage. Science, vol. 14, 1889, pp. 444–446.

Second arrangement of results; by theoretic combinations of acids and bases.

	Parts in 1000 of water.					Per cent. of total solids.				
	I.	II.	III.	IV.	V.	I.	II.	III.	IV.	V.
Sodium chloride	202.0	118.6	88.5	135.9	157.4	90.7	79.1	65.9	81.3	80.5
Potassium chloride			18.9					14.1		
Magnesium chloride	2.5	14.9	11.9	11.3	20.1	1.1	9.9	8.9	6.7	10.3
Sodium sulphate	18.3	9.3	10.9	14.2	10.5	8.2	6.2	8.1	8.5	5.4
Potassium sulphate		5.3		4.3	4.7		3.6		2.6	2.4
Calcium sulphate		.9	2.0	1.5	2.8		.6	1.5	.9	1.4
Chlorine (excess)		.9	2.0				.6	1.5		
	222.8	149.9	134.2	167.2	195.5	100.0	100.0	100.0	100.0	100.0

Note. The first sample of water was collected by Stansbury, and its analysis is reported on p. 419 of the "Expedition to the Great Salt Lake." The second was collected by the Fortieth Parallel Survey, and is reported in Systematic Geology, vol. 1, p. 502, and Descriptive Geology, vol. 2, p. 433. The third was collected by Dr. W. Marcet in August, 1873, and is reported in the Chemical News for Nov. 7th, 1873 (vol. 28, p. 236) by H. Bassett. The fourth and fifth were collected by J. E. Talmage in December, 1885, and August, 1889, and are reported in Science, vol. 14, 1889, p. 445. Gale reported the salts as here given in the first column of the second table. Allen's report includes two forms, the salts being given in one and the alkalis and acids in the other. Allen's figures, as printed, are not perfectly consistent; the report of the *combined* salts has been used in deriving the figures here published. Bassett's report was published in the form here given in the third column of the first table. The entire error of analysis is computed in chlorine in the second table, columns II and III. Talmage's results were published in the form given in the first part of the second table. Gale's and Talmage's errors of analysis do not appear.

Sources of Saline Matter.—The sources of the saline material may be considered in two classes; the first including the rivers, the second the littoral springs. The Bear, the Weber, the Jordan and a small number of creeks rise in uplands above the horizon of the Bonneville shore and bring to the lake water which is sensibly fresh, containing only minute quantities of mineral matter. A cordon of springs about the shore of the lake rise through the Bonneville beds, and are so far charged with salts leached from the sediments as to be perceptibly brackish. With these should be classed also the Malade River, the upper course of which is fresh, while the lower is rendered brackish by the accession of saline water from thermal springs rising in the bed of the stream within the Bonneville area. With only our present knowledge it is impossible to say whether the fresh rivers or the brackish springs furnish the greater saline tribute to the lake. The rivers only have been subjected to chemical examination.

The constitution of the Jordan water was determined from a sample collected in Utah Lake, the source of the river, and this determination is taken to represent about one-third of the inflow of the lake. Bear River was sampled at Evanston, where the stream has probably two-thirds of its maximum volume. Since this river furnishes about half the water supply of the lake, the sample is taken to represent one-third of that supply. The two analyses exhibit the constitution of two-thirds of the fresh-water tribute of the lake, and it will be assumed that their mean shows the character of the entire fresh-water tribute. In the following table this mean is compared with the analysis of the lake water as reported by Allen:

TABLE X. *Accumulation Periods for Substances contained in the brine of Great Salt Lake.*

Substance.	Parts in 1000.				V. Accumulation Period.
	I. Bear River Water.	II. Utah Lake Water.	III. Mean of I and II.	IV. Great Salt Lake Water.	*Years.*
Chlorine	.0049	.0124	.0086	84.00	34,200
Sulphuric acid	.0105	.1306	.0705	9.87	490
Sodium	.0082	.0178	.0130	49.65	13,400
Potassium	....	Trace	Trace	2.40	
Calcium	.0432	.0558	.0495	.25	18
Magnesium	.0125	.0186	.0155	3.77	850
Boron	....	....	....	Trace	
Phosphorus	....	....	....	Trace	

Rate and Period of Salt Accumulation.—At the time when Allen's sample of brine was collected the lake had a mean depth of about 19 feet. The annual inflow to the lake has been approximately estimated as sufficient to add $5\frac{1}{2}$ feet to its depth.[1]

The lake volume is therefore equaled by the inflow in three and a half years, and in that period the saline strength of the lake is increased by an amount equal to the saline strength of the inflow. Disregarding for the present the supply from littoral springs, and considering only the supply from rivers, we may, by the aid of these considerations, deduce from the table the time necessary to store up in the lake the observed amount of each of its mineral constituents. The results of such computation appear in the right-hand column of the table.

One of the most conspicuous features of these results is their variety. The streams carry enough calcium to charge the lake to the observed extent in eighteen years, but 34,000 years are necessary to similarly charge it

[1] Lands of the Arid Region, p. 72.

with chlorine. The explanation lies in the relative supply of these substances and their relative solubility. In the mountains from which the rivers flow, calcium is afforded in unlimited quantity, while the supply of chlorine is relatively very small. Chlorine, on the other hand, existing as it does in combination with sodium, is highly soluble; while calcium, existing for the most part in combination with carbonic acid, is sparingly soluble. Chlorine therefore accumulates in the lake, while calcium is precipitated. It is a matter of observation that calcium carbonate gathers on the shore of the lake as oolitic sand, and it is probable that it also falls to the bottom as a marly constituent of the lacustrine sediment. Calcium has therefore reached its limit and is an unvarying constituent of the brine. The annual accession is balanced by the annual precipitation.

The same remark applies to the magnesium. It is presumably precipitated with the calcium, just as it was from the waters of Lake Bonneville, and chemical analysis shows that a small portion of it is accumulated in the oolite of the shore.

The short period necessary to accumulate the lake's store of sulphuric acid, 490 years, indicates that it, too, has passed the saturation limit and is being precipitated. It appears to exist in the lake in the form of sodium sulphate, and it is probably precipitated in that combination. The fact that sodium sulphate is discharged from the lake by the extreme cold of winter indicates that it must exist at ordinary temperatures in quantitities not far from the saturation limit; and it is found to be the first mineral to separate from the brine when evaporated by insolation.

There remain two substances whose long accumulation periods permit us to doubt whether they have reached the stage in which accession and loss are equal. Sodium and chlorine, in their combination as sodium chloride, constitute the most abundant mineral, and no analysis has indicated that the brine is fully saturated therewith. If it be true, as surmised, that the annual supply of sulphuric acid is discharged from the lake by the precipitation of sodium sulphate, the accumulation period for sodium chloride is not properly represented by the period computed for sodium. It is more likely to be represented by the period estimated for the chlorine, namely, 34,200 years.

If now we recall to attention the tribute of the littoral springs, temporarily ignored, it is at once apparent that our table underestimates the annual tribute of sodium chloride and correspondingly overestimates its accumulation period. We have no present means of determining the extent of this overestimate, but we can safely say that the period necessary to charge the lake with common salt by means of the present sources and rate of supply is not more than 25,000 years. Shall we conclude that 25,000 years ago the lake was fresh? or is there reason to believe that sodium chloride, like the other constituents, is being precipitated by the lake as rapidly as received? To this question a satisfactory answer can not be given, but there are several considerations favoring the second alternative. First, the circumstances connected with the old storm line, to which reference has already been made, indicate that the lake was smaller and therefore more concentrated, for at least a few decades preceding the settlement of the country, than it has been since. It may well be that a portion of the salt was thrown down during this prehistoric period, and that it was combined with mechanical sediment in such way as to be preserved from resolution. Second, it is known that under special circumstances salt is now precipitated at some points on the margin of the lake. Where a broad expanse of water near the shore is exceedingly shallow, the local evaporation is not compensated by the circulation, and the resulting high concentration leads to a discharge of salt. In passing from Grantsville to Stansbury Island in 1881, Mr. Russell rode for a mile across a deposit of this character an inch in thickness. Such a deposit as this would undoubtedly be redissolved if the lake rose, or if it fell so as to permit the action of rain; but the fact of its formation indicates how trivial are the conditions which may determine precipitation. On the whole, it is not unreasonable to suppose that each of the minima which occur in the ordinary history of the oscillations of the lake marks an epoch of precipitation, when a portion of the saline matter is discharged and a smaller portion is so combined with other sediments as to remain a permanent deposit. While it can not be true that the annual precipitation counterbalances the annual supply, it is quite conceivable that a century's precipitation disposes of a century's supply.

There seems thus a possibility, if not indeed a probability, that none of the substances which have been quantitatively determined in the brine and in the tributary rivers are undergoing accumulation in the lake; but it does not follow that this equation of supply and discharge has subsisted for a long period. There are certain soluble but very rare substances, such as the compounds of boron, lithium, iodine and bromine, which tend to accumulate in inland lakes of great antiquity and have come to be regarded as the diagnostic characters of age. Only one of these has been detected in the water of Great Salt Lake, and that one is not found in measurable quantity. The conclusion that the brine is recently accumulated accords with the facts derived from the Bonneville history, for at the time of the outflow the salts stored in the lake must have been discharged beyond the limits of the basin. The age of the Great Salt Lake brine can not then be greater than the antiquity of the second Bonneville flood.

We might conclude that the age of the brine is precisely equal to the antiquity of the Bonneville flood were it not for the possibility that the lake has since then been freshened by desiccation. Russell finds excellent reason to believe that in the Lahontan basin, which is in many respects a duplicate of the Bonneville, the flood epoch has been followed by one of very low ebb, in which the residuary lakes have so dried away that all their saline matter has become entangled with mechanical sediment.[1] A more recent accession of water has produced a number of slightly brackish lakes, whose feeble brines contain in their constituents no hint of great age. If the Salt Lake basin has passed through a similar recent epoch of desiccation, it is not easy to see how we should become cognizant of it. Provided the antiquity of the epoch was sufficient to permit the subsequent accumulation of the sodium chloride, the character of the brine would be substantially as we find it. For the present, at least, we must regard it as an open question whether the existing lake with its characteristic brine dates from the cessation of Bonneville overflow or from a subsequent epoch of extreme aridity.

Fauna.—The animal life of the lake has been described by Packard, who finds it to consist of two species only, a brine shrimp, *Artemia gracilis*

[1] Geol. Hist. of Lake Lahontan, pp. 224–230.

Verrill,[1] and the larva of a fly, *Ephydra gracilis* Packard. These are very abundant in certain seasons of the year. They feed upon algæ, of which three species have been recognized. The meagerness of this fauna is to be ascribed to the rarity among animal species of the power to live in concentrated brine. Packard ascribes the phenomenal abundance of the *Artemia* to the absence of enemies, for the brine sustains no carnivorous species of any sort. The genus is not known to live in fresh water or water of feeble salinity, but it commonly makes its appearance when feebly saline waters are concentrated by evaporation. It has been ascertained that a European species takes on the characters of another genus, *Branchinecta*, when it is bred through a series of generations in brine gradually diluted to freshness, and conversely, that it may be derived from *Branchinecta* by gradual increase in the salinity of the medium. It is found, moreover, that its eggs remain fertile for indefinite periods in the dry condition, so that whatever may have been the history of the climate of the Bonneville Basin, the present occurrence of the *Artemia* involves no mystery. During the Bonneville epoch its ancestors may have lived in the fresh waters of the basin, and during the epoch of extreme desiccation, when the bed of Great Salt Lake assumed the playa condition and was dry a portion of the year, the persistent fertility of its eggs may have preserved the race. Or, if the playa condition with its concomitant sedimentation was fatal to the species, it may be that the alternative fresh water form survived in upper lakes and streams of the basin, so as to restock the lower lake whenever it afforded favorable conditions.

THE GENERAL HISTORY OF BONNEVILLE OSCILLATIONS.

We may now assemble the conclusions derived from the discussions in preceding chapters and in the preceding sections of this chapter, and exhibit a complete history of the oscillation of lake surface within the Bonneville Basin, so far as it is known.

The relation of the alluvial cones to the shore-lines, and the condition of the low passes on the rim of the basin, show that before the Bonneville

[1] A monograph of the Phyllopod Crustacea of North America. By A. S. Packard, Jr. U. S. Geol. and Geog. Surv. of the Terr. 12th Ann. Rept., Part 1, 1883, pp. 295–592. *Artemia gracilis* on pp. 330–334.

flooding the water level was low. This we may call the pre-Bonneville low-water epoch. It was of great duration compared with those enumerated below.

The first Bonneville epoch of high water is stratigraphically represented by the Yellow Clay. Peculiarities of the shore-lines, and the phenomena at Red Rock and other passes, show that the water did not rise to the rim of the basin and was not discharged.

After the deposition of the Yellow Clay the water subsided, and the basin was nearly or perhaps completely desiccated. The stratigraphic evidence of this subsidence is found in the unconformity between the Yellow Clay and the White Marl and in the alluvial deposits occurring at that horizon. The possibility of complete desiccation is suggested by the difference in character between the antecedent and subsequent deposits, which difference may have been occasioned by a change in the conditions of sedimentary precipitation. This may be called the inter-Bonneville epoch of low water.

The second Bonneville epoch of high water is represented stratigraphically by the White Marl. Before the close of the epoch the water overflowed at Red Rock Pass, forming a channel of outflow which was excavated to a depth of 375 feet. The Bonneville shore-line records the water surface at the date of initial outflow. The Provo shore-line records its position after the channel of outflow had attained its maximum depth.

The existing state of affairs was brought about by the recession of the lake surface from the Provo shore, and is stratigraphically represented by the formation of local alluvial deposits on the surface of the White Marl. The sedimentary deposits and shore embankments marking the high-water stages have been more or less eroded by the modern streams, and the ancient deltas especially have been deeply trenched. The basin has been divided into a number of minor hydrographic units. This modern epoch may be called the post-Bonneville epoch of low water.

Nothing is known of the absolute duration of these epochs, and in the study of their relative duration no trustworthy means has been found for comparing a high-water epoch with a low-water epoch. The deposit marking the first high-water epoch is thicker than that marking the second, and we may hence conclude that the first epoch was the longer, but the amount of this difference is rendered indefinite by the fact that the base of the lower deposit is not exposed. The comparison is further complicated by the difference in the two deposits, the lower containing in the center of the basin a larger per cent. of clay than the upper. If it be true that the water was so constituted during the second flood as to precipitate a relatively large share of the clay near the shore, and that the difference of constitution did not affect the precipitation of the calcareous matter, a time ratio may be based upon the calcareous factors of the two elements of the exposed section. A computation under this postulate indicates that the first high-water epoch was not less than five times as long as the second.

Data do not exist for the quantitative estimation of the relative duration of the low-water epochs, but their order of magnitude is unmistakable. A comparison of the few alluvial wedges referable to the inter-Bonneville epoch with their local representatives formed during the post-Bonneville epoch shows the former to be invariably the larger, and indicates that the time between the two Bonneville floods was longer than post-Bonneville time. The pre-Bonneville low-water epoch represented by the great alluvial cones of the mountain flanks is still less amenable to numerical statement, in that its beginning is undefined; but it is unquestionable that it far transcended in length the inter-Bonneville epoch.

It will be observed that in all respects our knowledge of the high-water epochs is relatively definite. Not only are we able approximately to compare the two high-water epochs in duration, but we know that on the second occasion the water rose higher than on the first. But of the degree of desiccation attained in the pre-Bonneville and inter-Bonneville epochs we are practically without information. We have observed and approximately determined two important maxima of an undulating curve, and have demonstrated that they are the only great maxima of the curve; but we know practically nothing of the remainder of the curve and are unable to indicate the position of any minima, properly so called.

The knowledge we have gleaned is graphically exhibited in Fig. 34, where the upper and lower horizontal lines represent the horizons of the Bonneville shore and the surface of Great Salt Lake. Horizontal distances represent time, counted from left to right. The curve represents the height of the oscillating water surface, and the shaded area indicates ignorance.

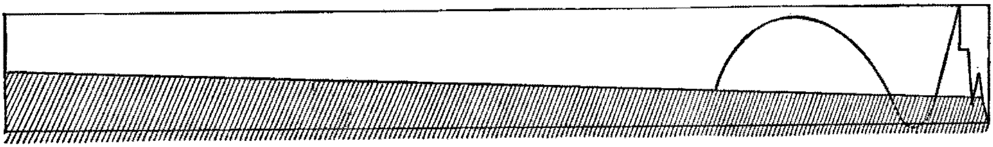


FIG. 34.—Rise and Fall of water in the Bonneville Basin.

THE TOPOGRAPHIC INTERPRETATION OF LAKE OSCILLATIONS.

One of the most important subjects to which the discussion of the Bonneville history should contribute is that of geologic climate. The oscillations of the lake were in all probability caused by oscillations of climate; and if we can satisfy ourselves as to the nature of the particular climatic movements associated with the rise and the fall of the lake, we can immediately, by changing the notation of our curve, convert it into a record of geologic climate. But in order to be fully satisfied that the curve has climatic significance, it is necessary at the outset to give consideration to other possible modes of interpretation. For this purpose we revert once more to the fundamental conditions controlling the size of a closed lake. The size depends on the ratio between the supply of water and the rate of evaporation. Rate of evaporation is purely a function of climate; but water supply depends quite as much on topographic configuration as on meteorologic conditions. We are therefore called upon to inquire whether the water supply of the Bonneville Basin may have been modified by topographic changes in such way as to account for the demonstrated rise and fall of the lake.

It is conceivable, first, that local oscillations of land surface, or volcanic eruption, or the bursting of barriers may at one time have increased the Bonneville drainage district at the expense of some other district, and may afterwards have diminished it. It is conceivable, second, that crust movements may have affected the altitude of the mountains whence the water supply of the basin flows, in such way as to cause them to intercept a greater share of atmospheric moisture at some times than at others. It is conceivable, third, that still grander crust movements have, by raising and lowering a great area including the basin, produced corresponding modifications of its general climate.

Hydrographic Hypothesis.—The possibility that the Bonneville drainage district has gained or lost by the slow shifting of water partings or the diversion of rivers has already been considered in the first section of this chapter; and it is there shown that the only important changes it is admissible to postulate are such as affect the supply afforded by Bear River. It is quite possible that the Blackfoot, which now belongs to another drainage district, once contributed its waters to the Bear; and on the other hand, it is quite possible that the main trunk of the Bear was once turned from the Bonneville Basin to that of the Columbia; but the first of these possibilities is quantitatively and the second is qualitatively inadequate to explain the Bonneville oscillations. If the Blackfoot were now to be restored to the Bear River, there would result an increase in the area and depth of Great Salt Lake, but such change is not to be compared in magnitude with the changes involved in the Bonneville history; the depth of the lake would be increased only five or ten feet at most. If the main trunk of Bear River were to be converted into a tributary of the Columbia a more important result would be produced, but the Bonneville status would not be restored; on the contrary, the area and depth of Great Salt Lake would be diminished.

It may be added that the condition of the basaltic sheets occupying the passes between the Bear River and the tributaries of the Columbia does not indicate that they are sufficiently recent to be appealed to in explanation of the changes during the Bonneville epoch. There are lavas within the lake area which, judged by their condition with respect to weathering, are newer than those on the northern passes, and yet are demonstrably older than the epoch of the Yellow Clay.

Orogenic Hypothesis.—The mountains affording the chief water supply of the basin are the Wasatch and the Uinta. The Wasatch is known to have increased in height, by faulting, since the last Bonneville flood, and both ranges are known to have been somewhat uplifted since the deposition of Neocene strata. It is highly probable that they experienced upward movements during Pleistocene time; and it is indubitable that every such movement would result in an increase of the local precipitation and of the consequent magnitude of the streams. On the other hand, it is highly improbable that either of these mountains has been subject to displacements of such nature as to reduce its height. The conjoint influence of rhythmic upheaval and equable degradation undoubtedly produces alternate gains and losses in altitude, and there must be corresponding gains and losses in the precipitation and outflow; but however plausible such a hypothesis may appear upon a merely qualitative statement, it must be regarded as quantitatively inadequate. We have an approximate measure of the extent of the degradation in the lacustrine deposits which derive their material chiefly from that source, and we can not suppose, for example, that the removal of the entire mass of the White Marl from the uplands at the east would sufficiently affect their altitude to diminish the water-supply of the basin as it has been diminished since the White Marl epoch.

There is, moreover, a general objection to any explanation appealing to merely local changes, whether of drainage or altitude. The history of Lake Lahontan, as developed by Russell, corresponds in a remarkable way with that of Bonneville. It includes two maxima and two only, the first being the longer and the second the higher.[1] It is therefore in a high degree probable that the phenomena have a common cause, and such cause must be of a general nature.

Epeirogenic Hypothesis.—This difficulty is escaped by the third hypothesis, in which a large area, including both lake basins, is conceived to have been successively elevated and depressed to an extent sufficient to reform its climate. Of the adequacy of such a cause there can be no question, but we are without evidence of its actuality. There are, indeed, in the basins of the Columbia and Frazer, systems of terraces indicative of recent changes in the relation of the ocean to the continent; but these serve only to indicate the fact of wide-spread change and do not demonstrate such changes as are necessary to account for the flooding of the Lahontan and Bonneville Basins. If that flooding is the index of a local climate wrought by continental movement, the humid condition should theoretically be the result of continental elevation and the last change should have been a subsidence;

[1] Geol. Hist. of Lake Lahontan, p. 237.

whereas, in the basins of the Columbia and Frazer, the last change appears to have been an elevation.

Since the suggested continental movements could affect the lakes only through the mediation of local climate, the hypothesis which appeals to them is essentially a climatic hypothesis; and its further consideration may be deferred until its proper place is reached in the discussion of the influence of changes in terrestial climate.

THE CLIMATIC INTERPRETATION OF LAKE OSCILLATIONS.

OPINIONS ON CORRELATION WITH GLACIATION.

Turning now to the subject of climatic interpretation, we find an almost universal agreement among geologists in the view that the lake maxima were in some way associated with the history of glaciation. The idea that the rise of a lake contained in a closed basin is a phenomenon properly correlated with the formation or extension of glaciers appears to have been independently suggested by Jamieson, Lartet, and Whitney. Jamieson, speaking in 1863 of the climate of Central Asia,[1] said:

> The great basin of the continental streams, larger than the area of Europe, is remarkable for its inland lakes from whence no streams ever reach the ocean, owing to the great heat drying up the water. Now this heat and dryness being much lessened during the glacial period, there must have resulted a much smaller evaporation, which would no longer balance the inflow. These lakes therefore would swell and rise in level, . . .

Two years later, Lartet wrote:

> The level of the Dead Sea must therefore have been constantly regulated by the conditions of equilibrium between atmospheric precipitation and evaporation. The extension of the waters of this lake, at a certain epoch, revealed by the sediments now laid bare, which cover such vast surfaces to the north and to the south of its present limits, bears witness to a great change supervened since then in the atmospheric conditions to which the hydrographic régime of the country was subjected. In the absence of fossils in the sediments anciently deposited by the lake, it is impossible to assign a precise age to the elevation of its waters. However, taking account of the probable duration of the phenomena which must have preceded and followed this important phase of the history of the Dead Sea, one would be led to attribute to it a date close to the end of the Tertiary and the beginning of the Quater-

[1] On the parallel roads of Glen Roy and their place in the history of the glacial period, by Thomas F. Jamieson, Quarterly Journal Geological Soc., London, vol. 19, pp. 235–259. The passage cited occurs on p. 258.

nary period. One would then be able to see in this rise of the surface of the lake an effect of the glacial phenomena whose influence seems to have extended, at these epochs, to neighboring regions. This, moreover, would accord quite well with the observation of traces of ancient moraines which Dr. D. Hooker thought he recognized on the slopes of Lebanon.[1]

Only a few months later, Whitney, treating, in the first volume of the Geology of California, of the former extension of Mono Lake, said:

Whatever cause gave rise to the immense body of ice, in the form of glaciers, which, as we have seen, formerly covered the summit of the Sierra in this region and extended down for 5,000 feet or more from the crest, this would undoubtedly have been sufficient to supply water enough to raise the lake to the height which the terraces about it show that it must once have had.[2]

It is not certain that he adheres to this view at present, for in his memoir on the Climatic Changes of Later Geological Times (1882), he characterizes the glaciation of the Sierra as an episode (p. 2), but regards the desiccation of the Great Basin as a continuous process of which the beginning dates far beyond the Pleistocene. On p. 190 he says:

Before advancing another stage in our discussion, however, we have to make it clear that the diminution of the rivers, the disappearance of the lakes, and all the other phenomena indicative of a gradual but persistent tendency to aridity over vast areas once fertile and well watered, do not form a transient phase of a precedent Glacial epoch, but are the result of some cause which began to act before that period, and is still continuing without any connection with it.

In my original description of Lake Bonneville I argued its correlation with the Pleistocene Period in the following language:

The Bonneville epoch and the Glacial epoch were alike climatal episodes, and they occurred in the same general division of geological time, namely, the division of which modern time is the immediate sequel. If it can be shown that the climatic changes were of the same kind, there need be no hesitation in assuming the identity of the epochs. The glacial climate we commonly regard as merely cold, and a low temperature was doubtless its chief characteristic; but it admits, nevertheless, of another view. The climatic condition essential to the formation of glaciers is, that the summer's heat shall be inadequate to dissipate the winter's snow, and this may be brought about, either by a lowering of temperature, or by an increase of winter precipitation. The profuse precipitation of our northwestern coast would maintain great glaciers if the climate were cold enough; rivers of ice would follow the higher valleys of the Rocky Mountains if the snow-fall were heavy.

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[1] Louis Lartet, Comptes Rendus de l'Académie des Sciences, Paris, Séance du 17 Avril, 1865. Vol. 60, p. 798.

See also Bull. de la Soc. Géol. de la France, 2d série, vol. 22, p. 457; Séance du 1 Mai, 1865.

[2] Geol. of Cal., vol. 1, p. 452.

To account for the origin of Bonneville Lake, we need to assume a climatal change, that would increase precipitation, or diminish evaporation; and both of these effects would follow, in accordance with familiar meteorological laws, if the humidity of the air were increased, or if the temperature were lowered. There can be no doubt, then, that the great climatal revolution, which covered our northeastern States with ice, was competent to flood the dry basin of Utah; and that it actually did so is at least highly probable.[1]

In volume 1 of the Fortieth Parallel report (1878) King classified Lake Lahontan as well as Lake Bonneville as a phenomenon of the Pleistocene or Quaternary period, and argued that their basins were dry at the beginning of the period. In the case of Lake Lahontan, from a discussion of the chemical history of a peculiar pseudomorph, thinolite, he drew the conclusion that the basin was flooded twice instead of once, the first flooding having "an enormously long continuance as compared with the second." He further concludes:

The first long-continued period of humidity is probably to be directly correlated with the earliest and greatest Glacier period, and the second period of humidity with the later Reindeer Glacier period.

The Quaternary lakes of the Great Basin are therefore of extreme importance in showing one thing—that the two glacial ages, whatever may have been their temperature conditions, were in themselves each distinctly an age of moisture and that the interglacial period was one of intense dryness, equal in its aridity to the present epoch.[2]

I afterward discovered the evidence of the inter-Bonneville epoch of low water, and thus demonstrated the duality of the Bonneville flooding. Announcing this discovery in the First Annual Report of the U. S. Geological Survey (p. 26), I say:

If it be true, as argued by Mr. King and the writer, that the Bonneville epoch was synchronous with the glacial epoch, then it may also be true that the subdivision of the glacial epoch into two subepochs, with an interval of warmth, finds here a manifestation.

Subsequent investigations in the Lahontan basin by Russell serve to call in question King's conclusions in regard to thinolite, but independent reasons were found for affirming the double maximum of the lake surface.[3]

Peale, who examined the Bonneville sediments in Malade and Cache Valleys, does not discuss their relation to glaciers or climate, but may per-

[1] Explor. West of the 100th Meridian, vol. 3 p. 97.
[2] Geol. Expl. 40th Parallel, vol. 1, p. 524.
[3] Third Ann. Rept. U. S. Geol. Survey, pp. 220–222; Geol. Hist. of Lake Lahontan, pp. 250–268.

haps be considered to imply a correlation, in that he refers them to the Pleistocene.[1]

A unique view of the subject entertained by Endlich can not be ignored in this connection, and, since it is found necessary to dissent therefrom, fairness seems to require its presentation somewhat fully in his own language. Speaking of the ancient glaciers of the mountains of Colorado, he says:

If we study the country adjacent to that where we find glacial evidence, we will observe that a by far larger area was at one time covered by water than to-day. The Great Salt Lake extended beyond the boundaries that now confine it, * * * * Here, then, we have a source of moisture far exceeding, in quantity, that carried eastward at present by the prevailing westerly winds. * * * I conclude, therefore, that the ancient glaciers of Colorado and regions similar to it, both as regards geographical location and orographic construction, owe their former existence mainly to the presence of those numerous sheets of water farther west. These have now disappeared, and incident upon their removal, whatever may have produced that, was the recession and final extinction of the ancient glaciers. Holding this view, I maintain that the lakes formerly filling so many valleys were in existence *before* any glaciers occurred in the Rocky Mountains proper. * * * It is highly probable, however, that the period of their greatest magnitude fell into the time of the general glacial epoch.[2] * * *

A fatal difficulty here is a failure to recognize the fundamental difference between closed and drained basins in their relation to the moisture of the atmosphere. Closed basins return to the air just as much water as they receive from it; drained basins do not. The prevailing westerly winds to which he refers sweep across the hydrographic district of the Great Basin before reaching the mountains of Colorado. At the present time the moisture they discharge in crossing the Great Basin is precisely equal to that which they absorb, so that they approach Colorado with humidity unchanged. When Lake Bonneville and some other lakes of the basin were so filled as to overflow to the ocean, the precise amount of their discharge was abstracted from the westerly winds in their passage, so that the winds left the district of the basin drier than they entered it. If the air currents reaching the Colorado Mountains from the west were then moister

[1] Dr. A. C. Peale in Ann. Rept. U. S. G. & G. Surv. of Terrs. for 1877, p. 641.

[2] Dr. F. M. Endlich; Ann. Rept. U. S. G. & G. Surv. of Terrs. for 1875, p. 225.

than now, their humidity must have been acquired before they reached the district of the lakes.

THE ARGUMENT FROM ANALOGY.

Reverting now to the correlation of lacustrine and glacial phenomena, as suggested and developed by Jamieson, Lartet, Whitney, King, Russell, and myself, the data on which the correlation is based will be examined in detail. Up to the present time all reasoning on the subject has been based upon analogy. The identity of the two classes of phenomena in time and cause has been inferred, first, from their recency; second, from their exceptional nature; third, from the parallelism of their recurrence; and, fourth, from the belief that it is possible to account for them by the same modifications of climatic conditions. These elements of analogy will be taken up in the indicated order.

Recency.—The recency of the lacustrine events and the recency of the glacial events are severally inferred from the excellent preservation of their vestiges. The atmospheric agencies which sculpture the land, rapidly obliterate all topographic features which do not conform to their types, and they attack with especial vigor masses of unconsolidated material which stand in relief. The embankments of the ancient shore-lines and the moraines of the ancient glaciers agree in their susceptibility to rapid modification by erosion, and they agree in exhibiting a condition of almost perfect preservation. In the case of the moraines, this remark applies only to those which were latest formed; but it is these which can most properly be compared, for the earlier-formed shore embankments are not visible, having been overplaced by those of later date. The recency of phenomena thus demonstrated is qualitative merely. So far as we are able to interpret the evidence from preservation, the embankments may be twice as old as the moraines, or the moraines twice as old as the embankments.

Episodal Character.—The exceptional nature of the Pleistocene glacial phenomena is generally recognized, and is illustrated in a striking manner in the immediate vicinity of the Great Basin. As first pointed out by Whitney, the great glaciers of the Sierra Nevada occupied an antecedent system of valleys, shown by their form to be the product of stream erosion. The period of ice was therefore preceded by a period when there was no ice, or little ice, and this antecedent period was of relatively great duration.

The episodal nature of the lacustrine phenomena of the Great Basin has been recognized by all observers, with the possible exception of Whitney; and the evidence in relation to the Bonneville Basin has been fully set forth in the preceding pages. The pre-Bonneville period was characterized by aridity, and it was long as compared to the Bonneville period. The formation and extension of glaciers and the formation and extension of lakes have thus the common character of episodes, interrupting a course of events which was resumed after their disappearance.

Bipartition.—A third point of analogy is parallelism of recurrence. The history of Lake Bonneville and the history of Lake Lahontan have been independently shown to be bipartite, and the similarity of the series of oscillations in the two basins gives great confidence to the conclusion that they were synchronous. If it be true, as believed by many geologists, that the history of the glacial period is similarly bipartite, the argument in favor of the synchronism and the common origin of the lacustrine and glacial phenomena acquires great strength. It is pertinent, therefore, to inquire what support the belief in a double glacial period finds in the facts of observation; but since this inquiry would involve too great a digression from the subject in hand, attention will be limited to the question of the support the belief finds in the opinion of those most competent to discuss the phenomena.

It is to be observed at the outset that a belief in the double nature of the glacial epoch implies a belief in its actuality as a general phenomenon of geologic climate. If the truth lies with those who affirm that the ancient glacial phenomena depend upon strictly local conditions, and are not widely synchronous,[1] it is evident that the bipartition of the phenomena can not be general, and that the only analogy pertinent to the present inquiry would arise from the discovery of evidence of recurrent glacial extension in the mountain ranges which border the Great Basin. Reference will be made

[1] See J. D. Whitney, Climatic changes of later Geological Time: Mem. Museum of Comparative Zoology, vol. 7, No. 2, pp. 191, 268, 387; J. F. Campbell, Glacial periods; Quart. Journ. Geol. Soc. London, vol. 35, p. 98; Rev. James Brodie, On the action of Ice in what is usually termed the Glacial Period: Brit. Ass. Rep't, 1875, p. 63. (Sections.)

in the sequel to a fragment of local evidence of this nature; but attention will at present be restricted to the testimony in regard to a general duplication of glacial history. The tendency of the testimony will be sufficiently indicated by citing those conclusions of field geologists which appear to represent the broadest survey of phenomena and to be least hampered by general theories.

Penck, who has studied the glacial phenomena of the northern face of the Alps, has supplemented the presentation of his own results by a historical digest of those of his predecessors.[1] He confirms the recognition by Morlot and others, of two great advances of the glaciers, and announces traces of a third. The greatest advance occurred in the second of the three ice epochs, and the least advance in the first.

Brückner, likewise a student of the northern face, agrees with Penck in recognizing three epochs of glaciation, but he considers the first advance slightly greater than the second and the third least of all.[2]

French geologists who have examined the western portion of the Alps are practically unanimous in asserting the unity of the phenomena. Falsan admits more or less protracted phases of progression and recession of the old glaciers, but denies the existence of any adequate evidence of an interglacial period.[3]

Those who have given special attention to the southern or Italian slope of the Alps are divided in opinion. Stoppani and Gastaldi regard the glacial period as a unit,[4] while Taramelli distinguishes two phases of glacial expansion, separated by a long interval marked by hydrographic changes and slight oscillations of level.[5]

James Geikie recognizes no fewer than four glacial epochs, separated by intervening epochs of mild climatic conditions.[6] In the English deposits

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[1] The Glaciation of the German Alps. . . . By Dr. Albrecht Penck. pp. 220, 261, 311, 322.

[2] Die Eiszeit in den Alpen. von Dr. Eduard Brückner. Mittheil. Geogr. Gesell. Hamburg, 1887–88, pp. 10–12.

[3] A. Falsan, Esquisse géologique du terrain erratique et des anciens glaciers de la région centrale du bassin du Rhône. Lyon, 1883. (Cited at second hand.) Also, La période glaciaire. Paris, 1889, pp. 242–245.

[4] A. Stoppani, Geologia d'Italia, Part 2, Milan, 1880. Gastaldi, Reale Accademia delle Scienze di Torino. Atti. 1872–73. 8°. Page 419, "Appunti sulla Memoria del Sig. Geikie F. R. S. E , On changes of climate during the glacial epoch."

[5] Taramelli, Atti della Reale Accademia dei Lincei, 1881–82, 3d series, vol. 13. Roma, 1882, p. 508.

[6] Prehistoric Europe, p. 265

the first glacial epoch is represented by the Cromer clay, the second by the great chalky bowlder clay, the third by the purple clay of Holderness, and the fourth by the Hessle Clay. In Scotland, France, Germany and Scandinavia the series of deposits are less perfect.

Archibald Geikie, having before him the same evidence, recognizes for England and Europe generally only two glacial epochs, the glaciers of the second being smaller than those of the first and to a greater extent local. He recognizes also the interruption of the first by warmer epochs, represented by interglacial beds, but these do not with him constitute an element of the primary classification.[1]

In northeastern Iowa, the stratigraphy of the superficial formations has been studied by McGee, who deduces the following history. First, the extension of the northern ice over the region; second, its withdrawal "and a period of mild climatal conditions which must have been of immense duration"; third, a second and last great glacial advance; fourth, a third slight advance of the ice, of which indirect results only were observed in northeastern Iowa.[2] The formation representing the long interglacial period is a "forest bed", a ligneous stratum separating two deposits of till. An equivalent forest bed in Ohio has been interpreted by Newberry in the same way.[3]

Upham, whose most important personal studies were in Minnesota and adjacent parts of Dakota and Manitoba, distinguishes "two principal glacial epochs . . . each subdivided by times of extensive recession and readvance of the ice . . . A long period intervened," during which the ice probably retreated as far as Hudson Bay.[4]

Chamberlin, whose studies of American glacial phenomena have been exceptionally comprehensive, gives the following generalized table of Pleistocene formations and events.[5]

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[1] Text Book of Geology, 1882, pp. 885–893, 896.

[2] On the complete series of Superficial Formations in Northeastern Iowa. By W. J. McGee. Proc. Am. Ass. Adv. Sci. vol. 27, 1879, pp. 198–231.

[3] The Drift Deposits of Indiana, by J. S. Newberry; in 14th Ann. Rep. Geol. and Nat. Hist. of Indiana, by John Collett, 1884, p. 90.

[4] Warren Upham; Proc. Am. Ass. Adv. Sci. vol. 32. 1884, pp. 222, 223. See also Geol. and Nat. Hist. Survey of Minnesota, vol. 1 of Final Rept., 1884, pp. 406, 484, 580.

[5] The Driftless Area of the Upper Mississippi. By T. C. Chamberlin and R. D. Salisbury. Sixth Ann. Rept. U. S. Geol. Survey, 1885, p. 212.

Epochs.	Subepochs or Episodes.	Attendant or characteristic phenomena.
I. Transition epoch	Not yet satisfactorily distinguished from the Pliocene.	
II. Earlier glacial epoch	First subepoch or episode.	Drift sheet with attenuated border; absence or meagerness of coarse ultra-marginal drainage drift.
	Interglacial subepoch or episode of deglaciation.	Decomposition, oxidation, ferrugination, vegetal accumulation.
	Second subepoch or episode.	Drift sheet with attenuated border; loess contemporaneous with closing stage.
III. Chief interglacial epoch		Elevation of the upper Mississippi region 1,000± feet. Erosion of old drift, decomposition, oxidation, ferrugination, vegetal accumulations.
IV. Later glacial epoch	First episode or subepoch	Till sheet bordered by the Kettle or Altamont moraine.
	Episode of deglaciation	Vegetal deposits.
	Second stage or subepoch	Till sheet bordered by the Gary moraine.
	Episode of deglaciation	
	Third episode	Till bordered by the Antelope moraine.
	Later stages	Marked by terminal moraines of undetermined importance.
V. Champlain epoch		Marine deposition in the Champlain and Saint Lawrence valleys and on Atlantic border; lacustrine deposits about the Great Lakes.
VI. Terrace epoch		Marked by fluvial excavation, notably of the flood plains of second glacial epoch.

According to Newberry "there were two maxima of cold separated by a long interval in which the climate was ameliorated"; but this climate was still cool, and the ice probably did not retreat far beyond the Great Lakes.[1]

While the conclusions of McGee, Upham, Chamberlin and Newberry are based primarily on studies in contiguous districts, include to a large extent the same phenomena, and agree in recognizing two maxima of cold, those of Chamberlin and Upham are the only ones in complete accord. Newberry differs from the others in that he regards the inter-maximum ice retreat as relatively small. Chamberlin and McGee, agreeing that glaciation was interrupted by a long epoch of warmth, and that it was also varied by episodes of local or temporary retreat of the ice sheet, differ in their reference of an important bed of till, and hence draw differently their lines of primary classification. McGee's interglacial period "of immense duration" is Chamberlin's "interglacial subepoch or episode of deglaciation", and McGee's "second and last great glacial advance" is Chamberlin's "second subepoch" of the "earlier glacial epoch."[2]

By later investigation McGee finds evidence as to epochs of cold in the phenomena of the deposits and erosions of the Atlantic border south of the Drift. From this investigation he concludes that the Pleistocene included

[1] North America in the Ice Period. By John S. Newberry. Pop. Sci. Monthly, vol. 30, 1886, p. 9.
[2] See McGee in Am. Jour. Sci. 3d series, vol. 35, 1888, pp. 458–461.

two and only two great epochs of cold; that these epochs were separated by an interval three, five, or ten times as long as the post-glacial interval; and that the earlier cold endured much the longer and was the less intense.[1] These inferences are harmonious either with Chamberlin's conclusions or with his own results in Iowa, taken separately, and they correspond closely with my reading of Bonneville history; by substituting the terms "wet" and "lacustral" for "cold" and "glacial," the Bonneville story can be summed up in the same words as McGee's story of the Atlantic border.

Wright early advocated the unity of the period of glaciation in America and still adheres to that view. In a recent publication he states that "most of the facts adduced to support the theory of distinct epochs are capable of explanation on the theory of but one epoch with the natural oscillations accompanying the retreat of so vast an ice-front."[2]

The latest word on the subject is from James Geikie,[3] whose digest of results obtained by geologists of continental Europe comes to hand while these pages are in proof. The plain of northern Germany was twice overrun by the Scandinavian ice sheet, and experienced a temperate climate in the interval. Students of Alpine drift recognize more than two epochs of glacier extension, and it is possible that the interglacial deposits of the northern plain do not all belong to the same interglacial epoch.

From this summary of opinions it appears that the relatively simple conception of Pleistocene history which belonged to the early stages of its investigation has been generally replaced by the view that its climate was characterized by great oscillations. This result has been reached separately and through independent methods by European and American students. But while the fact of oscillation is widely accepted for each continent, the progress of investigation seems not yet to have rendered the two histories so definite that the question of their similarity and synchronism can profitably be discussed. Whatever confidence we may have that the Pleistocene glaciation was a recurrent phenomenon, it must be admitted that parallelism of recurrence remains to be proven. It follows that, for the present at least,

[1] Am. Jour. Sci. 3d series, vol. 35, 1888, p. 463.
[2] The Ice Age in North America. By G. Frederick Wright. New York, 1889, p. 500.
[3] Address to the Geological section of the B. A. A. S., September, 1889.

parallelism of recurrence can not with confidence be appealed to in the correlation of the lacustral history with the glacial history.

Genetic Correlation.—The fourth point of analogy is genetic. It is generally believed that any climatic change competent to restore the glaciers of California and Utah would likewise restore the ancient lakes of the Great Basin. From this belief there has been no dissent, and it is certainly plausible; but it must nevertheless be admitted that meteorology in its present stage affords it no satisfactory basis. The general subject of climate is highly complex, and its laws are not so well understood that the results of new combinations of conditions can be foretold.

The size of lakes and the size of glaciers are determined by three processes:

A. Precipitation of rain and snow.

B. Evaporation of water, snow and ice.

C. Melting of snow and ice.

The essential elements of local climate upon which the local rates of these three processes depend are at least four in number, and may conveniently be indicated under five heads:

(*a*) The temperature of the air.

(*b*) The vapor tension or vapor content of the air, or the temperature of the dew point.[1]

(*c*) The general velocity of the wind.

(*d*) The degree of cylonic activity; and finally,

(*e*) The variation of these, and the distribution of their variations through the year.

[1] For the untechnical reader, these terms may stand in need of definition. The invisible moisture contained in the air is called aqueous vapor, and has the properties of a gas. By virtue of its elasticity it exerts a certain tension, and this tension is the measure of the amount present at any point. *Vapor tension* and *vapor content* are therefore synonymous. The amount of moisture air will hold without condensation is limited, and the limiting amount varies with temperature. For each temperature there is a maximum vapor tension known as the tension of saturation; for each vapor tension there is a minimum temperature known as the *dew point*. The temperature of the dew point at any place and time is thus an index of the existing vapor tension. *Relative humidity* is the ratio of the actual vapor tension to the saturation tension corresponding to the actual temperature; it is the humidity reckoned in terms of saturation as unity.

The more general terrestrial conditions which immediately determine these local elements may likewise be enumerated under five heads. They are:

(1) The latitude of the locality.

(2) The altitude of the locality, and the system of altitudes in its vicinity.

(3) The distribution of land and water in a very large district including the locality.

(4) The system of currents in oceans within this district (a function of 1 and 3).

(5) The wind direction (a function of 1, 3, and 4).

Directly or indirectly, each of these five conditions affects each of the five elements of local climate, so that there is a most intricate plexus of cause and effect. In a qualitative way much is known of the nature of these relations, but quantitatively very little is known. It is perhaps fair to say that the relations of temperature and humidity to latitude and altitude are the only ones whose numerical laws have been successfully investigated, either theoretically or empirically. Gradually the various climates of the earth are being explained and referred to their proximate causes; but the time has not come when the meteorologist can trace out the quantitative relations, or even in any fullness the qualitative relations, of a specific hypothetic change in one of the conditions of climate. Such a problem as the distribution of climates if the direction of terrestrial rotation were reversed can at present be solved only in a very rude way.

In the presence of such complexity, theories are necessarily based upon partial views, and the hypothesis or opinion that the magnitudes of enclosed lakes and of glaciers are similarly affected by climatic changes appears to depend upon such a partial view. This was certainly the case when I advanced the opinion in an earlier paper.

Let us assume that in the region of the Great Basin and the surrounding mountains the aqueous vapor, the wind velocity, the cyclonic activity, and the annual oscillations of these climatic elements remain constant, while the temperature alone undergoes variation. The cause of the temperature change lies of course in a modification of some climatic condition, and such modification would necessarily have its effect upon vapor, wind velocity, etc., but this effect is by the present assumption ignored. Conceive, first, a lowering of local temperature. The vapor tension remaining the same, the relative humidity of the air would be greater than at present; and cyclonic activity remaining the same, the increase in relative humidity would cause increase in precipitation of rain or snow. The wind velocity remaining the same, the lowering of temperature would retard evaporation, a smaller share of the moisture precipitated on the land surfaces of the Great Basin would return to the air, and a larger share would gather in streams and flow to the lakes. Evaporation from the lake surfaces would be slower, and the lakes, with increased supply and diminished dissipation, would grow deeper and broader, just as they did of old. In the mountains the lowering of temperature would increase the length of the season during which precipitation takes the solid form, and a greater proportion of the total precipitation would be in snow. The increased relative humidity of the atmosphere would occasion a greater total precipitation, and the winter's accumulation of snow would thus be doubly augmented. The same cause would diminish the annual evaporation of snow, and the shorter and cooler summer would have less melting power. In every way the accumulation of snow and ice would be promoted and its dissipation checked. The small glaciers which hang about some of the highest crests would wax in size and others would reoccupy the empty cirques, until finally a broad mantle of snow and ice would cover the high district of the Sierra, and ice streams would flow to the valleys on either side, just as of old.

Conceive now a rise of local temperature. The relative humidity of the air would be less than at present; the precipitation in rain and snow would be less; the evaporation would be more rapid, and a smaller share of the diminished precipitation would gather in streams and flow to the lakes. The lakes, with decreased supply and increased dissipation, would grow shallower and smaller. In the mountains the winter would be shorter, and a smaller share of the diminished precipitation would take the form of snow. The evaporation of snow would be more rapid, and the longer and warmer summer would have greater melting power. The supply of snow would be diminished and its dissipation would be promoted. The existing small glaciers would disappear.

Let us now assume that in the same region the temperature, wind velocity, etc., remain constant, while the vapor tension alone undergoes variation. Conceive, first, an increase of local vapor tension. The temperature remaining the same, the relative humidity of the air is increased, and this increase in relative humidity causes increase in precipitation of rain and snow. It induces also a slower evaporation. The supply of water to the lakes is increased, their superficial waste is diminished, and they grow in size. On the mountains the snowfall is increased, though its period remains the same. The dissipation of snow by evaporation is less, the melting of snow by direct insolation is sensibly unchanged, but its melting by summer rains is accelerated. In the region of the Sierra glaciers the summer precipitation is so small as compared with the winter that this last factor can not be important; and we need not doubt that accumulation of snow would exceed dissipation, causing an extension of the glaciers. Conceive now a diminution of vapor tension. The preceding relations are evidently reversed. The lakes of the Great Basin receive less from the streams and part with more to the air, and therefore shrink. The glaciers of the Sierra receive less snow, lose more by evaporation and lose slightly less by melting, and they will therefore shrink.

It thus appears that a local change in temperature alone or a local change in moisture alone would cause the lakes of the Great Basin and the glaciers of the Sierra simultaneously to enlarge or simultaneously to contract. But when we consider their concurrent change, no such definite conclusion is possible. If rise of temperature is accompanied by diminution of vapor tension, there will be a common shrinkage of lakes and glaciers, for these climatic changes have the same tendency. Similarly, if fall of temperature is accompanied by increase of vapor tension, lakes and glaciers will grow; but a rise of temperature and an increase of vapor, or a fall of temperature and a decrease of vapor, will have antagonistic effects upon both lakes and glaciers, and the nature of their resultant can not be determined without quantitative data. We need greatly to extend our knowledge, not only of climatic laws, but of the climate and physical geography of the Great Basin, to enable us to determine what increase of vapor tension is adequate to neutralize the effect of one degree's rise of temperature upon the size of the lakes; and we need in addition greatly to extend our knowledge of the climate of the Sierra Nevada to enable us to determine what increase of vapor tension will neutralize the effect of one degree's rise of temperature upon the size of the glaciers. It is only in the case that these two increments of vapor tension are equal, that increase of lakes and increase of glaciers will be invariably coordinate. If they are unequal, then it is possible to assume simultaneous changes of temperature and vapor tension under whose influence the lakes will expand, while the glaciers shrink, and vice versa.

But this view of the case is still only partial. Any change in the altitude of the district, in the position of the adjacent coast of the Pacific, in the nature of the currents of the North Pacific, or in the direction of the prevailing wind, would not only modify the temperature and humidity of the district under consideration, but would affect the wind velocity, the cyclonic activity, and the cycle of annual climatic change. A variation of wind velocity would make itself felt in the rate of dissipation of lakes and glaciers; a variation in cyclonic activity would manifest itself in the supply of water and snow to lakes and glaciers; and a variation in the annual cycle of climate might affect lakes and glaciers not only unequally but diversely.

Too little is known of these last mentioned influences to warrant any attempt to discuss them here. For this reason, and for this only, they will be ignored in the following paragraphs; but it is understood that the considerations about to be advanced are subject to whatever modification pertains to the omitted factors. Restricting attention to the two elements of local climate, temperature and vapor tension, we will now endeavor to ascertain how the lakes and glaciers of the district would be affected through them by various postulated changes of climatic conditions.

Let us inquire, first, what will result from a general change of altitude, or more specifically, from a bodily uplift of the entire district, including the Great Basin and the adjacent mountains. It is well known that both temperature and vapor tension are inverse functions of altitude; the temperature of the district will be lowered by the uplift, and the moisture normal to the new altitude will be less. The atmosphere covering this district is part of a great eastward-tending current which derives its moisture from the North Pacific Ocean. The hypothetic change of altitude will not affect its humidity where it enters the district. Its vapor tension can be reduced to the normal only by precipitation, and if not thus reduced, there will be an increase of relative humidity, owing to the lowering of temperature. We shall have, then, for the district, either an increase of precipitation or an increase of relative humidity. The former would augment the supply of water for the lakes and of snow for the glaciers; the latter would retard evaporation and thus diminish the waste of water and ice. The lowering of temperature likewise will not only retard evaporation, but will retard melting, and will extend the season in which precipitation takes the form of snow. Thus, in every way, the growth of lakes and glaciers will be favored. Conversely, a general depression of the district will diminish lakes and glaciers.

Let us inquire, in the second place, how the climate will be affected by changing the distribution of land and water. Evidently, the number of different changes which might be postulated is unlimited, but there is one particular change to which the district is peculiarly sensitive, and which may stand for a large class. This change is an eastward or westward movement of the coast line of California, so as to diminish or increase the belt of land between the Sierra Nevada and the ocean. Let us postulate a westward movement, or an increase of the land. The general movement of the atmosphere in this region is from the ocean to the land, and the moisture gathered from the surface of the ocean is the store whence all the precipitation of the land is derived. The addition of a belt of land will increase the area of uncompensated precipitation, and will thus diminish the general vapor tension of the atmosphere of the district. It has been pointed out by Dutton,[1] that the portion of the ocean under consideration has a temperature lower than the normal for the latitude, so that the air current grows warmer in passing over the land. The intervention of an additional belt of land will add its quota of heat to the air, and thus render the general temperature of the district higher. An addition to the coast will therefore induce

[1] On the cause of the arid climate of the western portion of the United States, by Capt. C. E. Dutton, Am. Jour. Sci., 3d series, vol. 22, p. 247. See also, Hann's Handbuch der Klimatologie, p. 136.

a diminution of vapor and a rise of temperature, and these changes, as we have seen, are competent to diminish lakes and glaciers. The reverse effects will of course be wrought by a diminution of the coast area.

Third, let us endeavor to see how our district would be affected by a modification of ocean currents. The influence of such currents upon climates is exerted through their temperature; and we will postulate a rise in the temperature of the current which follows the coast of California from north to south. A warmer ocean will give a higher temperature to the landward-flowing air, and at the same time impart to that air a greater load of aqueous vapor. Since the oceanic district in question is now cooler than the land district whose atmosphere it tempers, a warming of the ocean will tend to diminish the contrast of temperatures. The warming of the air during its landward progress will therefore be less, and there will be a tendency towards a higher relative humidity. Precipitation will thus be promoted. Evaporation will be favored by the higher temperature, but opposed by the higher relative humidity; and it is not easy to see which tendency will prevail. The melting of snow and ice will be promoted both by the higher temperature and by the greater length of the summer, while the winter, or the season in which precipitation takes the form of snow, will be shortened. So long as only a small change is considered, the merely qualitative statement does not clearly show whether the increased rate of snowfall will be more or less than compensated by the increased rate of melting; and the uncertainty in regard to evaporation leaves us in doubt whether the lakes will swell or shrink.

If, however, we pass to an extreme case, there is no room for doubt. A great increase of oceanic temperature, say ten or twenty Fahrenheit degrees, would reverse the contrast of temperature between land and shore. The eastward-flowing air, instead of being warmed by the land, would be cooled; and the resulting precipitation would far surpass any possible increase of evaporation. The Great Basin would become a basin of great lakes. The same temperature change would so abridge the winter season in the mountains, and so enhance the melting power of the summer, that no glacier could possibly survive. The converse follows.

Finally, let us ask what will result from a change in the direction of the general air current. This direction belongs to the great system of atmospheric circulation, and a large change is practically out of the question. We are at liberty, however, to assume small changes, based upon local conditions; and we will postulate that the wind becomes more southerly. With such a course, it will derive its temperature and moisture from a portion of the Pacific Ocean warmer than that now traversed by it; and the principal effects in the mountain district under consideration will be identical with those deduced in the last paragraph, as resulting from a warmer ocean. Minor effects will be conditioned by the configuration of the belt of land traversed by the wind before reaching the interior district, and the distribution of climate within the district will be modified; but the probable importance of these considerations is not sufficient to warrant their discussion.

It appears, then, that lakes and glaciers would simultaneously increase if the district as a whole were to be uplifted, or if the Pacific Ocean were to encroach upon the California coast; and the conclusion is less confidently reached that the lakes of the Great Basin would increase, and the glaciers of the Sierra Nevada decrease, if the North Pacific Ocean were warmer, or if the coastward winds traversed a warmer tract. But the subject is by no means exhausted. We might consider the various combinations of these four postulated changes of condition, or, going beyond them, we might turn our attention to those more remote causes of change to which theories have appealed in explanation of Pleistocene glaciation. Whether we attempted to trace out the consequences of far-reaching geographic changes, of variations in the eccentricity of the earth's orbit, or of the terrestrial wandering of the earth's axis of rotation, we should equally find ourselves involved in a maze of complexity, and ultimately brought face to face with the imperfection of the science of meteorology.

Reviewing the immediately preceding discussion, we see that the partial view which takes account of temperature only, or of aqueous vapor only, results in a definite conclusion. The broader but still partial view which takes account of temperature and aqueous vapor conjointly, but neglects other climatic elements, leads to no definite conclusion. Certain climatic conditions, manifesting themselves through temperature and humidity, affect lakes and glaciers in the same way, while other climatic conditions affect them in opposite ways.

Reviewing the entire discussion of climatic analogies, we are forced to the conclusion that the weight of the analogic argument for the correlation of lakes and glaciers has been overestimated. The fact remains that the lake epoch and the ice epoch belong to the same short division of geologic time; so does the further fact that each was a peculiar episode, interrupting a distinct and very different course of events. These two facts establish a presumption in favor of their correlation, but this presumption gains only moderate support from the parallel bipartition of the two sets of phenomena, since the duality of the glacial epoch is not generally accepted; and it gains no support, as we have just seen, from the consideration of the climatic conditions affecting the lakes and glaciers of the Great Basin. The correlation of the phenomena remains as a working hypothesis, but before it can regain its position as a fully credited theory, it must be sustained by new arguments. Fortunately, the data for its further discussion have been developed by the geologic researches in the Great Basin, and to these data we shall presently proceed.

THE EFFECT OF A CHANGE IN SOLAR ENERGY.

The present place, however, is more convenient than any other for the discussion of a climatic question whose answer is of prime importance in the interpretation of the geologic data just referred to. The question is that of the influence of a general change of temperature upon the growth of glaciers. If the radiant energy of the sun were to become greater or less, how would the glaciers of the earth be affected? Would an increase in the accession of solar heat, or would a decrease in its accession, cause the present glaciers to expand and new areas to be glaciated?

It is a familiar fact that the glaciers of the present day are restricted to regions where the temperature is low. They are more numerous and of greater size in polar regions, and there only do they reach the ocean; in temperate and tropical climates they occur only on high mountains, and their lower limit varies with the altitude, being highest at the equator and lowest at the poles. These facts of distribution have occasioned the prevalent opinion that cold is the primary condition of glaciation, and that the climate of the glacial epoch or epochs was a cold climate. If it were believed by all, as it is by some, that Pleistocene glaciation was produced by a variation in solar radiation, the majority would conceive that variation as a diminution. Nevertheless, there are not wanting investigators who entertain the opposite view; and so long as these include men of such weight as Frankland,[1] Tyndall,[2] Croll,[3] King,[4] Whitney,[5] and Becker,[6] the majority should at least refrain from dogmatic assertion. I am therefore not content, as one of that majority, to let the subject pass with a mere expression of opinion.

Generally speaking, the vapor tension of the atmosphere is greatest at sea level, and it decreases rapidly upward. If the air did not circulate, but remained stationary, the elastic force of the aqueous vapor would cause it to be diffused upward, and the product of evaporation from the ocean surface would be continuously added and diffused until there was complete saturation throughout. The theoretic static condition of the atmosphere with reference to moisture is one of saturation. The actual condition of imperfect saturation is caused by the vertical movements of the air. These, in accordance with well known laws, produce precipitation, and it results that the vapor tension of the air at every level is, generally speaking, considerably below the tension of saturation. Strachey, and afterward Hann, by studying the records of numerous observations at different altitudes and in different regions, have deduced the general law of vertical distribution of moisture.[7] It is, that the relative humidity of the air is not a function

[1] On the physical cause of the Glacial Epoch, By E. Frankland. Philosophical Magazine, vol. 27, 1864, p. 321.

[2] The Forms of Water, by John Tyndall, p. 154. Also, Heat considered as a Mode of Motion, Chap. VI.

[3] Climate and Time in their Geological Relations, By James Croll, New York, 1875, p. 79.

[4] The Geological Exploration of the Fortieth Parallel, by Clarence King, vol. 1, p. 525.

[5] The climatic changes of later geological times, by J. D. Whitney, Mem. Mus. Comp., Zool. vol. 7, No. 2, pp. 265–6, 321, 388.

[6] Temperature and glaciation, by G. F. Becker, in American Journal of Science, 3d series, vol. 26, pp. 167–175; also vol. 27, pp. 473–476.

[7] On the distribution of aqueous vapor in the upper parts of the atmosphere, by Lieut. Col. Richard Strachey, F. R. S., Proceedings Royal Society of London, vol. 11, 1860, p. 182.

On the diminution of aqueous vapor with increasing altitude in the atmosphere, by Dr. Julius Hann, Zeitschrift Oest. Met. Gesell., 1874, vol. 11, p. 193. (Cited from translation by Cleveland Abbe in Smithsonian Report for 1877, p. 376.)

Strachey notes that the conclusion was originally reached by Dr. Joseph Hooker, but Hooker's inference was based only upon observations in the Himalayas.

of altitude, or, in other words, that for each altitude the vapor tension bears the same relation to the tension of saturation. It is not to be supposed that this law is ordinarily illustrated by the condition of a local atmospheric column at a given instant; it is exemplified only through the comparison of the means of large bodies of observations.

Notwithstanding the empiric nature of this law, it is possible to extend its application somewhat beyond the existing order of things; for it is evident that under the influence of atmospheric circulation the humidity of each isothermal and isohygral stratum of the atmosphere is determined by the humidity of the stratum beneath it, the humidity of the lowest of all being determined by the rate of evaporation from the surface of the ocean. A universal rise in the temperature of the atmosphere, unless it was sufficient to materially accelerate the circulation, would have the effect merely of raising all the isothermal strata and inserting a warmer stratum at the base of the series. This, by virtue of its higher temperature, would accelerate the oceanic evaporation, and thus be enabled to maintain the relative humidity required by Strachey's law. This conclusion implies that rates of oceanic evaporation are proportional to the saturation tensions of the air at the surface of the ocean, so long as the relative humidity is unchanged; a proposition readily deducible from the accepted law of evaporation.[1]

In stating the above propositions, it has not been possible to incorporate continuously the qualification that they are of the most general character and ignore the extreme variability in time and place which characterizes both temperature and humidity. Despite this qualification, they appear to

[1] In an article "On the dependence of water evaporation on the temperature of the water and the movement of the air", published in the Repertorium fur Meteorologie, St. Petersburg, 1877, Article 3, p. 6, Stelling deduces and applies the following formula:

$$v = A\,(S - s) + B\,(S - s)\,w,$$

in which v is the rate of evaporation, S is the saturation vapor tension corresponding to the temperature of the evaporating water, s is the vapor tension of the air in contact with the water, w is the velocity of the wind, and A and B are constants. Since for the present purpose we may ignore local variations, we are enabled to simplify the formula by regarding the contiguous air and water as of the same temperature, and by regarding the wind as constant. With this modification the formula becomes:

$$v = \text{Constant} \times (S' - s), \qquad \text{or} \qquad v = \text{Constant} \times S' \left(1 - \frac{s}{S'}\right),$$

in which S' is the saturation tension of the air. The fraction $\frac{s}{S'}$ expresses the relative humidity, and since this is by postulate constant, we have v, the rate of evaporation, a simple function of S', the saturation tension of the air.

me to warrant the following corollary. If a general rise should take place in terrestrial temperature, affecting all local temperatures alike, the local moisture condition would be similarly affected. The local capacity for moisture being everywhere greater, the local vapor tension would likewise be greater, but the relative humidity for each locality would remain the same. The evaporation not only from the ocean, but from lakes and surfaces of ice and snow, would be increased in the ratio of the increase in the local saturation tension.

The increase in capacity for moisture for every unit of temperature change is not in precisely the same ratio at all temperatures, being somewhat less for high temperatures. But the difference is so small that no material error is introduced by saying that the evaporation of moisture from the entire earth's surface is proportional to the saturation tension corresponding to the mean temperature of the surface. Since the total evaporation is precisely equal to the total precipitation, it follows that the latter likewise is a simple function of the saturation tension, and the distribution of temperature remaining the same, the local precipitation follows the same law of change as the local evaporation.

Up to this point it has been assumed that the movements of the atmosphere in direction and velocity are unaffected by a general change of temperature, and it now remains to consider the validity of this assumption. The rate of evaporation is known to depend in part on the velocity of the wind, and the rate of precipitation is known to depend in part upon the amount and intensity of cyclonic action. We will give first consideration to wind velocity.

The mean temperature of the surface of the earth, reckoned from the freezing point of water, is about + 16° C. The absolute zero of temperature is considered to be — 273° C., so that the mean absolute temperature of the earth's surface may be taken as 289°. If the constitution of the atmosphere were fixed, it is probable that there would be required, to increase of temperature of the earth's surface by 10°, an augmentation of solar heat amounting to $\frac{10}{289}$ or $\frac{1}{29}$ of the present amount. In fact, however, the constitution of the atmosphere is variable; at higher temperatures it contains a larger amount of aqueous vapor, and its power to absorb and retain heat and thus acquire temperature is reciprocally augmented by aqueous vapor. For this reason, the ratio of solar radiation to be added for 10° rise of temperature is something less than $\frac{1}{29}$. Being unable to evaluate this qualification, we shall make use of the fraction unchanged, with the understanding that it is too large. Owing to the difference in attitude of the various portions of the earth with reference to the sun, the distribution of solar energy is unequal, and hence arise the principal contrasts of temperature on the earth's surface. These contrasts cause the atmospheric circulation, by means of which a partial equalization of temperature is effected. The difference between the solar energy received in high latitudes and that received in low, or the differential solar energy, is the force manifested in the winds, and its work is the friction of the circulation. The differential energy is directly proportional to the total solar energy. The law of aerial friction is not known, but it is commonly assumed to be a function of the square of the velocity. If this assumption is correct, then the square of the velocity of circulation varies as the solar energy, and an increment of $\frac{1}{29}$ in solar energy will produce an increment of $\frac{1}{58}$ in velocity. Considerations connected with the conveyance of heat through the circulation of moisture show that this estimate is somewhat too large, but as we are unable to give them a quantitative expression, we pass them by. The formula for rate of evaporation given by Stelling (see note to page 285) makes that rate a direct function of the velocity of the wind, but in such way that on the average the rate varies only about $\frac{1}{3}$ as rapidly as the wind. The ratio of wind acceleration for 10° rise in the mean temperature of the earth's surface being less than $\frac{1}{58}$, the ratio by which evaporation would be accelerated through wind velocity by the same rise of temperature is less than $\frac{1}{174}$. The smallness of this ratio assures us that the acceleration of the wind may safely be disregarded in a discussion of such general changes of temperature as may reasonably be postulated to account for Pleistocene glaciation.

The conditions under which cyclones are generated are comparatively obscure; but in the ultimate analysis they are necessarily referred to differential temperatures created by the sun. It is probable, therefore, that, like the general winds, they would be affected little by a general rise in the temperature of the atmosphere.

It is to be noted that an increase in wind velocity, by increasing evaporation, would raise the relative humidity, and thereby increase the precipitation. An increase in cyclonism, on the other hand, by increasing precipitation, would decrease the relative humidity, and thereby increase evaporation. The conjoint effect upon evaporation and precipitation is therefore cumulative, while the effect on relative humidity is, at least partially, compensatory.

Finding no ground for important qualification on account of varying intensity of atmospheric circulation, we return to the original deductions as substantially accurate: First, a general rise of terrestrial temperature will increase evaporation, general and local, in the ratio of the saturation tensions corresponding to the initial and final temperatures. Second, it will increase precipitation, general and local, in the same ratio.

We are now prepared to discuss the immediate conditions of glacier growth, and will first consider a region in which the temperature never rises above the freezing point. In such a region, the only factors affecting the accumulation of snow are precipitation and evaporation. If the former is in excess, there is an accumulation, and its amount is measured by the difference of the two factors. Since each of these factors follows the same law in regard to temperature, that law applies also to their arithmetical difference; and a change in the mean annual temperature will affect the snow accumulation in the same ratio that it affects the saturation vapor tension of the air. If the temperature rises so as to exceed the centigrade zero during a portion of the year, the annual cycle of climate becomes immediately divided into two portions, which it will be convenient to call winter and summer. Snow accumulation, then, has a higher rate, by reason of the higher temperature, but this higher rate is restricted to a shorter period. With progressive advance of annual mean temperature, the rate of snow accumulation is progressively increased, while its period is progressively shortened, until finally, when the annual temperature cycle falls entirely above the freezing point, snow accumulation ceases altogether.

As soon as the temperature cycle includes summer, a third factor is introduced—melting. Snow is melted in part by contact with warm air, in part by heat radiation from the lower part of the atmosphere, in part by direct insolation, in part by the heat liberated in the formation of dew, and in part by warm rain. The rate of melting is thus a complex function of the temperature of the air, the humidity of the air, the clearness of the sky, and the temperature of the rain. But these four factors are so related among themselves that a single one, the temperature of the air, may fairly be regarded as the measure of the rate of melting. The temperature of the lower air is itself conditioned by the clearness of the sky, the humidity of the air is, broadly speaking, conditioned by its temperature, and the temperature of the rain is conditioned by that of the air. The total annual loss by melting depends likewise on the length of summer, and for present purposes its measure may be assumed to be the product of the length of summer into the mean temperature of summer, expressed in centigrade degrees.

For the purpose of bringing together the conclusions of the preceding paragraphs, we shall now resort to a graphic method. By the aid of a few temporary postulates, the law of snowfall and the law of snow-melting may each be given the form of a curve, and the relation of these curves will exhibit the law of névé accumulation. In Fig. 35 the line X X′ is a scale of temperatures, each point representing a mean annual temperature of a particular district. The temperatures are reckoned in centigrade degrees, and at every tenth degree a vertical is erected. Vertical distances represent rates of snow accumulation and of snow melting. For the construction of the curves, three postulates were made. First, that whatever the mean temperature of the locality, its temperature range or the difference between the mean temperatures of its coldest and warmest months is 20° C. Second, that its annual curve of temperature change is of the usual type for cold regions. Third, that the rate of precipitation is uniform throughout the year. The line C D E is the curve of snow accumulation. For all temperatures below —10° its

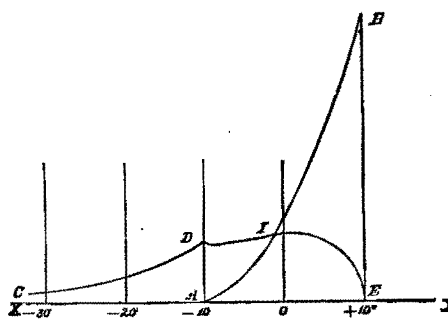

FIG. 35.—First Diagram of Glaciation Theory. Horizontal distances represent Mean Annual Temperature in Centigrade degrees. The ordinates of *C D E* are rates of Snowfall (less evaporation). The ordinates of *A B* are rates of Melting.

ordinates are proportioned to the corresponding saturation tensions. For each point between —10° and +10°, the ordinate represents the product of the corresponding saturation tension by the length of winter, expressed as a fraction of the year. The line A B is the curve of melting. Each of its ordinates represents, for the corresponding mean annual temperature, the product of the length of summer into the mean temperature of summer. To the left of A it coincides with the axis A X. Each of these curves represents a system of ratios, and the unit in each system is arbitrarily assumed. Any other assumption of relative magnitude might have been made with equal propriety, but such assumption would not affect the essential characters of the curves.

Since each ordinate of the curve C D E represents a rate of snow accumulation, as affected by precipitation and evaporation, while each ordinate of the curve A B represents a rate of melting, the differential ordinate included between corresponding points of the two curves (to the left of their intersection) represents that portion of the winter's snow which survives the summer's melting. It represents the net accumulation. Its maximum value is at A, corresponding to the mean annual temperature of —10°. With progressive fall of temperature it diminishes, at first rapidly and afterward slowly. With progressive rise of temperature it diminishes, at first slowly and afterward rapidly to the point of intersection, I.

We may now, before drawing final conclusions, examine our postulates, and inquire what errors they introduce. In addition to those stated above there are several implied postulates which are worthy of consideration.

First, it is assumed that the annual temperature range, or, more precisely, the range of the monthly means of temperature, is 20° C. This is not far from the average temperature range in existing glacier regions, but there are some localities where the range is somewhat less, and others where it is much greater. The assumption of a different range would produce in the diagram a pair of curves differing in proportions but identical in type.

Secondly, it is postulated that a change in the general temperature is not accompanied by a change in the local annual temperature range, or, in other words, that the temperature range is constant. The precise nature of errors introduced by this postulate is not easily seen, but considerations analogous to those to which attention was called in discussing the variations of wind velocity suggest that a rise in general temperature would produce a slight expansion of local temperature range. The corresponding corrective modification of the curves would fall entirely to the right of the ordinate A D, and would be unimportant.

Thirdly, it is postulated that the local annual curve of temperature is of the type usually observed in cold regions. If observation afforded us information in regard to the temperature cycles of névé districts, their type would be the one to employ in the construction of our curves; but there is no reason to believe that the error incurred by our ignorance of this point is considerable.

Fourthly, it is postulated that the curve derived from the monthly means fully represents the temperature oscillations of the year. This is manifestly untrue, for not only is there a diurnal oscillation, often comparable in range to the annual, but there are also non-periodic oscillations of considerable magnitude. It is a matter of ordinary experience that a melting of snow often takes place during the warm portion of a day whose mean temperature is below the freezing point, and that precipitation sometimes takes the form of snow during the cold part of a day whose mean temperature is above the freezing point; and that snows may fall in the midst of summer and thaws occur in the midst of winter. Thus the actual temperature range in any individual year is greater than the range obtained by the method of monthly means. It is impossible to make satisfactory allowance for this in the construction of our curves, for the reason that the importance of the diurnal and non-periodic oscillations varies greatly with latitude and with distance from the ocean. The curves as drawn represent sufficiently well the relations of snow accumulation and melting at maritime stations, but not at interior stations. The general nature of the modifications necessary to adapt them to interior stations is easily indicated. With the mean annual temperature at 0° C., the ratios of precipitation and melting are unaffected by the neglected oscillations. With the mean annual temperature at or near $-10°$, the ratio of precipitation is diminished and that of melting increased. With the mean annual temperature at $+10°$, the ratio of precipitation is increased and that of melting diminished. The application of these corrections to the diagram would lower the curve C D E in the immediate vicinity of D, smoothing out the angle at that point, would leave it unchanged where it intersects the ordinate of 0°, and would carry the point E farther to the right. It would raise the curve A B at A, and lower it at B, leaving the central portion unchanged. The point A, or the intersection with the horizontal axis, would be thrown to the left.

Fifthly, in the construction of the curves no allowance was made for evaporation during summer. The curve D E includes only winter evaporation, the curve A B only summer melting. The rate of evaporation for snow and ice has its maximum at 0°, its law changing at that point. In the general law for aqueous evaporation, the rate of evaporation is a function of the difference between the saturation tension corresponding to the temperature of the evaporated substance and the actual vapor tension of the evaporating air. Since snow and ice can not rise in temperature above 0°, they can only be evaporated when the aqueous tension of the air in contact with them is less than the saturation tension for 0°. If it rises above that, moisture is deposited on the ice as dew, instead of being abstracted from it. In all but very exceptional cases the range of summer temperatures under which névé can evaporate is small—from 0° to 5° or 6°. The effect of the evaporation is to retard the wasting of the ice, for the energy consumed by it is deducted from that available for melting, and a unit of solar heat can melt seven times as much ice as it can evaporate.[1] The correction, if applied to the curve of melting, would slightly increase its upward concavity.

Sixthly, the winter evaporation embodied with the winter precipitation in the curve D E is tacitly assumed to have a rate corresponding to the mean annual temperature; its rate is really less, being a function of the mean winter temperature. An error is thus manifestly introduced, and this error is greatest for the annual temperatures corresponding to short winters. A corresponding correction of the diagram would raise the line D E by amounts increasing progressively from D to E.

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[1] The conditions determining the evaporation of ice and the formation of dew on glaciers are clearly set forth by Heim, who cites experimental verifications by Dufour and Forel. See "Handbuch der Gletscherkunde," by Dr. Albrecht Heim, p. 238–241, and Bull. Soc. vaudoise des sc. nat. 1871, pp. 4 9–410.

Seventhly and finally, it is postulated that the precipitation is uniform throughout the year. Perhaps no better postulate could be made if we wished to express the general fact for the entire earth or for a hemisphere; but our attention is really restricted to a peculiar class of localities, namely those in which the climatic conditions are somewhat favorable to the formation of névés. It is evident that the massing of precipitation in winter is a favorable condition, and we might with propriety assign to our typical locality a precipitation curve including a winter maximum and a summer minimum. Such a precipitation curve would increase all the ordinates of the line D E of the diagram, except those at D and at E.

Of these postulates, only the fourth and seventh materially affect the problem under consideration. The diagram (Fig. 35) represents sufficiently well the névé conditions at stations of maritime climate where the precipitation is equally distributed through the seasons, but it fails to represent them for stations of continental climate, and for stations at which the annual curve of precipitation has a decided maximum. It is desirable to give graphic expression to these classes of stations also, but it is unnecessary to consider them separately, since the modifications which they occasion affect different portions of the diagram. Both types are combined in Fig. 36, the computations for which assumed a mean diurnal temperature range of 10°, and a midwinter precipitation twice as great as that of midsummer.

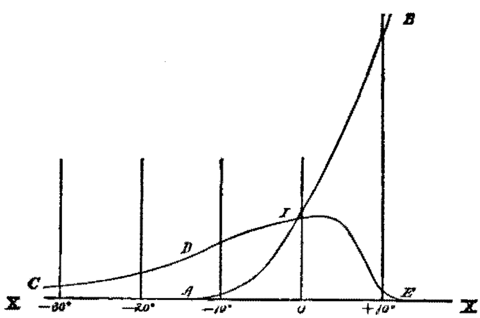

FIG. 36.—Second Diagram of Glaciation Theory. Horizontal distances represent mean annual temperature in Centigrade degrees. The ordinates of *C D E* are rates of Snowfall (less evaporation). The ordinates of *A B* are rates of Melting.

The vertical distances between corresponding points of the lines C D I and X A I, as before stated, represent annual additions to the névé at a particular locality, each individual vertical corresponding to a particular mean annual temperature of the place. The position of the maximum vertical indicates the temperature at which the annual névé increment reaches its maximum. The position of the intersection of the two lines indicates the limit to névé formation, or the annual temperature above which névé does not gather.

We may repeat, too, that as the ordinates of the two curves express ratios only, the amplitude given to the curves of the diagram is a mere matter of convenience. Their relative amplitude, on the other hand, is a matter of importance, to which some attention must be given before the curves can be properly interpreted. Assuming that the amplitude, with reference to the axis, of the curve of melting, A B, is fixed, the amplitude of the curve of snowfall, C D E, varies with the precipitation as controlled by local conditions. For localities of great precipitation its amplitude is great, and the point of intersection, I, falls to the right of its mean position. For localities of less precipitation the amplitude is less, and the point of intersection falls farther to the left. For localities whose precipitation does not exceed the evaporation, the amplitude becomes negative, the curve falls below the axis, and the expression for the névé increment has no positive value. Now, for the localities of existing névés the highest mean annual temperature is approximately 0°, and it may be assumed without material error that for the most favorable localities the amplitude of the snowfall curve is such as to bring its point of intersection with the melting curve on the ordinate corresponding to 0°. The snowfall curve of the diagram therefore has an amplitude near the maximum, and represents a locality of great precipitation (as compared to other localities at the same temperature) and highly favorable to the accumulation of névé.

In different localities the highest annual temperature consistent with névé accumulation may be as low as —10° or as high as 0°, or, more accurately (giving heed to the first postulate), the range of the limit is from the climate whose mean midsummer temperature is 0° to the climate whose mean annual temperature is 0°. The maximum névé increment in the case represented by the diagram is at —9°. With the greatest admissible amplitude of the snowfall curve it would be at about —8°. With a very small positive amplitude it would be a few degrees below —10°. It does not vary far in either direction from —10°, or (admitting the qualification of the first postulate) from the annual temperature corresponding to a midsummer temperature of 0°.

For each locality there is a definite temperature limit above which névé can not accumulate. Starting from this limit, the maximum rate of névé increment is reached by a fall of temperature amounting to something less than half the annual range for the locality. With continued lowering of temperature, there is progressive diminution in the amount of snow annually added; but, within the range of temperature the consideration of which is demanded by our practical problems, there is no indication of an inferior temperature limit to the accumulation of snow.

In applying these principles of névé increment to the correlation of glacier expansion with its appropriate temperature change, it is convenient to consider two cases. First, let us conceive a mountain slope all parts of which have the same type of annual snowfall curve. The actual snowfall at each level depends upon the temperature corresponding to that altitude. A certain temperature marks the lower limit of névé increment, and therefore the lower limit of névé. From this limit upward to the summit, the whole surface receives an annual increment of snow, which is not dissipated in place but is eventually converted into ice and flows downward to be melted below the névé limit. The maximum increment to the névé occurs some thousands of feet above the limit—according to local conditions it may be 1,000 feet or 10,000 feet. A volume of ice equivalent to the total annual névé increment passes each year from the névé zone to the zone of melting, and the distance to which the ice advances is a function likewise of the annual supply afforded by the névé. Assume, now, that the general temperature rises and is continued at a higher rate until the forces once more reach an equilibrium. With the rise of the isothermal planes the névé limit rises, and likewise all elements of the névé sheet. The zone of névé accumulation loses a strip at its upper margin and the total amount of the névé increment becomes less. The annual flow of ice from the zone of névé to the zone of melting is correspondingly less, and being sooner melted, it maintains a narrower zone of melting. Thus in every way a rise of temperature diminishes the glaciated area.

Consider now a spot which by its topographic configuration is rendered favorable to the accumulation of névé, although surrounded by a region unfavorable to such accumulation. Assume that the temperature is at first high, and then falls with secular slowness. As soon as it passes the local limit, the formation of névé begins. With still lower temperatures, the annual increment becomes greater, up to a certain maximum, and afterward becomes less. As soon as the temperature permits the accumulation of névé, motion ensues, and a stream of ice flows from the locality. The stream is at first small, rapid, and short: rapid, because ice moves most freely when near its melting point; small, because it is rapid; and short, because little descent is necessary to bring it into the zone of melting. As the temperature falls, the motion is retarded by diminishing plasticity, and to maintain the annual discharge a greater cross-section is necessary. The annual discharge, being equal to the annual névé increment, is at first increased and afterward diminished. Its increase conspires with the impairment of plasticity to enlarge the cross-section; its final decrease at very low temperatures tends in the opposite direction, and may ultimately overpower the effect of diminishing plasticity and diminish the cross-section; but the temperature of maximum cross-section must lie far below the temperature of maximum névé increment. Within the limits of our practical problem, the depth and breadth of the glacier increase with fall of temperature;[1] and its length increases at the same time, because the conditions of melting are less and less favorable the lower the temperature. Conversely, a rise of temperature diminishes at once the glaciated area and the depth of the ice.

A moment's reflection will show that into these two cases all actual cases are resolvable; and as their indication is identical, we conclude in general that a universal rise of terrestrial temperature, such as would be produced by an increased supply of solar heat, would everywhere diminish the magnitude of névés and glaciers.

It has been previously pointed out that an increase of glaciation in the Sierra and the Wasatch by means of a general elevation of the district

[1] Snow is ordinarily welded into ice by the freezing of interstitial water; but at low temperatures there is no interstitial water, and the welding can be accomplished only by great pressure. In regions where the temperature never rises to 0°, a great depth of snow is necessary to the consolidation of the lower layers. From the nature of the case, this dry welding can not be observed in nature, but its actuality has been demonstrated in the laboratory by the experiments of Mr. E. Hungerford (Amer. Jour. Science, vol. 23, 1882, p. 434). If our existing glaciers include any which arise in this way, those of the Antarctic regions are probably of this class. In small districts of great cold, such as the tops of high mountains, the dry snow is drifted freely by the wind and finds its way to lower levels instead of accumulating in great mass where it falls.

It is conceivable that an extremly cold climate would demand for the consolidation of its snow a greater pressure than would ever be realized by its accumulation, but such a hypothetical case is beyond the limits of the Pleistocene problem.

would be accompanied by a lowering of the temperature of the district; and that a similar lowering of the temperature would accompany an increase of glaciation by the encroachment of the Pacific on the California coast, by the lowering of the temperature of the Pacific, or by a small change in the direction of the great air current. Adding now that a lowering of temperature through the lessening of solar heat would increase the glaciation, we may continue the discussion of the Pleistocene lakes with the assurance that if they were contemporaneous with the ancient glaciers of the Sierra Nevada, they occurred during epochs of relative cold.

THE EVIDENCE FROM MOLLUSCAN LIFE.

The hydrographic basins of Lake Bonneville and Lake Lahontan have the same latitude, lie at sensibly the same altitude, and are in general characterized by identical physical conditions. They are moreover contiguous, and separated by no barrier. There is thus every reason to group them together as a single homogeneous faunal district, and it will be advantageous so to regard them in discussing the climatic interpretation of the vestiges they contain of Pleistocene life. The Bonneville fauna has been enumerated in an earlier chapter. The Lahontan fauna is described by Russell in his monograph.[1] Each is meager, but taken together they afford bases for climatic inference in two biologic divisions, the division of fresh-water mollusks and the division of vertebrates.

The fresh-water mollusks were collected as opportunity offered by Russell's parties and my own, and specimens were sent to Call for examination. His preliminary results were of such interest that it was determined to afford him an opportunity to study the fossils in the field and to collect their living representatives in the same district. He accordingly visited Utah and Nevada in the summer of 1883 and spent two months in gathering the recent and Pleistocene shells. The combined collections were afterward studied by him and became the subject of an essay on the Pleistocene and recent mollusca of the Great Basin, which was published as a Bulletin of the Survey.[2] The statements which follow are partly based on this publication.

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[1] Geological History of Lake Lahontan, pp. 238-249.

[2] On the Quaternary and Recent mollusca of the Great Basin. By R. Ellsworth Call. Bull. U. S. Geol. Survey No. 11, 1884, pp. 13-67.

As appears from the following table, 18 species have been obtained from the Bonneville strata and 23 from the Lahontan. Eight of these are identical, making the whole number of species from the entire district 33. The number of recent species known in the same district is 36, and 26 of these are specifically identical with the Pleistocene forms. The entire known fauna of the district, recent and Pleistocene, comprises 43 species.

TABLE XI.—*Fresh-water Shells in the Bonneville-Lahontan Area.*

R = *Recent.* B = *Bonneville.* L = *Lahontan.*

Unionidæ	Margaritana margaritifera, Linn	R	....	L
	Anodonta nuttalliana, Lea	R	B	L
Corbiculidæ	Sphærium dentatum, Hald	R	B	L
	striatinum, Lam	R	....	L
	Pisidium compressum, Prime	R	....	L
	abditum, Hald	R		
	ultramontanum, Prime	....	....	L
Limnæidæ	Helisoma corpulentus, Say	R	....	L
	ammon, Gould	R	....	L
	trivolvis, Say	R	B	L
	subcrenatus, Carp	R		
	Gyraulus parvus, Say	R	B	L
	vermicularis, Gould	R	....	L
	Menetus opercularis, Gould	R	....	L
	Limnophysa palustris, Müll	R	B	L
	sumassi, Baird	R	B	L
	humilis, Say	R	....	L
	bulimoides, Lea	R	....	L
	bonnevillensis, Call	....	B	
	desidiosa, Say	R	B	
	caperata, Say	R		
	Limnæa stagnalis, Linn	R		
	Radix ampla, Migh	R		
	Physa gyrina, Say	R	B	
	humerosa, Gould	R	....	L
	ampullacea, Gould	R		
	heterostropha, Say	R	B	
	elliptica, Lea	R		
	lordi, Baird	....	B	
	Pompholyx effusa, Lea	R	....	L
	Carinifex newberryi, Lea	R	....	L
	Ancylus newberryi, Lea	....	....	L
	sp. indet	R		

TABLE XI.—*Fresh-water Shells in the Bonneville-Lahontan Area*—Continued.

R = *Recent.* B = *Bonneville.* L = *Lahontan.*

Rissoidæ	Amnicola dalli, Call	R		
	longinqua, Gould	R	....	L
	porata, Hald	....	B	
	cincinnatiensis, Anth	....	B	
	Fluminicola fusca, Hald	R	B	L
	Pyrgula nevadensis, Stearns	R		
	Bythinella binneyi, Tryon	R		
Valvatidæ	Valvata virens, Tryon	R	B	L
	sincera, Say	R	B	
Pomatiopsidæ	Pomatiopsis lustrica, Say	....	B	

Considering that the search which has brought to light these 43 species has been far from exhaustive, alike in the existing waters and in the Pleistocene strata, it is somewhat remarkable that five-sixths of the fossil forms are known also in the recent waters of the district; and we are permitted, if indeed we are not compelled, to regard the Pleistocene and recent faunas as actually identical.[1] The differences between the known faunas are therefore referable to accidents of discovery, and can not be given a climatic interpretation. If however we restrict attention to the 26 identical species and compare the fossil with the living representatives, we find a varietal difference of very striking character. The fossil shells are smaller than the living shells of the same species. This fact was discovered by Mr. Call during his preliminary examination of the fossils and was afterward verified by an elaborate series of measurements. Not all of the 26 species were collected in sufficient numbers to afford a good determination of the average size, but enough of them were well represented to give assurance of the generality of the law of difference.

[1] This inference admits of a mathematical expression. If the streams and the strata contain not only the same number of species but the same species, and if each of these is equally discoverable, then the most probable number of identities or coincidences between the known living species and the known fossils is expressed by the product of the number of living species known into the number of fossil species known, divided by the total number of species in the entire fauna. We do not know this total, but it surely exceeds 43; considering how very small a portion of the entire field has been searched, there can be no exaggeration in estimating it at 60. The mathematical formula then gives $\frac{36 \times 32}{60} = 20$ as the most probable number of identical forms in the fossil and recent collections. In point of fact, not all species are equally discoverable. Some are relatively conspicuous and others relatively ubiquitous, and these would be more likely to occur in both collections and thus increase the number of identical forms. The number of coincidences actually observed, 26, is therefore in apparent harmony with the number theoretically deduced.

Depauperation and Cold.—To account for this difference in size, several hypotheses were suggested, but only two appeared worthy of discussion, and to these Mr. Call directed his attention. The first hypothesis is that of cold, the second that of salinity. It was already known that the life of each molluscan species is conditioned by a certain range of temperature and by a certain range of salinity, and it was naturally inferred that a lowering of temperature insufficient to cause extinction might induce depauperation, and that a similar effect might be produced by the presence in the ancient lake waters of a small percentage of saline matter. For the purpose of testing these inferences, comparative measurements were made of shells now living in waters of various temperatures, and also of shells now living in waters differing in salinity—all specimens being obtained from the Bonneville-Lahontan district.

Church Lake, near Salt Lake City, Utah, has an altitude of about 4,300 feet; Little Gull Lake, in the Mono Basin, at the eastern base of the Sierra Nevada, lies three degrees farther south, and has an altitude of about 7,700 feet. The temperature of the second locality is not known as a matter of observation, but a comparison of topographic relations, and especially of the terrestrial floras, leads to the belief that there is about as much difference as that indicated by the altitudes, the climate at Little Gull Lake being 8 or 10 degrees (F.) colder. From these two lakes the same species, *Physa ampullacea*, was obtained in the same month, and comparative measurements were afterward made of series of adult shells. The ratio of size (linear) was found to be 100 (Church Lake) : 86 (Little Gull Lake).

Honey Lake, California, and Warm Spring Lake, Utah, lie at nearly the same altitude and latitude. Their temperatures are not known by observation, but as Warm Spring Lake, being of small area, has for its principal tributary a large spring of water at 128° F, it is highly probable that its molluscan life is conditioned by the higher temperature. Specimens of *Limnophysa palustris* were collected from both lakes and afterward measured, the averages showing a ratio of 100 : 88 in favor of the specimens from the warm lake.

These two illustrations support the hypothesis that within the climatic range of the Great Basin a low temperature of lake water is less favorable to the growth of gasteropods than a high temperature.

Depauperation and Salinity.—In seeking for natural examples illustrating the effect of salinity, there was not the same success in the elimination of coincident differences of station. Some of the brackish lakes of the Lahontan district contain living shells, but these are not available for comparison, because the same species have not also been discovered in the fresh waters of the district. Recourse was therefore had to brackish springs, and the shells inhabiting these were compared, one species with the denizens of a fresh-water lake and another with the denizens of fresh-water ponds. The brackish springs affording the shells rise from the Bonneville marls at the eastern base of the Promontory range in Utah, and are not thermal. Their waters were not analyzed, and their salinity was tested only by taste. It was estimated to be less than 0.5 per cent. Specimens of *Limnophysa palustris* from these springs were compared with other specimens from Honey Lake, and found to be only seven-eighths as large, the precise ratio being 87 : 100. Specimens of *Physa gyrina* were compared with other specimens from fresh ponds near Salt Lake City, and found to have a linear ratio of 82 : 100. It appears, then, that salinity is quite as competent as cold to determine the depauperation of fresh-water gasteropods.

We are thus led to inquire whether there is any independent evidence in regard to the freshness or salinity of the waters of the Pleistocene lakes. In the case of Lake Lahontan the presumption is strongly in favor of salinity, for the lake has no outlet, and though it may possibly on more than one occasion have buried its saline matter under playa deposits and thus freshened its water, we cannot say, with reference to any of the collected shells, that they belong to any such fresh-water epoch. The testimony afforded by the depauperation of the Lahontan shells is therefore not available in the climatic problem. The case of Lake Bonneville is different, for during its second expansion it freshened its water by overflow, and the sediment deposited during the second rise is clearly differentiated. We cannot indeed demarcate the portions of this bed which belong respectively to the epoch of rising water, to the epoch of outflow, and to the epoch of desiccation; but we know from the phenomena of the shore-lines that the rise of the water was slow, that the discharge was long sustained, and that the final subsidence was rapid down to the level of the Stansbury shore-line. We are thus enabled to assert with much confidence that the upper layers of the White Marl between the levels of the Provo and Stansbury shore-lines were deposited while the lake was freshened by outflow. And finding that shells gathered from those layers are small in size, we accept their depauperation as evidence of a colder climate. The subjoined table shows measurements of 25 adult shells collected from these layers near the town of Kelton, and gives comparative measurements of 18 individuals found living in Utah Lake, the largest body of fresh water within the Bonneville area. The ratio of linear dimensions is approximately 3 : 4, the recent shells being the larger. It is noteworthy that while each series exhibits considerable range in size, only two or three of the living shells are as small as the largest of the fossils.

TABLE XII. *Measurements of Fluminicola fusca.*

Living in Utah Lake.		Fossil in Upper Bonneville.	
Length.	Breadth.	Length.	Breadth.
mm.	*mm.*	*mm.*	*mm.*
12.50	8.10	9.94	6.62
12.00	7.80	9.50	6.40
11.90	8.20	9.10	5.50
11.72	7.14	9.00	5.56
11.50	8.00	8.50	5.56
11.30	7.64	8.44	5.60
11.00	7.70	8.36	5.70
10.80	8.00	8.34	5.22
10.50	6.70	8.30	6.10
10.50	6.52	8.30	5.54
10.50	6.40	8.20	5.32
10.24	6.50	8.10	5.08
10.22	6.90	8.10	5.50
10.10	7.00	8.08	5.28
10.00	7.24	8.06	5.56
9.70	6.72	8.00	5.34
9.70	6.52	7.96	6.50
9.52	7.00	7.94	5.50
10.76	7.23	7.82	5.40
		7.80	6.20
		7.72	5.38
		7.60	5.00
		7.58	5.40
		7.46	5.32
		7.24	4.98
		8.22	5.50

THE EVIDENCE FROM VERTEBRATE LIFE.

The Pleistocene mammals thus far discovered in the Bonneville and Lahontan Basins are few in number. Proboscidean bones (*Elephas* or *Mastodon*) were found in the "Intermediate Gravels" of the Lahontan Basin (equivalent to gravels of the Inter-Bonneville epoch), in the Upper Lahontan beds (equivalent to the White Marl), and in a bog resting on the White Marl. Bones of a horse (*Equus*), of an ox, and of a llama, and an obsidian arrow head, were found in the Upper Lahontan.[1] Bones of musk-ox discovered near Salt Lake City, though of doubtful age, are presumptively Pleistocene.

The list is greatly extended by including the fauna discovered by Mr. C. H. Sternberg near Christmas Lake, Oregon. The locality was afterward visited by Mr. Russell, who found the containing formation to be a lacustrine deposit surrounded by a shore-line, and otherwise agreeing in its physical relations with the Bonneville and Lahontan and other Pleistocene beds of the Great Basin. The horizon of the vertebrate remains is close to the top of the formation, indicating approximately the same date as that of the White Marl. Cope has studied the bones biologically, and from him we learn that the fauna includes the coyote, a beaver, and two species of gopher; and of extinct mammals, the mammoth, an otter, a giant sloth, two species of horse, three of llama, and a deer. It includes also the coot, three living grebes, three living geese and one extinct species, an extinct cormorant, and an extinct swan.[2]

In order to ascertain the bearing of these vestiges on the question of the contemporaneous climate, attention will be given to the present climatic and geographic range of such of the species as yet survive, and also to the present range of the genera to which extinct species belong.

Man is now cosmopolitan. It is known that in Pleistocene time he lived near the margins of European and American ice sheets, but his contemporaneous equatorial range is not ascertained. The coyote, *Canis latrans*, ranges southward to the plateau of Mexico and northward to the Saskatchewan Plains. Near its northern limit the local annual temperature is

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[1] Russell. Geological History of Lake Lahontan, pp. 238-9, 246-9.

[2] Bull. U. S. Survey Terrs., vol. 4, 1878, p. 389.

about twenty degrees lower than at Christmas Lake; near its southern limit, more than twenty degrees higher.

Thomomys talpoides, a pocket gopher, ranges from Kansas to the Assiniboin River, its range including climates slightly warmer and also from ten to fifteen degrees cooler than that of Christmas Lake. *Thomomys clusius*, being known only in its type specimen, has no range. The climate of its sole known locality, Bridger's Pass, Wyo., is five or ten degrees cooler than that of Christmas Lake.

The beaver reported is *Castor fiber*, the European species; but as the distinctness of the American form has been denied, it is possible that no discrimination is here intended. The European beaver lives in northern and central Europe; the American ranges from Arizona to the Arctic Circle.

The musk-ox is now restricted to that part of North America lying north of the sixtieth parallel. The most genial climate of its range is far more severe than that of the Salt Lake Valley, but may perhaps be compared with that of the recesses of the Wasatch and Uinta mountains. During the Pleistocene it abounded on the plains of Siberia as well as in Germany, France and England.

The other mammalian species are all extinct, and one only is known to have climatic significance. The mammoth was characteristic of the European Pleistocene, and was distinguished from living elephants by its hairy coat.

The modern otters belong to temperate and sub-arctic faunas, and so do deer of the genus *Cervus*. The llamas are at home in the mountains of South America, and range southward to Terra del Fuego.

Modern representatives of the horse genus live in tropical and temperate climates, but in Pleistocene times they shared with otters and deers the boreal climate of England.

Of the climate suited to the fossil sloth, *Mylodon sodalis*, we have no better evidence than is afforded by his association with this fauna.

The coot, the grebes, and the geese all range far to the north and to the south of the Christmas Lake locality. The coot ranges from Alaska to Central America. *Podiceps occidentalis* is known to range from Mexico to northern Manitoba, *P. californicus* from Guatemala to Great Slave Lake, *Podilymbus podiceps* from South America to British Possessions. *Anser canadensis* extends from the Arctic Circle to Mexico, *A. albifrons gambeli* from Alaska to Texas, *A. nigricans* from the Arctic Circle to the peninsula of California.

The extinct swan and cormorant likewise belong to genera of considerable range. Though *Cygnus* and *Graculus* occur chiefly in the temperate zone, they overpass both the tropic and the polar circle.

The avian life manifestly throws no light on the question of climate, and the same may be said of man, the coyote, the beaver, the otter, the deer, the horses, the llamas, and the sloth. The presence of the gopher comports with the idea that the climate of the lacustrine epoch did not differ widely from the present climate. The mammoth favors the view that the climate was cooler. The musk-ox speaks more decidedly of cold, but his evidence is doubly indefinite; first, because he may have lived on the adjacent high mountains instead of in the Salt Lake Valley; second, because we do not know whether he lived during a lacustrine or during an interlacustrine epoch.

All told, the evidence from vertebrate life appears to me not merely inconclusive but valueless. Temperature is one of a complex of factors constituting climate. Climate is one of a complex of conditions limiting the distribution of vertebrate species. It is not safe to assume in the case of an individual species that temperature is the important or controlling factor and then draw inferences in regard to temperature; only the cumulative testimony of a fauna can yield trustworthy conclusions.

The available biotic evidence is therefore restricted to the testimony of the fresh-water mollusks, and this, if I understand it aright, points to the conclusion that the lake epochs were epochs of relative cold. So far as it goes, it favors the correlation of ice maxima with water maxima.

THE EVIDENCE FROM ENCROACHING MORAINES.

As first announced by Emmons, the glacier that formerly descended Little Cottonwood Canyon from the Wasatch summits left its moraines within the area of Lake Bonneville.[1] A little farther south, two other

[1] S. F. Emmons. Geol. Explor. of the 40th Parallel, vol. 2, p. 354.

moraines, belonging to the same group of glaciers, lie at about the same level; but with these exceptions all vestiges of the Pleistocene glaciers of the basin lie above the Bonneville shore-line.

In the Lahontan Basin there are no similar instances of contiguity, but several occur in the Mono Basin, and their phenomena are believed to be germane to the present discussion. The Pleistocene history of Mono Lake is recorded, like that of Great Salt Lake, in a sheet of sediments rising from the water's edge to a system of encircling shore traces. As determined by Russell, the expanded lake had no outlet,[1] so that its oscillations must have been determined purely by climate. The Mono drainage basin is one of the many components of the Great Basin, and is contiguous to the hydrographic basin of Lake Lahontan. Like Lahontan, its water supply is derived mainly from the Sierra Nevada, which overhangs it on the west. Analogy suggests that its lake surface rose and fell in response to the same climatic changes that created and abated Lake Lahontan and Lake Bonneville, and this view is sustained by the evident freshness of its fossil shore-lines. In one respect, however, the correlation is incomplete. The Bonneville sediments and the Lahontan are each clearly divisible into two series, separated by a horizon of unconformity by erosion; but in the Mono Basin no satisfactory division has been made out. To my mind, this negative evidence, which may fairly be referred to imperfection of exposure, has less weight than the climatic analogy, and I am decidedly inclined to regard the maximum flood of the Mono Basin as the equivalent and contemporary of the maximum flood in each of the larger basins. I shall therefore discuss the relation of the ancient shore-lines and sediments to the moraines at the mouths of the Sierra canyons as a part of the evidence in regard to the Bonneville climate. First in order, however, are the phenomena of the Bonneville Basin.

Wasatch-Bonneville Moraines.—The western front of the Wasatch is determined by a great fault. From the line of this fault an alluvial plain descends westward to the Jordan River and Great Salt Lake, while eastward springs a steep face of solid rock, the escarpment of the upthrown orogenic block.

[1] Quaternary History of Mono Valley, California, by I. C. Russell, Eighth Ann. Rept. U. S. Geol. Survey, 1889, p. 300.

At intervals the rock face is divided by narrow clefts or gateways, whence streams issue from the interior of the range. Between each pair of adjacent streams is an acute ridge of rock, whose roof-like cross-profile marks it as the product of aqueous sculpture. The end of each is truncated by the great fault, and the truncated terminals, standing in line, constitute the rock face at the margin of the plain. The plain was covered by the water of the ancient lake, and the Bonneville shore-line is scored partly on the alluvium and partly on the face of solid rock. Little Cottonwood Canyon heads in the highest part of the range, among peaks with an altitude of 12,000 feet, and after a curving course of twelve miles ends at the rock face in a gateway whose threshold is slightly lower than the Bonneville shore-line. The glacier which anciently followed it issued from the gateway, and at its maximum development encroached upon the plain about one mile, recording its position at various stages by lateral, frontal, and terminal moraines. Within the throat of the canyon, scattered erratics are the only debris, but immediately outside are massive lateral moraines. At the mouth of the canyon its walls are of gray quartzite, which in weathering assumes a dark brown color, but in the heart of the range they are of white granite, and the morainal debris at the margin of the plain is nearly all granitic. This contrasts strongly with the dark quartzite, and enables the observer to trace out the distribution of the erratics from a single commanding position. The lateral moraine at the south is of typical form—an acute ridge of granite bowlders. Where it joins the mountain, its crest stands 340 feet above the flood plain of the creek; but it falls away rapidly, and at a mile it has reached the level of the plain, beneath which it sinks. Before disappearing, it divides into four or five members, all of which curve toward the axis of the glacier in such manner as to indicate that they were the lateral portions of successive frontal moraines. The northern or right-hand lateral moraine is of a very different type, being broad and flat-topped, and rising only about 100 feet above the adjacent flood-plain of the creek. Its surface exhibits fewer bowlders than does the left moraine; and a fresh section at one point betrays an obscure horizontal arrangement of its material. Scattered bowlders of granite are to be seen on the adjacent wall of quartzite for more than 200 feet above it, and these extend northward along the mountain side for half a mile beyond the canyon. Their upper limit becomes gradually lower as the distance from the canyon increases.

A clearer conception of these relations may be derived by consulting Pl. XLII, where the morainal masses are colored blue. Their proper interpretation appears to be, that after the glacier had built two lateral moraines upon the plain in the usual way, it expanded toward the north, overthrowing and overflowing the moraine on that side and destroying its characteristic form.

The plain into which the branches of the southern lateral moraine sink and disappear is alluvial. It not merely surrounds the outsides of the moraines but occupies the space between them, and extends up the canyon a half mile or more. At its upper limit in the canyon, the creek channel excavated from it is shallow, but its depth gradually increases, being 60 feet near the ends of the moraines, and nearly 200 feet at a point two or three miles beyond. Where the greatest section is exposed, the alluvium has a depth of 65 feet, consisting of gravel, coarse and fine, with a preponderance of granitic pebbles and occasional passages of sand. Beneath it, is a greater depth of fine sand, laminated and ripple-marked, and abounding in mica flakes. This sand is evidently a subaqueous deposit and records an epoch during which the lake stood higher than the Provo shore-line. The gravel above it does not exhibit the cross lamination characteristic of deltas, and must be classed as an alluvial deposit. It marks a time when the lake stood lower than the Bonneville shore-line, and is probably referable to the Provo epoch. To establish the validity of this reference, an attempt was made to trace the alluvium continuously to the Provo shore-line, but this was frustrated by a system of recent displacements which traverse the plain in various directions, giving rise to terraces which can not in every case be distinguished from the stream terraces with which they are associated. After making all allowance for displacements, however, it is sufficiently evident that when the ancient alluvium was deposited, the descent of the stream was less rapid than at present, and this slower descent is most satisfactorily accounted for by assuming a barrier of lake water. The alluvium is therefore referred to some epoch of the expanded lake.

The next canyon to the southward is distinguished from Little Cottonwood Canyon by having a steep grade throughout. Instead of beginning in the recesses of the range, it heads upon the western face and descends abruptly to the plain. At its lower extremity are moraines equally massive with those of Little Cottonwood Canyon. They include two lateral moraines about a mile in length, springing from the angles of the canyon walls, and uniting in an exceptionally heavy terminal. Just within the mouth of the canyon is a well-defined frontal moraine, and the branching of the laterals indicates that a second frontal was formed between this and the terminal, but has been buried by the alluvium accumulated above the terminal. The outflowing stream, Dry Cottonwood Creek, has indented the terminal, but cascades in passing it, and has much work to perform before it will have established a uniform grade through it. The base of the terminal is in this case not buried by alluvium, but the configuration of the neighboring plain suggests that it may once have been partially covered and afterward denuded by streams. (See Pl. XLII, where the creek is erroneously called "Big Cottonwood".)

Two miles farther south, a similar high-grade canyon, whence issues Big Willow Creek, is furnished at its mouth with a similar moraine system, of which the terminal is the most conspicuous element. It stands free upon the surface, with no evidence of an alluvial or lacustrine covering.

The alluvial plain does not at all points reach the mountain side at the same altitude, but is highest at the mouths of the large canyons. In the vicinity of the moraines, its highest point is at the mouth of Little Cottonwood Canyon, and it is there a few feet above the horizon of the Bonneville shore-line. Elsewhere the shore-line is scored upon the steep mountain front. It is to be seen a short distance north of the northern moraine of Little Cottonwood Canyon; it appears again between the moraines of Dry Cottonwood and Big Willow Canyons; and it reappears beyond the latter; but no trace of it was detected upon the moraines themselves. In the case of the Little Cottonwood moraines, the alluvial cover prevents examination at the horizon of the shore-line; but the other moraines are fully exposed to view.

Before attempting the interpretation of these glacial phenomena, it will be well to recite again the lacustrine history with which they are to be compared. Lake Bonneville was twice formed and twice dried away. It attained its maximum size during its second term, and the records of the second rising so far mask and obliterate the records of the first, that these are discoverable at comparatively few points. The shore-line observed in the vicinity of the moraines, and the alluvial and lacustral deposits exposed on the banks of Little Cottonwood Creek, all belong unquestionably to the second Bonneville epoch, and that epoch alone can we hope to compare with the epoch of the moraines. When the lake reached the horizon of the Bonneville shore-line, during its second rising, it found outlet, and its further rise was prevented. The erosion of the barrier was exceedingly rapid until the water had fallen to the Provo level. The resistance of this limestone held the lake at a constant height for a long period, and from this level the water finally receded by desiccation. Had the rim of the basin been so high as to prevent outflow, we can not say how far the lake would have risen before the passage of the climatic maximum permitted it to fall again. We may be sure, however, that the climatic maximum was somewhat later than the epoch of the Bonneville shore-line. On the other hand, the lake area at the Provo stage was only two-thirds as great as at the Bonneville, and the peculiar climatic changes that expanded the lake were fast declining when the water finally fell from the Provo shore-line. The climate of maximum efficiency for the production of lakes therefore occurred after the epoch of the highest shore-line and before the close of the epoch of the Provo shore-line.

If the glaciers had attained their maximum extent either during or before the epoch of the Bonneville shore-line, their terminal moraines would have been subject to wave action at that horizon, and scored with shore marks; but the two terminal moraines which are well exposed to view exhibit no shore-lines. If the glaciers had attained their maximum after the close of the Provo epoch, the Little Cottonwood moraines should rest upon the alluvium, instead of being partially buried beneath it. It appears quite consistent with the phenomena to suppose that the epoch of maximum glaciation was covered by the longer epoch of the Provo shore-line. The greater part of the alluvium outside the moraines may have been deposited while they were in process of formation, the inter-morainal portion being added after the ice had retreated.

We are thus led to assign the same narrow time limits to the epoch of the climatic maximum tending to produce lakes and to the epoch of the climatic maximum producing glaciers; and one farther step will lead us to the conclusion that the two maxima are identical. But before taking that step, we must examine the evidence from the Mono Basin.

Sierra-Mono Moraines.—The Pleistocene history of the Mono Basin was systematically investigated by Russell. Only a few days were spent by me in the valley, and these were devoted chiefly to the features described in the following paragraphs. In preparing these paragraphs, I have availed myself of Russell's work wherever necessary, but the local descriptions are mostly at first hand. The reader who cares to pursue further the history of the valley will find it fully presented in Russell's paper.[1]

Lake Mono has an altitude of 6,730 feet. When expanded by the Pleistocene climate, it carved a maximum shore-line 670 feet higher. The eastern face of the Sierra Nevada is here remarkably abrupt, and the Pleistocene high-water mark runs very near its base. In glacial times the broad back of the Sierra bore a great field of névé, the surface of which ranged in altitude from 10,000 to 12,000 feet. From this streamed glaciers east and west, and five of the eastward-flowing entered the Mono basin. One stopped before reaching the level of the old shore-line, the other four reached it or passed beyond it. These will be enumerated in order from north to south, with whatever description is necessary to show the relation of the observed glacial phenomena to the lacustral.

The Mill Creek glacier emerges from its rocky channel and debouches upon the plain at the horizon of the old shore-line. Beyond its walls of rock its dimensions are indicated by lateral moraines, which rapidly converge and at the same time bend northward. They are steep-sided ridges, studded with large bowlders. They extend less than a mile upon the plain, and though no terminal moraine is visible, we are assured by their convergence that they represent the full length of the glacier. The old shore-line

[1] Eighth Ann. Rept., U. S. Geol. Surv., pp. 261-394.

is distinctly marked not only on the outer face of the right moraine but on the extremities of both, and for a short distance on the inner faces of both. Its character is that of a cliff and terrace, but the notch is not deeply cut, and the extremities are but slightly truncated.

Seven miles farther south Leevining Creek issues from the mountain face at about the altitude of the old shore-line. The modern lake is there close at hand, and the mountain face is steep. Upon the steep slope, the creek has built a large alluvial structure which projects a cape more than a mile into the lake. This mass of alluvium has not the symmetrical form of an alluvial cone, but descends somewhat unequally and irregularly, being evidently a compound delta, the component parts of which were formed at different levels of the lake. The glacier following the valley of this creek had for several miles a uniform width of 1¼ miles, and this width was not diminished at the mouth of the canyon. Like the Mill Creek glacier, it curved northward at that point, its left margin following the flaring mouth of the canyon, while its right, as indicated by the surviving lateral moraine, swung free. One mile of this free moraine is preserved, but no terminal is to be seen. There are, however, two well marked frontal moraines lying respectively three-quarters of a mile and two miles back from the end of the lateral. The old shore-line is scored on the outside and inside of the lateral moraine, and appears also on the opposite side of the glacial channel against the face of the mountain. It can be traced only a short distance up the glacier valley, because its features have been recently obliterated by the creek. The end of the moraine has evidently been cut away by the waves, but the extent of this removal is unknown. The surviving portion affords no indication, by size or direction, that the end of the glacier was close at hand. When the lake stood about 33 feet lower than its highest shore-line, the creek built a small delta at the mouth of the glacial valley, the front of the delta reaching to the end of the truncated lateral moraine. The head of the delta was at the foot of the lower frontal moraine. Near its head there is a terrace eight feet higher, which appears to be a fragment of an earlier built delta that was destroyed during the construction of the lower one. The creek channel now lies entirely below these delta plains.

The next glacier descending to the lake level issued from Bloody Canyon, six miles farther south, and at the time of its greatest development stretched four miles upon the plain. Its position on the plain is marked by a pair of lateral moraines, which gradually converge as they descend the slope. From beneath the right member of this pair issue the extremities of two other pairs, marking earlier courses of the same glacier. These older moraines do not rise so high above the plain as those later formed, and are less acute in profile. They have evidently been subjected to atmospheric agencies for a relatively long time, and it seems probable not only that their crests have been worn and rounded, but that their bases have been buried by the slow accumulation of alluvium. The waves of the ancient lake barely reached the extremities of these moraines, older and newer. The flood plain of the streamlet which issues from between the newer moraines coalesces at their extremities with the terrace wrought by the waves, so that we cannot say in this case whether the lake water entered the valley between the moraines. The moraines end in low sea cliffs, and there is no terminal, though the convergence of the laterals indicates that the ice projected a little farther. That a terminal properly belongs to the system seems to be shown by a series of frontals, deposited at intervals farther up the ice channel.

The Rush Creek moraine surpassed all the others in size, having a width of 1⅝ miles where it entered the plain. Its lateral moraines stand free for a distance of three miles, and each one is characterized by several parallel crests, continuous with corresponding frontals. Three frontals of some magnitude follow each other in rapid succession near the end of the laterals. The position of the terminal, or extreme frontal, is not certainly known. The old shore-line is but faintly traced in this portion of the basin, where it margined a shallow bay, but its horizon was determined to fall near the base of the outermost frontal. A half mile farther down the slope the plain is interrupted by a few small islands of morainal matter, unmistakably characterized as such by the presence of gigantic erratic bowlders. These mark the position of what may be another frontal moraine, but is probably the terminal moraine.

With one voice these four localities tell us that Mono Lake occupied its maximum level after the glaciers of the Sierra had retreated from their most advanced position. But their testimony goes no farther. The narrow range of levels common to the two may have been occupied first by the ice and afterward by the water, or it may have been occupied by both together. We can only say that the ice was first to retreat.

Combining this result with that afforded by the moraines of the Bonneville Basin, we conclude that the epoch of greatest glaciers fell within the second period of lake expansion, but did not coincide with the epoch of greatest water-supply; it occurred somewhat earlier. If the two sets of phenomena were consequent upon the same series of climatic changes, then the lacustral changes lagged behind the glacial.

That such a lagging admits of plausible explanation may readily be shown. The névé and glaciers of the Mono district occupied a portion of the catchment basin of the lake. The precipitation which they accumulated during their growth was subtracted from the precipitation tributary to the lake, and the same was afterward returned to the lake when they were finally melted. Their mass of ice may therefore be regarded as a portion of the water-supply of the lake, arrested in its progress. When the climatic conditions were favorable for the growth of lake and glaciers, the growth of the glaciers antagonized and delayed the growth of the lake. When the climatic conditions favored the wasting of lake and glaciers, the waste of the glaciers fed the lake and thus antagonized its depletion. The ascending and descending phases of the lake thus fell behind the corresponding phases of the glaciers, and the maxima and minima, or turning points, were correspondingly displaced.

It is to be observed that this explanation is quite distinct from the theory, alluded to by Whitney,[1] that the Pleistocene lakes were the sequel of the Pleistocene glaciers, being created by their melting. Such a relation is quantitatively impossible. In the Mono basin, indeed, the mass of snow and ice upon the mountains may have been equal to the volume of water in the valley, but in the Lahontan and Bonneville basins it was far too small. King's map of the Pleistocene glaciers of the Bonneville Basin indi-

[1] The Climatic Changes of Later Geological Times, p. 185.

cates a superficial extent of 710 square miles, an area only $\frac{1}{28}$ as large as the water surface of Lake Bonneville. One thousand feet is a liberal estimate of the mean depth of the ice, while the mean depth of Lake Bonneville was about 700 feet. The body of water was therefore about twenty times larger than the body of ice.

The evidence from the moraines is thus shown to be consistent with that from the molluscan fauna, and they jointly confirm the presumption derived from the recency and exceptional nature of the lakes and glaciers, that the two phenomena were coordinate and synchronous results of the same climatic changes. The correlation of the phenomena, originally based on analogy merely, is thus sustained, and it now stands on a surer foundation.

It follows as a corollary that the glacial period of the Sierra Nevada, the Wasatch, and other mountains of the western United States was divided into two epochs separated by an interglacial epoch; and this has not been independently shown. The bifurcation of the Bloody Canyon moraines demonstrates a temporary retreat of the glaciers, but that retreat was not necessarily great. The following explanation of the bifurcation, advanced by Russell[1] and McGee[2] appears to be fully sustained by the phenomena. After the glacier had constructed on the plain its oldest pair of lateral moraines, it retreated to a point near the canyon, and there deposited a heavy frontal moraine. Readvancing, it was opposed by this frontal, and found a point of least resistance in the left lateral moraine, which in each pair is lower than the right. Overriding that, and finally demolishing it, it took a new course upon the plain, and this new course was afterward modified by the same process, the obstructing frontal being near the extremity of the laterals. At almost any point in the history thus deduced from the moraines, there might have occurred a great retreat of the glaciers, involving even their temporary extinction, without the production of any features we should be able to detect.

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[1] Eighth Ann. Rept. U. S. Geol. Survey, p. 357.

[2] Meridional deflection of ice streams, by W. J. McGee, Am. Jour. Sci., 3d Series, vol. 29, p. 386.

SUMMARY OF CHAPTER.

The Bonneville Basin originated by distortion of the earth's crust, and came into existence long before the Bonneville epoch. Little is known of its earliest climatic and physical conditions, but it was comparatively dry for a long period immediately preceding the formation of the great lake. During this period, alluvial cones were formed about the bases of all its greater mountain ranges, and the smaller ranges were wholly or partly buried by valley deposits. The valley deposits may have been entirely alluvial, but were probably also partly lacustral, the lakes being of small extent.

There followed two epochs of high water, with an interval during which the basin was nearly or quite empty. The first of these epochs was at least five times as long as the second. The second scored its water mark 90 feet higher than the first, and would have encroached still farther on the basin sides had it not been checked by outflow. During the epoch of outflow, the discharging current eroded the rim, and thus lowered the lake 375 feet; and after the outflow had ceased, the water fell by desiccation, with one notable interruption, to its present level in Great Salt Lake. The inter-Bonneville epoch of low water was of greater duration than the time that has elapsed since the final desiccation.

The final drying of the basin divided it into ten or twelve independent interior basins. Two of these now contain lakes, the others for the most part contain playas, or playa lakes with beds of salt. The Sevier Basin is exceptional in that its lake was 30 miles in length when first surveyed, and has since disappeared, the water of its tributary stream being appropriated for irrigation.

Since 1845, the date of the first record, the surface of Great Salt Lake has oscillated through a range of 10 feet, reaching maxima in 1855 and 1873, and minima in 1847–50 and 1861. Since 1879 there has been little change. A progressive fall in the future is indicated, not as a matter of climate, but as a result of the rapidly increasing utilization of the tributary streams for the purposes of agriculture. The changes in level have been associated with changes in area and volume. The maximum area was about 25 per cent. greater than the minimum, and the maximum volume about 75 per cent. The salinity, which is high, has varied inversely with the volume, and the predicted decrease in volume will lead to the precipitation of a portion of the mineral contents.

A comparison of the lake's oscillations with the meteorologic record of the region appears to show that the height of the lake in any year is a cumulative function of the precipitation during preceding years, but establishes no relation between lake oscillations and temperature oscillations.

The modern oscillations of lake surface are exponents of the irregular rhythm of climate due to the interaction of complex conditions otherwise constant. The great oscillations which alternately created and destroyed Lake Bonneville are of a different order, and require for their explanation more permanent changes of conditions. An examination of the topography of the basin shows that such diversion of water-courses and other local geographic changes as may possibly have occurred are inadequate to account for the rise and fall of the lake. The history of the Bonneville oscillations is moreover closely paralleled by that of the Lahontan oscillations, and it is believed that they belong to a series of climatic changes affecting not only these two basins but the adjacent subdivisions of the Great Basin. The question whether the lakes are phenomena of the Pleistocene period, their expansion being wrought by the same climatic factors which enlarged the glaciers, has previously been answered in the affirmative on the basis of certain analogies. A review of these analogies indicates that two are valid, while two others are not. The common recency of lakes and glaciers, as indicated by the freshness of the vestiges, affords a presumption in favor of their identity in time, and a farther presumption is afforded by the fact that the lacustral and glacial phenomena each interrupted a series of events of a different character. The argument from the parallelism of the lacustral and glacial histories, each being characterized by two principal maxima, is weakened by the fact that the highest authorities on the Pleistocene period are not agreed in regard to its bipartition. The belief that any climatic cause competent to increase glaciation would likewise increase lakes appears on analysis to be ill-founded, certain possible combinations of conditions being competent to cause simultaneously an increase in the area of ice and a decrease in the area of water.

The discarded arguments from analogy are replaced by other arguments of a more direct and satisfactory nature.

A discussion of the conditions controlling the climate of the western United States shows that any change competent to increase the glaciers on on the mountains would lower the temperature of the lake basins. An appeal may therefore be made to the fauna of the lake epoch for information in regard to climate. The mammals give no intelligible answer; but the fresh-water mollusks declare by their depauperation that the conditions of life were then less favorable. In the case of Lake Lahontan, and in the case of the first Lake Bonneville, the unfavorable condition may possibly have been impurity of water; but the second Lake Bonneville was freshened by outflow, and the dwarfing of its mollusks is best explained by low temperature.

The moraines of three Pleistocene glaciers descend from the Wasatch Mountains to the level of the Bonneville shore-line; the moraines of four glaciers descend from the Sierra Nevada to the level of the old shore-line of Mono Lake; and the relations of these moraines to the shores of the lakes and the associated deposits indicate that the maximum stage of the lakes coincided closely with the epoch of maximum glaciation.

These phenomena sustain the theory that the Pleistocene lakes of the western United States were coincident with the Pleistocene glaciers of the same district, and were produced by the same climatic changes. It follows as a corollary that the glacial history of this region was bipartite, two maxima of glaciation being separated, not by a mere variation in intensity, but by a cessation of glaciation.

CHAPTER VII.

LAKE BONNEVILLE AND VOLCANIC ERUPTION.

In this chapter it is proposed to show the relations, and especially the chronologic relations, between the volcanic history and the lake history of the Bonneville Basin. The only species of volcanic rock there erupted during or near the Bonneville period is basalt, and this appears to have been thrown out alike before, during, and since the lacustral epochs. The description of the various lava fields will in a general way follow the inverse order of their formation, but precedence will be given to the more typical localities.

Of the various volcanic districts of Utah, that which is most interesting in this connection occupies the eastern portion of the Sevier Desert in the vicinity of the towns of Holden, Fillmore, Corn Creek, Kanosh, and Deseret. The Pavant Range there forms the eastern limit of the desert plain, and is itself composed of uplifted strata ranging in age from Carboniferous to Tertiary. The volcanic buttes and tables, all very small as compared to the mountain range, rest upon the open plain, at distances varying from 10 to 30 miles. Nearest to Fillmore is the Ice Spring lava field, with its cluster of craters. Just south of it are the Tabernacle field and crater. Still to the southward and 10 miles away are two considerable buttes, not far from the town of Kanosh, and west of these lies a high basaltic table several miles in extent. North of the Ice Spring field there is a continuous volcanic tract, some 10 miles in extent, for the most part coincident with the plain, but including also a large mesa opposite Holden, and a large tuff cone, Pavant Butte. West of this tract and south of the town of Deseret lies a basalt table, and farther south stands a tuff cone, Dunderberg Butte.

The Ice Spring craters, the Tabernacle lava beds, and Pavant Butte were first visited by the writer in 1872, and an account of them may be found in the report of the Wheeler Survey.[1]

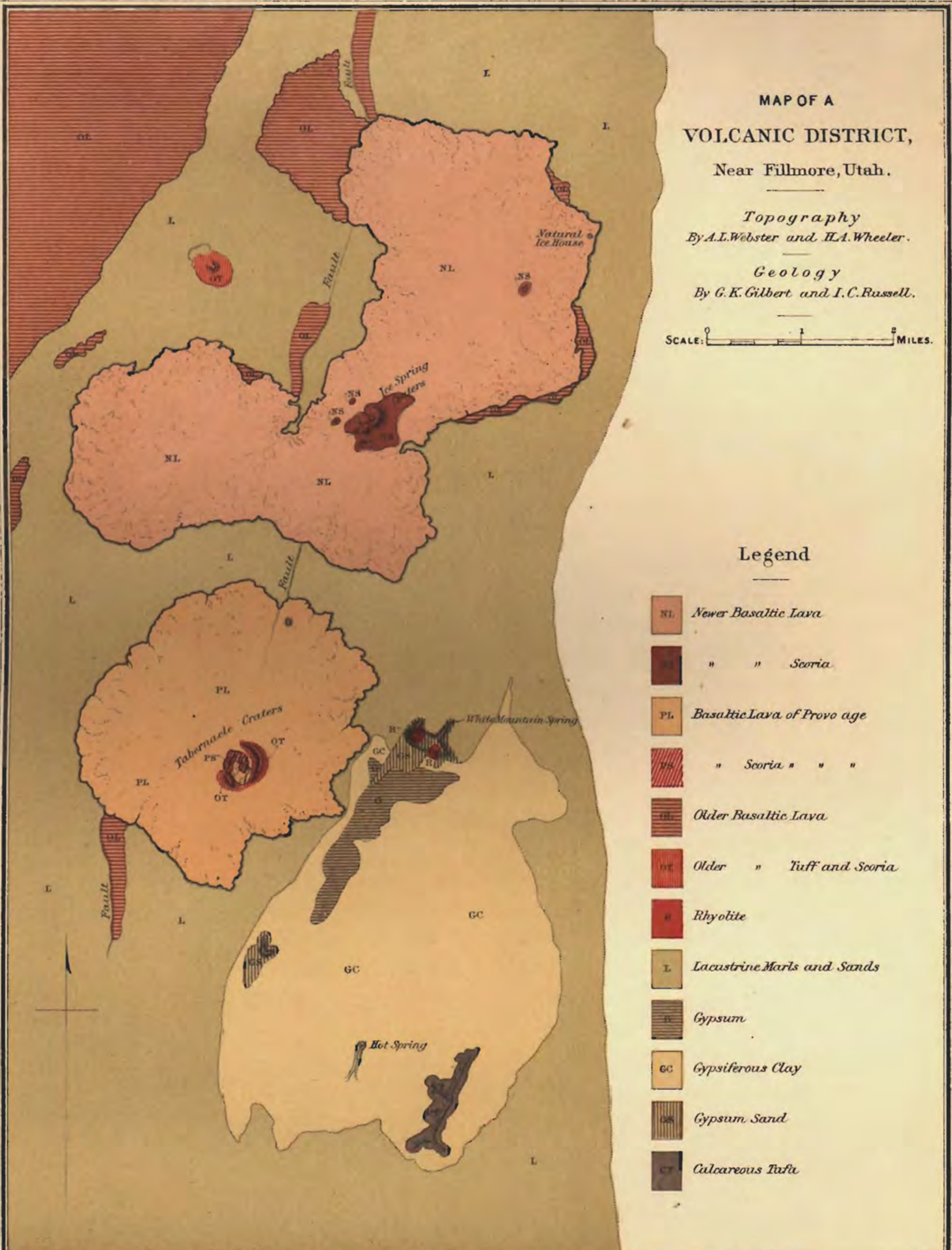
ICE SPRING CRATERS AND LAVA FIELD.

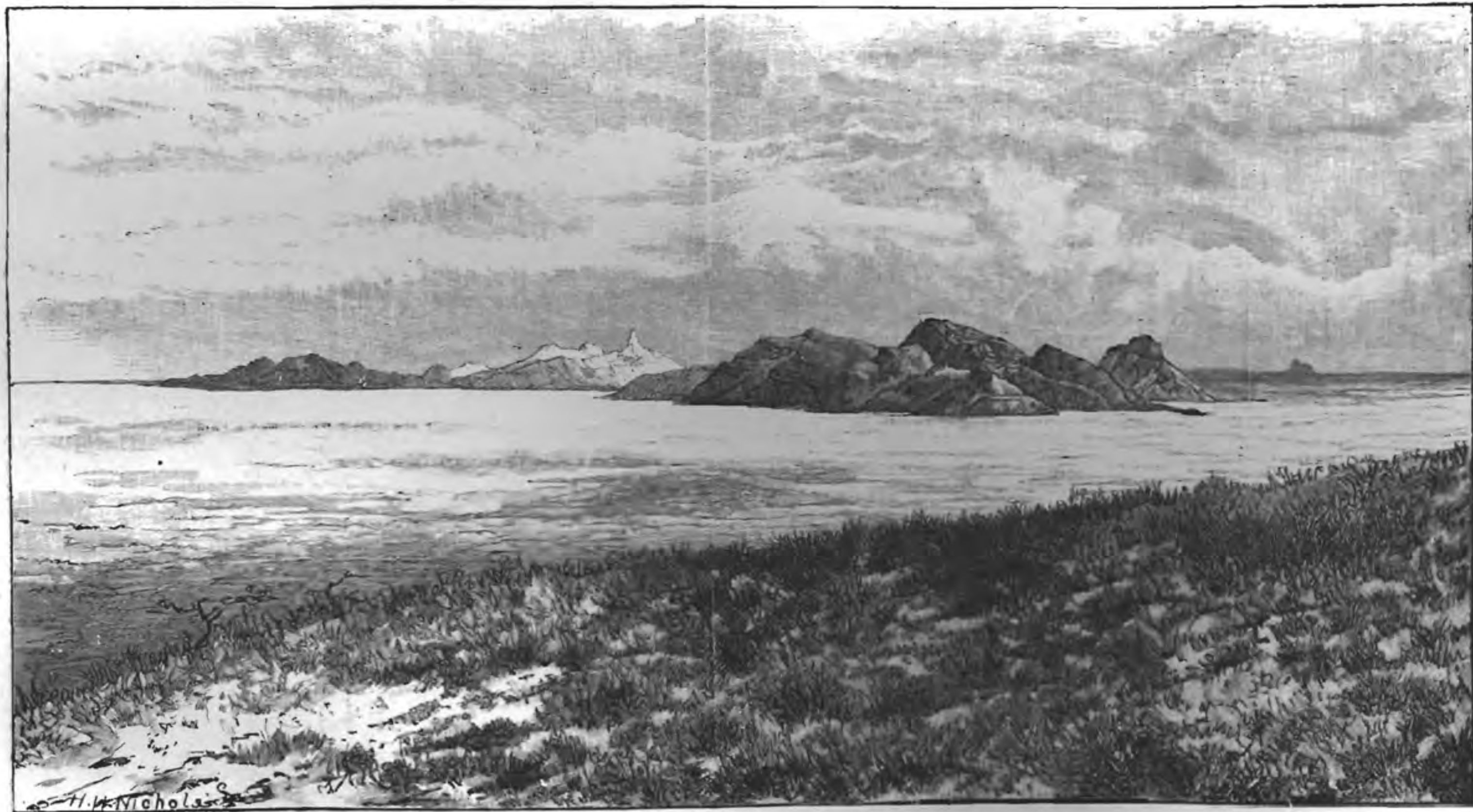
The lavas of this locality are the most recent within the Bonneville area, and their phenomena are typical of subaerial eruption.

The craters are grouped closely together, and the manner in which they overlap each other, as well as their relations to the various lava flows, demonstrate that they were formed successively rather than synchronously. Three only are preserved entire, but fragments of nine more were discovered, and it is probable that the denudation of the locality would reveal beneath the accumulated lava and scoriæ the remains of numerous others. Of the discovered crater rings no two are concentric. There have been at least twelve successive eruptions, through as many independent vents, within a radius of 1500 feet, and none of these eruptions appear to have been large. It would seem that the subjacent terrane opposes so little resistance to the upward progress of the lava that a new opening is made more easily than an old one is reopened after a cessation of activity has permitted congelation in the conduit. The immediately subjacent formations are in this case probably the White Marl, the Yellow Clay, and other feebly coherent valley deposits.

The dimensions and general relations of the craters and lava fields will be best understood if the reader will examine Pls. XXXV, XXXVII and XXXVIII in connection with the following description. One of the largest of the scoria hills is the Crescent, a crater fragment showing nearly one-half of the original circle. It rises 250 feet above its eastern base, and the entire crater appears to have had a diameter of 2200 feet. It is composed of scoriaceous fragments, in the main loosely aggregated, but in part bound together by harder layers which appear to have been produced by splashings of molten lava from the crater. These give it a rude concentric stratification, in the main inclined outward, parallel with the outer slope, but also inclined inward at a very high angle conformable with the inner

[1] Surveys West of the 100th Meridian, vol. 3, pp. 136–144.


MAP OF A
VOLCANIC DISTRICT,
Near Fillmore, Utah.
Topography
By A.L. Webster and H.A. Wheeler.
Geology
By G.K. Gilbert and I.C. Russell.
SCALE: 0 1 2 MILES.
Legend
NL Newer Basaltic Lava
NS " " Scoria
PL Basaltic Lava of Provo age
PS " Scoria " " "
OL Older Basaltic Lava
OT Older " Tuff and Scoria
R Rhyolite
L Lacustrine Marls and Sands
G Gypsum
GC Gypsiferous Clay
GS Gypsum Sand
CT Calcareous Tufa
Fault
Natural Ice House
Ice Spring Craters
Tabernacle Craters
White Mountain Spring
Hot Spring



VIEW ON GREAT SALT LAKE DESERT, SHOWING MOUNTAINS HALF BURIED BY LAKE SEDIMENTS.

slope. One end of the Crescent is buried beneath a lava crater, the Miter, the other is cut off by a stream of lava flowing from the same.

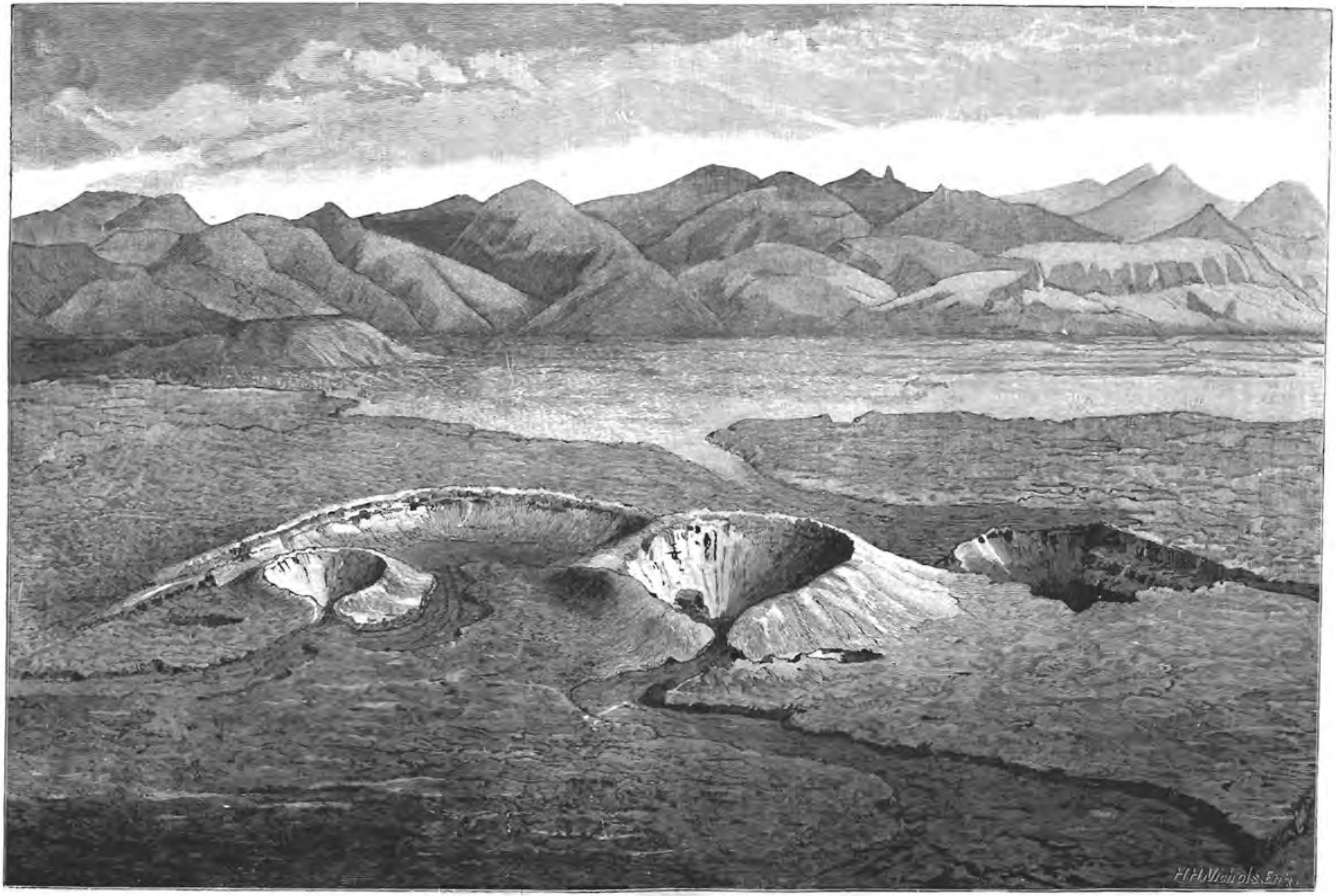
The Miter is perhaps the most recent of the craters. Nothing overlaps it, and it has lost nothing by erosion. Apparently the only change since its formation has been a cracking away of fragments from its harder components and the accumulation of these in taluses. Its rim is nearly circular, with a diameter of 950 feet. Its highest side, on the east, rises 250 feet above its outer base and 275 feet above the central depression. Its history has involved at least two overflows. After it had reached about its present size the lava rose within it, breached its north side, and discharged. The discharge was followed by explosive eruption and the breach was repaired. A final upwelling found escape at the west and trenched the rim deeply on that side. The northerly sill of discharge is 120 feet above the central depression, the westerly 75 feet. The material is identical with that of the Crescent, and the perfect preservation of the cone enables the imagination to picture vividly the manner of its formation. Its principal constituent is scoriaceous lava in angular fragments. Over the surface are sprinkled clots of similar scoriaceous material, spongy within, bulbous without, and coherent to the angular fragments beneath them. These are evidently drops spattered from the molten mass below, and retaining their plasticity up to the moment of striking, so that they fitted themselves to and adhered to the surfaces against which they fell. They are volcanic bombs whose aerial flight was too short to permit them to harden.

Between the Miter and the Crescent stands a low cone, resembling the Miter in form, but only 400 feet in diameter. It is composed almost exclusively of angular scoriæ. Six fragments of craters project from beneath the talus of the Miter at various points, another lies outside the Crescent, and still another joins the inner face of the Crescent to the small crater just mentioned. A circular hole, more than 100 feet in diameter and 40 or 50 feet deep, is doubtfully classed as a crater, for it is not clear that matter has been ejected from it. Its interior exhibits only fragments fallen from its walls.

The Terrace crater lies just south of the Miter, and differs from the others in type. Its walls are for the most part low, and are characterized by a gentle outward slope. At their culminating point they are scoriaceous, but elsewhere they are of relatively compact lava, with a rude stratification, as though formed by the addition of successive sheets. Its formation was evidently attended by very little explosive action, and there is some ground for believing that its cavity was produced by the refusion of scoriaceous matter, the product of some earlier eruption. Its outline is irregular, with an extreme length of 1100 feet and a width of 700 feet. At one stage in its history it was occupied by a molten lake about 14 acres in extent, and the partial congelation of the surface of this lake left a terrace at one margin. The subsequent history of the crater includes the formation of four narrower terraces at lower levels. The first lowering of the molten lake appears to have been accomplished by the breaching of the crater wall at the south, and a consequent outflow. The subsequent lowerings were caused by the retreat of the lava down the conduit by which it had originally entered the crater from beneath. This conduit remains open and can be explored for 25 feet, when progress is stopped by water. It is a circular tube 12 feet in diameter, and inclined 10 or 15 degrees from the vertical. The stony arrested drops still pendent from its sides testify by their small diameter to the high fluidity of the lava. The depth of the crater below its general rim is 260 feet, below the sill of its last outflow 220 feet, and below the scoriaceous crag that overlooks it on one side 350 feet.

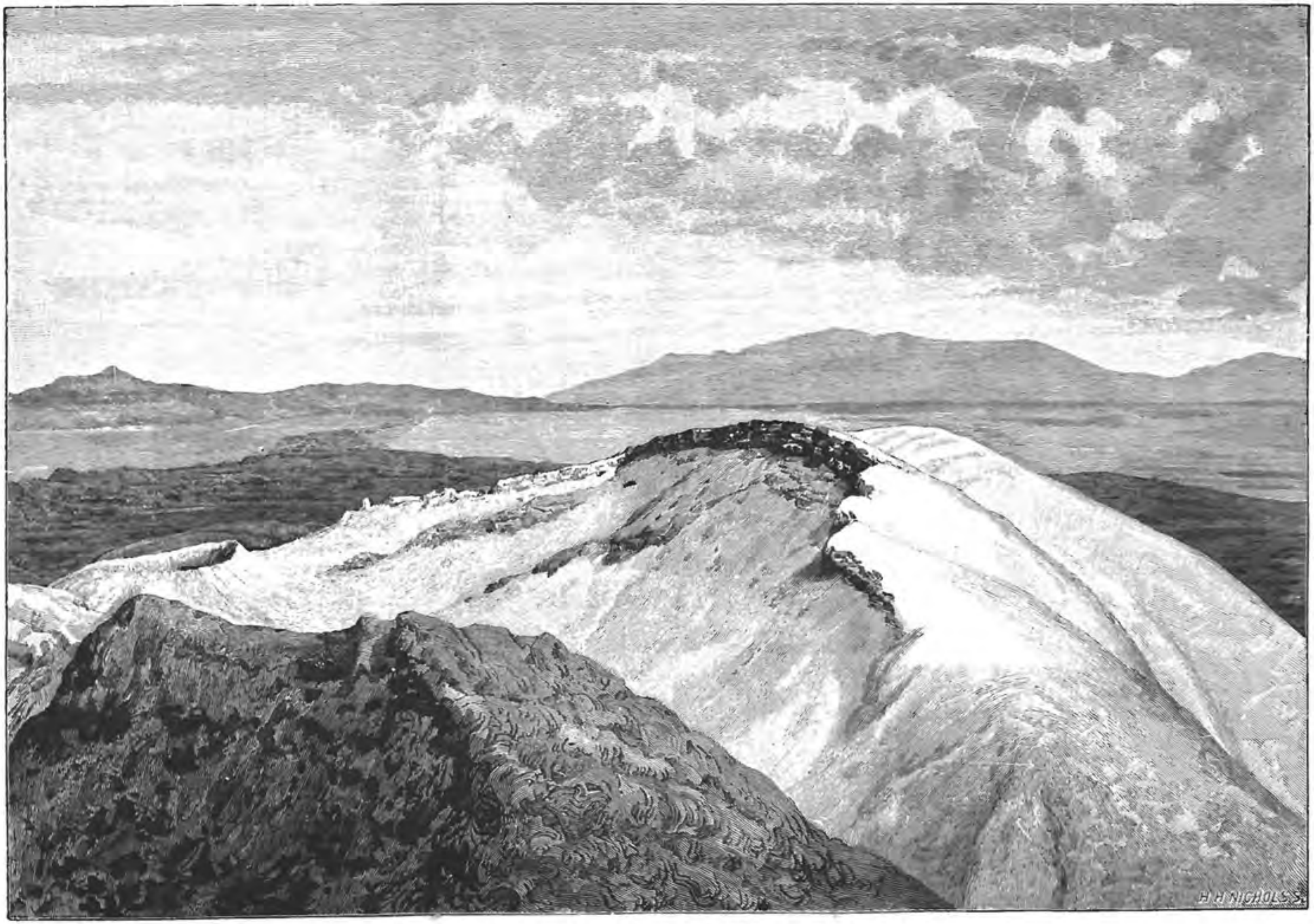
Three thousand feet to the west of the above craters there is a short fragment of crater wall, with its concavity turned toward the east. It is nearly buried by the lava streams flowing from the others, but what remains in view indicates a diameter of half a mile. It bars the progress of the lava in that direction and helps to give to the outline of the field its bi-lobed form.

The streams flowing from these craters have formed two confluent fields, the first extending 3.5 miles northward, with a general breadth of two miles, the second 3.25 miles westward, with a general breadth of 1.5 miles. Their area is about 12.5 square miles. Their marginal depths will average about 30 feet, and their mean depth is estimated at 50 feet. The volume of the ejected material is approximately one-eighth of a cubic mile. The



CRESCENT. MITER. TERRACE.

ICE SPRING CRATERS; BIRD'S-EYE VIEW FROM THE WEST.



ICE SPRING CRATERS; THE CRESCENT AS SEEN FROM THE MITER.

greater part of this lava is nearly compact, dark gray in fracture, and black on the surface. The fields are everywhere exceedingly rough, corresponding to the "aa" of the Sandwich Island nomenclature.[1] The surface is a heap of ragged, loose blocks, piled in tumultuous waves whose crests are 20 to 30 feet above their troughs. Near the craters these rugosities of surface disappear, and the compact basalt is covered to an unknown depth by a spongy layer as light as the lapilli, but more even in texture, and maintaining the somber hue of the streams. The scoriæ of the craters is sometimes gray, but is more commonly red or yellow. At a few points on the surfaces of the streams are small patches of scoriæ, colored like the craters, and one of these which was examined has a conical form, suggestive of formation *in situ* by eruption from the body of the stream. It is possible, however, that it is merely a fragment of a fixed crater that was floated off.

The angle of flow was not measured, but is certainly small. In the vicinity of the craters the grade is conspicuous to the eye, and the lava must be there one or two hundred feet higher than at the margin of the field. All of the later streams appear near the craters to flow in channels depressed fifteen to twenty feet below adjacent surfaces, and yet these adjacent surfaces resemble very closely the surfaces of the streams. The explanation appears to be that each of these outpourings varied in volume, now swelling, now shrinking. When most copious it spread beyond its channel like an aqueous stream, and deposited, not its sediment, but its crust. The walls of the channels display a confirmatory stratification.

That the entire history of the lava field is post-Bonneville, admits of no question. It lies within the area of the lake at so low an altitude that no point of the craters reaches to the level of the Bonneville shore-line, while the marginal portions of the stream are below the level of the Provo shore-line. But the craters show no trace of wave work, and on the surfaces of the lava streams no lacustrine sediments appear. The lake beds surround the lava, but neither rise toward it nor rest against it. A local fault, which is seen in one place to have displaced the Bonneville White Marl, disappears beneath the lava field in such a way as to show that the latter was subsequently spread.

[1] Hawaiian Volcanoes, by Capt. C. E. Dutton: Fourth Ann. Rept. U. S. Geol. Survey, p. 95.

At various points there crop out from beneath the Ice Spring field margins of an older lava or lavas, of uncertain date. They are distinguished from the newer by the weathering of their surface, which has partially lost its original rugosity, and bears patches of soil so as to support a scanty growth of grass and bushes. At two points these are seen to be displaced by the fault above referred to, and at one place a bed of lava passes under an exposure of the White Marl. If all these older lavas have approximately the same date, they are probably older than the Bonneville shore-line.

While the recency of the Ice Spring volcanoes as compared to the Provo epoch is sufficiently clear, their absolute antiquity is a matter of doubt. The state of preservation of the latest ejecta is fairly to be compared with that of similar material produced by Vesuvius two or three centuries ago, but the mineralogic differences between the two lavas and the climatic contrast between the two localities may determine very different rates of disintegration. At the Utah locality disintegration has produced no soil even in crevices. A study of the surface details of the more compact lava gives the impression that they have withstood atmospheric influences. The scoriæ have yielded somewhat; in their original constitution they consist within of thin septa dividing spheroidal bubbles, and without of a slightly thicker skin against which the outer phalanx of bubbles are flattened. From the scoriaceous crusts of streams near their sources this skin has chiefly disappeared. It is well preserved only on the brinks of the cinder cones, and not on all of those. After my first visit to the locality, I exhibited to the American Association for the Advancement of Science a bomb from the Miter crater, and stated that its skin had been exposed to the elements since the time of its formation.[1] A more careful examination on the ground has satisfied me that I was wrong. The taluses on its outer and inner slopes show that the crest of the crater is slowly breaking away, so that the bombs to be seen near the crest may have been until recently covered and protected by lapilli.

I discovered no accumulation of fine fragments from the disintegration of scoriæ. They have been absorbed by the crevices and the surface remains clean. Indeed the formation of a soil is indefinitely postponed by

[1] Proc. Am. Assoc. Adv. Sci., vol. 23, 1875, part 2, p. 30.

the necessity to first fill the all-pervading crevices of the cinder cones and the aa. Only on the cindery crusts of streams near the craters has a beginning been made. This is not apparent on the surface, but when the rock-froth is broken into, its inner cells are found half filled with an exceedingly fine cream-colored dust—evidently an eolian deposit. A few sage bushes have discovered this and established themselves. No minerals were seen in the bubbles or other cavities, but the interior of the flue of the Terrace crater is decorated with dendritic growths of calcareous matter.

The name of the Ice Spring lava beds is derived from what may be regarded as a natural ice house, existing in one of the deeper hollows of the aa. It is in a natural pit among the lava blocks, and so sheltered by an overhanging ledge that it never receives the direct rays of the sun. At the time of my visit there was a pool of ice water a few inches broad and half an inch deep, and at its margin, clinging to the rock, a film of ice a few inches across. My visit was on September 28, and it is currently reported that ice can always be found. The conditions of the phenomenon appear to be: first, the accumulation in the crevices of the shattered rock of cold water from melting snow; second, protection from solar heating by means of a heavy cover conducting heat poorly; third, shelter against winds, which would bring warmth by convection; and fourth, evaporation. Similar phenomena have been described at various places in the Appalachian Mountains.

PAVANT BUTTE.

Pavant Butte, which stands ten miles north from the Ice Spring lava field and 17 miles by road from Fillmore, is an acute peak, about 800 feet high. It is the tallest of all the volcanic hills, and, standing alone upon the plain, is a conspicuous landmark. Its general form is that of a cratered cone, but the crater is open at the south, and the circling crest has an acute culmination at the north.

Its material is a volcanic tuff; that is to say, it consists of light lapilli cemented into a coherent mass. The vesicles of the lapilli are not filled, but the fragments are so firmly held together that they are frequently broken across when the mass is fractured. Scattered through the mass are occasional bowlders of basalt, some angular, others rounded, and these must have reached their position by ejection from the vent, but nothing was seen that could be called a bomb, and none of the scoriæ appear to have fallen in a plastic condition. All of the scoriaceous matter is fragmental, and the fragments rarely exceed an inch in diameter. Considerable portions of the outer slope have the fineness of coarse sand. The prevailing color is a pale yellow, but some of the weathered surfaces are gray. In this respect the butte is strongly contrasted with the cinder cones of the Ice Spring locality, where deep colors, especially red and reddish brown, predominate.

It has been pointed out by students of existing volcanoes that lapilli are cemented into tuff when their deposition takes place in the presence of water. This commonly happens when they are ejected so as to fall in water, or when heavy rains, accompanying the eruption, wash them down to neighboring lowlands in the form of volcanic mud. In the present instance the state of flowing mud was not reached, for they are heaped about the vent in steeply-inclined layers of original deposition. The associated lake phenomena suggest, and indeed demonstrate, that Lake Bonneville afforded the moisture necessary for cementation, and that the eruption was subaqueous. The Bonneville shore-line is trenchantly drawn about the sides of the butte at mid-height. The Provo shore-line appears at its base, and the interval is destitute of all trace of wave action. It will be remembered that in the order of time the Intermediate shore-lines were formed first, then the Bonneville, and finally the Provo. The presence here of the Bonneville and Provo traces shows that the butte was not built after the epoch of the Bonneville shore-line. The absence of Intermediate shores tells us that it was completed after their date. A portion of the mole may have been thrown up in the earlier part of the second lake epoch or at any previous time, but if so, it was completely buried by the product of the final eruption at the time of the Bonneville shore-line.

This determination of date depends on our knowledge of the shore-line history derived from other localities, but the same information may be obtained from data purely local. At numerous points on the north side there is exhibited an unconformity in the bedding of the tufa, and a study of this unconformity shows that after the waves had notched the profile on that side, producing a sea-cliff and a terrace, the renewal of eruption partially filled the notch, the newer layers dipping at a higher angle than the old.

We thus learn by consistent and cumulative evidence that an eruption took place here while Lake Bonneville was at its highest stage, and beneath a body of water 350 feet deep. The resulting cone was built not only to the surface of the water but 450 feet higher. Eruption ceased with the fall of the water and has not been resumed.

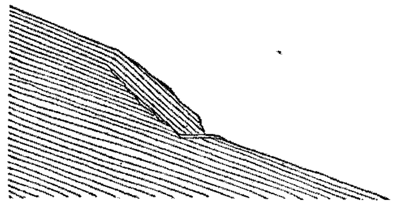


FIG. 37.—Diagram to illustrate the Alternation of Volcanic Eruption and Littoral Erosion on Pavant Butte.

Notwithstanding the recency of the cone, its sides are conspicuously furrowed by erosion, and it is in that respect contrasted with most fragmental volcanic cones of the vicinity. Where the lapilli are uncemented, all rain is swallowed by the interstices, and escapes gradually and quietly at the base. On Pavant Butte this is prevented by the cement, and the rain flows down the surface, accomplishing its usual work of erosion. The sides of the furrows exhibit to some extent the internal structure of the mass, and show it to be a fine type of its kind. There are no partings between the layers of tuff, but lines of deposition are plainly to be seen, and these exhibit on the inner side a dip toward the crater at 35 degrees, and on the outer face an opposite dip of from 15 to 25 degrees, the two systems being joined along the crest by anticlinal curves. A figure illustrating this arrangement is here reproduced from the Wheeler report (Fig. 38).

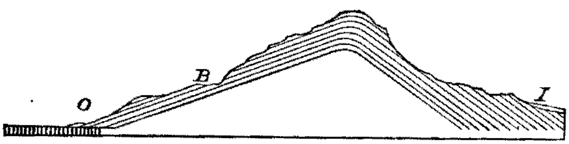


FIG. 38.—Section of Pavant Butte. *O*=Outside of Crater. *I*=Inside of Crater. *B*=Bonneville shore-line.

The general distribution of yellow and gray colors indicates that the yellow is original and the gray a result of weathering. The sections exposed by recent erosion show the main mass to be yellow, but there are occasional thin bands of gray, and these are inferred to record the temporary cessation of eruption. The old sea-cliff against which the newer tuff rests unconformably does not show the gray color, a fact consonant with our belief that the latest eruption interrupted rather than followed the destructive work of the Bonneville waves.

From the northwestern base there jut a number of ragged spurs, consisting, like the main mass, of tuff, but exhibiting dips toward the hill instead of from it. A study of their dips shows that the spurs are remnants of an older crater rim, on whose ruins the surviving rim was built. The diagram, Fig. 39, shows by full lines the observed relation of dips, and by dotted lines the theoretic structure of the parts concealed or removed. The earlier crater was somewhat smaller than the later, and its center was farther north. The tuff exhibits, throughout, the gray color referred to weathering. The date of the structure is uncertain. Its tuffaceous[1] character indicates subaqueous eruption. Its color suggests prolonged exposure to the atmosphere after the chief work of demolition was performed. It may have been built during the earlier part of the epoch of the White Marl, while the oscillating lake was beginning the formation of the Intermediate shore-lines, or still earlier in the epoch of the Yellow Clay.

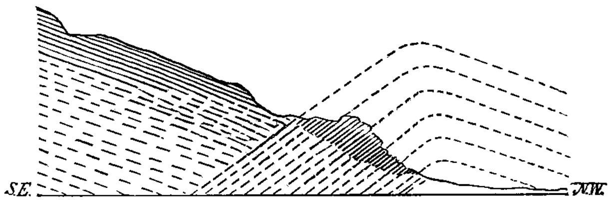
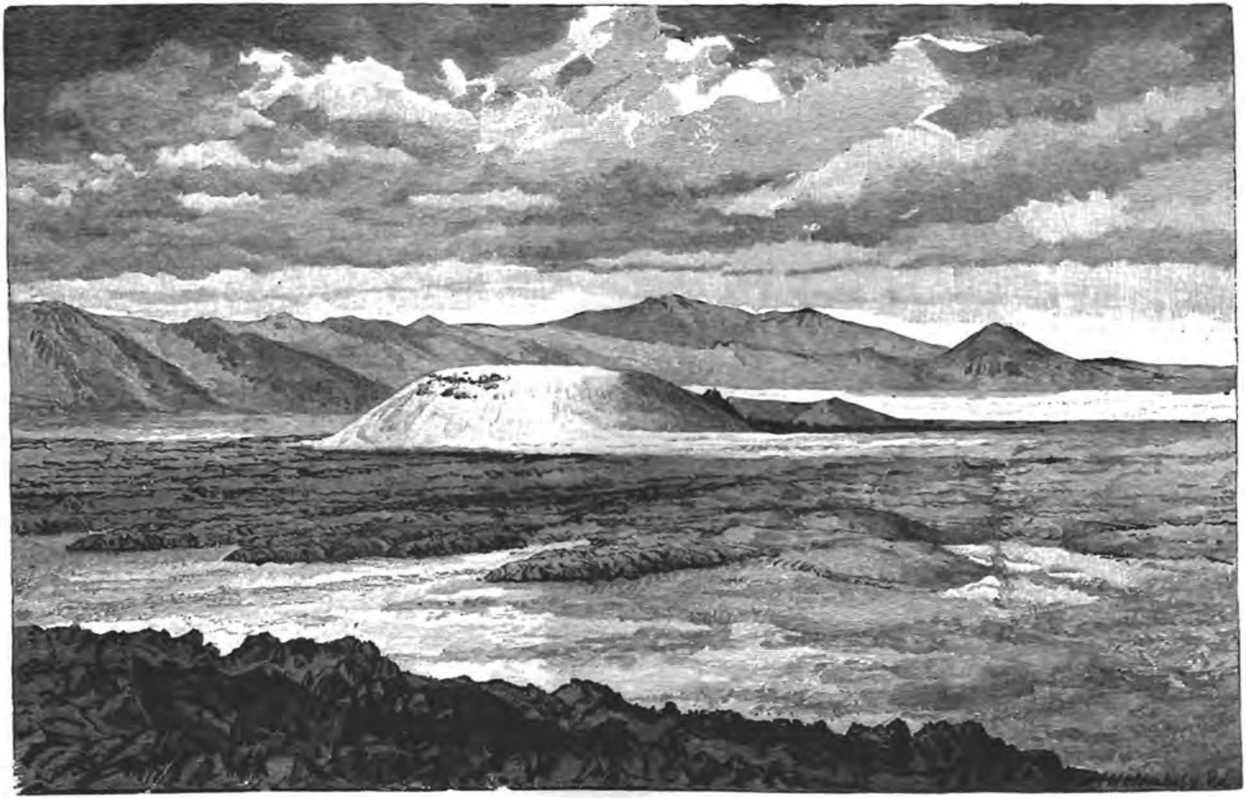


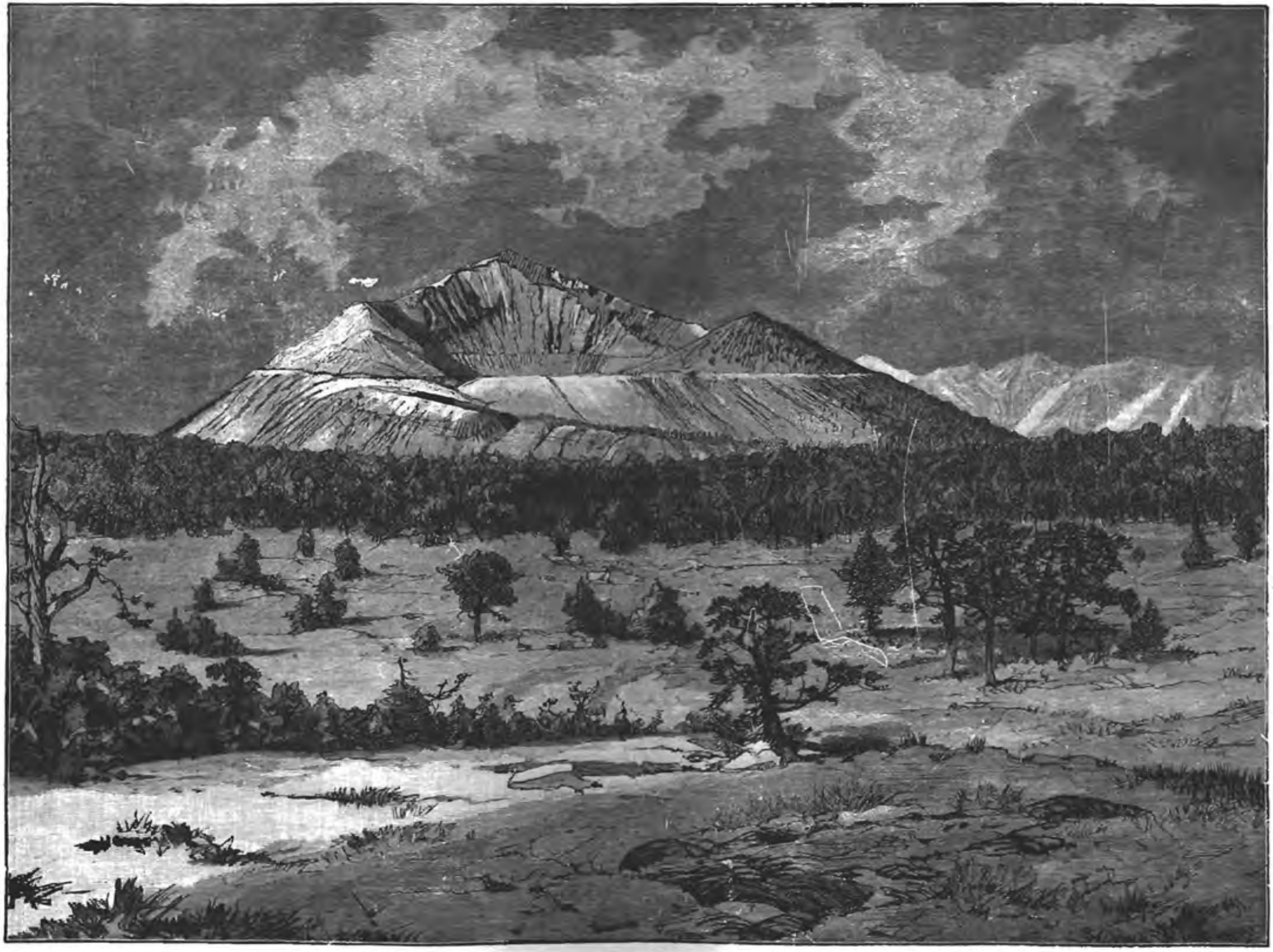
FIG. 39.—Section at base of Pavant Butte, showing Remnant of earlier Tuff Cone. The dotted lines indicate theoretic structure of parts concealed or removed.

The surface of the plain for a short distance in all directions from the cone is composed of debris derived from it. Beyond this southward outcrops the White Marl, and beneath the White Marl a field of lava. The White Marl seems to be but two or three feet thick, and as there appears no reason why the open plain at this point should not receive the full deposit, it is inferred that only the upper portion is visible, the lower being beneath the lava. As the Bonneville and Provo shore-lines are contemporaneous with the upper portion of the Marl, the question arises whether the lava bed may not be contemporaneous with the later tuff, and derived from the same vent. The surface of the lava is as perfectly preserved as that of the Ice Spring field, but is of an entirely different type, corresponding to the pahoehoe of the Sandwich Islands. It exhibits fine examples of the curved convolutions

[1] Tufa and tuff, etymologically the same word, have both been used to designate a calcareous deposit from solution and also a coherent aggregate of lapilli. Following Geikie, I have in these pages allotted the two words in severalty to the two functions, applying *tufa* and *tufaceous* to the deposit from solution, and *tuff* and *tuffaceous* to the volcanic product.



THE TABERNACLE CRATER AND LAVA BEDS, FROM THE NORTH.



PAVANT BUTTE, FROM THE SOUTH.

or wrinkles that are so suggestive of coils of rope. At the time of my examination I was disposed to refer these to the inter-Bonneville dry epoch, for it appeared to me a priori that a lava stream flowing beneath the water would part with its heat so rapidly that its smooth surface would be shattered into fragments. But I am informed by Captain Dutton that where Hawaiian lava streams of the smooth type have entered the sea, their surface characters have not been affected. The evidence comprised in the thinness of the White Marl and the perfect preservation of the lava surface beneath it may therefore be accepted as showing that a lava was here spread under the water during the second lacustrine epoch; and the close association of the field with the Pavant tuff is probable. Its area is undetermined, for it is overlain not only by the marl, but also in places by a belt of sand dunes. In a southwesterly direction it is visible at intervals for several miles.

TABERNACLE CRATER AND LAVA FIELD.

The typical phenomena of the Ice Spring and Pavant localities simplify the interpretation of the Tabernacle eruptions. The Tabernacle field lies immediately south of the Ice Spring, and is mapped on Pl. XXXV. It is approximately circular, with an average diameter of three miles and an area of about seven square miles. The point of issue is not central but lies near the southeast margin.

The crater has two rims, an outer and an inner. The outer rim is the older and is composed chiefly of yellow tuff. It contains also some slag-like material colored dark red and grey. Its contours, which are in detail the result of weathering, are smooth, except where broken by slaggy crags. Its surface is largely composed of discrete lapilli, just beneath which the tuff may be found in place. Two-thirds of the original annulus is preserved, the part toward the northwest having been absorbed or buried by later eruptions. The span of the annulus from crest to crest is 2200 feet, and the ridge is highest on the east side, where it rises 120 feet above the lava field. Probably a part of its base is concealed by the lava. Its profile as seen from the Miter crater (Pl. XXXIX) resembles the Mormon Tabernacle at Salt Lake City, suggesting an appropriate name. The internal structure of the ridge is not well displayed, but an outward dip was observed in the higher part.

The inner rim is characterized by a great abundance of scoriaceous matter that evidently reached its position while still pasty and adhesive. It is not greatly inflated, and its general habit is rather slaggy than scoriaceous. The rim is exceedingly uneven, and abounds in rough pinnacles.

Comparing these features with those of Pavant and the Ice Spring craters, we infer with confidence that water was present in the crater during the greater part of the formation of the outer rim and was absent during the formation of the inner rim.

When compact hand specimens of the Tabernacle and Ice Spring lavas are compared, little difference is seen, but their streams differ widely in habit. The Tabernacle field, though by no means smooth, is far less rugged than the Ice Spring. Some of the surface is broken into blocks, which are so far displaced that they are not easily traversed on horseback; but the greater part is comparatively even, and exhibits the ropy structure characteristic of pahoehoe. A conspicuous character of the streams was the congelation of their upper portions and the subsequent escape of the liquid matter beneath. This is shown in a few places by the preservation of tubular caves, and more frequently by depressed areas, where the lava crust has manifestly settled down as its support was withdrawn. The constituent streams of the field are partially separable, and the latest may be traced to the inner rim of the crater.

At its outer margin the lava field terminates in most directions in a cliff—not such a cliff as results from the undercutting of a lava bed resting on softer material, but a cliff of original formation contemporaneous with the upper surface. At a point on the eastern side it was measured and found to have a height of 65 feet.

On the face of this cliff, near the top, is a band of calcareous tufa adhering to the basalt, and above it there was detected at some points a terrace of wave erosion. These are features of the Provo shore-line. The crater rims bear no trace of wave work, and this negative evidence is reinforced by the absence of all lacustrine deposits from the crater, from the general surface of the field, and from the sunken areas and caves. The inner rim and the field were never submerged; the outer may possibly have been covered at the epoch of the Bonneville shore, but not at that of the Intermediate shores.

Lying just above the Provo level, and yet showing no trace of submergence, the lava field must have been formed after the fall of the water from the Bonneville level to the Provo. Bearing the Provo shore mark, it must have been spread before the close of the Provo epoch. It therefore originated during the Provo epoch. The inner rim of the crater has the same date. The outer rim is older than the inner and younger than the Intermediate shores; it belongs to the Bonneville shore epoch or to the earlier part of the Provo epoch. The presence in it of some slaggy matter suggests irregularity in the supply of water and indicates the later date. The most probable history is as follows: When the Pleistocene lake fell to the Provo level, it had a depth of from fifty to seventy-five feet over the present site of these craters and lava fields, and there it remained for many centuries. An eruption occurred beneath its surface. At first, or at least during an early stage, the eruption was explosive, its violence, possibly stimulated by the water, being so great that the circle of maximum deposit was more than a thousand feet from the vent. Eventually the growing rampart shut out the water, the explosions became less violent, and the ejecta became pasty. Quiet eruption followed, developing a low, black island, which received a wave record before the final desiccation. The closing phase of eruption was explosive.

The geologic date of this lava field is so well determined that special interest attaches to the degree of freshness of its surface. Decay has progressed far enough to obliterate the finer convolutions and somewhat obscure the coarser—two to six inches across. Probably salient parts have yielded an inch to atmospheric waste. The minor depressions contain an inch or two of soil, and small cracks are filled. Large cracks remain open. Judged by its color, the soil is less the product of local disintegration than of eolian deposition. The principal vegetation is the common sage of the country. In the caves the eolian deposit, reinforced by the droppings of bats and probably other animals, has a depth of one or two feet.

The ground just north of the Tabernacle field is traversed by a fault, with a throw of fifteen or twenty feet to the west. It divides the lava, also, and was traced with diminishing throw half way to the crater. In the opposite direction it disappears at the edge of the Ice Spring field, being overplaced by that eruption.

At the side of the fault is a low hill of scoriæ, against and around which the Tabernacle lava flowed. It is a vestige, ill preserved, of some long anterior but dateless eruption. Another vestige, equally vague as to time, appears in an inclined fragment of a basalt sheet, brought up by a fault at the south margin of the Tabernacle field. This fault is overplaced by the Tabernacle lava.

PLEISTOCENE WINDS.

The circular wall of a crater often grows more rapidly on one side than another. This must sometimes be occasioned by the obliquity of the flue, but observers have generally referred it to the deflection of flying fragments by the wind. If a group of extinct craters are oriented in the same way, it seems legitimate to infer the prevailing direction of the wind at the time of their formation. In the Fillmore district there is practical harmony of orientation. The Crescent, the Miter, and the smaller crater between them have their highest walls at the east. That of the Terrace crater is at the northeast. The outer rim of the Tabernacle culminates on the east side, the inner rim on the north. The apex of Pavant Butte stands north of the crater. The entire range of the seven is from north to east, and the indication is that winds from the south, southwest, and west prevailed. There are no meteorologic stations competent to tell us whence the winds blow at the present time, but the prevailing air movement is recorded by nature in a satisfactory manner. In the vicinity of George's Ranch, at the south end of the eastern lobe of the Sevier Desert, the Provo shore-line consists of a series of massive bay bars, composed largely of sand. These are the source of a broad train of dunes which traverse the desert, and which demonstrate by their northeasterly course the prevalence of southwesterly winds. The phenomena consist with the theory that the general air currents of this region during the Pleistocene were similar in direction to those of the present time.

FUMAROLE BUTTE AND LAVA FIELD.

The most important locality remaining to be described is at the northern edge of the Sevier Desert, close to the head of the Old River Bed. A basaltic mesa five miles across in either direction is half divided by a valley opening to the northeast. (See Pl. XXXI, near bottom.) At its head this valley is a mile wide, and is floored by red scoriæ. In it stands a rough tower about 160 feet high with a truncated and obscurely crateriform summit. The predominant colors of the tower are red and gray, and its material ranges from firm scoriæ to compact basalt. These are roughly bedded, and exhibit a centripetal dip at a high angle. The interrelations of these features are easily understood, at least in a general way. The tower, Fumarole Butte, marks the position of the volcanic vent. About this vent scoriæ were piled (as restored in the diagram) in an annular mole, and from it escaped the lava of the surrounding mesa. The last phase of eruption was non-explosive, and compact rock was formed in the flue. Subsequent erosion carried away much of the scoriaceous rim, but left the resistant core and the equally resistant lava field.

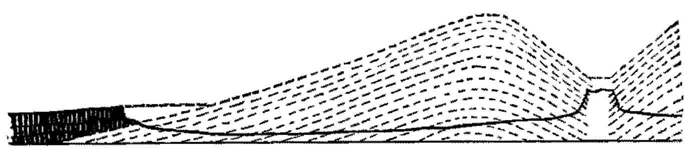


FIG. 40.—Theoretic section of Fumarole Butte. The Cinder Cone is restored by dotted lines.

Before visiting this butte I had listened with incredulous interest to the statement that smoke or steam was sometimes seen to rise from it, but personal observation subsequently removed all doubt. About the outer edge of the summit are thirty or forty crevices from which warm, moist air gently flows. The permanence of the phenomenon is attested by the verdure lining the openings—a deep green moss glistening with moisture and vividly contrasting alike with the somber rocks and the sparse, ashen vegetation without. In different openings I found the temperatures 62°, 70°, 72°, and 73.5° Fahr., all above the atmospheric mean for the locality, which is approximately 55°. At the time of observation the outer air had a temperature of 30°, and was dry. A little mist formed over some of the openings, but was reevaporated within a few feet. On days that are moist, cool and still, a conspicuous cloud must arise. It can hardly be doubted that this thermal manifestation testifies to a residuum of volcanic heat in the old flue.

A group of hot springs at the southeastern base of the mesa may have the same significance. Their temperatures range from 110° to 178° Fahr.

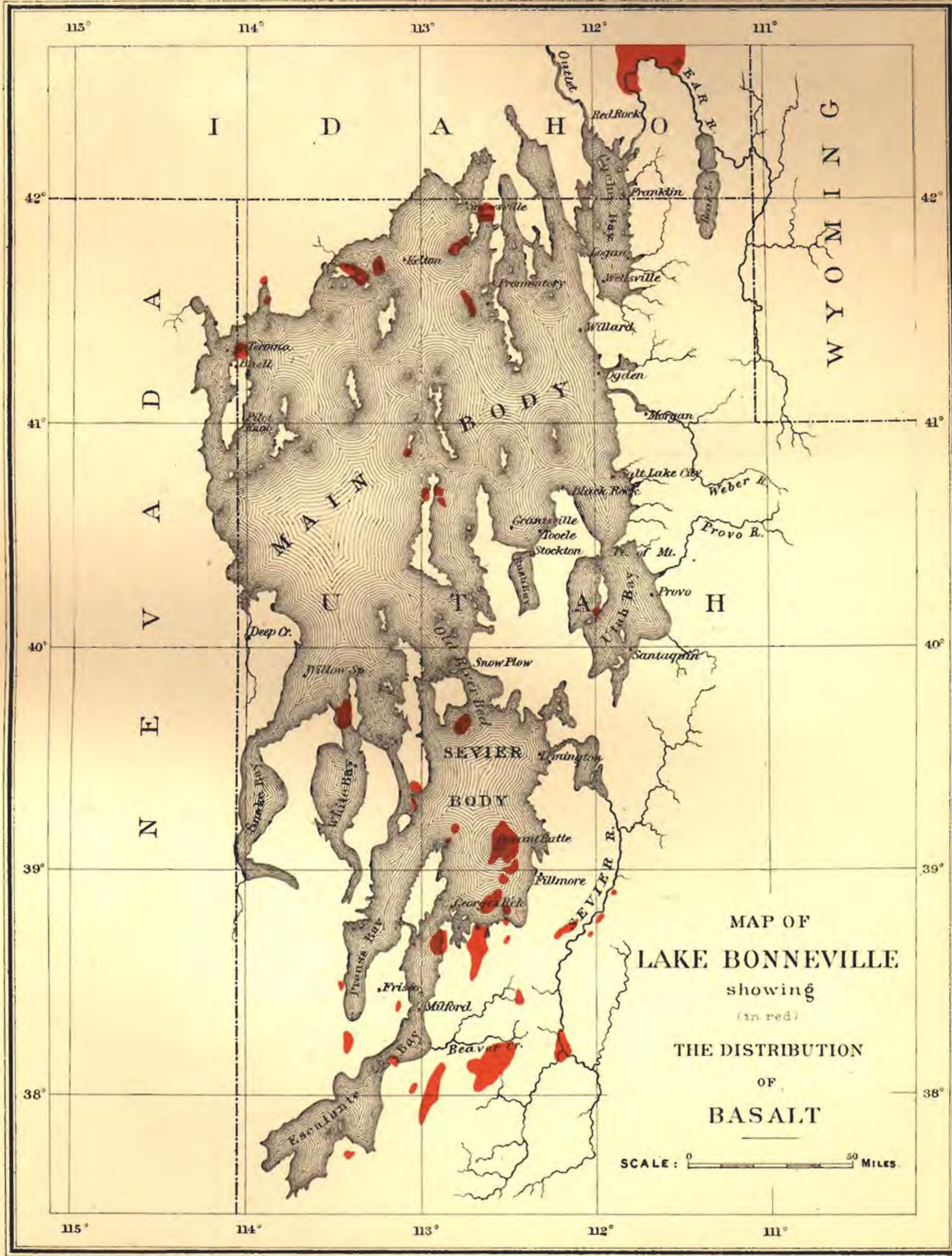
Just north of the mesa is a basaltic hill whose apex overlooks the mesa and has about the height of the butte. This hill is terraced by wave action, exhibiting especially the Bonneville and Provo shores. The Bonneville terrace appears also about thirty feet above the base of the butte, and a single point of the mesa was high enough to receive it. The relation of these shore benches to the valley about the butte shows clearly that the excavation of the valley was antecedent and was subaerial. The littoral excavation was trivial in comparison.

The wet-weather drainage of the mesa crosses its bounding cliff at numerous points, and at each of these a narrow, notch-like valley has been eroded from the basalt. These notches were cut before the Bonneville epoch, and during that epoch were partly filled by lake deposits. Subsequent erosion has not wholly removed these deposits, and the remnants show that both Yellow Clay and White Marl were present.

These facts demonstrate that not only the volcanic eruption but the principal erosion of the volcanic formations took place in Tertiary time.

The surface of the mesa has lost all details of its original configuration. One can not say whether the flowing lava assumed the rough or the smooth type. It is far from smooth, but its unevenness apparently depends on inequality of disintegration and erosion. The rock is superficially red from decomposition, and is generally bare of soil, the slopes of surface sufficing for the rapid removal of disintegrated material. The margins of the table on the east and south (where alone they were examined) are cliffs by sapping—that is to say, blocks of rock have fallen away in consequence of the yielding of a softer substratum. Probably the lava was spread on the plain before the first establishment of drainage on the line of the Old River Bed. The carving of that channel lowered the base level of erosion for the region and induced the general degradation of the plain, so that the field of obdurate basalt became a hill of circumdenudation. The greater share of this process also must be referred to the Tertiary.

The most impressive phenomenon of the locality is the secular persistence of the volcanic heat. At the time of eruption the rocks adjacent to the conduit or conduits became heated, and the lava remaining in dikes and chimneys added to the store of heat. Since that time conduction has steadily


MAP OF
LAKE BONNEVILLE
showing
(in red)
THE DISTRIBUTION
OF
BASALT
SCALE: 0 50 MILES.
IDAHO
NEVADA
UTAH
WYOMING
MAIN BODY
SEVIER BODY
115°
114°
113°
112°
111°
42°
41°
40°
39°
38°
Outlet
Red Rock
Franklin
Logan
Wellsville
Kelton
Promontory
Willard
Ogden
Morgan
Salt Lake City
Black Rock
Weber R.
Provo R.
Grantsville
Tooele
Stockton
Pt. of Mt.
Provo
Utah Bay
Santaquin
Terrace
Buell
Pilot Peak
Deep Cr.
Willow Sp.
Snow Plow
Old River Bed
Leamington
Snake Bay
White Bay
Fillmore
Sevier R.
Preuss Bay
Frisco
Milford
Beaver Cr.
Escalante Bay
Bear R.

carried this heat in all directions, and the convection of subterranean water has helped to discharge it to the atmosphere, and yet enough remains to sustain a fumarole ten centigrade degrees warmer than the air. The period of heat dissipation includes the whole of the Pleistocene period and an antecedent period of erosion probably of equal length.

OTHER LOCALITIES OF BASALT.

The remaining basaltic masses of the lake area, so far as they were inspected, do not declare their age by visible phenomena of superposition, but the majority can be referred with probability to the Tertiary from a comparison of their condition of preservation with that of the Tabernacle field on the one hand and the Fumarole on the other. This statement applies to all localities mapped in Pl. XLI north of the fortieth parallel excepting that on Bear River. It applies also to two localities at the west edge of the Sevier body of the lake, to two near Preuss Bay, to two which trench on Escalante Bay, to the buttes near Corn Creek (southwest of Fillmore) and a large table west of them, and to a table lying west of Pavant Butte and south of the town of Deseret.

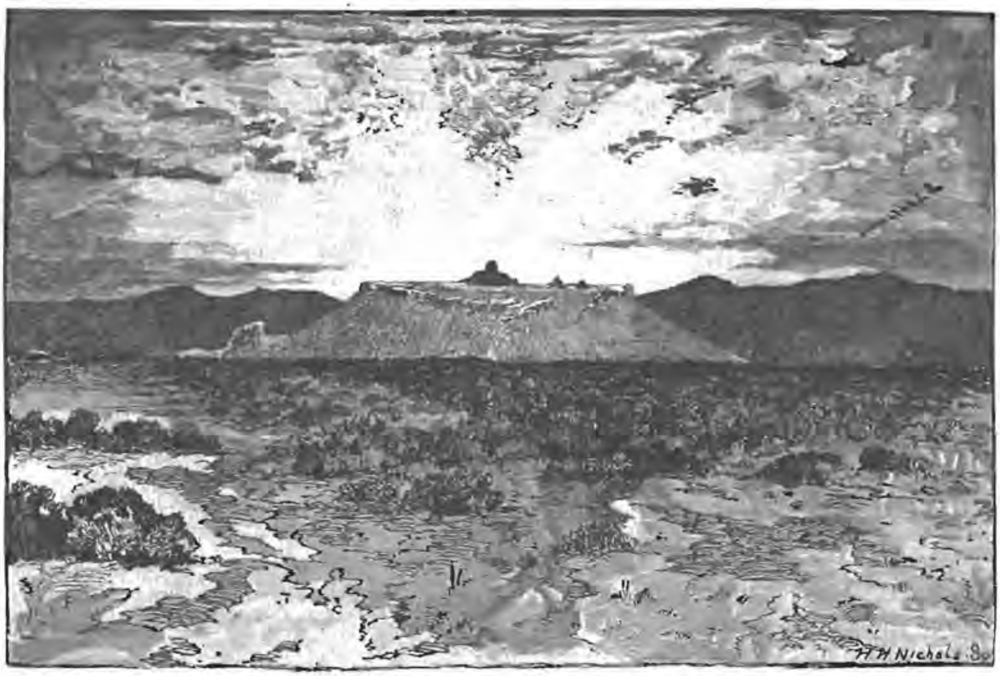


FIG. 41.—Dunderburg Butte.

Between this last-named table and the north end of the Beaver Creek range stands Dunderberg Butte, the remnant of what may have been a large cone of scoriæ. Its lapilli are coherent, but have not the yellow color of the tuff cones. Their mass is traversed by dikes and sheets of vesicular basalt. Some of the basalt vesicles contain calcite and zeolitic minerals. The top is flat, except where dikes project, having been truncated by the waves at the Provo epoch. The date of eruption can be judged only from the progress of demolition. It was probably Tertiary, but may have been inter-Bonneville.

Equally in doubt are a basaltic table north of Pavant Butte and another south of it and extending nearly to the Ice Spring field.

PLEISTOCENE ERUPTIONS ELSEWHERE.

The same criteria of discrimination may be applied with equal propriety outside the lake area, so far as the conditions of rock decay are similar. Carefully applied, they would serve to classify the greater number of basaltic eruptions of the Arid Region as severally Tertiary or Pleistocene. While engaged in general geologic exploration, I have seen in Utah, Idaho, Nevada, California, Arizona and New Mexico about two hundred fields of lava, judged by their color and habit to be basaltic, and as many as three hundred and fifty cones of basaltic scoriæ. My attention was usually not called to their state of preservation, but the data contained in note books and memory nevertheless afford a basis for judgment, and I have attempted a classification, with the following result: Of the streams and fields, 15 per cent. are judged to be Pleistocene; of the cones, 60 per cent.; the remainder are regarded as Tertiary. Of the eruptions thus classed as Pleistocene a certain number admit of no question, and these are enumerated in the following paragraph.

On the Markagunt Plateau in southern Utah, close to its western edge, are three or more lava fields of the rougher type, all fresher in appearance than the Tabernacle field, and with them are ten or twelve cinder cones, red and black. It is said that Panguitch Lake, a few miles toward the northeast, owes its existence to the damming of its valley by a lava stream nearly as fresh. On the face of the cliff which bounds the Pownsagunt

Plateau on the south, a cinder cone marks the position of a vent from which a black stream has flowed down the slope toward the valley of Kanab Creek. This stream has weathered somewhat more than has the Tabernacle lava, but recency is indicated by the small amount of subsequent erosion in a country whose whole configuration indicates rapid degradation. In the heart of the Uinkaret Mountains of northern Arizona, surrounded by scores of basaltic streams and craters, the majority of which are probably Tertiary, there is one field of intense blackness rivaling the Ice Spring field in freshness. South of the Grand Canyon of the Colorado there is a similar forest of cratered cones about the base of San Francisco Mountain, and as one surveys them from that peak, his eye is arrested by a lava field at the east on which vegetation has not yet encroached, and by several craters near it of exceptional perfection. On the source of the San Jose in New Mexico a stream of lava preserves the wrinkles of viscous flow, and its surface has scarcely yielded to the corrasion of a brooklet that crosses it. At the southwestern base of the Zuñi Plateau, near El Moro, is a long, broad lava stream, comparable in age with the Tabernacle field. In southeastern California, on the grand alluvial cones of the eastern front of the High Sierra there are a dozen bright red and black cinder cones marking vents whence basalt has descended toward Owen's River. Farther north, in the same structural meridian, a small basaltic mass overlies one of the glacial moraines of Mono Valley.

RHYOLITE.

Besides basalt, the only important volcanic rock of the Bonneville area is rhyolite. It stands next also in point of recency, but is far older than Lake Bonneville. So far as observation extended, its most recent example is a body lying just east of Coyote Spring, at the south end of the Sevier Desert. This had an original depth of three hundred feet or more, and an extent in each direction of several miles; but it has been so dissected by erosion along its lines of drainage that its original configuration is suggested rather than shown. Its system of valleys has a general depth of at least two hundred feet, and these are so related to the Bonneville shore-line as to show their earlier formation.

Just east of the Tabernacle lava field is a hill of grey rhyolite one or two hundred feet high. It is a worn remnant, with nothing in its aspect to aid conjecture as to its original extent. Its base is concealed by the lake beds, and its sides show terracing by the waves of Provo and Intermediate times. Lying to the leeward of a gypsum playa, it has acquired a white mantle of gypseous sand dunes, whence it is called "White Mountain" (see page 223 and Pl. XXXV).

A portion of the Dugway range, on the south margin of the Great Salt Lake Desert, is of rhyolite and rhyolitic tuff. It is of such antiquity that the original shapes due to eruption have been replaced by those of atmospheric sculpture. From its gorges, as from other mountain gorges, there are spread great fans of alluvium, and across these completed fans are traced the shore-lines of Bonneville.

SUMMARY AND CONCLUSIONS.

The extravasation of rhyolite in the immediate vicinity of Lake Bonneville was long anterior to the epoch of the lake. The same may be said of the earlier extravasations of basalt, but the period of basaltic eruption includes the period of lake extension. In the Fillmore district basalt was extruded at various times during the epoch of the White Marl (later Pleistocene), and from one vent there were eruptions after the final desiccation (post-glacial).

The states of preservation of lava beds of various determined epochs afford a rude scale for the chronologic classification of lava beds not otherwise correlated, and warrant the conclusion that in Utah, Nevada, New Mexico, Arizona, and California the majority of basalt flows are Tertiary; a small minority are Pleistocene, and of these a few are post-glacial. The post-glacial eruptions are found in each of the indicated States and Territories except Nevada, and belong to eight distinct volcanic districts.

Although human history fails to give satisfactory record of the occurrence of any of these eruptions, their antiquity, as measured in years, can not be great, and an application of the general law of probabilities leads us to look forward to a resumption of volcanic activity. The subterranean reaction of which basaltic extravasation is the consequence has continued in the broad region not only through the Pleistocene but through a much longer period of preceding time. The intermittence of eruption does not argue discontinuity of the subterranean process, for, whatever that process may be, it involves the production of an unstable equilibrium that is converted to stable equilibrium only by eruption, and such conversion is always rhythmic. The abrupt cessation of a process so widely spread and so long sustained is highly improbable, and its gradual cessation would naturally include not only growing infrequency of eruption but the successive extinction of eruption districts. The number of post-glacial eruptions and the number of districts among which these were distributed alike assure us that the end is not yet.

Their distribution in time and space indicates that the volcanoes and the lakes have been genetically independent. The Fumarole volcano broke out during an epoch of aridity, long before the first expansion of the lake; the Pavant and the Tabernacle were built on sublacustrine foundations; the Ice Spring volcanoes continued the series after the water had subsided. Outside the basin there was a parallel volcanic history, and though the volcanic districts are irregularly disposed, one can not say that they are either more or less abundant in the vicinity of the site of the lake.

CHAPTER VIII.

LAKE BONNEVILLE AND DIASTROPHISM.

The displacements of the earth's crust which produce mountain ridges are called *orogenic*. For the broader displacements causing continents and plateaus, ocean beds and continental basins, our language affords no term of equal convenience. Having occasion to contrast the phenomena of the narrower geographic waves with those of the broader swells, I shall take the liberty to apply to the broader movements the adjective *epeirogenic*, founding the term on the Greek word ἤπειρος, a continent. The process of mountain formation is *orogeny*, the process of continent formation is *epeirogeny*, and the two collectively are diastrophism.[1] It may be that orogenic and epeirogenic forces and processes are one, but so long at least as both are unknown it is convenient to consider them separately.

The mountain ranges so thickly set in the Bonneville district, and generally in the Great Basin, are orogenic phenomena; the concavity of the Bonneville Basin, whereby it is constituted an area of interior drainage, is epeirogenic. Neither process of displacement belongs exclusively to the remote past, but both are associated with the lake history. The evidence of this association is of three kinds, consisting (1) of the phenomena of faults, (2) of departure of shore-lines from horizontality, and (3) of the anomalous position of Great Salt Lake.

EVIDENCE FROM FAULTING; FAULT SCARPS.

In the district of the Great Basin the characteristic structure of mountain ranges is one in which faults play an important part. Foldings of strata are not wanting, but the greater features of relief appear to have

[1] See note on page 3.

been wrought by the displacement of orographic blocks along lines of fault. Sometimes a mountain range consists of a great block of strata cut off along one side by a profound fault, and inclined in the opposite direction until it descends beneath the plain constituted by the alluvial deposits of the adjacent valley. More frequently there are other faults within the range, trending parallel to its length, and having throws on the same side with the throw of the greater fault at the base.

It was probably these internal faults which originally suggested the structure of the ranges as faulted orographic blocks; but the structure was soon connected with a certain set of topographic features, and came to be recognized by means of these. A range consisting of a faulted block generally has a bold front on the side of the fault, and is less abrupt on the opposite slope. On the side of the bold front the line separating the rock of the mountain from the alluvium of the valley is simple and direct, while on the opposite side it is tortuous. On the side of the fault the strata usually dip away from the adjacent valley; on the opposite side, toward it. It was not until after the structure had been discovered and described by several geologists that the more decisive evidence afforded by the fault scarp was brought to bear. The writer first became aware in the summer of 1876 that lines of faulting may sometimes be traced upon the ground by means of low cliffs or scarps due to displacement of so recent date that the atmospheric processes of sculpture have not yet restored the ordinary forms of topographic detail. Since that time he has observed many such scarps in various parts of the Bonneville Basin, and in other portions of the Great Basin, and the observation has been still further extended by others, especially by Russell.[1]

The observed fault scarps for the most part follow the outcrops of fault planes whose position had previously been inferred from the configuration of the adjacent mountains, but they have served also to betray a number of faults whose existence might otherwise not be suspected. An illustration of this is found on the west side of the Aqui range of mountains, where the strata constituting the range dip down apparently beneath the alluvium

[1] Fourth Ann. Rept. U. S. Geol. Survey, pp. 445, 448, 449, 452. Geological history of Lake Lahontan, Chap. X.

of Skull valley. The typical aspect of the faulted mountain front is here wanting, and the actual fault, demonstrated by a superficial scarp, naturally escaped the attention of the geologists who have described and figured the structure of the range.

A case of more frequent occurrence is that in which the fault along the base of the range is compound, one portion following the visible edge of the rock, and another portion lying some furlongs or even some miles valley-ward. The orogenic block between the two fault planes lies far lower than the one constituting the mountain range, and may be far higher than the one beneath the valley. Occasionally some portion of it is visible, but it is usually completely buried by the alluvium constituting the foot slope of the mountain, so that the surface affords no intimation of its existence, unless some recent faulting records the position of its margin by a scarp.

It was at the base of the Wasatch Range that the fault scarp was first discriminated as a distinct topographic feature, and up to the present time that range has afforded the best illustrations. A description of the phenomena there exhibited will now be given somewhat in detail, following the order from south to north. It should be premised that the fault scarps were at no time a leading subject of investigation; the region was traversed upon other errands, and the faults were observed incidentally. The record therefore, although involving much detail, is far from full or exhaustive.

The Wasatch Range, using the term in the most restricted sense, may be said to extend from the town of Nephi, near which it culminates in Mount Nebo, northward to the Gate of the Bear River, where its axis is very low. The general course is a little west of north, and there are two angles just north of Mount Nebo, which have the effect of offsetting the axis some miles to the eastward. Near the town of Santaquin there is a low spur projecting westward and continued across the valley in a line of hills. Forty miles farther north a higher spur, known as the Traverse Range, runs westward. A third spur lies just north of Salt Lake City, and a fourth a few miles north of Ogden, near the town of Bonneville. These orographic features and the positions of the localities described in the following paragraph can be best made out by the aid of the large map of Lake Bonneville.

From Nephi to the pass near Santaquin the range is lofty, and has a rather high alluvial foot slope toward Juab valley. At a variable distance from the mountain base this foot slope is traversed by a fault scarp from ten to thirty feet in height. It is for the most part single, but in places it is divided into two parts, and it was observed at several points to fade out, being coincidently replaced by a similar scarp a few rods up or down the slope, and lapping past it. Toward the north it swings nearer to the mountain base, and it was finally seen to leave the valley altogether and strike across the neck of the Santaquin spur. Juab Valley lies at such an altitude that the water of Lake Bonneville covered only its lowest part, and the shore-lines lie far lower on the slope than the fault scarp. There is thus no direct relation establishing the order of sequence of the lake and the displacements, but the relative recency of the last displacement is inferred from the state of preservation of the scarp.

Evidence of faulting was next seen in the ancient deltas on the Spanish Fork, deltas lying in the reentrant angle produced by the inflection of the mountain axis north of Mount Nebo. There were distinguished two deltas, synchronous with the Bonneville and Provo shore-lines, the Bonneville delta being widely trenched by erosion and containing the head of the Provo between its surviving segments. The fault scarps are numerous, producing a confused topography, and their zone is at least a mile broad. The majority traverse the upper delta only, and the abrupt manner in which certain scarps terminate at the edge of this demonstrates that they were produced after the formation of the upper delta and before the completion of the lower. The greatest throw of a single fault observed on the upper delta is more than 150 feet; the greatest throw on the lower delta is about 40 feet. The throw of all the faults is toward the west, but the strips of delta plain lying between the parallel faults are inclined toward the east. The net displacement was evidently such as to increase the height of the mountain with reference to the valley, but its amount was not ascertained. Thence to Hobble Creek, five miles, the zone of displacement follows the margin of the alluvial slope where it adjoins the mountain face, and usually includes from two to half a dozen fault scarps. These in the main trend parallel to the base of the mountain range, but a few scarps depart from it at high angles.

At Hobble Creek the fault scarps are numerous, and they are well exhibited on the surface of the Bonneville delta. Their total throw was estimated, with the aid of an aneroid barometer, to be 125 feet. Their states of preservation indicate that they are of various dates, and the latest formed is so fresh that vegetation has not yet entirely covered its slope. A little farther north a fault is seen to traverse a beach line of the Intermediate series, giving the contiguous portions of the beach a difference in altitude of about thirty feet.

Near the city of Provo, a small mountain torrent issues from a gorge called Rock Canyon. At the mouth of the canyon is a delta terrace at the Bonneville level, with a radius of about 1,700 feet, and divided midway by the stream. The stream has opened a passage several hundred feet broad, and is flanked on one side by a stream terrace. The greater portion of the delta terrace on both sides of the stream is corrugated by faulting, being ridged to such an extent that elevated aqueducts have been resorted to in conducting water over it for purposes of irrigation. Figure 42 exhibits two

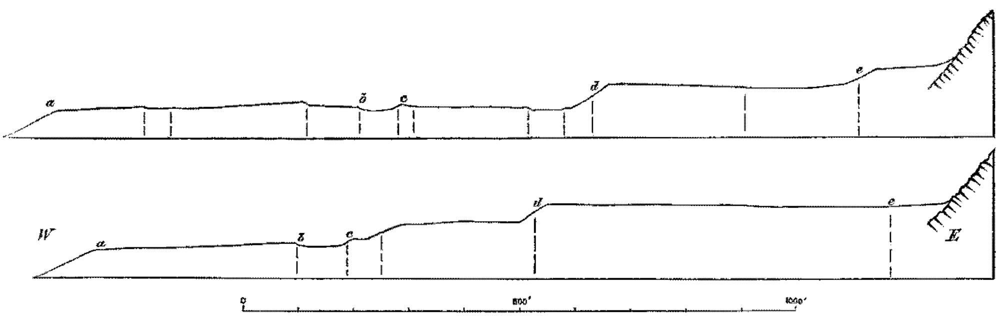


FIG. 42.—Profiles (1,000 feet apart) of the Rock Canyon Delta, illustrating its displacement by Faulting

measured profiles traversing the southern half of the delta at right angles to the strike of the fault scarps. If the reader will bear in mind that these deltas are normally characterized by simple profiles, sloping with great uniformity from apex to margin, he may obtain from the diagrams some idea of the nature of the irregularities introduced by faulting The rock of the mountain is indicated at the right, and the cliff, *a*, at the extreme left is that belonging to the margin of the delta The positions of faults are shown by vertical broken lines, and the letters *b c d e* mark fault scarps which traverse both lines of section. The lines of section are about 1,000 feet apart, and their differences fairly represent the ordinary variability observed in the details of fault belts when followed in the direction of their strike. A little farther north than the position of the upper profile the faults *b* and *c* approach each other, and the fallen block between them wedges out. Where they join, the trough gives place to a ridge about five feet high, and this ridge, after running a short distance on the plain of the delta, reaches the edge overlooking the stream and follows down the stream cliff to the flood plain. A portion of the fault scarp *d* likewise descends the stream cliff, but all the other scarps of the terrace end at its northern margin. It thus appears that the greater part of the displacement took place before the creek performed its last work of lateral corrasion on the south side of its channel, but that two of the movements are of later date. The phenomena are of special interest because they exhibit the hades of faults, features very difficult of observation where the faulted material is alluvium. The hade is nearly vertical, but inclines slightly toward the valley. These features are shown in Figure 43, in which the stream cliff is represented as seen from

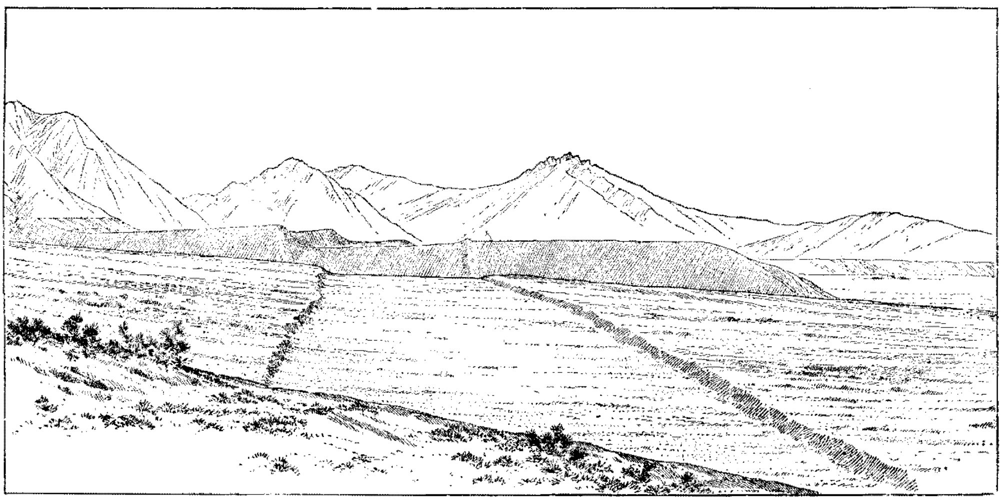


FIG. 43.—South half of Rock Canyon Delta, showing Fault Scarps.

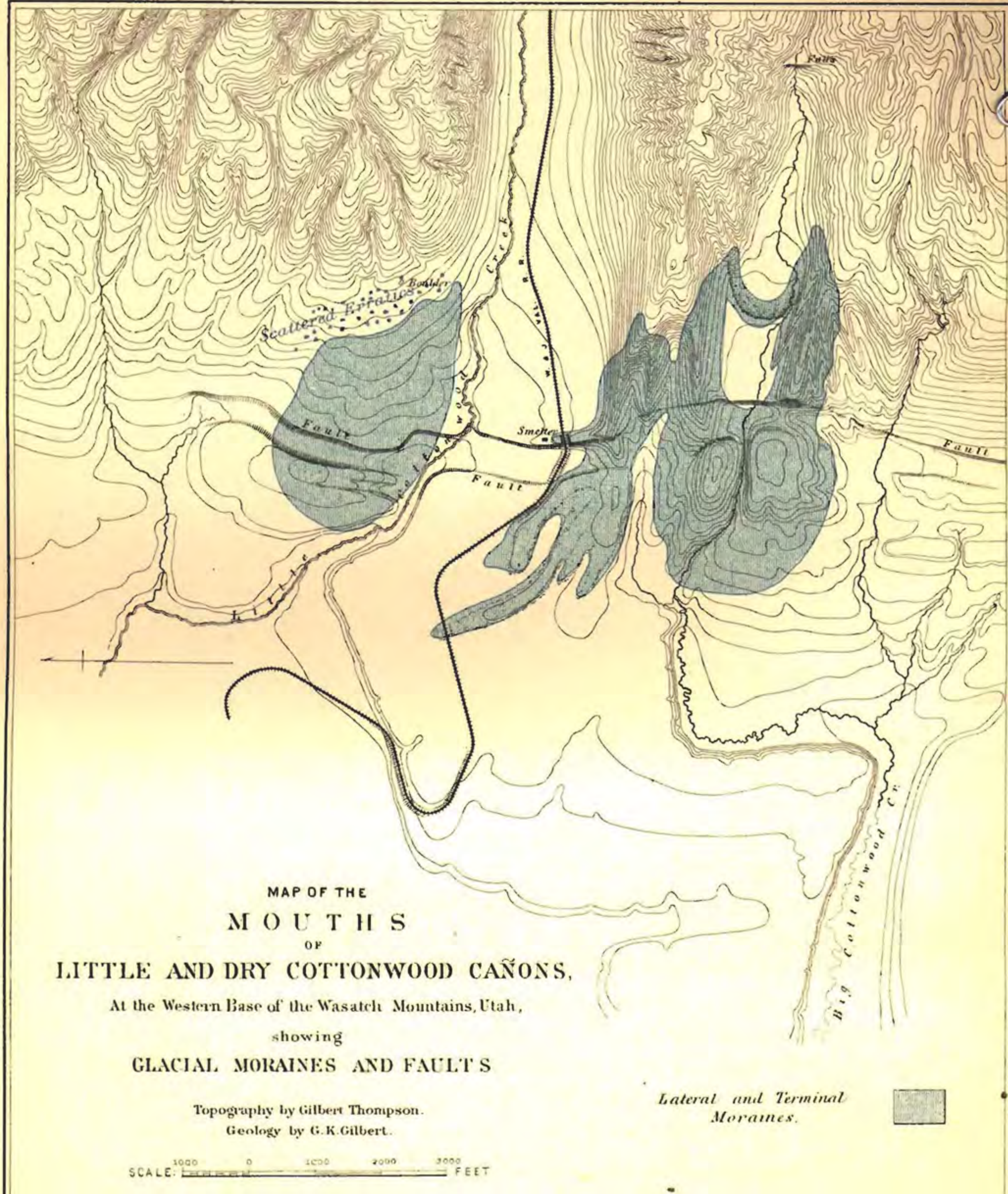
the north, the artist standing on the northern half of the divided delta and looking across the valley of the stream. The creek itself is hidden by a stream terrace which occupies the foreground of the sketch, and it will be observed that this terrace is likewise traversed by two small fault scarps, facing each other. Their height is only from two to four feet, and by contrast with the greater scarps on the delta terrace beyond, they serve to show how small a portion of the entire disturbance has occurred since the principal excavation of the stream channel.

The next observation was made at the American Fork, which debouches from the mountain twelve miles farther north. There, too, a delta of the Bonneville shore-line is centrally divided by stream erosion. Both halves of the delta are traversed close to the mountain base by a fault scarp 60 or 70 feet high. The same displacement traverses the flood plain of the stream, but its throw there is only 15 feet, showing that the entire displacement of the delta was not accomplished in a single movement. The last disturbance of the flood plain was so recent that a rapid still marks the acclivity it produced in the bowlder-paved stream channel.

A few miles northward the scarp was seen to traverse the Pleistocene alluvial plain at the mouth of Dry Canyon, and also the moraine with which that plain is associated. This locality is close to the point where the Traverse Range joins the Wasatch, but the fault was not traced far enough to ascertain its relation to the junction. There can be no question, however, that the great fault passes between the two ranges, and it is probable that a recent movement has characterized it here as elsewhere. On the north side of the Traverse Range the fault scarp at the base of the Wasatch was traced quite to the junction and seen to rise in the groin between the two masses.

In the next ten miles northward, there issue from the Wasatch three creeks, known as Dry Cottonwood, Little Cottonwood, and Big Cottonwood,[1] and the fault was continuously traced by its scarps past all these. In the vicinity of the streams and in the intervals between them the surface disturbances are complicated, and for a distance of about 5 miles there run opposing scarps, between which a block has been depressed. At the mouths of Dry Cottonwood and Little Cottonwood canyons the scarps cross a system of moraines, described in Chapter VI and represented in Pl. XLII, and materially modify their forms. The lateral and terminal moraines of Dry Cottonwood Canyon originally constituted a loop, the extremity of which was notched by the creek. The depressed block, traversing the lateral moraines, has carried down segments of them, leaving the distal portions as

[1] In Pl. XLII the name "Big Cottonwood" is erroneously attached to Dry Cottonwood Creek.



Julius Bien & Co, lith.

Drawn by G. Thompson

TROUGH PRODUCED BY FAULTING, NEAR MOUTH OF LITTLE COTTONWOOD CANYON UTAH.

a pair of outlying hills. The southern lateral moraine of Little Cottonwood, an acute and originally symmetric ridge, has assumed the profile represented in Fig. 44. The northern lateral, being broad and flat, exhibits a conspicuous trench where crossed by the depressed block (see Pl. XLIII). The walls of this trench are among the freshest of the fault scarps, being bare of vegetation along their upper courses, and in places too steep to be climbed. On the side nearest the mountain their height is from 40 to 60 feet. Here again it is evident that the total displacement was accomplished by a series of efforts, for between the two moraines the phenomena of the depressed block appear in the alluvial plain of Little Cottonwood Creek, and the greatest scarp in the plain has a height of only 20 feet. At Big Cottonwood Creek the total displacement is about 40 feet, and at a point between the two streams a single scarp was observed with a throw of 100 feet. Fig. 45, giving a profile of fault scarps near Big Cottonwood Creek, is not based on measurement, but reproduces a rough field sketch. It is probable that faults traverse the ancient deltas of Little Cottonwood Creek at a distance of some miles from the mountain base, but this fact was not fully established.

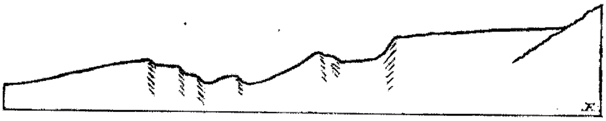
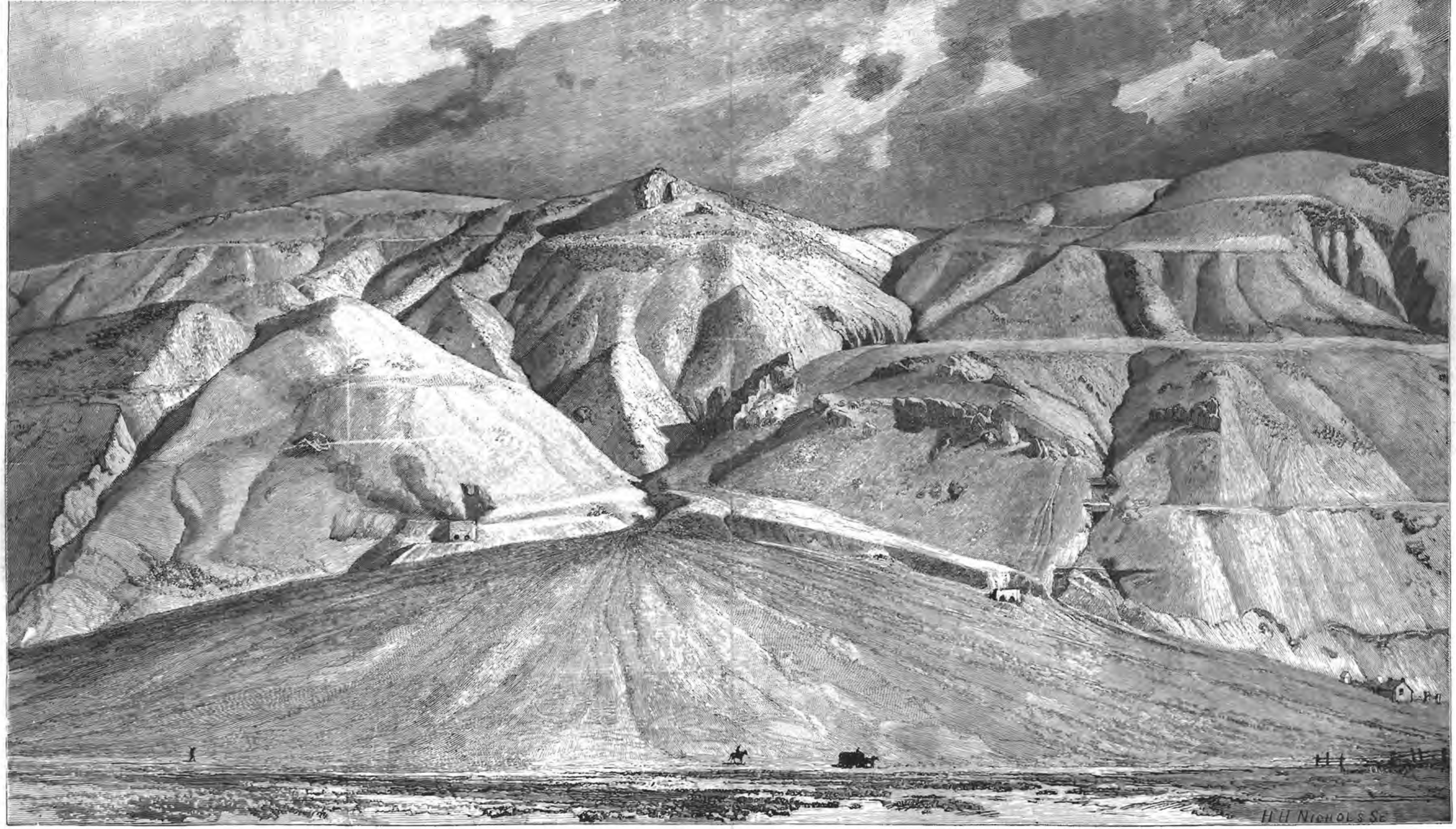


FIG. 44.—Profile of the South Moraine at the mouth of Little Cottonwood Canyon, showing the effect of Faulting.

FIG. 45.—Profile of Fault Scarps near Big Cottonwood Canyon.

From a point about one mile north of Big Cottonwood Creek to Salt Lake City, a distance of ten miles, the fault records are obscure, and it is probable that there have been no very recent movements. No scarps at all were seen close to the rock of the mountain. It was thought that an old one could be traced a short distance along the middle of the alluvial slope below Fort Douglas, and there is a more decided indication at the foot of the same slope in the eastern suburbs of Salt Lake City. Both of these are ancient as compared with the scarps previously described, and they may even have been washed by the later waters of Lake Bonneville.

Salt Lake City is built just south of a spur which projects four or five miles westward from the front of the Wasatch. This spur represents an orogenic block distinct from that of the main range. It is separated from the mountain mass by a fault plane along which the Wasatch block has, relatively speaking, risen, and it is separated from the valley on the remaining three sides by a curved fault plane along which the block underlying the valley has, relatively speaking, fallen. The first of these faults has been determined from the rock structure, as I am informed by Mr. J. E. Clayton of Salt Lake City. It is also indicated at its northern end by a fault scarp, which can be traced for a short distance up the groin. The fault on the side of the valley is exhibited at the west and northwest by a series of scarps, which begin in the northern suburbs of Salt Lake City near the Warm Springs. At this point the flat alluvial plain of the Jordan reaches the steep rock face of the spur, the line of separation being marked by an abrupt change of slope. A little north of the springs there can be seen clinging to the rock at a height of 40 feet a line of conglomerate fragments, formed within the plain by the cementation of debris to the limestone, and brought by faulting into the present position. The surface of the plain below is thrown by the same faulting into irregular waves, and at one point it is distinctly terraced. On one of the faulted benches an ore-reducing establishment has been built, utilizing a lower bench as a dumping ground for its slag. Between this point and the hot spring an alluvial cone, built against the face of the spur, is traversed by a typical scarp, which was sketched by Mr. Holmes. The sketch is reproduced in Pl. XLIV, where may be seen not only the scarp but its relation to other elements of the local geologic history. The face of the spur consists of a paleozoic limestone, inclined at various high angles. The horizontal terraces it bears are shore marks of the ancient lake. It is evident that the principal features of its relief had been carved before the production of these terraces, so that the main displacement—that to which the spur owes its origin—must have occurred long before the Bonneville epoch. The alluvial cone may or may not have been constructed before the epoch of the lake, but by the absence of shore-lines and lake beds from its surface we are assured that its outer layers at least are of post-Bonneville deposition. The displacements pro-



FAULT SCARP CROSSING ALLUVIAL CONE, NEAR SALT LAKE CITY.

Drawn by W. H. Holmes.

ducing the fault scarps are therefore subsequent not only to the lake but to a certain amount of post-lacustral alluviation.

The portion of the alluvial cone that lies above the fault scarp is channeled by the stream, and a study of the system of terraces bordering this channel shows that the total displacement of 30 feet was produced by at least three independent movements, the measures of the parts being 15 feet, 5 feet, and 10 feet.

At this point and elsewhere in the vicinity the scarp is utilized by burners of lime, who construct their kilns against its face and use the terraces above and below for the two approaches needed in the management of the kilns. The proprietor of the kiln represented in the plate enjoys the further convenience of quarrying his limestone from the adjacent cliff.

The hot spring at the apex of the spur is on the line of the fault, and a scarp can be traced from it in either direction. The powder houses standing a little farther northward are partly above and partly below the fault scarp. Many of the fault features in this vicinity, including those figured in Pl. XLIV, may be seen from the car windows of trains passing between Salt Lake City and Ogden.

From the point where the spur joins the main ridge northward to the ancient delta of the Weber, a continuous scarp follows the mountain base, its throw ranging from 25 to 75 feet. Opposite the village of Farmington its course is less direct than the trend of the mountain front, causing it to ascend and descend the narrow alluvial foot slope in the manner represented in Fig. 46. The broad Weber delta, which belongs chiefly to the Provo epoch, is crossed from side to side by the scarp, the general throw being from 40 to 50 feet. A recent alluvial cone resting upon the southern half of the delta has suffered a displacement only one-third as great as the adjacent delta. On the northern half of the delta the scarps constitute a system similar to that in the delta of Rock Canyon, and there are transverse branches running half a mile westward into the plain. At one point the falling of a block has produced on the surface a closed basin, which with a little artificial improvement has been made to serve for the storage of water for irrigation.

Thence to North Ogden Canyon scarps were seen at numerous points, usually in groups of two or more. Fig. 47 gives an unmeasured profile

FIG. 46.—Shore-lines and Fault Scarp at the base of the Wasatch Range near Farmington, Utah.

across the displacement near Ogden Canyon, and contains an extreme illustration of the reversed slope frequently given to blocks of alluvium between parallel faults. A few miles farther north a small closed basin has been formed in this manner. In the same vicinity one of the fault scarps crosses the line of the Bonneville shore terrace, displacing it about 20 feet.

FIG. 47.—Profile of Fault Scarps near Ogden Canyon, Utah.

At North Ogden Canyon the axis of the range turns westward for a few miles, and then resumes its northerly course. At the salient angle a low spur is appended, similar to that at Salt Lake City, but of smaller dimensions. The scarp runs behind the spur, and none was seen about its face; but it can not be doubted that its boundary on the valley side also is determined by a fault. A hot spring rises near its western base. Thence northward to the town of Willard the fault scarp follows the mountain base with an average throw of 20 feet, and it gradually diminishes and disappears before reaching the next settlement, Brigham City. Beyond Brigham City a single locality only, near the settlement of Honeyville, gave evidence of recent movement on the plane of the great Wasatch fault.

The total distance from Nephi to Honeyville is 125 miles, and it is probable that more than 100 miles of that distance is characterized by post-Bonneville fault scarps. The average displacement is 30 or 40 feet.

North of Honeyville the crest line of the Wasatch falls so low that it was overflowed by the Bonneville waters. The axis rises beyond into a range of importance, but the name Wasatch is not there applied. If the western margin of this range is determined by a continuation of the Wasatch fault, no record of the fact was observed in recent scarps. A few scarps were seen on the opposite (eastern) side of the range, especially in the vicinity of Clarkston. Twenty miles farther north, and approximately in the same structural trend, there are fault scarps at the western margin of Marsh Valley, but these are outside the Bonneville Basin.

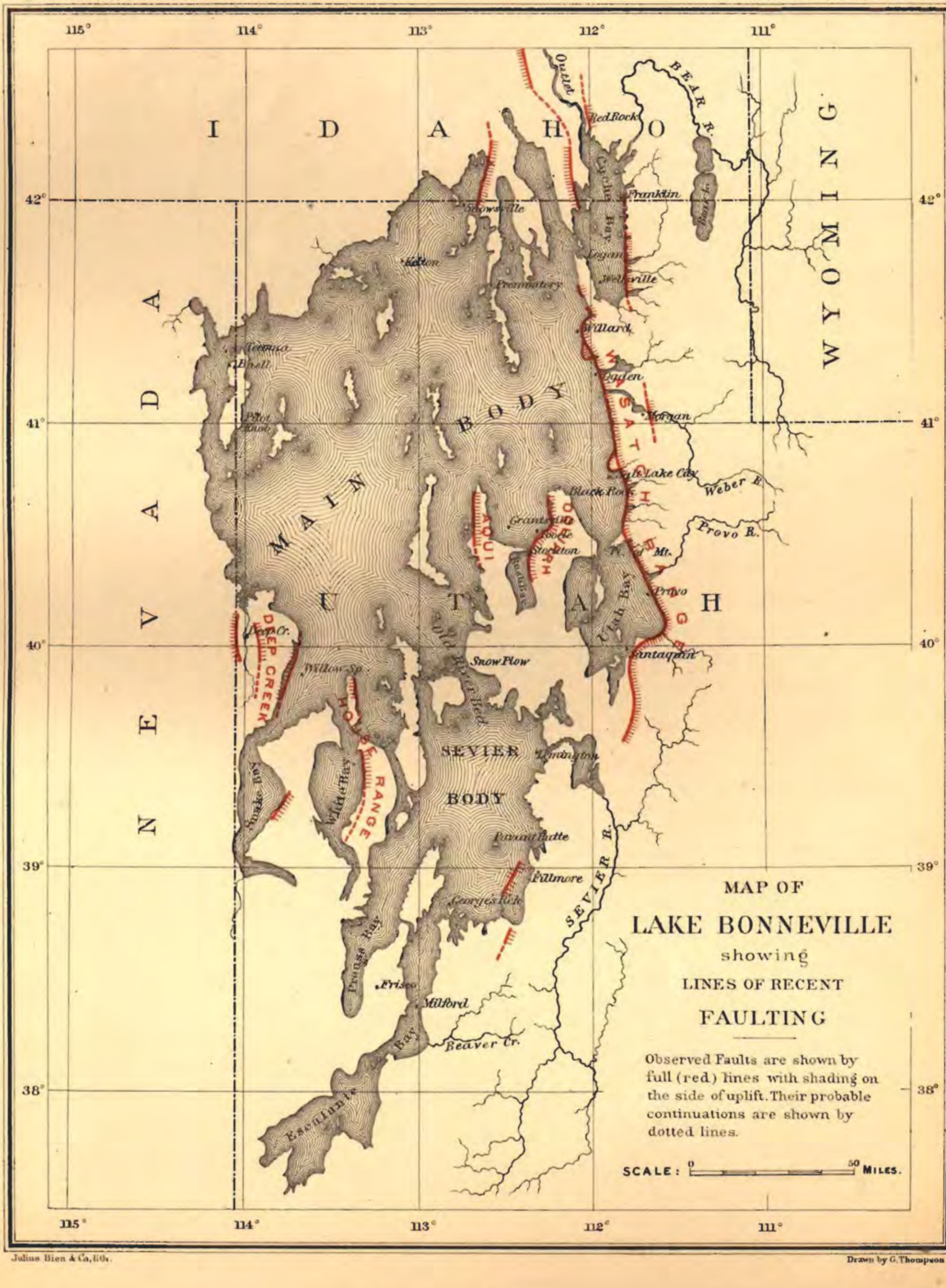
The fault mentioned at Clarkston follows the western margin of Cache Valley. The eastern wall of the valley is an important mountain range, whose bold western front has the topographic configuration of a worn fault cliff. At its base there are obscure indications of late movements, either during or just after the lake epoch, and at one point, near Logan, a post-lacustrine fault scarp crosses a delta of Provo date. The displacement is about six feet. At the north end of the valley a weathered scarp was observed near the base of the alluvial cone of Marsh Creek, close to the outlet channel of Lake Bonneville. The direction of its throw indicates that it belongs to the eastern side of the valley, but it is several miles from the mountain front proper.

The range bordering Cache Valley on the east extends southward parallel to the Wasatch, and exhibits in Morgan Valley, at its intersection by the Weber River, an old fault scarp, judged from its imperfect preservation to be pre-Bonneville.

Passing west of the Wasatch meridian, we have at the north a single instance of recent faulting. The small range lying east of the town of Snowsville is marked at base by a low scarp,—a scarp more defaced by erosion than are the Bonneville terraces lower down on the same slope. In the same meridian and far to the south are the faults described in the last chapter as associated with the Ice Spring craters. They are probably referable to the volcanic phenomena rather than to those of mountain uplift; and the same remark applies to a scarp observed by Mr. Russell 20 miles farther south.

Midway between these are two fault lines, associated with the Oquirrh and Aqui ranges. These ranges are parallel to each other and to the Wasatch, and agree with that range in having their main lines of displacement on the western side. The scarp at the western base of the Oquirrh runs southward from Lake Point a distance of four miles, exhibiting a throw of 25 feet. Its position is at the base of the steep mountain face, and the Bonneville and Provo terraces are carved in the rock above. It was next seen a few miles farther south, where it follows the contour of an embayment of the mountain side. It is there partly above and partly below the level of the Bonneville shore-line. Near the town of Tooele it appears to strike across a transverse spur, reappearing southward at the mouth of what is called Dry Canyon, and continuing thence to East Canyon and the canyon which contains the mining hamlet of Lewiston. At the mouth of East Canyon it intersects alluvial terraces in such way as to show two separate movements with an aggregate throw of 50 feet. Although the course of the scarp was not traced, it is believed that it could be followed continuously for a distance of 25 miles. The southern portion runs above the horizon of the lake shores, and is therefore not directly comparable with them, but it is considered probable that post-Bonneville movements have occurred at all points of observation. The scarp on the Aqui Range is low, and there is small basis for judgment as to its date. It was best seen in the vicinity of Knowlton's ranch.

Following westward along the system of ranges which separate the main body of Lake Bonneville from the Sevier body observation is purely negative until the House Range is reached. It is proper to say, however, that so much attention was given to mountain foot slopes in connection with the study of shore-lines that the absence of notable fault scarps may be asserted


MAP OF
LAKE BONNEVILLE
showing
LINES OF RECENT
FAULTING
Observed Faults are shown by full (red) lines with shading on the side of uplift. Their probable continuations are shown by dotted lines.
SCALE: 0 50 MILES.
115° 114° 113° 112° 111°
42° 41° 40° 39° 38°
IDAHO
NEVADA
UTAH
WYOMING
MAIN BODY
SEVIER BODY
WASATCH RANGE
OQUIRRH
AQUI
DEEP CREEK
HOUSE RANGE
BEAR R.
Weber R.
Provo R.
SEVIER R.
Beaver Cr.
Outlet
Red Rock
Franklin
Cache Bay
Logan
Wellsville
Snowsville
Kelton
Promontory
Willard
Ogden
Morgan
Salt Lake City
Black Rock
Grantsville
Tooele
Stockton
Provo
Utah Bay
Santaquin
Pilot Knob
Deep Cr.
Willow Sp.
Snow Plow
Old River Bed
Leamington
White Bay
Snake Bay
Pavant Butte
Fillmore
Georges Rk.
Preuss Bay
Frisco
Milford
Escalante Bay

of the southern portion of the Cedar Range, of the eastern face of the Simpson and the western face of the McDowell, of Granite Rock, and of the northern portion of the Dugway Range.

The House Range was long ago recognized as a faulted monocline in which the direction of displacement is reversed midway. The northern third of the range exhibits a westerly dip, and is faulted along the eastern base; the southern part has an easterly dip and is faulted on the western base.[1] This determination was subsequently confirmed by the discovery of a well defined fault scarp in the vicinity of Fish Spring, and an obscure and probably very ancient scarp at the western base of the southern division.

The next mountain body to the west is the Confusion Range, an assemblage of small ridges, and associated with these a single scarp was found. This lies near Knoll Springs, on the east side of Snake Valley. It is low and worn, and follows the rock base closely.

The Deep Creek Range, which forms part of the western boundary of the Bonneville Basin, is faulted on both sides. In the vicinity of the old overland road crossing the ridge from Willow Spring to Deep Creek settlement, to which vicinity observation was restricted, the range is flanked on the east by a broad and high alluvial slope. No fault scarp was seen, but near the lower margin of the slope a partial section of the lake sediments shows that they were disturbed during the period of their deposition. The Yellow Clay at one place suffered uplift and erosion before the deposition of the White Marl, so that there is unconformity of dips, and at another point the Yellow Clay and White Marl together are so greatly disturbed that their inclination is toward the mountain. The superficial topography that must have been created by these disturbances was obliterated by wave work, and at the locality of the section the upper edge of the inclined block was planed away in the formation of a terrace of the Provo shore.

On the west side of the range an ancient and nearly obliterated scarp crosses the alluvial slope near its upper edge. On the opposite side of Deep Creek Valley a better preserved fault scarp follows the eastern base of the Gosiute range. It lies far above the Bonneville shore-line, and was not critically examined.

[1] Surveys West of the 100th Meridian, vol. 3, pp. 27-28.

GENERAL FEATURES OF FAULT SCARPS.

Except in the volcanic district of the Sevier Desert, the fault scarps follow the bases of mountain ranges or run parallel to them. Where there is but a single scarp, it invariably faces toward the valley and away from the mountain. Where there are several scarps, frequently one or more face toward the mountain, but the one nearest the mountain always faces toward the valley, and the net displacement is always of such nature as to increase the height of the mountain with reference to the valley. The mountains are rising or the valleys sinking.

The scarps are rarely found at the contact of the rock of the mountain with the alluvium of the valley; they usually occur in the alluvium several scores or hundreds of feet from the contact. The segments of alluvial plain included between parallel scarps rarely retain their original slope. In a few instances, and for short distances, their rate of descent toward the valley is increased by the disturbance, but as a general rule the slope valleyward is diminished, or even reversed. The tendency of the dissevered blocks to incline away from the side of the downthrow is almost as pronounced as in the case of land slides. The assumption that the attitudes of these alluvial surfaces are representative of the attitudes of large down-reaching masses continuous with them seems untenable, because such masses would mutually interfere.

The hade of a fault is usually difficult of determination unless exposed by mining operations, and the difficulty is peculiarly great where the walls are of incoherent detritus. The freshest of the fault scarps have some talus, and prove only that the hade does not depart widely from verticality. The best observation was made in the Rock Canyon delta, where, as already described, several scarps descend a stream cliff standing at the angle of stability. They show a hade toward the valley of less than five degrees.

That this approximate verticality is more than a superficial feature of the great Wasatch fault, is seriously questioned, for several reasons. In the first place the faults within the Basin Ranges, so far as my observation shows, hade at considerable angles, and it is highly probable that this fault belongs to the same system. Second, the secular motion of the mountain being upward with reference to the valley, it is probable that the rock face at the contact with alluvium has been little wasted by erosion, and is essentially the protruded foot-wall of the fault, and if so, the visible fault in alluvium is not in the plane of the great fault, but is a branch with less hade. Finally, the last hypothesis affords an easy explanation of the superficial details of the faulting, as will appear by the following explanation.

Fig. 48 is constituted of four diagrams illustrating the supposed method of faulting. In the first diagram the line *x y* represents in section the Wasatch fault, with an assumed hade of 30°. To the right of this line is

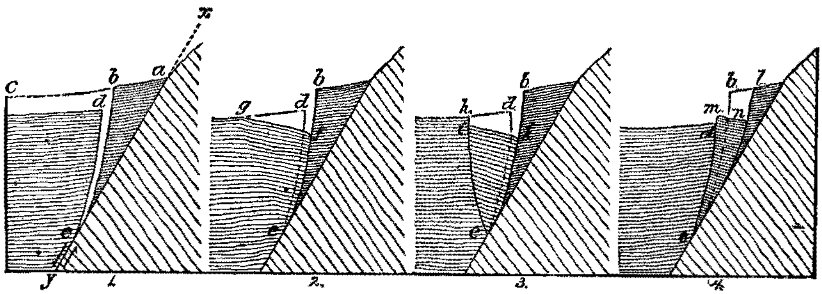


FIG. 48.—Diagram to illustrate Theory of Grouped Fault Scarps in Alluvium.

the firm rock of the mountain, its surface being somewhat reduced by erosion above the point *a*, where the alluvial slope of the valley side adjoins it. To the left of the line *x y* the material represented is detrital and incoherent, being chiefly alluvial. The alluvial surface previous to the last faulting is represented by *a c*. The direction of motion in faulting is parallel to the plane *x y*, and the plane of motion is assumed to coincide with that plane up to the point *e*, and then curve to *b*, so that a triangular prism of alluvium, *a b e*, remains attached to the rock, constituting the foot-wall of the fault. This movement opens a fissure, *b e d*. The material traversed by it being incoherent or feebly coherent, the fissure cannot remain open, but is immediately filled by the settling of one or both of the walls. The remaining three diagrams indicate hypothetical methods of closing the fissure. In the second diagram it is supposed that the hanging wall yields without definite fracture, but by differential movement distributed throughout the mass, so that the triangular prism included between the points *g d e* is made to assume the form and position *g f e*. There then remains a fault scarp, *b f*, giving an exaggerated measure of the actual throw of the fault *b d*, and accompanied at its base by a reversed inclination of the surface *g f*. In the third diagram it is assumed that the hanging wall is divided by a fracture, *h e*, and that the prism *h d e* settles and spreads so as to occupy the space *i k e*. There result two fault scarps, *b k* and *h i*, facing in opposite directions and approximately representing by their difference the true throw *b d*. The fourth diagram supposes that the triangular prism *b l o* is cleaved from the upper part of the foot-wall and slides down so as to take the position *m n e*. This gives two fault scarps, *l n* and *m d*, whose sum would ordinarily afford an overestimate of the actual movement of the great fault plane. If now we consider that there have been repeated movements along the same general plane of faulting, and that these repetitive displacements have often divided the alluvium in different places, it becomes evident that these hypothetic elementary profiles can be so combined as to produce all the complicated profiles actually observed.

While, as just mentioned, a number of successive movements may occasion the same number of separate scarps, they may also coincide in locus and produce but one, and it is probable that coincidence is the rule. In general, each scarp represents a series of distinct movements.

Indeed, so far as the phenomena of the Bonneville Basin instruct us, the process of faulting might be conceived as one of continuous slow motion, and it is only through the phenomena of earthquakes in other districts that we become acquainted with the rhythmic and paroxysmal nature of displacement on surfaces of fracture. The features of the fault scarps accord fully with the general theory that the growth of mountains is a gradual process, secular in duration, though catastrophic in detail.

The freshness of some of the scarps points to an antiquity measured in years rather than centuries. A large number have been produced since the final retirement of the Bonneville waters. A few were synchronous with the Provo shore-line. One movement belongs to inter-Bonneville time. Of earlier dates, nothing can be said with precision. Inside the lake area, it is to be supposed that scarps older than the Bonneville shore-line were obliterated by littoral sculpture and lacustrine sedimentation. Outside the Bonneville shore-line the only discovered index of antiquity is the state of preservation, a criterion affording no precision. Discrimination is further embarrassed by the recurrence of displacement along the same lines, so that the qualified indications of date in the preceding pages apply as a rule only to the latest of the local movements.

LOCAL DISPLACEMENTS VERSUS LOCAL LOADING AND UNLOADING.

The phenomena of earthquakes indicate that the orogenic forces, whatever they may be, slowly generate and accumulate strains in the crust, until finally the cohesion or static friction is overcome, and a sudden yielding results in a fault and an earthquake. In such a district as the Bonneville Basin, where the planes of faulting, superficially at least, are approximately vertical, it seems probable that the determination of rupture may be hastened or retarded by anything affecting the weight of the orogenic block on either side of the plane of movement. It is commonly held by students of physical geology that the degradation of the uplifted block and the accumulation of sediment on the downthrown block constitute an unloading and a loading, which conspire with and aid the forces primarily concerned in the displacement, and it is maintained by some that when once the displacement along a great fault line has been initiated, the process of loading and unloading is competent to continue the depression of the lower block and the upheaval of the higher without further aid from the forces that initiated the disturbance. Now the filling of the Bonneville Basin with water added a very considerable weight to the valleys, and therefore to the down-thrown blocks, and made no corresponding addition to the uplifted blocks represented in the mountain ranges. The contemporaneous glaciers were indeed sustained by uplifted blocks, but these were restricted to a short section of the Wasatch, and in that section their weight was much less than that of the water in the adjacent valley.[1] It is therefore theoretically conceivable that during the presence of the lake the process of faulting along the mountain bases was stimulated, and that after the evaporation of the water the process was correspondingly retarded. That the load of water was quantitatively sufficient is readily shown. If the transfer of rocky matter from the mountain block to the valley block is the cause ordinarily operative in

[1] The area of ice on the Wasatch Range may be compared with the contemporaneous area of water in Lake Bonneville by reference to Pl. XLIX. The areas of ice there represented on the Wasatch and Uintah Mountains are copied from King's map in Volume I of the Fortieth Parallel Report.

generating the stress which renews movement along the fault plane between the blocks, then the depth of rock necessary to be removed from one block and added to the other in order to overcome the adhesion on the fault plane is measured by one-half the resulting movement. For the Wasatch range this measure is less than five feet. The load of water held by the valley blocks was equivalent in the vicinity of Great Salt Lake to a layer of rock of the density of the surrounding mountains and with a thickness of 300 feet, and at the Provo stage the load of water was equivalent to 200 feet of rock. The stress due to the water was therefore many times greater than that needed to overpower the adhesion, and the load of water was competent to act, provided the orogenic blocks possessed the theoretic susceptibility to load.

If the orogenic blocks rest on a plastic substratum, or if they are otherwise conditioned so as to obey the hydrostatic law and yield freely to external stresses, then the valley blocks should have been depressed several hundred feet by the addition of the water, should have partially recovered from this depression during the abrupt lowering of the lake from the Bonneville shore to the Provo, and should have risen still further during the final desiccation of the basin, except in regions where the orogenic forces operated with sufficient rapidity to counteract the tendency. Instead of this, we find that the post-Bonneville movement of the valley blocks, wherever it has occurred, has been one of depression, and so far as the phenomena go we find no evidence that the depression of the valleys was more rapid during the epochs of the Bonneville and Provo shores than it has been in more recent times.

We are forced to conclude that the mountain ranges of the Bonneville Basin and the valleys between them do not, with reference to each other, obey the law of flotation.

It follows with equal cogency that the faults do not penetrate to a layer characterized by fluidity or semi-fluidity—implying by these terms the power to flow under small shearing strain—but terminate in a region of rigidity—implying by that term the ability to withstand relatively large shearing strain. I conceive them to terminate at the upper limit of the region of plasticity by pressure—implying by that phrase that at and below a certain depth the rocks of the crust, however rigid, are subject to such pressure that their yielding under shearing strains exceeding the elastic limit is not by fracture but by flow. I conceive the orogenic blocks as confluent with the subjacent layer, excepting such as may wedge out by the convergence of fault planes.

MOUNTAIN GROWTH.

The height of a mountain, considered as a topographic feature, is the altitude of its crest, not above sea-level, but above the surrounding country. From this point of view it is pertinent to inquire whether the mountains of the Bonneville basin are now growing. The question is more easily asked than answered, but its consideration may not be unprofitable even though the result is indefinite.

In the case of mountains whose uplift takes place along fault planes, the amount of faulting is a measure of the uplift. If the faulting is at one margin only and the other margin suffers no displacement, then the general uplift above the adjacent valleys is one-half the uplift at the fault lines. The processes of degradation tend constantly to pare away the mountain top and thus reduce its height, and in the district under consideration the processes of valley sedimentation likewise reduce the mountain height by building up the valleys and thereby raising the plane of reference. Whenever and wherever diastrophism is the more active, the mountain grows; when degradation and sedimentation are more active, the mountain becomes smaller. The post-Bonneville faulting of the Wasatch Range is restricted, so far as known, to the western base, and there amounts to about 40 feet. The general uplift of the range may therefore be taken at 20 feet. The product of the simultaneous degradation of the mountain finds its way to Utah Lake and Great Salt Lake, where its coarser part is accumulated in the deltas of the Provo, the Jordan and the Weber, while its finer portion is spread over the lake bottoms. But the deltas and lake beds afford no simple measure of the mountain waste, for the same rivers receive also detritus from other land areas, and in the same lakes are gathered the silts from other streams. The deposits, moreover, are unexplored, and if they were explored, it would be no easy matter to discriminate the post-Bonneville deposits from the Bonneville beds beneath them. The problem might be attacked by a consideration of the annual outwash of the mountain torrents, but if this difficult measure were made, we should still need to know the antiquity in years of the last Bonneville flood, a factor for the present entirely unknown.

But though a categorical answer is unattainable, a qualified result is not necessarily so. The recent uplift of the Wasatch Range is greater than that of any other range in the basin. That of the Oquirrh may be one half as great, but no other range is at all to be compared in this respect, and many ranges show no fault scarps whatever. It may therefore be said with confidence that if any range of the district is actually growing at the present time, the Wasatch is growing, and this brings us to a theorem of Powell's which here finds illustration. Powell pointed out[1] that a high mountain is subject to more rapid degradation than a low one, and that the rate of degradation is a geometric function of the height. It is therefore impossible for a mountain to become tall unless it is uplifted rapidly, and when uplift ceases or becomes slow, only a short measure of geologic time is necessary to reduce the height. High mountains are therefore always young mountains. They may be constituted of very ancient rocks,—their initial uplift may have taken place at a remote date, but the great upheaval which produced the present mountain is geologically recent. The Wasatch, springing boldly from a base plain 8,000 feet below its pinnacles, is a young range, and as its recent uplifting has been more rapid than that of any of its neighbors, we may fairly assume that present uplift is in excess of present waste, and that the mountain is now growing.

EARTHQUAKES.

The extreme recency of the last orogenic movements in the most populous portion of Utah, and the high probability of their recurrence in the future, have a practical bearing as well as a scientific, for it is now generally understood that earthquakes are due to paroxysmal yieldings of the earth's crust, and it is equally well known that the dangers attending earthquakes can be greatly diminished by precautionary measures. It is

[1] Geology of the Eastern Portion of the Uinta Mountains, by J. W. Powell, Washington, 1876, p. 196.

indeed true that the fault scarps at the base of the Wasatch Mountains have not been directly connected with earth tremors, but the association of identical phenomena has been elsewhere observed. The earthquake of 1872, one of the most violent ever felt in the United States, originated in Owen's Valley, California, and its origin was accompanied by the sinking of strips of land in such way as to produce fault scarps identical in their general features with those described in the preceding pages. The principal scarp follows the base of the alluvial foot slope of the Sierra Nevada, and has a maximum height of about 20 feet. Where this height is attained, there is a companion fault scarp, 10 feet high, facing in the opposite direction, so that the net displacement is about 10 feet. At other points the main scarp is associated with others running nearly parallel and facing in the same direction. As I saw them, eleven years after their formation, they appeared little fresher than some of the Wasatch scarps.

The earthquake that shook Sonora and southern Arizona on the third of May, 1887, produced a fault scarp which was critically examined by Goodfellow and traced for a distance of 35 miles. It intersects the alluvium along the base of a mountain range or ranges, and has an average height of seven feet. Like the Wasatch scarp, it is often divided or furnished with branches, but unlike that of the Wasatch it is exceptionally small where it intersects the alluvia of streams issuing from the mountains.[1]

The association of earthquakes with fault scarps has likewise been determined in New Zealand, where McKay and Hector not merely refer certain scarps to earthquakes of the years 1848 and 1855, but recognize them as the indices of modern slips on old planes of dislocation, and use them in tracing out important structure features.[2]

It is legitimate to infer that the belt of fertile valleys that follows the western base of the great mountain range of Utah is an earthquake district, and this despite the fact that since its first settlement in 1850 no important tremors have been recorded. It is a matter of geologic history that the Wasatch range is gradually rising, and that this rise is not uniform in time

[1] George E. Goodfellow. The Sonora Earthquake. Science, vol. 11, p. 162.

[2] On the geology of the eastern part of Marlborough Provincial district. By Alexander McKay. In Colonial Mus. and Geol. survey of New Zealand; Reports of Geological explorations during 1885. Faults on pp. 129–133. Also James Hector, in same volume, p. xv.

and place, but is accomplished by small and sudden displacements more or less localized, with intervals of rest. Of the lengths of these intervals we have no means of judging, and no one can predict the date of the next movement, but it is beyond question that such movement will take place, and that when it occurs, the adjacent valley will experience an earthquake. Neither is it possible to predict with great confidence what portion of the district will be next affected, but if the orogenic force is approximately constant and the rhythm in its visible work is due to the necessity for accumulated energy to overcome friction, then the localities with fresh fault scarps may reasonably be assumed to be exempt from faulting for a longer period than those in which only ancient fault scarps are seen. Reasoning thus, I was led to sound a note of warning in Salt Lake City, which stands close by an exceptional section of the range, where the fault scarps are so ancient as to be largely obliterated.[1] Its situation with reference to the growing Wasatch is identical with that of Lone Pine with reference to the growing Sierra Nevada, and it is largely built of adobe, a material ill suited to withstand earthquake shocks. In the village of Lone Pine every house was thrown down by the shock of 1872, and 27 persons lost their lives,—a literal decimation of the population.[2]

The relation of joints to the earthquakes of the Bonneville Basin is discussed in the closing paragraphs of Chapter V.

EVIDENCE FROM SHORE-LINES.

MEASUREMENTS.

The first precise determination of the height of the Bonneville shore-line above the modern lake was made by the Wheeler Survey in 1872, a line of levels being run from Great Salt Lake to the old water mark against the Wasatch range near Fort Douglas. In the same year Howell of that corps observed the barometer on what was supposed to be the same shore-line at various points in the southern part of the Escalante Desert. The

[1] The warning was embodied in a letter to the Salt Lake City Tribune of September 20, 1883, afterward reprinted in the American Journal of Science, 3d series, vol. 27, January, 1884, pp. 49–53.

[2] I quote these figures from J. D. Whitney, who visited Owen's Valley a few weeks after the shock and published a careful and highly valuable description of the phenomena. "The Owen's Valley Earthquake", Overland Monthly, vol. 9, 1872, pp. 130–140 and 266–278.

altitudes deduced from his observations were about 300 feet higher than the altitude at Fort Douglas. Unfortunately, the barometric result was not entitled to great confidence, so that only a presumption of difference of altitude was established; but this presumption gave rise to two hypotheses, which served in turn to direct subsequent investigation. It was surmised by Howell and the writer that changes might have occurred, since the epoch of the shore-line,[1] in the actual and relative altitudes of the different points measured, and it was suggested by King that the shore-line in the Escalante Basin might be found to belong to an independent lake, higher than Lake Bonneville and tributary to it.[2]

King's suggestion led to a careful examination of the strait connecting Escalante Bay with the Sevier body of the old lake, and to the determination that it did not contain a river channel, but was occupied by standing water with an approximate depth of 50 feet, and a width at the most constricted point of about 2 miles. As will appear in a subsequent paragraph, the synchronism of the Escalante shore-line with the Bonneville shore-line of the more northerly basin has not been established, though the observation at the strait renders it clear that the body of water occupying the Escalante Desert was continuous with a body of water in the deeper basins at the north.

The idea that changes in altitude have supervened since the production of the Bonneville shore-line, opened a most attractive field of investigation, for it seemed possible by measuring the height of the old shore-lines at many points to obtain definite knowledge of the amount and distribution of the post-Bonneville displacements of the earth's crust in the lake area. Earlier quantitative studies of upheaval and subsidence had been practically restricted to the sea coast, because there the ocean affords a datum plane for measurement; but here was an opportunity to pursue similar inquiries in an interior district.

In subsequent work every opportunity was improved for the determination of the present height of the records of its water surface. Measurements were made with the engineer's level at points where the water of Great Salt Lake could be conveniently used as a datum plane, and other

[1] Survey west of the 100th meridian, vol. 3, p. 93.

[2] Geol. Expl. 40th parallel, vol. 1, p. 491.

measurements where the same purpose was served by points on railroads. At a few points Locke's hand level mounted on a Jacob's staff was the instrument used, and at other points triangulation was employed with measured base lines. In some regions remote from good points of reference, and especially in the Escalante Desert, the barometer was employed. Spirit-level determinations were made, not only of the height of the Bonneville shore-line, but of the Provo. The local difference between the two was also measured at some points where neither could be referred to Great Salt Lake. For the purposes of the investigation the altitudes of these various points above the sea are unimportant, since only their relations to one another can be discussed, and it has been found convenient to refer them all to the water surface of Great Salt Lake; and since that surface is a fluctuating one, a particular point has been arbitrarily assumed within the range of modern fluctuation. That point is the zero of the "Lake Shore" gauge. As the relation of the altitudes to sea level will not be again referred to, it is proper to say here that the zero of the "Lake Shore" gauge is 95 feet lower than the track of the Pacific Railroad at Ogden, and 4,208 feet higher than mean tide. The implied altitude of Ogden, 4,303 feet, is that accepted by Gannett in his dictionary of altitudes.[1]

As the various measurements employing the water of Great Salt Lake as a datum were executed on different days and in different years, it was necessary to take account of the fluctuations of the lake surface, and this was done by means of the series of gauge observations already described (see page 233).

A more important difficulty was encountered in connecting the lines of leveling with the plane of the old water surface, for it was never possible to decide just how the mean level of the old water surface was related to a particular feature of its shore record. At some places the measurement was made to a cut-terrace, and at others to an embankment, and wherever both these were found in juxtaposition and measured, it was ascertained that the embankment stood higher than any part of the cut-terrace. It was found, moreover, that the difference between these two features was

[1] A Dictionary of Altitudes in the United States, compiled by Henry Gannett: Bull. U. S. Geol. Survey No. 5. 1884.

less in sheltered localities than on coasts facing the open lake, where the fetch of the waves was great. The inference of the plane of the water surface drawn from the local shore record was thus necessarily a matter of judgment, and this judgment was usually exercised upon the ground, where the most satisfactory consideration could be given to the local conditions. Despite all precautions, an uncertainty of several feet attaches to each such determination, and this uncertainty is included in the estimation of the probable errors of the measurements of altitude.

Most of the barometric observations and all the barometric computations were made by Mr. A. L. Webster. He has also combined, unified, and tabulated all the determinations of altitude, and has prepared a report upon them which appears (Appendix A) at the end of this volume. For all matters of detail the critical reader is referred to his report.

DEFORMATION OF THE BONNEVILLE SHORE-LINE.

A summary of the measurements is contained in tables XIII, XIV, and XV, and their geographical distribution is indicated to the eye in Pls. XLVI, XLVII and XLVIII. Attention will first be directed to the table and plate which exhibit the measured altitudes of the highest water line.

TABLE XIII.—*Height of the Bonneville Shore-line, at various points, above Great Salt Lake (Zero of "Lake Shore" gauge).*

Locality.	Height.
	Feet.
1. Santaquin, south of Utah Lake	902 ± 3
2. Lemington, U. S. R. R	902 ± 5
3. Milford, U. S. R. R	904 ± 10
4. Red Rock Pass, north end of Cache Valley	906 ± 4
5. Franklin, Cache Valley	940 ± 3
6. Logan, Cache Valley	942 ± 4
7. Point of the Mountain; 22 miles south of Salt Lake City	950 ± 3
8. Ogden	980 ± 5
9. Fort Douglas, near Salt Lake City	980 ± 5
10. Tecoma, Nevada	981 ± 5
11. Willard, east shore of Great Salt Lake	985 ± 3
12. Black Rock, north end of Oquirrh Range	1008 ± 3
13. Stockton, head of Tooele Valley	1014 ± 5
14. Kelton Butte, near Ombe Station, C. P. R. R	1019 ± 3

TABLE XIII.—*Height of the Bonneville Shore-line, at various points, above Great Salt Lake (Zero of "Lake Shore" gauge)*—Continued.

Locality.	Height.
	Feet.
15. Promontory, 10 miles south of Promontory Station, C. P. R. R	1050 ± 3
16. North end of Aqui range; 12 miles northwest of Grantsville	1070 ± 3
17. Two miles east of Thermos Spring, Escalante Desert	893 ± 25
18. Pavant Butte, Sevier Desert	902 ± 15
19. Seven miles south of Milford	921 ± 20
20. Four miles south of Thermos Spring, Escalante Desert	921 ± 25
21. Seven miles south of Thermos Spring, Escalante Desert	927 ± 25
22. Fillmore, east edge of Sevier Desert	938 ± 8
23. South Twin Peak, south end of Sevier Desert	939 ± 20
24. Kanosh Butte, south end of Sevier Desert	953 ± 15
25. North Twin Peak, south end of Sevier Desert	971 ± 20
26. Antelope Spring, Escalante Desert	1008 ± 30
27. Sulphur Spring, Escalante Desert	1015 ± 25
28. Pinto Canyon, Escalante Desert	1175 ± 35
29. Shoal Creek Canyon, Escalante Desert	1227 ± 35
30. Meadow Creek Canyon, Escalante Desert	1256 ± 35

It appears by inspection that the range of altitude is about 350 feet, the determination of the amount having an uncertainty of less than 50 feet. The distribution of altitudes does not follow any simple law, but yet exhibits certain general features. There appear to be two areas in which the water mark is especially high, the first coinciding approximately with the central meridian of Great Salt Lake, and the second occupying the Escalante Desert, especially its southern portion. Along the eastern border of the basin, from the extreme north to the extreme south, there is a general increase of altitude from east to west. At the south this is continued westward to the limit of the area covered by the observations, and is greatly accented. At the north, where the observations have the greatest range in longitude, the westward rise is replaced beyond the Promontory Range by a westward decline. It appears, moreover, that to all these general rules there are local exceptions, and that where a rise in a certain direction is continuously indicated by a series of localities, its rate from point to point is not uniform.

A comparison of the measured heights of shore-line with the system of faults in the same region indicates in general that they are not closely related, and in particular that the faults cannot be appealed to as a sufficient explanation of the displacements of the shore-line. A good illustration of this is found in the latitude of Salt Lake City, where the height of the shore-line has been measured on three adjacent parallel ranges. On the Wasatch it is 980 feet, on the Oquirrh 1,008 feet, and on the Aqui 1,070 feet. Now each of these ranges has suffered a post-Bonneville faulting at its western margin, as represented in Fig. 49, and the throw of each fault is to the west. The effect of these faults, if there were no other diastrophic

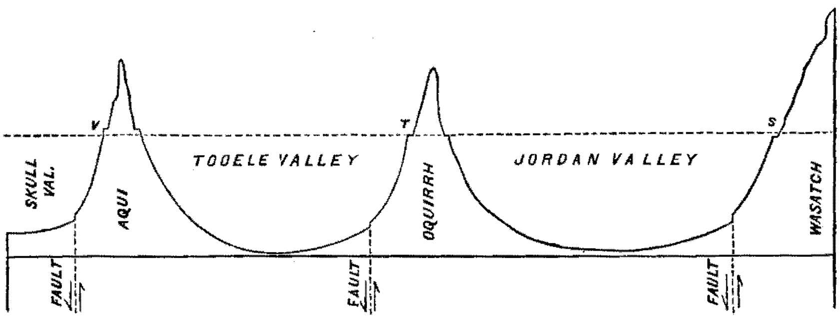


FIG. 49.—Generalized cross-profile of mountains and valleys, illustrating post-Bonneville diastrophic changes. Vertical scale greatly exaggerated. Lower horizontal line = level of Great Salt Lake. Dotted line = 1,000 feet above Great Salt Lake. *V T S* = Bonneville shore-line.

changes, would be to lift the Wasatch higher than the Oquirrh, and both higher than the Aqui, but the shore measurements show the reverse of this. If we assume that the portion of the earth's crust included between each pair of the observed faults is rigid, so as to move as a unit without flexure, then the post-Bonneville changes determined by the observations on faults and shore-lines are correctly represented (except in exaggeration of vertical scale) in fig. 50, where the base line indicates the level of Great Salt Lake,

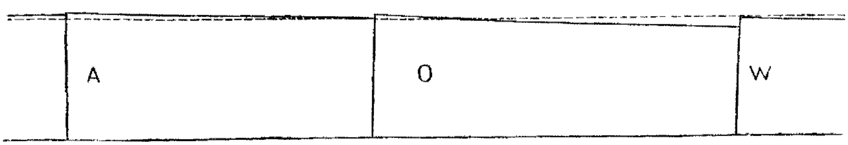
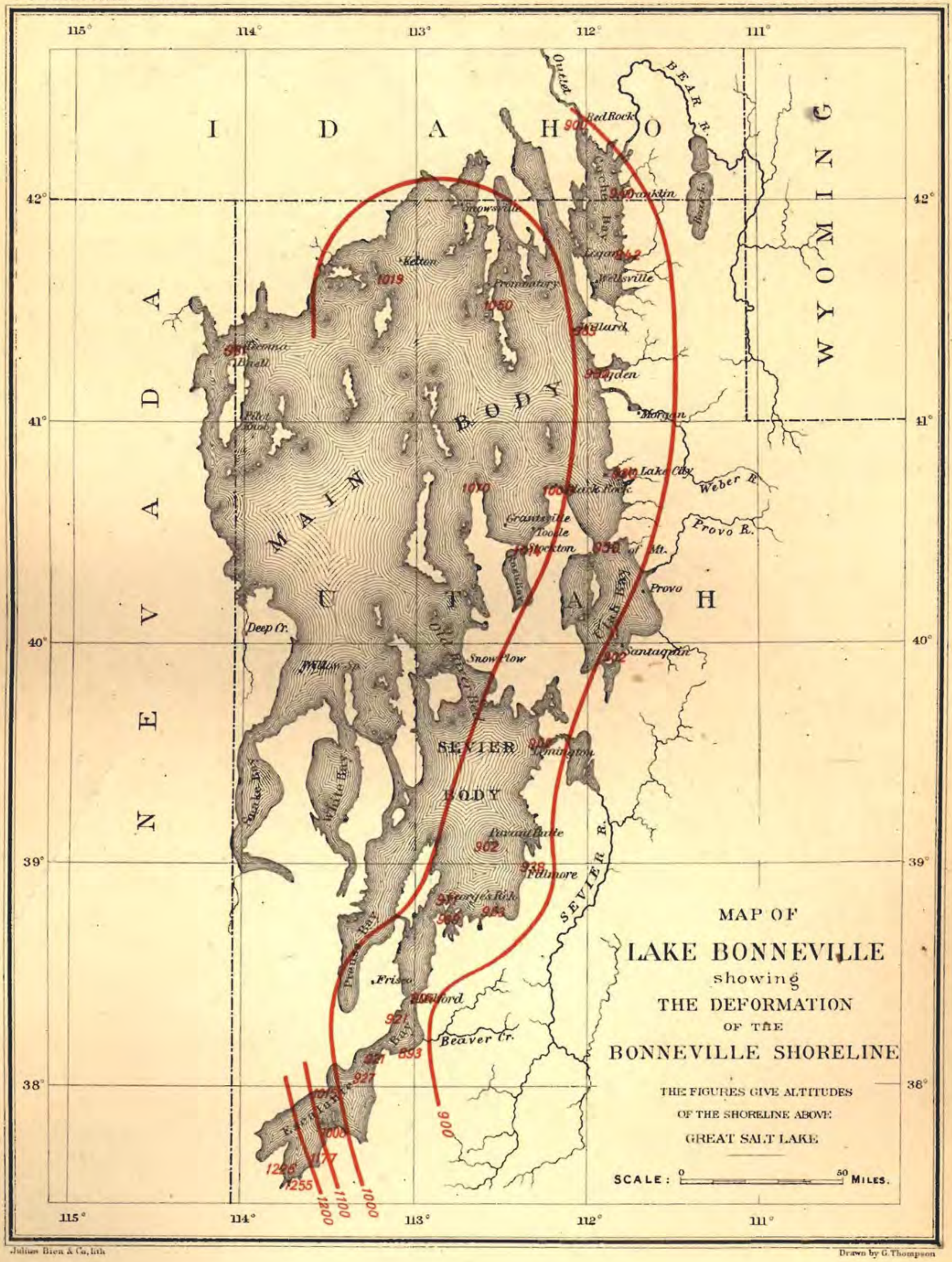


FIG. 50.—Diagram of post-Bonneville diastrophic changes. Base line = level or Great Salt Lake. Dotted line = original position of plane of Bonneville shore-line. Inclined lines = present position of same plane. *A O W* = positions of Aqui, Oquirrh and Wasatch Ranges.

the dotted line parallel to it represents the original horizon of the Bonneville shore-line, assumed to be marked in some way on the orogenic block, and the sloping lines represent the position the shore-line has assumed by diastrophic changes since the Bonneville epoch. The indication is that each orogenic block is canted to the eastward (right), and that each block considered as a whole stands higher than its eastern neighbor, notwithstanding its relative depression along the plane of contact. If the phenomena of this group of localities were general, we should have an exceedingly interesting relation between the general deformation of the shore-line and the system of faults; but they are not general, and we can only say that the principal diversities of shore-line altitude appear to be independent of, and often in spite of, changes by faulting. The changes revealed by the measurement of shore-lines affect broad areas, and are essentially epeirogenic, while those demonstrated by the fault scarps are definitely associated with mountain ranges, and are orogenic. The shore-lines are indeed deformed by both systems of disturbance, but the epeirogenic are the greater. Just as the Great Basin is characterized by broad epeirogenic undulations, dividing it into a series of minor basins, and by relatively narrow mountain corrugations, which rest upon the broader undulations like ripples on the ocean wave, so I conceive the post-Bonneville epeirogenic displacements to be the greater of the features represented by the deformation of the shore-lines, and the orogenic displacements to combine with them as local details or irregularities.

It would be desirable from this point of view to eliminate the orogenic factor and study the epirogenic changes by themselves, but our knowledge of the fault system is too imperfect to permit this, and it will therefore be assumed, somewhat arbitrarily, that the epirogenic undulations are smoother and simpler than the measurements would indicate, the apparent irregularities being due to local faulting as well as to errors of measurement. On the basis of this assumption isogrammic lines have been drawn on Plate XLVI, connecting, so far as possible, points at which the Bonneville shore-line has now the same altitude. They are drawn at equal intervals of 100 feet, and serve to express in another way the general features of distribution of altitude described above. If we conceive of the plane of the ancient water surface, both actual and ideally projected through the contiguous land, as having been deformed by subsequent epeirogenic changes, then these lines are contours on the deformed surface.



MAP OF
LAKE BONNEVILLE
showing
THE DEFORMATION
OF THE
BONNEVILLE SHORELINE
THE FIGURES GIVE ALTITUDES
OF THE SHORELINE ABOVE
GREAT SALT LAKE
SCALE: 0 50 MILES.
IDAHO
NEVADA
UTAH
WYOMING
MAIN BODY
SEVIER BODY
BEAR R.
Weber R.
Provo R.
SEVIER R.
Beaver Cr.
Red Rock
Franklin
Logan
Wellsville
Promontory
Kelton
Snowsville
Willard
Ogden
Morgan
Salt Lake City
Black Rock
Grantsville
Tooele
Stockton
Provo
Santaquin
Deep Cr.
Willow Sp.
Snow Plow
Old River Bed
Fillmore
Pavant Butte
Frisco
Escalante
Pilot
Preuss Bay
White Bay
Snake Bay
Utah Bay
Bear L.
Outlet
1019
1050
1070
902
938
893
921
927
1200
1100
1000
900
1255
1296

It has been tacitly assumed up to this point that all these measurements of the Bonneville shore-line relate to the same epoch, or, in other words, that the various sections of the highest shore mark in all parts of the basin were formed at the same time; but in view of the demonstrated mutability of the land surface on which the water marks are traced, this assumption is manifestly open to question. It may well have happened that at one high stage of water in the basin the maximum water line was scored upon a land surface in one attitude, and at the following high stage upon the same land surface in a different attitude, and that the two water lines severally reached their greatest heights on the land at different points. The highest water line in one part of the area would then represent one flood stage and elsewhere the other, so that the maximum line as a whole would not be synchronous. It might also happen that during the maintenance of one high stage changes would occur in the relative height of different portions of the land, causing some parts to emerge and others to become more deeply submerged. This also would produce a lack of synchronism in the highest shore-line. The questions arising from these possibilities must in general be difficult of solution, but in the case of the Bonneville shore-line we fortunately have a test of wide application. The reader will recall that in the detailed account of the shore there were described a number of series of bars differing by a few feet in height, and demonstrating that just previous to the establishment of the outlet the lake surface had undergone a corresponding series of oscillations. A comparative study of these systems of bars showed that the oscillations had been essentially the same at all localities, and it is thus known that throughout the area of their occurrence the shore-line belongs to the same high-water stage. The demonstration applies to the entire main body of the lake and its principal dependencies, and to the Sevier body and Preuss Bay, but it does not apply to Escalante Bay. The most southerly points at which the peculiar bar system was observed lie in latitude 38° 40′. The lack of positive data in the region of the Escalante Desert is not of great significance, for opportunities for observing this special feature are everywhere rare, and there would be no reason for giving special consideration to that region in this connection, were it not that the displacements there exhibited are of exceptional magnitude. The crowd-ing together of the contours of deformation in that region suggests that the epeirogenic forces may there have had a longer period for the accumulation of their results, and raises the question whether the Escalante Desert may not have received an arm of the lake during its first period of flood, and then have been so greatly elevated as to remain dry during the period of the second flood. The only evidence that can be brought to bear upon this question without new field work is obtained by comparing the Escalante shore record, as to state of preservation and strength, with the records in other valleys of similar character. Mr. Howell and Mr. Webster, who were the chief observers of the Escalante shore, both report it as faint and difficult of determination, and my own observations, limited to a few localities only, confirm their report. The best region for comparison is Snake Valley, where, as in the Escalante Desert, the bay was shallow as well as narrow, and judging from my own observations, the Snake Bay shore record is notably more conspicuous than that of Escalante Bay.

In view of these considerations the Escalante data will be disregarded in the subsequent discussion of the deformation of the Bonneville shore.

TABLE XIV.—*Height of the Provo shore-line, at various points, above Great Salt Lake (Zero of "Lake Shore" gauge).*

Locality.	Height.
	Feet.
1. White Mountain spring, east side of Sevier Desert	553 ± 10
2. Franklin, Cache Valley	569 ± 5
3. Logan, Cache Valley	577 ± 2
4. Point of the Mountain; 22 miles south of Salt Lake City	580 ± 3
5. Willard, east shore of Great Salt Lake	624 ± 5
6. Black Rock, north end of Oquirrh Range	640 ± 4
7. Tooele Valley between Tooele and Stockton	640 ± 5
8. Kelton Butte, near Ombe station, C. P. R. R.	663 ± 3
9. Promontory, 10 miles south of Promontory station, C. P. R. R.	672 ± 3
10. North end of Aqui Range; 12 miles northwest of Grantsville	679 ± 3

DEFORMATION OF THE PROVO SHORE-LINE.

We will now turn to the consideration of Table XIV and Pl. XLVII, which record in their several ways the various determinations of the height of the Provo shore-line. The special criterion by which the identity and synchronism of the Bonneville shore-line were established throughout the greater part of the basin cannot be applied in the case of the Provo. Where the embankments successively formed during Provo time are separated from one another so as to be independently measured, they exhibit differences of height, but these differences are neither uniform nor constant at the various localities where they were observed. The conclusion has already been reached (page 133) that there were changes of relative height while the wave record was being made. Nevertheless, it was always easy to recognize the Provo shore-line and discriminate it from others by reason of the exceptional magnitude of the wave work accomplished at that level. The cut terraces are broader than any other within the basin, and the embankments are larger. At most points it is impossible to determine from the features of the shore what was the local history of oscillation during the persistence of the outlet, for the later work of the waves has effectually obliterated the earlier. It is highly probable that those of its features to which measurement was extended represent the final portion of the long period during which the water stood at approximately the same height.

The number of measurements is smaller than in the case of the Bonneville shore-line, only 10 having been secured; but these are so much more harmonious that it was found possible to draw a system of smooth contours representing intervals of 25 feet only. A comparison of Pls. XLVI and XLVII shows at a glance that these correspond in position and arrangement with the contours adjusted to the Bonneville data in the same area. The area of maximum elevation indicated by them lies over the western portion of Great Salt Lake. There is a descent thence to the east, and more gently to the southwest and south, while a single station indicates descent to the northwest also.

TABLE XV.—*Difference in altitude of the Bonneville and Provo shore-lines at various points.*

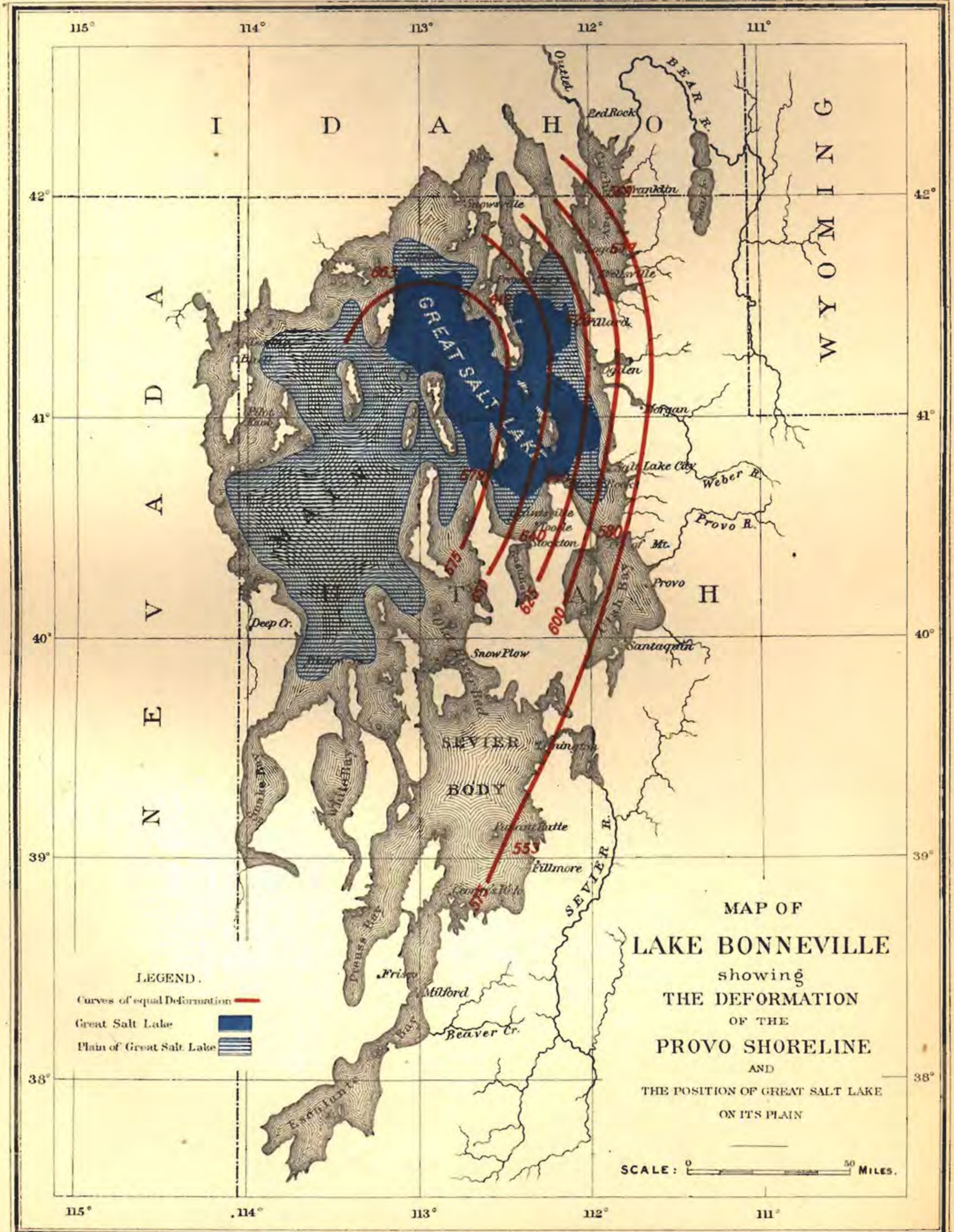
Locality.	Height.
	Feet.
Preuss valley, South series of embankments	341 ± 2
Preuss valley, Middle series of embankments	345 ± 2
Kelton Butte, near Ombe Station, C. P. R. R	356 ± 3
Black Rock, north end of Oquirrh Range	360 ± 3
Willard, east shore of Great Salt Lake	361 ± 5
Snowsville, north edge of Great Salt Lake Desert	365 ± 2
Logan, Cache Valley	365 ± 3
Point of the Mountain, 22 miles south of Salt Lake City	370 ± 3
Franklin, Cache Valley	371 ± 2
Promontory, 10 miles south of Promontory Station, C. P. R. R	374 ± 3
Tooele Valley between Tooele and Stockton	374 ± 3
Tooele Valley between Tooele and Grantsville	380 ± 3
Wellsville, Cache Valley	382 ± 2
Fish Spring, south edge of Great Salt Lake Desert	382 ± 5
Fillmore, east edge of Sevier Desert	385 ± 8
North end of Aqui Range; 12 miles northwest of Grantsville	389 ± 3
Cup Butte, Old River Bed	392 ± 3
Snowplow, Old River Bed	397 ± 2
Terrace Mts., 8 miles southeast of Matlin Station, C. P. R. R	411 ± 3
Dove Creek, between Matlin and Ombe, C. P. R. R	413 ± 2

DEFORMATION DURING THE PROVO EPOCH.

Table XV and Pl. XLVIII show the measured differences in altitude of the Bonneville and Provo shore-lines at various points. The localities at which these differences were measured coincide partly with localities of the two preceding tables, but are also in part independent; for it was sometimes found possible to make the differential measurement where the lack of an available datum point prevented the reference of either to the level of Great Salt Lake.

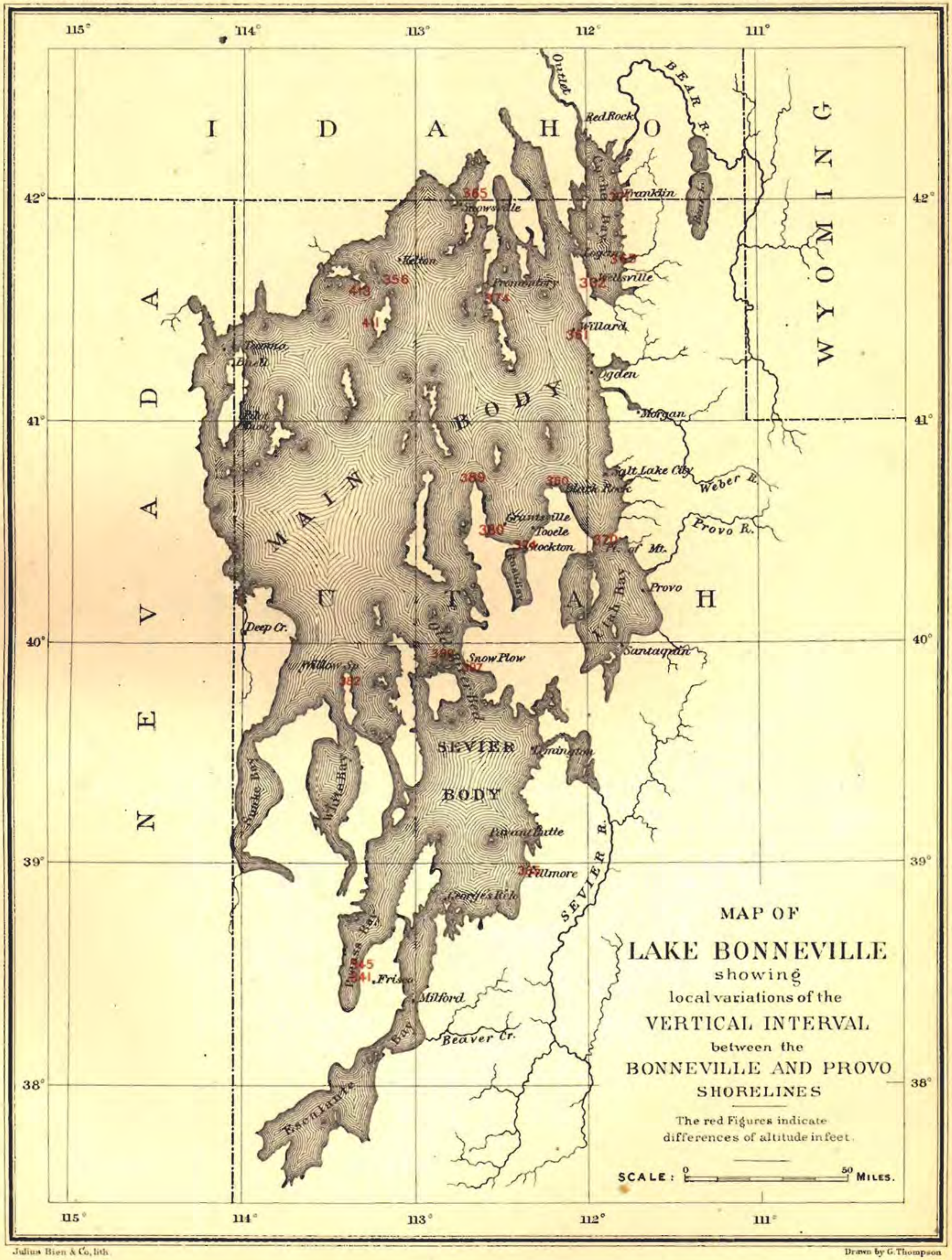
The range of variation is not large, and whatever order may characterize them is so far concealed by irregularities that it was found impossible to classify them by any system of smooth contours. But, as will presently appear, when they are classified with reference to the contours of the Bonneville and Provo shore-lines, they betray a certain amount of harmony.

It will be recalled that when the lake attained its maximum height and outflowed, the water was discharged with great rapidity down to the level



Julius Bien & Co. lith.

Drawn by G. Thompson



Julius Bien & Co, lith. Drawn by G. Thompson

of the Provo shore, at which level the lake stood for a relatively long time. This time may have been continuous or may have been more or less interrupted by the temporary retreat of the water to lower levels. Including such interruptions, if any occurred, it has been called the Provo epoch. The table and map of differences between the Bonneville and Provo shore-lines represent the changes of altitude occurring in Provo time, or from the end of the epoch of the Bonneville shore-line to the end of the Provo epoch. The differences of level of the Provo shore-line represent changes wrought since the end of the Provo epoch, and those of the Bonneville shore-line changes since the beginning of the epoch of outflow.

POSTULATE AS TO CAUSE OF DEFORMATION.

The area of maximum elevation, as indicated by these data from the Bonneville and Provo shore-lines, coincides with the middle portion of the main body of Lake Bonneville; and this coincidence suggests the hypothesis that the disappearance of the lake and the epeirogenic rise of the center of its basin stand in the relation of cause and effect. In the ensuing discussion this relation will be postulated, though it must be clearly understood that the available data do not demonstrate it, but merely endow it with a certain degree of probability; and since a somewhat elaborate structure will be founded upon it, it is especially desirable that the weakness as well as the strength of the postulate be clearly perceived

The postulate is in some sense graphically expressed by Pl. L, where the contour lines of the preceding plates are so modified as to make closed curves representing a dome-like figure of deformation, slightly elongated in the direction of the axis of the lake. The data used in the construction of this system of lines are selected from the measurements of the Bonneville shore-line, excluding all that depend upon barometric work—a principle of selection which omits all measurements with high probable error, as well as those made in the Escalante Desert, which are independently questionable.

The first consideration favoring the postulate is the one just mentioned, that, so far as trustworthy measurements indicate, the area of maximum uplift coincides with the center of the principal area of deep water in the old lake.

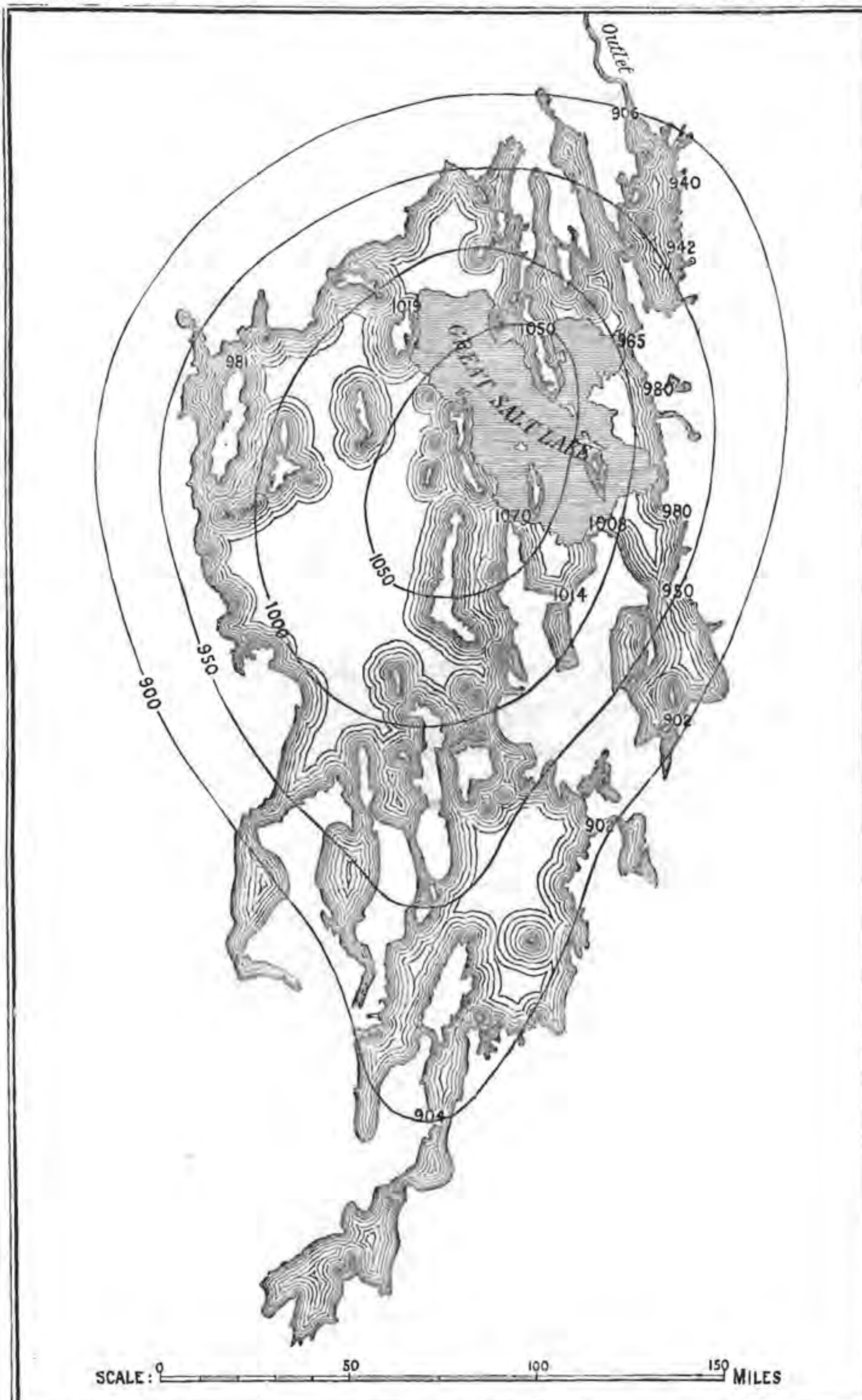
A second favorable consideration arises from a comparison of the changes occurring severally during the Provo epoch and since the Provo epoch with the total changes since the formation of the Bonneville shore-line. To make this comparison, the various measurements were classified with reference to areas marked out by the hypothetic contours. In Table XVI, the column of figures at the right contains measurements of the height of each shore-line and of their difference, so far as these were measured within the area circumscribed by the 1050-foot contour. The next column at the left contains the measurements made at localities falling within the area limited on one side by that contour and on the other by the 1000-foot contour; and so for the remaining two columns.

TABLE XVI.—*Comparison of post-Bonneville, post-Provo and Provo Deformations (figures give feet).*

Areas between contours on Plate L	900 to 950	950 to 1000	1000 to 1050	Above 1050
Determinations of Bonneville shore-line above Great Salt Lake	902	950	1008	1070
	902	965	1014	....
	904	980	1019	....
	906	981	1050	....
	940	....	....	....
	942	....	....	....
Mean	916	969	1023	1070
Determinations of Provo shore-line	553	580	640	679
	569	624	640	....
	577	....	663	....
	......	....	672	....
Mean	566	602	654	679
Determinations of difference between Bonneville and Provo shore-lines	341	361	356	389
	345	365	360	....
	365	370	374	....
	371	382	374	....
	385	382	380	....
	......	392	411	....
	......	397	413	....
Mean	361	378	381	389

By arranging the determinations in this way and then taking means, it was hoped to eliminate so much of the irregularity due to orogenic dis-


MAP OF
LAKE BONNEVILLE
showing
(in blue)
THE
GLACIATED DISTRICTS
OF THE
BONNEVILLE BASIN
SCALE: 0 50 MILES.
IDAHO
NEVADA
UTAH
WYOMING
MAIN BODY
SEVIER BODY
UINTA
WASATCH
TUSHAR
BEAR R.
SEVIER R.
Outlet
Red Rock
Franklin
Logan
Wellsville
Willard
Ogden
Morgan
Salt Lake City
Black Rock
Grantsville
Tooele
Stockton
Provo
Santaquin
Snow Plow
Kelton
Promontory
Deep Cr.
Pilot Knob
Willow Sp.
Fillmore
Frisco
Milford
Beaver Cr.
Snake Bay
White Bay
Preuss Bay
Escalante Bay
Pavant Butte
Weber R.
Provo R.
Utah Bay
Cache Bay
Old River Bed
115°
114°
113°
112°
111°
42°
41°
40°
39°
38°



THEORETIC CURVES OF POST-BONNEVILLE DEFORMATION.

placement and to errors of measurement as to render the data fairly comparable. The measurements of the Bonneville shore-line having been used as a basis for drawing the contours, their means, as a matter of course, constitute a series; and it was anticipated that the Provo determinations, having given rise on Pl. XLVII to very similar contours, would likewise furnish, as they do, a progressive series of means; but a similar correspondence could not have been confidently predicted for the observations of difference in altitude of the two shores, for these are so irregular in detail that representative contours could not be drawn. Nevertheless, their means as thus classified fall into line with remarkable regularity. It appears to be a legitimate inference that the epeirogenic deformation occurring during the Provo epoch was identical in locus and general character with that occurring subsequently, and with the total deformation of which it is a part; and this accords with the postulate, for if the withdrawal of the entire mass of water produced the quaquaversal uparching of the basin, then the partial emptying of the basin by the draining off through the outlet of a layer of water 375 feet deep should produce a similar uparching, differing only in amount.

Opposed to the postulate, we have the general fact that the Great Basin appears to have been characterized by epeirogenic movements, varied in character, through Tertiary and Pleistocene time, and that as these movements successively created and destroyed lake basins, they must be supposed to have generally originated in a different way. It is therefore possible that the coincidence in time and place of the uplift under consideration with the disappearance of Lake Bonneville is a coincidence merely.

A second and very serious element of weakness in the postulate inheres in the fact that the observations are mainly confined to the eastern half of the basin. Only two points of observation lie west of the maximum area, and only one measurement was made in the extreme western portion of the basin. The area well covered by points of determination is at most not more than two-thirds of the entire area to which the postulate is applied.

These considerations pro and con hardly admit of explicit summation. The predilections of each geological reader will determine the relative weight he assigns to them, and his consequent confidence or lack of confidence in the conclusions which follow.

There are at least three ways in which the removal of the water may have given rise to the observed variation of altitudes. First, the geoid may have been locally deformed by a change in the local attraction; second, the surface of the land may have been deformed by local expansion due to the post-Bonneville change of climate; third, the earth itself may have been locally deformed in consequence of the removal of the weight of the water. These three hypotheses will be considered in order; and it will be found advantageous to inquire with reference to each how the deformation it is competent to produce compares in amount with the observed deformation. The maximum measure of the observed deformation is $1070-902=168$ feet; but as this may, and probably does, involve local orogenic displacements, it will be better to use for the present purpose a measure obtained by comparing a number of the highest measurements collectively with a number of the lowest. The mean of the five observations of height falling within the 1000-foot contour is 1032 feet. The mean of the four lowest determinations is 903 feet, and their difference, 129 feet, will be compared with the various amounts inferable from the three hypothetic causes.

HYPOTHESIS OF GEOIDAL DEFORMATION.

The surface of a body of standing water is level, but is not plane. Being a part of the surface of the earth, it is approximately ellipsoidal. If there were no inequalities of surface, and the density of the earth were uniform throughout, or varied only in accordance with certain laws, a level surface carried completely around the globe would be a perfect ellipsoid. The actual inequalities of surface and irregularities of density produce local irregularities of attraction and corresponding irregularities of the level surface. To distinguish the deformed level surface from the spheroid to which it approximates it is called the "geoid". Any change in the superficial distribution of matter modifies the geoid, and the removal of the lake water from the Bonneville Basin was such a change. The effect of refilling the basin would be to increase the local attraction and locally uparch the geoidal surface; its emptying unquestionably tended to flatten the geoidal surface. Assuming the configuration of the country unchanged, the Bonneville surface was more sharply convex than the Salt Lake surface, and the engineer's level should now find the Bonneville shore-line higher on central islands than on peripheral slopes. The theoretic change corresponds in kind with the observed; does it agree in amount? My mathematical resources not being adequate to this question, it was submitted to my colleague, Mr. R. S. Woodward, who gave it full consideration. It happened that the cognate problem of the deformation of the geoid by a continental ice mass was submitted to him at about the same time by Dr. T. C. Chamberlin, and he was thus led to a comprehensive discussion of the general subject to which the special problems belong. In the application of his formulæ to the present case no account was taken of topographic details, but the mass of water in the main body of Lake Bonneville was assumed to have the form of a circular lens two degrees (138 miles) in diameter with a maximum depth of 1000 feet. It was found that the maximum depression of the geoidal surface referable to the subtraction of such a mass is 2.01 feet, an amount too small to be considered in comparison with the observed deformation of 129 feet. The phenomena are therefore not to be explained as changes in the plane of reference, but must be referred to changes in the relative altitude of portions of the basin.

The reader will find an abstract of Mr. Woodward's treatment of the problem in Appendix B.

HYPOTHESIS OF EXPANSION FROM WARMING.

The second hypothesis involves considerations of temperature. The temperature of the earth's crust at the surface is identical with the mean annual temperature of the contiguous fluid, air or water, and at all subterranean points it is warmer, the change of temperature with depth being gradual. Every change of climate produces a corresponding change in the surface temperature of the crust, and this change is slowly propagated downward. When the Bonneville Basin was full of water, there can be little question that the surface temperature was lower than at present, and it is possible that the corresponding difference between the temperatures of the adjoining land, then and now, has not been equal in amount, in which case the post-Bonneville warming of the crust beneath the lake area has been greater than the coincident warming of the crust underlying contiguous areas. Rise of temperature carries with it expansion, and the hypothesis is that such differential expansion produced the observed differential altitudes. Our quantitative data are here less precise than in the case of the preceding hypothesis, but it is not difficult to assign to them reasonable limiting values, so as to obtain a practical test of the hypothesis. The mean annual temperature at Salt Lake City is 51° F., and this may be assumed for the entire basin. Its ancient climate was somewhat colder, but the moderate development of glaciers permits us to entertain the assumption that the difference was small. The lake, as we know from its wave work, was not frozen, and as it had great depth, we are assured by the analogy of modern examples that its bottom temperature was that of water of maximum density, about 39°. The surface temperature of the crust in the lacustral area was therefore 12 degrees lower than now. If we assume that the surface temperature of the surrounding land was only two degrees lower than now, we are certain to underestimate the climatic change, and thus allow a maximum or limiting difference between the crustal changes under the old lake and under the old land. The problem then takes the form: What uplift can be referred to the expansion of the upper portion of the earth's crust consequent on a superficial rise of temperature of 10 degrees occurring at the close of the Bonneville epoch. The remaining constants necessary for its solution are obtained by assuming the coefficient of expansion of the rock involved to be 0.000006 for each degree, by adopting Sir William Thomson's coefficient of diffusion of heat in the earth, and by assigning to post-Bonneville time a duration of 100,000 years, an estimate intentionally large. For the computation of the vertical rise of the basin from these numerical data I am indebted once more to Mr. Woodward, who has recently reviewed the subject of subterranean temperatures from the mathematical side. His result (see Appendix C) is 1.28 feet, an amount quite too small for our consideration in this connection.

HYPOTHESIS OF TERRESTRIAL DEFORMATION BY LOADING AND UNLOADING.

The third hypothesis explains the phenomena by assuming that when the Bonneville Basin was filled with water, the earth yielded to the weight of the water, permitting a depression of the loaded area, and that when the water was afterward removed, there was a corresponding rise of the unloaded area. The manner of yielding, the amount of vertical change, and the figure of deformation all depend on the constitution of the earth, and as that constitution is unknown, it is necessary to make assumptions regarding it in order to discuss the quantitative sufficiency of the hypothesis. If the earth were perfectly rigid, the removal of the Bonneville load would not affect its form; if the earth were completely liquid, the removal of the load would cause the load to be replaced by the uprising of an equal weight of matter. Neither of these extreme conceptions can be entertained, for the visible portion of the earth is neither liquid nor perfectly rigid, but between them is room for an infinite variety of special assumptions under each of which some deformation of the basin must be assigned to the unloading.

In order to learn the order of magnitude of the greatest possible deformation, let us assume for a moment that the earth is constituted by a thin solid crust resting upon a liquid substratum, and that the rigidity of this crust is very small in comparison with the stresses applied to it by the removal of the water from the Bonneville Basin. The floor of the basin will then rise under the action of these stresses in some sort of arch, whose interior will be filled by liquid matter derived from surrounding regions. The weight of the liquid matter thus introduced will be approximately equal to the weight of the water removed by evaporation, and the height of the crustal arch will be related to the depth of the water in (approximately) the inverse ratio of the densities of the two liquids. The liquid rock may be assumed to agree in density with the average density of visible rocks at the surface, 2.75, and this gives us as the height of the resulting arch the quotient of 1000 feet by 2.75, or 364 feet. This is the height attainable by the arch on the supposition that the strength of the crust is a vanishing quantity, and it is the superior limit of all possible values for the height of the arch. With the strength a vanishing quantity, the vertical stresses due to unloading are equilibrated by vertical stresses due to gravitation, and the height of arch is 364 ft; with the strength finite, the stresses of unloading are equilibrated partly by stresses of gravitation and partly by elastic strains, and the height of arch is a function of the stresses of gravitation. While the nature of this function is more complex than that of simple proportion, it is fair to infer from a comparison of the observed height of the arch of deformation, 129 ft., with the limiting height, 364 ft., that under this hypothesis the stresses from unloading are satisfied chiefly by elastic strains and secondarily by gravitational stresses.[1] That this implies great strength of crust becomes apparent when the magnitude of the load removed and the width of the affected area are considered. For the sake of illustration, assume that 129 feet of uplift satisfy the stresses due to 355 feet (129×2.75) of the removed water; there remain the stresses due to 645 feet to be satisfied by strains in the crust. Call the basin floor a beam, 120 miles long, supported at the ends, and sustained throughout by flotation so far as its own weight is concerned. Call the modulus of rupture of its material 3,000 pounds to the square inch, and introduce no factor of safety. Consider the beam to be subjected to upward stress by the removal of 645 feet of water from its entire upper surface, and compute by the engineer's formula the depth of beam necessary to stand the strain. It is about 32 miles.[2] The illustration is a rude one, because the floor of the basin, being attached all about its periphery, is stronger than a beam supported only at the ends; because a crust graduating into a liquid beneath is weaker than a homogeneous crust; because the modulus of

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[1] If we postulate a thick crust it is proper to postulate also that the matter flowing in beneath the dome has a greater density than superficial rock. With the density 3.5—an extreme assumption—the limiting height of arch is 286 feet.

[2] The engineers' formula is

$$W = \frac{4}{3} R \frac{bd^2}{l},$$

where W is the breaking stress in pounds, the stress being evenly distributed over the upper surface of the beam; R is the modulus of rupture of the material in pounds per square inch; b is the breadth of the beam, d its depth and l its length. In the case under consideration $W = Dqlb$, in which D is the depth, in feet, of water removed, and q is the weight, in pounds, of a column of water one inch square and one foot in height. Substituting this value for W in the formula, transposing and reducing, we obtain

$$d = l \sqrt{\frac{3}{4} \frac{Dq}{R}}.$$

$q = .434$ pound. Making $l = 120$ miles, $D = 645$ feet and $R = 3000$ pounds, we find $d = 31.7$ miles.

viscous distortion is less—possibly far less—than the modulus of rupture; and for other reasons; but it nevertheless assists the imagination in realizing the relation of bulk to strength. With its aid I trust the reader will follow me in the conclusion that the hypothesis of local deformation of the earth by local unloading affords results of the same order of magnitude as the observed distortion of the plane of the Bonneville shore, and is quantitatively adequate.

The first and second hypotheses having been found quantitatively inadequate, the third is the only one meriting further discussion. A thorough treatment is on the one hand highly desirable and on the other beset with difficulties. It is desirable because it promises to throw some light on the condition of the interior of the earth; a solid earth would not yield the same deformation as an earth partly liquid; a highly rigid earth would behave differently from one of feebler rigidity. It is difficult because it must deal with magnitudes and pressures far beyond the field of experimentation, and can be accomplished only by the aid of comprehensive mathematical analysis. It requires an analytic theory of the strains set up by a stress applied locally to the surface of the earth and of the resulting deformation, and this theory must be so general as to include divers assumptions as to the variation of elasticity with depth from the surface, and as to the relation of the strains to the limits of elasticity.[1] The evolution of such a theory is beyond my power, but in the belief that it is worthy of the attention of the mathematician and physicist, I will endeavor to state the problem.

Assume, first, that the rigidity of the earth is uniform throughout, or at least for some hundreds of miles from the surface, its modulus of elasticity being that of granite, for example. Then conceive the application to the surface of a lenticular body of water equivalent to Lake Bonneville,

[1]As defined by Sir William Thomson, "Elasticity of matter is that property in virtue of which a body requires force to change its bulk or shape, and requires a continuous application of the force to maintain the change, and springs back when the force is removed, and if left at rest without the force, does not remain at rest except in its previous bulk and shape." Elasticity of bulk and elasticity of shape are distinct properties, which coexist in solids, but not in liquids. Rigidity is synonymous with elasticity of shape. Solids differ in regard to rigidity in two ways. They have different moduli of rigidity and different limits of rigidity or elasticity. The modulus of rigidity depends upon the stress necessary to produce a unit of deformation, or upon the deformation produced by a unit of stress. The limit of rigidity is reached when the force applied is so great that after its removal the solid does not return to its original shape.

but symmetric. To imagine the result, it is necessary to divest the mind of the ideas of brittleness and great strength ordinarily associated with granite and other massive rocks. Brittleness is a surface phenomenon only; at a depth of a few thousand feet, or at most a few miles, the tendency to fracture is effectively opposed by pressure. Strength is conditioned by magnitude, and in relation to magnitude it is a diminishing function. Structures of the same form and material are not strong in proportion to their size but are relatively weaker as they are larger until finally they can not sustain their own weight. In a general way strength increases with the square of the linear dimension; weight and other loads increase with the cube. Giving due weight to these considerations, it is not improper to compare the earth when loaded by the water of Lake Bonneville with a bowl of jelly upon which a coin has been laid. The results in either case are, first, the depression of the area beneath the load, second, the formation of an annular ridge about it, and third, the production of strains within the mass. Conversely, the removal of the water of Lake Bonneville would produce an uprising of the central area of the basin and an annular depression all about, and would either relieve the strains previously produced by the addition of the water, or, if these strains had been otherwise relieved, would set up a new system with opposite signs. It is easy to understand from the homologous phenomena of jellies that the precise figure of the superficial deformation would depend on the modulus of elasticity of the earth material. With a low elasticity the central arch would be high; with a high elasticity the figure of deformation would be comparatively low.

There are two elements of complexity that inhere in the subject. In the first place, the deformation of the earth is resisted not only by the elasticity of the material but by gravitation, which always tends to give the surface the normal configuration of the geoid. In the second place, the stresses created by the removal of the Bonneville water would have certain effects through the property of bulk elasticity as well as that of shape elasticity. It is not improbable that a suitable discussion of the subject would demonstrate that the deformations ascribable to bulk elasticity are too small for consideration in connection with those referable to shape elasticity, but to this extent at least they would need to be considered.

Add now a third element of complexity, by assuming that the strains set up by the removal of the water are not entirely within the limit of elasticity of the material. Wherever they exceed the elastic limit, change of another sort occurs, probably not fracture, as in laboratory experiments on the limits of elasticity, but flow—such flow as Tresca's experiments have demonstrated for colloids.[1] The plastic yielding of the rock in the region of greatest strains would cause a partial redistribution of strains in adjacent regions, and would correspondingly modify the figure of deformation. The height of the central arch would be increased.

Now add yet one other element of complexity, by assuming that the modulus of shape elasticity and the limit of shape elasticity vary (simultaneously and harmoniously) in accordance with some law involving the distance from the surface. They may increase from the surface downward, or they may decrease from the surface downward, and in the latter case liquidity will at some depth be reached. The actual deformation should be comparatively low if the elasticity increases downward, and comparatively high if the elasticity diminishes downward.

The application of an analytic theory of these relations could yield the best results only with a better determination than we now have of the elasticities of rocks, and with a better determination of the figure of the deformation of the Bonneville Basin; but even with the imperfect data at hand it might establish a presumption for or against the existence of a liquid substratum beneath the rigid crust, and if the mathematical difficulties were surmounted, there can be little question that the observational data would be supplied, for their procurement is opposed by little beside their expense.

Without waiting for the mathematician, we may conclude in a general way that the floor of the Bonneville area arched upward when the load of water was removed, and that this deformation was permitted by the feeble elasticity or the imperfect elasticity, or both, of the portion of the earth affected; the conclusion being qualified by whatever weakness inheres in the postulate that the coincidence in time and place of crust unloading and crust deformation is not fortuitous.

[1] Mém de l'Inst. Savants étrangers, vol. 18, 1868.

EVIDENCE FROM THE POSITION OF GREAT SALT LAKE.

In an earlier chapter attention has been called to the fact that in the central portion of the basin of the main body of Lake Bonneville mountain ridges are so nearly buried by lacustrine sediments that only their summits remain visible, jutting forth from the plain after the manner of islands. The amount of sedimentation implied is great, and its magnitude is likewise indicated by the general evenness of the plain. Wherever the writer has crossed a portion of this plain, he has found himself, after leaving the foot slope of the contiguous mountains, upon a playa floor with no discernible inclination, and nearly bare of vegetation. The saltness of the soil testifies that water does not flow across it, but rather stands upon it and evaporates. Another evidence of the general evenness of surface is the shallowness of Great Salt Lake, which has a mean depth of less than 15 feet.

At the present time the principal contribution of débris toward the filling of the basin comes from the east. On the coast of Great Salt Lake deltas have been observed only at the mouths of the Jordan, the Weber, and the Bear, all rising in the Wasatch and Uinta Mountains and entering the lake on the eastern side. The western coast shows capes only where rocky hills stand near, and bays are found where it receives the intermittent drainage of the surrounding valleys. In Bonneville times the same contrast existed. The deltas of the old lake are found almost exclusively where it received streams from the east, namely, the rivers just mentioned, their principal tributaries, which then entered the lake directly, and the Sevier River. No delta terraces were observed about the northern, western, and southern margins, unless possibly in the Escalante Desert.

If this deposition, so great in amount, and derived so largely from the east, were the only factor concerned in the determination of the configuration of the desert floor, that floor would be a gently-sloping plain, with its higher margin at the east and its lower at the west, and Great Salt Lake would lie at the base of the Gosiute Mountains instead of the Wasatch. The easterly position of the lake is unquestionably due to crustal movement, either orogenic or epeirogenic. (See Pl. XLVII.)

Let us first consider the possibility of an orogenic cause. The most conspicuous recent orogenic change in the region is that shown by the fault scarps at the base of the Wasatch Range. These scarps show differential movement, either ascent of the mountain or descent of the valley, or both. The great size of the mountain range, as argued on an earlier page, assures us that a rising of the range is at least a part of the displacement, but is not opposed to the idea that the sinking of the valley is a correlative and perhaps equal part. It is consistent with this idea that the water of Great Salt Lake between the Bear and Weber deltas, and again between the Weber and Jordan deltas, approaches within about a mile of the great fault at the mountain base.

Epeirogenic causes may be considered from two points of view: first, as belonging to a system of changes correlated with the emptying of the basin by evaporation; second, as belonging to the more general system of changes to which the basin, as such, may be ascribed. Taking the first point of view, we have a post-Bonneville rising of the central area amounting to more than 100 feet, and it is conceivable that this has divided the plain into two basins, of which the lake occupies one, while the other contains only occasional playa lakes, such as the scant rainfall of the tributary regions is able to produce. Too little is known of the configuration of the desert west of the lake to determine whether it is partitioned off by a barrier of such sort, or is in time of great rainfall tributary to Great Salt Lake. But there are other reasons why the hypothesis can not be seriously entertained. In the first place, the area of maximum uplift, so far as our measurements determine it, coincides with the western portion of the lake instead of with the line of low ridges beyond it. The old shore-line is higher on Promontory Ridge than on the Terrace Mountains to the westward.

It must also be borne in mind that the present condition of the basin as affected by climate is substantially identical with the pre-Bonneville condition, and the arid phase was of long continuance before the Bonneville flood. Whatever central elevation is recorded by the surviving shoreline is merely the correlative of central depression during the lake period, and to assume the post-Bonneville uplifting of the plain into a barrier adequate to contain the lake is to assume that during the existence of the lake the central depression was filled by sediments so as to produce a lake bottom almost absolutely level. From what we know by observation of the slopes on which the Bonneville sediments were able to lie, we can not believe that this was accomplished, but rather that throughout the deeper portion of the lake there was an equable deposition over gentle slopes, the depth of deposit increasing rather toward the source of the material at the east than toward the center of the lake. It is probable that post-Bonneville changes in the configuration of the plain, so far as they have depended epeirogenically on the removal of the water, have been the simple converse of changes due to the previous imposition of the water, and have practically restored the preexisting condition.

Turning to epeirogenic considerations of a more general nature, we see that the Bonneville Basin is a region of depression, surrounded on the south, west and north by regions of somewhat greater elevation, and on the east by a tract whose mean altitude is several thousand feet higher—an irregular plateau, along the edge of which the Wasatch Range stands as a parapet. The forces which produced this basin and the plateau to the east of it are of necessity independent of the loading and unloading of the basin, and of a more general nature. Whatever they may be, it is not irrational to appeal to them as the cause of the local depression containing Great Salt Lake and to regard that depression as a result of the mere continuance, with possibly greater localization, of the process which created the larger basin.

Whether, then, we regard the peculiar position of the lake as a result of orogenic or of epeirogenic displacement, we are compelled to forego the assignment, even tentatively, of a special hypothesis as to its cause. Perhaps the most valuable conclusion to be drawn is that, as deposition within the basin, during humid and arid phases of climate alike, has continually tended to build the eastern half of the plain higher than the western, and, as this tendency has continued to the present time, the subsidence opposing and thwarting it has likewise continued to a late epoch and is probably still in progress.

THE STRENGTH OF THE EARTH.

The writer has been led by the discussion of these phenomena to a conception of the rigidity or strength of the earth, more definite than he had previously entertained. It would not be proper to call this conception a conclusion from the data here presented, or a result to which they rigorously and necessarily lead. It is rather a working hypothesis suggested by the study of Lake Bonneville.

If the earth possessed no rigidity, its materials would arrange themselves in accordance with the laws of hydrostatic equilibrium. The matter specifically heaviest would assume the lowest position, and there would be a gradation upward to the matter specifically lightest, which would constitute the entire surface. The surface would be regularly ellipsoidal, and would be completely covered by the ocean. Elevations and depressions, mountains and valleys, continents and ocean basins, are rendered possible by the property of rigidity, but the phenomena of diastrophism, and especially those of plication, show that this rigidity has its limits, and the phenomena of volcanism demonstrate that its distribution is not uniform. It has been computed by Darwin[1] that if the earth were homogeneous throughout, the stress differences occasioned by the weight of continents would be as great as those necessary to crush granite. The stress difference necessary to produce viscous flow in granite and allied rocks is not known, but if different from the crushing stress, it is less; and Darwin's discussion therefore tends to show that the earth, if homogeneous, would require a strength equal to or greater than that of granite. That the earth is not homogeneous as regards density (and does not consist of symmetric homogeneous shells) is shown by the massing of land areas in one hemisphere; and the hypothesis that the crust has low density beneath continents and high density beneath oceans is sustained by observations on the local direction and local force of gravitation at various points.[2] The general proposition, tacitly postulated by Babbage and Herschel, advocated more

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[1] On the stresses caused in the interior of the earth by the weight of continents and mountains, by G. H. Darwin. Phil. Trans. Royal Soc., pt. 1, 1882.

[2] On the argument from geodetic station errors see John H. Pratt, Figure of the Earth, p. 201.

On the argument from pendulum observations see H. Faye in Revue scientifique for Feb. 20 and March 27, 1886.

recently by Dutton and Fisher, and entertained by most modern writers, is that the radial elements of the sphere have the same weight on all sides, the product of the height of each unit column into its mean density being everywhere the same. With such a distribution of densities the stresses and strains resulting from the existence of continental elevations do not disappear, but they are less than those derived by Darwin on the hypothesis of homogeneity. How much less has not been shown, but it is fair to say that, so far as the evidence from continents is concerned, the question of the degree of rigidity of the earth's nucleus is still an open one.

If a weight be added to a limited portion of the surface of the globe, there will result a system of strains beneath and about the area, and a deformation of the surface accordant with the system of strains. If the weight is small, and if the effect is not complicated by preexistent strains, the resulting strains will at every point fall within the limit of elasticity of the material, and the deformation will be small. If the weight is sufficiently large, the resulting strains will in some places exceed the limit of elasticity, and other consequences will follow. Among these, rupture and faulting may in special cases be included, but the ordinary and predominant result will be viscous flow. The viscous flow will consume time, and when it has ceased, there will remain a system of elastic strains. Beyond the elastic limits, the laws of change for loading the surface of the earth (and similarly for unloading) are quasi-hydrostatic.

The point on which the Bonneville phenomena appear to throw light is the magnitude of the load necessary to overpower rigidity. The phenomena of faulting at the base of the Wasatch, whether considered by themselves or in connection with the filling of the adjacent valley with water and its subsequent emptying, appear to my mind best accordant with the idea that the Wasatch Range and the parallel ranges lying west of it are not sustained at their existing heights above the adjacent plains and valleys by reason of the inferior specific density of their masses and of the underlying portions of the crust, but chiefly and perhaps entirely in virtue of the rigidity or strength of the crust. The phenomena of deformation of the Bonneville shore-line accord best with the idea that the imposition of the Bonneville load of water and its subsequent removal strained the subjacent portions of the crust beyond the elastic limit, the stresses due to the loading and unloading being partly equilibrated by crustal strains, and partly relieved by crustal flow and a resulting redistribution of the stresses due to gravitation. It is indicated that the limit of terrestrial rigidity falls somewhere between that measured by the weight of the Wasatch Range and that measured by the weight of the water of the main body of Lake Bonneville, or in more general terms, that a mountain of the first class is the greatest load that can be held up by the earth, and is therefore an expression of its strength or of the limit of elasticity of the material of its outer layers.

Fully to realize the nature of this measure, it is necessary to give it numerical expression, and to this end a few computations have been made.

It is evident that the maximum strain produced by a load depends in part on its distribution, and especially that a long ridge taxes rigidity less than a compact mountain mass of the same weight. It appears to me that a very long range causes no greater strains than a shorter one having the same cross section, and I have therefore conceived the Wasatch Range to be fairly represented for this purpose by a division of it including the highest peaks and having a length not quite double its width. This division extends from the Provo River northward to the low pass at the head of Parley's Canyon. Its estimated volume is 200 cubic miles.

Similar considerations lead me to base the estimate for Lake Bonneville on the main body instead of the entire lake, excluding not only the Sevier body but Snake Valley, White Valley, and Utah Valley bays. Thus defined, the load of water amounted to about 2000 cubic miles, equivalent in weight to 730 cubic miles of rock. On the assumption that the strains produced by the lifting of this load were only in minor part relieved by viscous flow, it is inferred that the limit to the superficial rigidity of the earth is expressed by a load of 400 to 600 cubic miles of rock (1670 to 2500 cubic kilometers).

There are four classes of topographic features with which this measure may advantageously be compared, and by which it may perhaps be tested. The first is mountains of addition, or mountains produced by the mere addition of matter to the surface of the earth. Most volcanic cones are of this class. The second class consists of mountains by subtraction, or residuary mountains due to the removal of surrounding material. The third class is intermediate, including addition and subtraction, as when the extrusion or intrusion of volcanic matter produces a resistant mass capable of preserving against erosion a residuary mountain. The fourth consists of valleys by subtraction, or valleys eroded from plateaus. Mountains and valleys due directly to diastrophism are not in point, because, as they are the superficial expression of unknown subterranean changes, we can not be sure in individual cases that their existence is independent of the subterranean distribution of densities. For similar reason, a volcanic mountain whose building has been accompanied by subsidence of the subjacent terrane can not be used for comparison.

The contour maps prepared by the geographic branch of the Survey enable me to give the volumes of some of the most important American examples of these various classes with a degree of precision quite sufficient for the purpose. By their aid each of the following features was referred, not to sea level, but to the plane of the surrounding country, and its volume was computed.

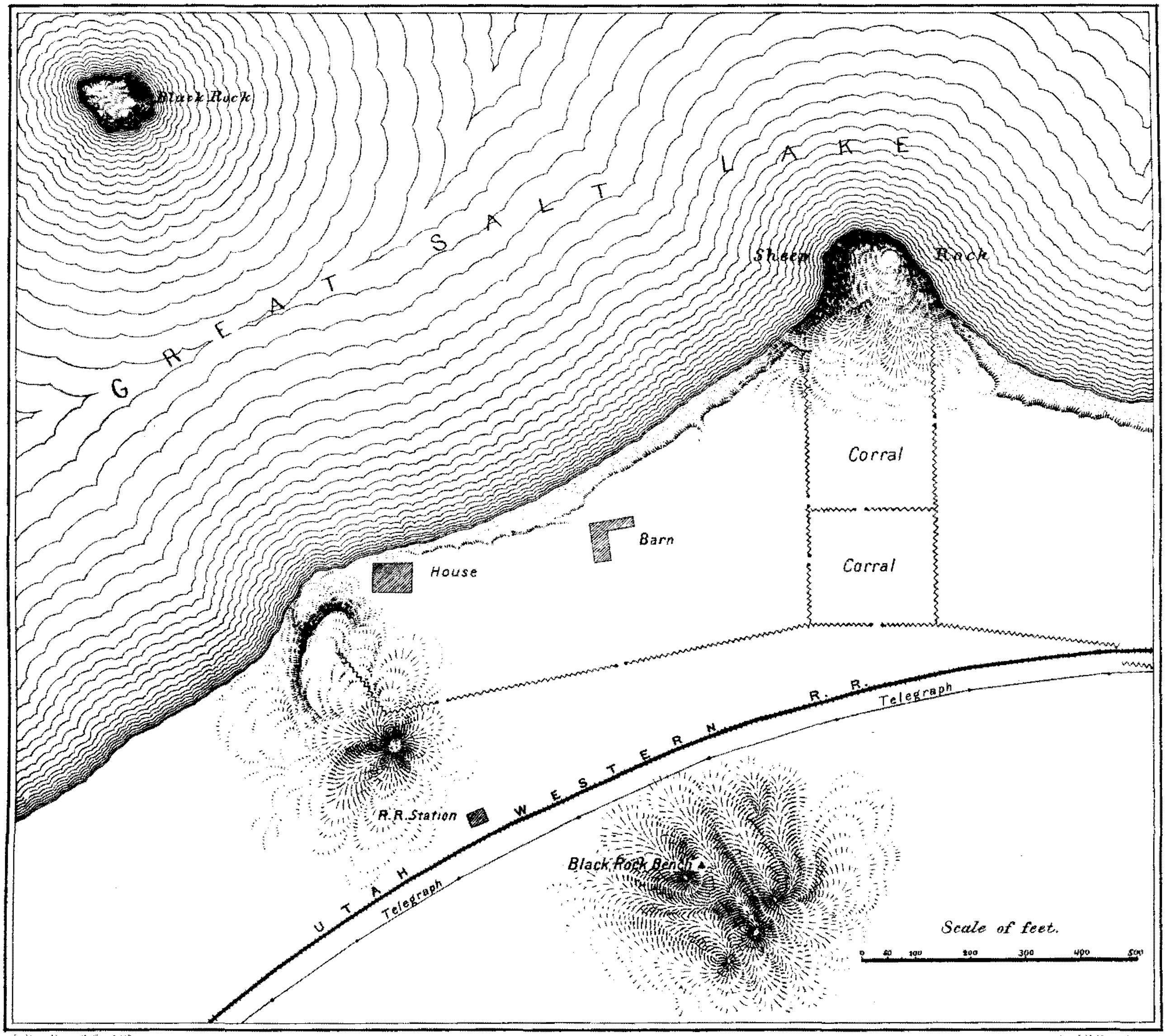
San Francisco Mountain is a volcanic cone standing alone on a high plain, and the strata about its base are almost undisturbed; it is a typical mountain by addition. Its volume is 40 cubic miles.

Mount Shasta is a volcanic cone standing in a region of disturbed strata, but there is no evidence of subsidence due to its load. Its volume is 80 cubic miles.

Mount Taylor is a volcanic cone standing on a plain floored with hard lavas. The degradation of the surrounding country has converted the volcanic plain into a great mesa or table mountain. The cone and mesa together, constituting a mountain by combined addition and subtraction, have a volume of 190 cubic miles.

The Henry Mountains and the Sierra La Sal consist each of a group of laccolites—volcanic additions by intrusion—and of other rocks preserved by them from the erosive reduction sustained by the surrounding plateau. Their volumes are respectively 230 and 250 cubic miles.

The Tavaputs plateau of the Green River basin, otherwise known as Roan Mountain, is a great mass of inclined strata carved out by the unequal



Julius Bien & Co. Lith Drawn by J.E. Henshawe

SKETCH MAP OF

BLACK ROCK AND VICINITY, UTAH

PREPARED TO SHOW THE POSITION OF THE GRANITE POST KNOWN AS THE

BLACK ROCK BENCH.

Surveyed in 1877, by G.K. Gilbert.

degradation of a still greater anticlinal. Its determining cause is a thick layer of resistant rock lying between thick layers of yielding rock, and it stands between two monoclinal valleys due to the excavation of the yielding layers. Its volume standing above the level of the adjacent valleys is about 700 cubic miles.

The Grand Canyon of the Colorado is a valley cut from a great plateau of stratified rock. The plateau has a fault structure of its own, but the canyon and the fault structure have different directions and are manifestly independent. The volume excavated to form the deeper part of the canyon, from the mouth of the Little Colorado to the mouth of Kanab Creek, is 350 cubic miles.

The Appalachian Mountains are traversed for nearly a thousand miles by a great valley following the outcrop of yielding rocks, and it is probable that we have here a valley by subtraction. For the same reason that determined the selection for measurement of a portion only of the Wasatch Range and of a portion only of Lake Bonneville, measurement was not made of the whole of this valley, but only of a limited part. It was assumed that a section with length fifty per cent. greater than breadth, and selected where the valley is broadest, fairly represents the strain-producing power of the whole valley. The portion thus selected lies 600 feet below the mean height of the Cumberland Plateau on the northwest and 1000 feet below the mean height of the mountain district of North Carolina on the southeast, and its volume, computed from the mean of these, is 800 cubic miles.

All of these various features except two fall within the indicated limit of 600 cubic miles, but the limit is exceeded by the Tavaputs Plateau with 700 and the Appalachian valley with 800 cubic miles. There are qualifying considerations in each case. The plane above which the volume of the Tavaputs Plateau was computed was that of the low valleys adjoining it; perhaps a more suitable plane of reference would have been the general level of the surrounding country. The density of the rock of the plateau is probably less than 2.75, the density assumed in reducing the volume of the abstracted lake water to equivalent rock volume. The Appalachian valley lies in a region of great corrugation, and its trend coincides with the strike of the orogenic structure. That structure unquestionably involves inequalities in the distribution of subterranean densities, and it is possible that the strains due to the valley are lessened by the presence beneath it of exceptionally heavy matter. But after giving due weight to these considerations, it must still be admitted that the measure of strength does not stand well the test applied. It is indeed possible that a true measure has been found, and that it is illustrated by the Bonneville, Tavaputs, and Appalachian phenomena, but we can not deny the equal possibility, first, that the strength of the earth varies so widely in different places that a measure discovered in the Bonneville basin serves merely to indicate the order of magnitude of a measure of the average strength, or second, that the unloading of the Bonneville basin occasioned no greater strains than the crust was able to endure, and that the coincidence of unloading and uparching was a coincidence merely.

CHAPTER IX.

THE AGE OF THE EQUUS FAUNA.

THE FAUNA AND ITS PHYSICAL RELATIONS.

As the Equus fauna is not known to occur in the Bonneville Basin, the presence of this chapter requires explanation. In considering the relation of the Bonneville history to glacial history, it has been found necessary to consider also the glacial and lacustrine records of the Mono and Lahontan Basins; hence the sixth chapter contains an exceptionally full discussion of the relation of the later lacustrine history of the Great Basin to general geologic chronology. The Equus fauna is so connected with that lacustrine history that the geologist can best discuss its age in that connection. The present chapter is a corollary to Chapter VI.

The same explanation serves to account for the discussion of the fauna by the present writer, who has not visited the chief localities of its occurrence, but derives his knowledge of its geologic relations from the writings[1] and notes of Russell and McGee.

Equus appears to have been first used in the nomenclature of geologic history by Marsh, in an address read to the American Association for the Advancement of Science in 1877.[2] The Equus beds are there made an upper division of the Pliocene, and they are characterized in a table accompanying the address by the genera *Equus*, *Tapirus*, and *Elephas*. An examination of the text shows that none of these genera are credited to the lower Pliocene, but that all are credited to the post-Tertiary. The characterization thus fails to separate the Equus fauna from the Pleistocene, and as no

[1] Fourth Ann. Rept. U. S. Geol. Survey, pp. 458–461. Science, vol. 3, 1884, pp. 322–323.

[2] The Introduction and Succession of Vertebrate Life in America. By O. C. Marsh. Proc. A. A. A. S., vol. 26, 1878, p. 211.

locality is mentioned, it leaves the fauna undefined. Two years later the fauna was characterized by Cope by the following list of mammalian species.[1] Those of the left hand column are extinct, those of the right hand column living.

Mylodon sodalis.	*Thomomys* near *clusius.*
Lutra near *piscinaria.*	*Thomomys talpoides.*
Elephas primigenius.	*Castor fiber.*
Equus occidentalis.	*Canis latrans.*
Equus major.	
Auchenia hesterna.	
Auchenia magna.	
Auchenia vitakeriana.	
Cervus fortis.	

As the species of this list were found together at one horizon and in the same locality, they afford a definite and tangible basis for discussion, and I shall consider them as the Equus fauna, despite the fact that they fail to include the genus *Tapirus* referred to it by Marsh. The locality was described by Cope as lying thirty or forty miles east of Silver Lake, Oregon,[2] and he styled it "Fossil Lake." Russell, who visited the place in 1882, speaks of it as a few miles eastward of Christmas Lake.

The formation in which the bones occur is lacustrine, as shown by its shells. It constitutes the floor of a desert valley, and has suffered scarcely any erosion, though the sand dunes traveling over it suggest that its surface may have been somewhat degraded by wind action. All about the sides of the valley are shore-lines, and above these shore-lines the lake beds are not found. Just as in the Bonneville and Lahontan basins, the physical relations indicate that the shore-lines and lacustrine sediments are coordinate products of the same expansion of lake waters.

The Christmas Lake basin is part of the Great Basin, and lies 150 miles northwest from the Lahontan shore-lines. Each closed valley of the intervening region has its ancient shore-line and associated lake beds. Each of the old lakes thus demonstrated stands witness to climatic oscillation, and their geographic relations leave no room for question that they pertain to the same climatic oscillation and therefore have the same date.

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[1] E. D. Cope: Bull. U. S. Geol. & Geog. Survey of the Territories, vol. 5, 1879, p. 48.
[2] American Naturalist, vol. 16, 1882, p. 194.

The mammalian remains obtained from the Lahontan beds include a great proboscidian (*Elephas* or *Mastodon*), a llama, one or more horses, and an ox. No skeletons were found, and the dissociated bones and fragments of bones are not such as to permit the recognition of species; but Prof. Marsh, to whom they were submitted, was able to say with entire confidence that the specimens as a whole belong to the Equus fauna. Having myself compared the Lahontan collection with the collection made by Mr. Russell at the Christmas Lake locality, I may be permitted to add that I share Prof. Marsh's confidence in the identity of the faunas.

The correlation receives additional support from the lacustrine shells. Russell reports from the bone beds near Christmas Lake the following species:[1]

Sphærium dentatum.
Pisidium ultramontanum.
Helisoma trivolvis.
Gyraulus vermicularis.
Limnophysa bulimoides.
Carinifex newberryi.
Valvata virens.

None of these are extinct, and all have been found in Lahontan strata.

Nearly all of the bones obtained from the Lahonton strata were found at a horizon somewhat above the middle of the upper division of lake beds. At "Fossil Lake" the bones were found at the top of the formation, but we know nothing of the thickness of the formation. Unless the Fossil Lake formation is much thinner than the Lahonton, the date of its discovered mammalian fauna is a trifle later.

The physical relations recited above, and the associated paleontologic relations, show that the Equus fauna, as illustrated by its type locality, belongs to the epoch of the Upper Lahontan. It therefore falls, as a matter of general chronology, in the later Pleistocene.

This conclusion differs widely from that reached by purely paleontologic methods, for these refer the fauna to the later Pliocene. Before they are considered, attention will be called to a possible ambiguity, and one of the lines of physical evidence will be amplified.

The term Pleistocene is used by geologists in two senses, one of which may be characterized as chronologic or general and the other as physical

[1] Fourth Ann. Rept. U. S. Geol. Surv., p. 460.

or local. In Europe the later part of Cenozoic time was distinguished by a series of physical events including one or more epochs of exceptional cold and exceptional expansion of glaciers. In European nomenclature Pleistocene is applied to the period of time occupied by these events, and also to the events themselves, and this without confusion. In North America the later Cenozoic history included a series of events of the same general character, and for these we have borrowed the name Pleistocene, or its synonym, Quaternary. The time covered by these events may or may not coincide with the Pleistocene period, and until it is shown so to coincide, our imported term is ambiguous. It is primarily in the physical rather than the chronologic sense of the term that the Upper Lahontan and the Fossil Lake beds are found to be late Pleistocene. Properly to characterize them in the chronologic sense—with reference to the period including the glacial and interglacial epochs of Europe—it is necessary to take account of the work of land sculpture and its relative progress in different places.

When a surface shaped by some agent other than atmospheric—a sea floor, for example, a moraine, a shore terrace, or a terrace modeled by man—is exposed to atmospheric agencies, its sculpture begins. For a long time its original features continue to be the characteristic ones, but they eventually become subordinate and finally disappear. The original forms at first are new and fresh, then old, worn, and hard to discover; and finally the fact that they once existed can be known only from the internal structure of the deposits to which they belonged. So long as the original form is discernible, it yields to the geologist evidence of relative newness or relative age. Such evidence as this is not readily formulated, but it is constantly employed by the field geologist in the study of the surface. Indeed it affords one of the most important bases of the wide spread opinion that glaciation was simultaneous in Europe and America.

The abandoned lake shores of Christmas Valley and of the Lahontan Basin, the lacustrine plains below them, and the correlated glacial moraines, are all of youthful habit, as youthful as the "parallel roads" of Glen Roy and other surface features marking the wane of glaciation in Scotland. The lake shores and sea shores associated with the latest Pliocene beds of

Europe are either unrecognized, or else, as in the case of the English Crag, known only by their internal structure. The plains of their upper surfaces, where not covered by glacial or volcanic deposits, are either obsolete or obsolescent. The topography created in the presence of the Equus fauna is young; that created in the presence of the European Pliocene fauna is old. With the aid of this additional link in the chain of physical evidence, the geologist ties the Equus fauna, not merely to the American glacial or Pleistocene history, but to the Pleistocene time division.

The ancient Lake Bonneville, the ancient Lake Lahontan, the ancient lake of the Mono Basin, the ancient lake of the Christmas Lake Basin, and numerous smaller extinct lakes of Oregon and Nevada, are tied together by community of physical characters—freshly bared sediments, conforming to the slopes of surface and surrounded by freshly formed shore-lines. Many have yielded shells of recent species. Two, those of the Lahontan and Christmas lake basins, have yielded the same mammalian fauna. The two largest, Lahontan and Bonneville, have yielded detailed and parallel physical histories. The analysis of climatic factors correlates them with ancient glaciation in neighboring mountains, and their shores are carved from and built around late-formed moraines of the Wasatch Range and the Sierra Nevada. The detailed history shows two lacustral epochs corresponding to two glacial epochs, and correlates the mammalian fauna with the later half of the later glacial epoch. Presumptively this date falls very late in the Pleistocene period. The phenomena of comparative sculpture show that it is at least later than the latest Pliocene of Europe.

THE PALEONTOLOGIC EVIDENCE.

So far as I am aware, Cope alone has stated the paleontologic grounds for referring the Equus fauna to the Pliocene. Comparing it with the sub-Appenine fauna of Europe (Pliocene), he says—"The characteristic of this fauna is the fact that the species belong mostly to existing genera. . . In the Equus beds of Oregon, a few extinct genera in like manner share the field with various recent ones, while not a few of the bones are not distinguishable from those of recent species." In a succeeding paragraph he adds: "As a conclusion of the comparison of the American Equus beds in general with those of Europe it may be stated that the number of identical genera is so large that we may not hesitate to parallelize them as stratigraphically the same."[1]

Three categories of evidence are here used: (1) the relative abundance of extinct genera in the two faunas, (2) the relative abundance of extinct species in the two faunas, (3) the abundance of genera common to both faunas.

The first and second categories embody the method devised by Lyell for the classification of Tertiary formations, a method based on the percentage in each fauna of living or extinct forms. Faunas with the lowest per cent of recent forms were grouped together as Eocene, those with a certain higher per cent were called Miocene, and so for the Pliocene. The method rests on a generalization from observation and on a postulate. The generalization is that from the earliest Eocene time the facies of life has gradually approached the present facies. The postulate is that the rate of change has been uniform in all places. If the postulate is true, the method of Lyell can yield exact time correlation; otherwise it can yield only approximate time results. Lyell himself disclaims belief in the postulate and regards his classification as chronologically imperfect.[2]

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[1] These passages occur on pages 47 and 48 of a paper on The Relations of the Horizons of Extinct Vertebrata of Europe and North America, published in volume V of the Bulletins of the U. S. Survey of the Territories. On page 49 the correlation of the Equus beds with the Pliocene is characterized as the "exact identification" of a restricted division. The author's confidence in the correlation was not materially shaken by a preliminary statement of the physical evidence made by the writer to the National Academy of Science in 1886. See American Naturalist, vol. XXI, 1887, p. 459. In the passage last referred to Cope says: "This gentleman [Gilbert] has expressed the belief that the beds of this age are not older than the glacial epoch, because they embrace the bases of some of the moraines of some of the ancient glaciers of the Sierra Nevada. It remains to be proven, however, that these moraines are of true glacial age, since they are of entirely local character. The presence of so many mammals of the fauna of the valley of Mexico would not support the belief in a cold climate."

When the moraines referred to were being formed, the Sierra Nevada bore cn its back a mer-de-glace as extensive as that of the Alps, and a host of glaciers flowed from this to the valleys below, reaching altitudes from 6,000 to 9,000 feet lower than the little glaciers that now cling to a few of its peaks. At the same time there were also great glaciers in the Wasatch Mountains. Whatever inferences these phenomena yield as to the contemporaneous climate of the Great Basin appears to me quite independent of the question of their correlation with a glacial epoch somewhere else. If the glaciers prove a cold climate in the Great Basin, then the animals that left their bones in the contemporaneous lake sediments of the Basin lived in a cold climate. If the animals could not live in a cold climate, then it is shown that the valleys of the Great Basin were warm despite the ice on the high mountains. The question of geologic date is not involved.

The value of the Equus fauna as an index of contemporaneous climate has already been discussed in chapter VI of this volume.

[2] Sir Charles Lyell. Manual of Geology, 5th ed. New York. p. 113.

The third category of evidence, the abundance of common elements in two faunas compared, is that ordinarily used in paleontologic correlation, and it applies to the older formations as well as to the Cenozoic. The method of using it is analogous to the assignment of commercial colors to their approximate positions on the prismatic scale, and may be characterized as a method of matching. Having in one district a number of faunas determined by physical relations to be successive, the paleontologist compares a single fauna of another district with each of these severally and "correlates" it with the one with which it has most in common. The principal check on this method lies in the consistency or inconsistency of its results with one another. When two faunas of one district are separately compared with the faunal scale of another district, their relative ages as inferred from the results of matching is usually the same as shown by their physical relations, but there are a few exceptions to this. Again when biotic data of two or more kinds, as for example vertebrate fossils, invertebrate fossils and fossil plants, are separately employed for correlation by matching, the results are often accordant, but they are also often discordant. How far the discrepancies of result are due to imperfection of method and how far to imperfection of data, is not known, but it is generally admitted that there are limits to the applicability of the method. The greatest discrepancies in its results have been found when the formations compared lie far apart, so as to fall in different faunal provinces; and it may be said in general that its value varies directly with the degree of resemblance of the faunas compared. Where the whole number of common forms or of common types is small, correlation is less precise than where the number is large.

In order to gauge the Equus fauna by the accepted scale, I have selected a series of European faunas more or less restricted geographically and of well-known age. They are (1) the Lower Pliocene of Montpellier, France, (2) the Upper Pliocene of the Arno Valley, Italy, (3) the Pleistocene of Great Britain, (4) the living fauna of Europe. The genera and species of the land mammals of these faunas have been compared with those of the Equus fauna and the accompanying table constructed.

The table includes only mammalian faunas. Cope has reported from the same Oregon locality ten species of birds[1] and two of fishes,[2] but these are not at present available for purposes of correlation. As it is known that the general rate of evolution differs in different classes of animals, the entire Fossil Lake fauna can not be considered together. The birds can not be separately used because of the scantiness of avian data in the European faunal scale. The fishes are themselves too few for profitable comparison.

TABLE XVII.—*Summary of Paleontologic Data for the Determination of the Age of the Equus Fauna.*

Terrestrial mammalian faunas.	Available for comparison.		*Method of Lyell.*—Percentage of extinct		*Method by matching.*—Number in common with the Equus fauna.	
	genera.	species.	genera.	species.	genera.	species.
Now living in Europe	many	many	0	0	4	1
Pleistocene (Great Britain)[1]	27	48	7	19	6	2
Equus (Fossil Lake)	9	13	[4]11	69	....	....
Upper Pliocene (Val d'Arno)[2]	18	29	11	100	[5]6	0
Lower Pliocene (Montpellier)[3]	14	15	21	100	2	0

[1] British Pleistocene Mammalia. By W. B. Dawkins and W. A. Sanford. Palaeontographical Society, vols. 18 and 32, 1866 and 1878.

Pleistocene climate, etc. By W. Boyd Dawkins, Pop. Sci. Review, vol. 10, 1871, pp. 388–397.

[2] C. I. Forsyth Major. Atti Soc. Tosc. Sci. Nat., vol. 1, pp. 39-40 and "Proc. verb.," vol. 1, p. v.

[3] Gervais, quoted by Major. Atti Soc. Tosc. Sci. Nat., vol. 1, pp. 224–225.

[4] In a publication subsequent to the one on which this table is based, Cope establishes a new genus, *Holomeniscus*, to which he transfers the species of *Auchenia* in the Equus fauna. This doubles the number of extinct genera in the fauna and raises its percentage from 11 to 22.

[5] This number includes the genus *Lutra*, which is not reported from this formation. As it is reported from the preceding and following formations, its existence at that time can not be questioned.

The numerical results by the matching method appear in the two columns at the right. The six genera of the Equus fauna found in the upper Pliocene are identical with those of the Pleistocene, and include those of the lower Pliocene and living faunas. The two genera found in the Pleistocene but not in the living fauna of Europe are *Equus* and *Elephas*, which persist in other continents. One species, *Castor fiber*, is common to the Equus, Pleistocene, and Recent faunas. *Elephas primigenius*, common to the Equus and Pleistocene, is said to occur in Europe exclusively in the Pleistocene. The evidence from genera is ambiguous. That from species

[1] Bull. U. S. Survey Terrs., vol. 4, 1878, p. 389.

[2] American Naturalist, vol. 12, 1878, p. 125.

tends to correlate the Equus fauna with the Pleistocene of Great Britain, but the number of common forms is so small that their testimony has little weight.

The numerical results by the Lyellian method appear in the middle pair of columns. The Equus fauna agrees with the Upper Pliocene in its ratio of extinct genera; and in its ratio of extinct species it stands rather nearer the Pliocene than the Pleistocene. The evidence from genera is weakened by the fact that the numbers involved are very small; of 9 genera from Fossil Lake 1 is extinct, of 18 from the Arno Valley 2 are extinct; the discovery of a few more bones might cause wide divergence of the ratios. The evidence from species is hard to interpret, because all of the Pliocene species are reported extinct. Does a fauna with one-third of its forms living stand nearer to one with no living forms or to one with four-fifths of its forms living? Perhaps the proper interpretation of this evidence would assign a date at the close of the Pliocene and beginning of the Pleistocene. It certainly does not agree with the physical evidence in indicating late Pleistocene.

If all this paleontologic evidence could be properly combined, giving each element its due weight, the resulting indication of date would be later than the upper Pliocene of the Arno Valley and earlier than the middle of the Pleistocene of Great Britain. It might fall in an assumed interval between the two time divisions, or it might fall in the earlier part of the Pleistocene.

At the very best, the date inferred from the physical facts and the date inferred from the biotic facts differ by more than half the extent of the Pleistocene period. Both can not be true; which should be accepted? For my own part I do not hesitate to prefer the physical evidence and the later date. I hold with Lyell that "we can not presume that the rate of former alterations in the animate world, or the continual going out and coming in of species, has been everywhere exactly equal in equal quantities of time;" and the Equus fauna seems to me to illustrate the principle. It may perhaps be found, when the fauna is much better known, that its features correspond closely with those of the contemporary fauna in Europe, but for the present it appears that the mammalian fauna of the

Great Basin experienced a greater change at the close of the Pleistocene than did that of Europe.

In the study of the Pleistocene of Europe, geology and paleontology have worked together with admirable results. The geologic relations have given to paleontology the sequence of its faunas; paleontology has reciprocated by correlating the deposits of extra-glacial regions with elements of the glacial history; and through such cooperation a bewildering multiplicity of data are being marshaled into a consistent though complex system. In America the same benefit should result from the same cooperation. Some Pleistocene deposits can be assigned dates through their relations to glaciation, and when the faunas and floras of these are known, paleontology can contribute much toward the discovery of the Pleistocene history of districts remote from glaciers. For this purpose the Lyellian method of percentages is, in my judgment, far less valuable than the method by matching; but the standard scale for matching should be an American scale, based on physical studies in the region of Pleistocene glaciation and its immediate vicinity.[1]

[1] While these pages are passing through the press, a volume is published by Messrs. Felix and Lenk, containing an account of Pleistocene lacustrine formations in the Great Valley of Mexico. In a general way the phenomena of the Bonneville and Lahontan basins are there repeated, but the history of the climatic oscillation has not been fully made out. In undisturbed strata, forming a continuous series with lake sediments now being deposited, there have been found bones of thirteen mammalian species, and two of these species are identical with members of the Christmas Lake fauna. (Beiträge zur Geologie und Paläontologie der Republik Mexico. Von Dr. J. Felix und Dr. H. Lenk. Part 1. Leipzig, 1890, pp. 65–68, 79–88.)

APPENDIXES.

APPENDIX A.

ALTITUDES AND THEIR DETERMINATION.

BY ALBERT L. WEBSTER.

In connection with the study of the records of the ancient Lake Bonneville, it became a matter of interest to ascertain the present relative altitudes of points scattered along its former perimeter. A complete and thoroughly satisfactory investigation of the subject being impracticable from economic considerations, it was made subsidiary to the more general historic study of the lake, and its results are accordingly incomplete or lacking where such study would not permit of a more extended investigation. As far as practicable altitudes were obtained of points representative of the entire shore-line. To accomplish this a large area of country had to be traversed, and it was necessary to employ all available means and methods for the collection of the data. All heights are referred for comparison to a common datum point, arbitrarily chosen, the zero mark of the lake gauge at the Lake Shore bathing resort.

The measurements and observations here brought together are not my own alone, but were made by many persons and at various times. In the following pages the attempt is made to arrange them in such order that the critical reader can readily learn the essential nature of all the data on which each separate determination of altitude is based.

SCHEME OF TABLES.

TABLE XVIII. Differences of altitude determined by trigonometric observations.
XIX. Differences of altitude determined by barometric observations.
XX. Reduction of various lake gauge zeros to the Lake Shore datum.
XXI. Gauge records, showing the height of the water surface of Great Salt Lake at various dates.
XXII. Differences of altitude from railroad survey records.
XXIII. Differences of altitude by special spirit-level determinations.
XXIV. Reduction of results to Lake Shore gauge zero as a common datum.
XXV. Comparative schedule of altitudes of points on the Bonneville shore-line
XXVI. Comparative schedule of altitudes of points on the Provo shore-line.
XXVII. Comparative schedule of altitudes of points on the Stansbury shore-line.
XXVIII. Differences in altitude of the Bonneville and Provo shore-lines at various localities.
XXIX. Differences in altitude of the Provo and Stansbury shore-lines at various localities.

By reference to this scheme of tables it will be seen that hypsometric material has been gathered from the five following sources:

(1) From determinations based upon trigonometric observations.
(2) From determinations based upon concurrent barometric observations.
(3) From the records of the fluctuations of the present Great Salt Lake.
(4) From the records of various railroad surveys.
(5) From especial determinations made with the surveyor's spirit-level.

TRIGONOMETRIC DATA.

The few results obtained by the first method and presented in Table XVIII were derived by computation from measurements of angles of elevation and depression with accompanying short base-lines. The angles were measured with the ordinary surveyor's transit, reading to minutes on the vertical limb. The base-lines were measured with a steel tape.

The results are recorded in feet and tenths of feet, but it is not intended to assert that they are true to the nearest tenth. They are probably true to the nearest foot. In combining determinations of various kinds it has been found convenient to use the same notation for all, and the tenth of a foot has been chosen as expressing the precision of the most accurate of all the measurements—the shorter lines of spirit-leveling. For the purposes of the Bonneville investigation it would be sufficient to stop at the decimal point, as all the results of measurement are combined with observations involving an uncertainty of several feet; but it is conceived that some of the data may have other uses, and for the sake of these the tenths are retained.

TABLE XVIII.—*Differences of Altitude determined by Trigonometric Observations.*

Vicinity of—		Feet.
Dove Creek	Bonneville shore-line *above* Provo shore-line	415.1
Kelton	do	361.1
Matlin	do	419.7
Matlin	Provo shore-line *above* Stansbury shore-line	310.0
Snowsville	Bonneville shore-line *above* Provo shore-line	365.0

BAROMETRIC DATA.

The section of country including the long southern arm of the old lake, now the Escalante Valley, was practically accessible to no better hypsometric method than that of concurrent barometric observation, and that method was accordingly adopted for its investigation.

This region in general lies two hundred miles south of Salt Lake City, and its nearest barometric base was the U. S. Signal Office in that city. It was deemed advisable to establish an intermediate sub-base station in the nearer neighborhood of the field of itinerary observation, to which to refer the new stations. The village of Fillmore, lying one hundred miles south of Salt Lake City, offered especial natural advantages for the location of such a sub-base. It includes within its limits a portion of the Bonneville shore-line, thus allowing but slight disparity in altitude between the reference station and new stations. It is moreover situated about midway between the southern field of study and the Salt Lake City primary base, and affords, by the comparison of its series of observations with that of the Signal Office, a criterion for judging of the value of results from the observations at the new stations.

Two barometers and psychrometers were left here in the charge of an observer, Mr. R. H. Smith, from July 29th to October 3rd, 1881. Upon the former of these, hourly observations were made each day from 7 A. M. to 9 P. M. inclusive; upon the latter, readings were taken daily at 7 A. M., 2 P. M. and 9 P. M.

The Survey did not establish a base station at Salt Lake City, but made use of the ordinary observations by the U. S. Signal Service observer. Through the courtesy of the Chief Signal Officer of the Army we were furnished with copies of such portions of the records as were needed for our work, viz., the readings of barometer, thermometer and psychrometer at 7 A. M., 2 P. M. and 9 P. M., during the period covered by the observations at Fillmore.

The altitude of the sub-base above the Signal Office at Salt Lake City was computed from a selected portion of the concurrent observations at the two places.

In order to avoid observations affected by abnormal atmospheric conditions, the "reduced" barometric readings at the two stations were platted graphically in close proximity, with a common time scale. A marked parallelism of the resulting curves between the dates of July 29th and August 17th led to the acceptance of the records included between those dates as a basis for the computation, and they alone were employed.

Three somewhat independent results were obtained for the difference of altitude by considering separately the means of the 7 A. M., 2 P. M., and the 9 P. M. reduced readings at the two stations, Williamson's method and tables being employed.[1] In each determination the terms $t+t'$ and $a+a'$ are identical, being derived from the means of the temperature and humidity terms of the 7 A. M., 2 P. M., and 9 P. M. records for the selected period.

	7 a. m.	2 p. m.	9 p. m.
	Inches.	*Inches.*	*Inches.*
h. Mean of reduced readings at Salt Lake City	25.668	25.641	25.613
H. Mean of reduced readings at Fillmore	24.947	24.907	24.898
$t+t'$ from means of 7 a. m., 2 p. m., and 9 p. m. temperature readings at Salt Lake City and Fillmore = 151°.92 F.			
$a+a'$ from means of 7 a. m., 2 p. m., and 9 p. m. relative humidity reductions for Salt Lake City and Fillmore = 0.60.	*Feet.*	*Feet.*	*Feet.*
From Table D_i with argument h	24,720.9	24,693.2	24,664.6
From Table D_i with argument H	23,973.8	23,931.7	23,922.3
First approximate difference of altitude	747.1	761.5	742.3
From Table D_{ii}	+66.86	+68.15	+66.44
Second approximate difference of altitude	813.96	829.65	808.74
Tables D_{iii} to D_{vii}, inclusive, with general arguments $t+t'$ = 151°.92 F., $a+a'$ = 0.60, lat. = 40°, and second approximate difference of altitude, give additional correction	+6.21	+6.32	+6.14
Difference of altitude	820.17	835.97	814.88
Accepted result, mean of the three determinations, 823.7 feet.			

[1] Professional papers of the Corps of Engineers, U. S. Army. No. 15, Appendix.

To the Fillmore station alone, as a base, have been referred all the itinerary barometric records taken in the district south of it.

At the new stations no "dry bulb" thermometer or psychrometer readings were taken, and where such data were necessary in the computation of their altitudes they were supplied from the Fillmore records alone.

TABLE XIX.—*Differences of Altitude determined from Barometric Observations.*

Vicinity of	Point and Reference.	Difference in Altitude.
		Feet.
Antelope Spring (Lower Escalante Desert).	Bonneville shore-line, 1 mile west of Spring, *above* Fillmore sub-base barometer.	38.7
Fillmore	Sub-base cistern barometer *above* U. S. Signal Office barometer at Salt Lake City, Utah.	823.7
Grantsville	Bonneville shore-line *above* Provo shore-line	381.3
Kanosh	Bonneville shore-line on Kanosh Butte *below* Fillmore sub-base barometer.	17.3
Meadow Creek	Bonneville shore-line, 1 mile east of entrance to canyon, *above* Fillmore sub-base barometer.	296.6
	Bonneville shore-line, 1 mile west of entrance to canyon, *above* Fillmore sub-base barometer.	294.5
Milford	Camp on east bank Beaver River, *below* Fillmore sub-base barometer.	218.6
	Bonneville shore-line, 1 mile northwest of Milford, *below* Fillmore sub-base barometer.	76.0
	Bonneville shore-line, 7 miles south of Milford, *below* Fillmore sub-base barometer.	48.9
North Twin Peak	Bonneville shore-line, east base of Peak, *above* Fillmore sub-base barometer.	1.2
Pavant Butte	Bonneville shore-line, east base of Butte, *below* Fillmore sub-base barometer.	67.6
Pinto Canyon	Bonneville shore-line, west of entrance to canyon, *above* Fillmore sub-base barometer.	214.1
Shoal Creek	Bonneville shore-line, north of entrance to canyon, *above* Fillmore sub-base barometer.	265.8
South Twin Peak	Bonneville shore-line, west base of Peak, *below* Fillmore sub-base barometer.	32.5
Sulphur Springs (Escalante Desert)	Bonneville shore-line *above* Fillmore sub-base barometer	45.2
Thermos	Bonneville shore-line, 2 miles east of Springs, *below* Fillmore sub-base barometer.	76.6
	Bonneville shore-line, 4 miles south of Springs, *below* Fillmore sub-base barometer.	48.7
	Bonneville shore-line, 7 miles south of Springs, *below* Fillmore sub-base barometer.	42.1
White Mountain	Camp, *below* Fillmore sub-base barometer	474.1

LAKE RECORDS.

At various times spirit-level lines have been run from the surface of Great Salt Lake to points on the ancient beaches in the near neighborhood of its present shore. The records of altitudes thus obtained are not, however, directly comparable, since the surface of the lake is in a state of continual fluctuation, the records of which have been referred to independent gauges. It was accordingly necessary to determine primarily the relative altitudes of the zeros of the various gauges.

Previous to 1875 the record of the rise and fall of the lake is purely a traditional one. Such evidence, however, as is reliable, has been presented by Mr. Gilbert in his chapter on "Water Supply," Powell's "Lands of the Arid Region," in which the records have been referred to the level of the Antelope Island Bar as a datum.[1]

In 1875 a granite monument, graduated to feet and inches, was erected by Dr. John R. Park, of Salt Lake City, at Black Rock on the southern shore of the lake, and upon this observations were made at intervals until October 9th, 1876, when it was abandoned. In connection with it, the Powell Survey placed a granite bench block on the shore near by. A line of spirit-levels was subsequently run, which showed the Black Rock Monument zero to be 36.5 feet below the Black Rock Bench.

In 1877 another gauge was erected at Farmington, on the east shore of the lake, in an inlet. A stone reference point, planted on rising ground near by, and known as the Farmington Bench, was found to be 12.9 feet above the zero of the Farmington gauge. Observations were made at intervals on the newly erected gauge until October, 1879, when it was rendered useless by the occurrence of a succession of heavy winds from the westward, which effectually barred the entrance of the inlet with sand, thus cutting off its direct communication with the lake. In anticipation of such an occurrence, a third gauge had been established at Lake Shore, five miles south of Farmington, and monthly records begun November 19th, 1879. This is known as the Lake Shore Gauge, and to its zero as a datum have been referred the various determinations of which this appendix treats. (See Table XXIV.)

A general falling tendency of the Lake for several years portended disqualification of this gauge, and rendered the erection of a deeper set scale a matter of precautionary advisability. A fourth gauge was accordingly established at Garfield Landing, three miles west of Black Rock. It consists of a stout strip of scantling, nineteen feet long, firmly spiked to one of the piles of the steamer pier. It is graduated to feet and inches.[2]

On the 23d of July, 1881, the Black Rock bench was found by spirit-level to be 38.7 feet above the surface of the lake; at the same time the water washed the 7 ft. 9 in. mark of the Garfield gauge. Thus the zero of the latter is 46.4 feet below the Black Rock bench.

Table XX indicates the steps by which the various gauges have been reduced to the Lake Shore zero.

[1] The traditional record is repeated, with an addition, in this volume, pp. 239–243. G. K. G.

[2] Since the preparation of this Appendix, the Garfield gauge has been destroyed and renewed. See p. 232. G. K. G.

TABLE XX.—*Reduction of various Lake Gauge Zeros to the Lake Shore Datum.*

Point.	Intermediate Datum.	Date.	Referred to Intermediate Datum.	Referred to Lake Shore Gauge Zero.
Lake Surface		Jan. 23, 1880		+ 2.5
A "Temporary Bench" at Farmington.	Lake Surface	.. do	+ 1.3	+ 3.8
Farmington Gauge Zero	A "Temporary Bench" at Farmington.	Nov. 3, 1879	− 0.1	+ 3.7
Farmington Bench	Farmington Gauge Zero	...do	+12.9	+16.6
Mean Lake Surface		Mar. 21 to Mar. 25, 1881.		+ 2.6
Garfield Landing Gauge Zero	Mean Lake Surface	... do	− 7.2	− 4.6
Lake Surface	Garfield Landing Gauge Zero	July 23, 1881	+ 7.7	+ 3.1
Black Rock Bench	Lake Surface	....do	+38.7	+41.8
Lake Surface	Black Rock Bench	July 12, 1877	−34.5	+ 7.3
Black Rock Monument Zero	Lake Surface	....do	− 2.0	+ 5.3
Lake Surface	Black Rock Monument Zero	Oct. 19, 1877	+ .8	+ 6.1
Antelope Island Bar in the "little channel."	Lake Surface	....do	− 9.5	− 3.4

A note of uncertainty relative to the results dependent on the Black Rock observation of July 12, 1877, must be introduced here. The observer's record of that observation reads as follows:

> *July* 12, 1877.—Water washed highest foot mark of graduation on Dr. Park's [Black Rock] monument; supposed to be the two-foot mark.

The scale is neither numbered nor lettered, but subsequent conversation with Dr. Park led to the acceptance of the record in conformity with the supposition of the observer.

Confirmatory evidence is found in the close agreement of this determination of the monument zero with a second determination, which joins the monument zero to the Farmington zero by reference to the lake surface. The difference in the two results is less than two-tenths of a foot. As an interval of fifteen hours elapsed between the readings of the two gauges the second determination was considered only as a general check for large errors, and was not used in the reduction.

A table and platted curve showing the rise and fall of the present Great Salt Lake from September, 1875, to June, 1889, will be found on pages 233–243 of the monograph of which these pages form an appendix. By means of the data contained in that table the lines of leveling at various times connected with the water surface of the lake were referred to the Lake Shore gauge zero. The specific data thus used are here repeated in Table XXI.

TABLE XXI.—*Gauge Records, showing the height of the Water Surface of Great Salt Lake at various dates.*

Gauge.	Date.	Reading.		Height of Gauge Zero above Zero of Lake Shore Gauge.	Height of Water Surface above Zero of Lake Shore Gauge.
		Ft.	*In.*	*Feet.*	*Feet.*
Black Rock	July 12, 1877	2	0	5.3	7.3
Do	Oct. 19, 1877	0	10	5.3	6.1
Farmington	May 2, 1879	1	4	3.7	5.0
Lake Shore	Nov. 9, 1879	2	6	0	2.5
Do	Nov. 12, 1880	1	9	0	1.7
Do	Nov. 29, 1880	1	8½	0	1.7
Do	Dec. 11, 1880	1	8½	0	1.7

RAILROAD RECORDS.

A fourth source from which data have been obtained to assist in the general compilation, is found in the records of various railroad surveys. The results appearing in Table XXII in some cases have been derived from Gannett's "Lists of Elevations", 1877, and such are indicated by a star (*); in other cases they are from transcripts of official profiles kindly furnished by the engineers of the different roads.

TABLE XXII.—*Differences of Altitude derived from Railroad Survey Records.*

Vicinity of	Points Determined and Points of Reference.	Feet.
Corinne	Corinne Station (Central Pacific R. R.) *below* Ogden Station	71.3*
Franklin	Franklin Station (Utah Northern R. R.) *above* Ogden Station	213.0
Lemington	Lemington Station (Utah Southern R. R. extension) *above* Salt Lake City Station.	455.0
Logan	Logan Station (Utah Northern R. R.) *above* Ogden Station	206.0
Milford	Milford Station (Utah Southern R. R. extension) *above* Salt Lake City Station.	707.5
Ogden	Ogden Station (Utah Central R. R.) *above* Salt Lake City Station	42.3*
Point of the Mountain	Summit (Utah Southern R. R.) *above* Salt Lake City Station	547.0
Red Rock Gap	Red Rock Gap Station (Utah Northern R. R.) *above* Franklin Station	286.0
Santaquin	Summit (U. S. R. R.) *above* Salt Lake City Station (U. S. R. R.)	772.0
Swan Lake	Swan Lake Station (Utah Northern R. R.) *above* Franklin Station	287.0
Tecoma	Tecoma Station (Central Pacific R. R.) above Salt Lake City Station (U. S. R. R.).	551.0*

SPECIAL SPIRIT-LEVEL DETERMINATIONS.

Table XXIII contains the results of spirit-level determinations, made with especial reference to the study of the ancient lake. Check lines have been run wherever practicable, and the mean of the original and duplicated work accepted. Results thus verified are marked by a star (*) in the table.

Measurements made with Locke's hand level are marked thus (†).

TABLE XXIII.—*Differences of Altitude by Special Spirit-Level Determinations.*

Vicinity of	Points and References.	Feet.
Aqui Range, North end	Bonneville shore-line *above* lake surface, July 28, 1877	1059.0
	Provo shore-line *above* lake surface, July 28, 1877	678.0
	Bonneville shore-line *above* lake surface, Nov. 25, 1880	1058.4*
	Provo shore-line *above* lake surface, Nov. 25, 1880	676.9
	Stansbury shore-line *above* lake surface, Nov. 25, 1880	331.0
Black Rock	Bonneville shore-line *above* lake surface, July 12, 1877	993.0
	Black Rock Bench *above* Black Rock Monument zero	34.6
	Provo shore-line *above* lake surface, July 12, 1877	633.0
	Stansbury shore-line *above* lake surface, July 12, 1877	247.0
Corinne	Corinne Station (C. P. R. R.) *above* lake surface, May, 1873, (Wheeler Survey)	22.6
Cup Butte	Bonneville shore-line *above* Provo shore-line	397.0†*
Fillmore	Sub-base barometer *above* Bonneville bar	19.4*
Fish Spring	Bonneville cut-terrace *above* Provo cut-terrace	369.0†
Franklin	Bonneville shore-line on Franklin Butte *above* Franklin Station (U. N. R. R.)	626.0
	Provo shore-line on Franklin Butte *above* Franklin Station (U. N. R. R.)	261.0
Kelton	Bonneville shore-line *above* lake surface, Aug. 11, 1877 (checked by triangulation)	1017.5
Lake Shore	Lake Shore Gauge zero *below* Salt Lake City Station, U. S. R. R	52.4*
Lemington	Bonneville shore-line *above* Lemington Station (U. S. R. R. extension)	386.6*
Logan	Bonneville shore-line *above* Logan Station (U. N. R. R.)	632.9
	Provo shore-line *above* Logan Station (U. N. R. R.)	276.2
Milford	Bonneville shore-line *above* Milford Station (U. S. R. R. extension)	152.7*
	Camp on east bank Beaver River *below* Milford Station (U. S. R. R. extension)	7.6
Ogden	Bonneville shore-line *above* Ogden Station U. C. R. R., (Prof. F. H. Bradley, Hayden Survey)	876.0†
Pavant Butte	Bonneville shore-line *above* Provo shore-line	329.1*
Point of the Mountain	Bonneville shore-line *above* Summit (U. S. R. R.)	358.0
	Provo shore-line *below* Bonneville shore-line	375.5
Preuss Valley	"North Group," Bonneville shore-line *above* Provo shore-line	343.2*
	"Middle Group," Bonneville shore-line *above* Provo shore-line	346.4*
Promontory	Bonneville shore-line *above* lake surface, Aug. 23, 1877	1037.7
	Provo shore-line *above* lake surface, Aug. 23, 1877	665.8
Red Rock Pass	Bonneville shore-line *above* Swan Lake Station (U. N. R. R.)	303.0
Salt Lake City	Bonneville shore-line *above* Salt Lake City, Meridian Monument	845.9*
	Meridian Monument *below* U. S. Signal Service barometer	12.5*
	Salt Lake City Station (U. S. R. R.) *below* Meridian Monument	72.6*
	Salt Lake City Station (U. S. R. R.) *above* Lake surface, Dec. 11, 1881	50.7*
Santaquin	Bonneville shore-line *above* Santaquin Summit (U. S. R. R.)	75.0
Snowplow	Bonneville shore-line *above* Provo shore-line	401.0*
Stockton	Bonneville shore-line *above* lake surface, Mar., 1873 (M. F. Burgess)	1011.0
	Provo shore-line *below* Bonneville shore-line	375.0
Tecoma	Bonneville shore-line *above* Tecoma Station (C. P. R. R.)	367.8
Wellsville	Bonneville shore-line *above* Provo shore-line	383.7
White Mountain (Fillmore.)	Provo shore-line on White Mountain *above* White Mountain camp	68.9
	Provo tufa deposits on Tabernacle Butte lava bed *above* camp	42.9
Willard	Bonneville shore-line *above* lake surface, Oct. 28, 1879	974.0†
	Provo shore-line *above* lake surface, Oct. 28, 1879	621.0†

COMBINATION OF DATA.

In the schedule following (Table XXIV) a collection and combination is made of results appearing in some of the six tables preceding, so as to reduce the stations to which they apply to the arbitrarily assumed Lake Shore zero datum. The table is arranged with reference to the latitudes of the points determined, beginning with the most northerly.

TABLE XXIV.—*Reduction of Results to the Lake Shore Gauge Zero as a Common Datum.*

Point.	Intermediate Datum.	From Table	Difference in Altitude referred to Intermediate Datum.	Altitude above the Lake Shore Gauge Zero Datum.
			Feet.	*Feet.*
Lake Surface, Dec. 11, 1880	Lake Shore Gauge Zero	XXI	+ 1.7	1.7
Salt Lake City Station (U. S. R. R.)	Lake Surface, Dec. 11, 1880	XXIII	+ 50.7	52.4
Ogden Station	Salt Lake City Station	XXII	+ 42.3	94.7
Franklin Station (U. N. R. R.)	Ogden Station	XXII	+ 213.0	307.7
Swan Lake Station (U. N. R. R.)	Franklin Station	XXII	+ 287.0	594.7
Bonneville shore-line, vicinity of Red Rock Pass.	Swan Lake Station	XXIII	+ 303.0	897.7
Franklin Station		XXIV		307.7
Bonneville shore-line on Franklin Butte	Franklin Station	XXIII	+ 626.0	933.7
Provo shore-line on Franklin Butte	......do	XXIII	+ 261.0	568.7
Ogden Station		XXIV		94.7
Logan Station (U. N. R. R.)	Ogden Station	XXII	+ 206.0	300.7
Bonneville shore-line, vicinity of Logan	Logan Station	XXIII	+ 632.9	933.6
Provo shore-line, vicinity of Logan	......do	XXIII	+ 276.2	576.9
Lake surface, Aug. 11, 1877; interpolated	Lake Shore Gauge Zero	XXI	+ 6.8	6.8
Bonneville shore line, vicinity of Kelton	Lake surface, Aug. 11, 1877	XXIII	+1017.5	1024.3
Provo shore-line, vicinity of Kelton	Bonneville shore-line	XVIII	— 361.1	663.2
Lake surface, Aug. 23, 1877; interpolated	Lake Shore Gauge Zero	XXI	+ 6.5	6.5
Bonneville shore-line, vicinity of Promontory	Lake surface, Aug. 23, 1877	XXIII	+1037.7	1044.2
Provo shore-line, vicinity of Promontory	......do	XXIII	+ 665.8	672.3
Lake surface, Oct. 28, 1879; interpolated	Lake Shore Gauge Zero	XXI	+ 2.6	2.6
Bonneville shore-line, vicinity of Willard	Lake surface, Oct. 28, 1879	XXIII	+ 974.0	976.6
Provo shore-line, vicinity of Willard	......do	XXIII	+ 621.0	623.6
Salt Lake City Station (U. S. R. R.)		XXIV		52.4
Tecoma Station (C. P. R. R.)	Salt Lake City Station	XXII	+ 551.0	603.4
Bonneville shore-line, vicinity of Tecoma	Tecoma Station	XXIII	+ 367.8	971.2
Ogden Station		XXIV		94.7
Bonneville shore-line, vicinity of Ogden	Ogden Station	XXIII	+ 876.0	970.7
Salt Lake City Station		XXIV		52.4
Salt Lake City Meridian Monument	Salt Lake City Station	XXIII	+ 72.6	125.0
Bonneville shore-line, vicinity of Salt Lake City (1st determination).	Meridian Monument	XXIII	+ 845.9	970.9

TABLE XXIV.—*Reduction of Results to the Lake Shore Gauge Zero as a Common Datum.*—Continued.

Point.	Intermediate Datum.	From Table	Difference in Altitude referred to Intermediate Datum.	Altitude above the Lake Shore Gauge Zero Datum.
			Feet.	*Feet.*
Lake surface, May, 1873. Interpolated from records not included in Table XXI.	....	....	....	8.5
Bonneville shore-line, vicinity of Salt Lake City. (2d determination. This elevation is taken from Vol. III, p. 92, Report of Surveys West of 100th Meridian).	Lake surface, May, 1873	....	+ 967.7	976.2
Lake surface, July 12, 1877	Lake Shore Gauge Zero	XXI	+ 7.3	7.3
Bonneville shore-line, vicinity of Black Rock	Lake surface, July 12, 1877	XXIII	+ 993.0	1000.3
Provo shore-line, vicinity of Black Rock	do	XXIII	+ 633.0	640.3
Stansbury shore-line	do	XXIII	+ 247.0	254.3
Lake Surface, July 28, 1877; interpolated	Lake Shore Gauge Zero	XXI	+ 7.0	7.0
Bonneville shore-line, north end Aqui Range (1st determination).	Lake surface, July 28, 1877	XXIII	+1059.0	1066.0
Provo shore-line, north end Aqui Range (1st determination).	do	XXIII	+ 678.0	685.0
Lake surface, Nov. 25, 1880; interpolated	Lake Shore Gauge Zero	XXI	+ 1.7	1.7
Bonneville shore-line, north end of the Aqui Range (2d determination).	Lake surface, Nov. 25, 1880	XXIII	+1058.4	1060.1
Provo shore-line, north end Aqui Range (2d determination).	do	XXIII	+ 676.9	678.6
Stansbury shore-line, North end Aqui Range	do	XXIII	+ 331.0	332.7
Salt Lake City Station (U. S. R. R.)	....	XXIV	....	52.4
Summit (U. S. R. R.), vicinity of Point of the Mountain.	Salt Lake City Station	XXII	+ 547.0	599.4
Bonneville shore-line, vicinity of Point of the Mountain.	U. S. R. R. Summit	XXIII	+ 358.0	957.4
Provo shore-line, Point of the Mountain	Bonneville shore-line	XXIII	− 375.5	581.9
Lake surface, Mch., 1873. Interpolated from approximate data not included in Table XXI.	....	....	....	8.0
Bonneville shore-line, vicinity of Stockton	Lake surface, Mch., 1873	XXIII	+1011.0	1019.0
Provo shore-line, vicinity of Stockton	Bonneville shore-line	XXIII	− 375.0	644.0
Salt Lake City Station (U. S. R. R.)	....	XXIV	....	52.4
Santaquin Summit (U. S. R. R.)	Salt Lake City Station	XXII	+ 772.0	824.4
Bonneville shore-line, vicinity of Santaquin	Santaquin Summit (U. S. R. R.)	XXIII	+ 75.0	899.4
Salt Lake City Station (U. S. R. R.)	....	XXIV	....	52.4
Lemington Station	Salt Lake City Station	XXII	+ 455.0	507.4
Bonneville shore-line, vicinity of Lemington	Lemington Station	XXIII	+ 386.6	894.0
Salt Lake City Meridian Monument	....	XXIV	....	125.0
U. S. Signal Service barometer at Salt Lake City.	Meridian Monument	XXIII	+ 12.5	137.5
Fillmore sub-base barometer	U. S. Signal Service barometer.	XIX	+ 823.7	961.2
Bonneville shore-line, vicinity of Fillmore	Fillmore sub-base barometer	XXIII	− 19.4	941.8

TABLE XXIV.—*Reduction of Results to the Lake Shore Gauge Zero as a Common Datum*—Continued.

Point.	Intermediate Datum.	From Table	Difference in Altitude referred to Intermediate Datum.	Altitude above the Lake Shore Gauge Zero Datum.
			Feet.	*Feet.*
Fillmore sub-base barometer		XXIV		961.2
Bonneville shore-line on Pavant Butte	Fillmore sub-base barometer	XIX	− 67.6	893.6
Provo shore-line on Pavant Butte	Bonneville shore-line on Pavant butte.	XXIII	− 329.1	564.5
Fillmore sub-base barometer		XXIV		961.2
Camp at White Mountain Spring	Fillmore sub-base barometer	XIX	− 474.1	487.1
Provo shore-line on White Mountain Butte	Camp at White Mountain	XXIII	+ 68.9	556.0
Provo tufa deposit on Tabernacle Butte lava outflow.	do	XXIII	+ 42.9	530.0
Fillmore sub-base barometer		XXIV		961.2
Bonneville shore-line on Kanosh Butte	Fillmore sub-base barometer	XIX	− 17.3	943.9
Bonneville shore-line, base of North Twin Peak	do	XIX	+ 1.2	962.4
Bonneville shore-line, base of South Twin Peak	do	XIX	− 32.5	928.7
Salt Lake City Station (U. S. R. R.)		XXIV		52.4
Milford Station, U. S. R. R. extension	Salt Lake City Station	XXII	+ 707.5	759.9
Bonneville shore-line, vicinity of Milford (1st determination).	Milford Station	XXIII	+ 152.7	912.6
Fillmore sub-base barometer		XXIV		961.2
Camp on Beaver River, vicinity of Milford	Fillmore sub-base barometer	XIX	− 218.6	742.6
Milford Station, U. S. R. R. extension	Camp on Beaver River	XXIII	+ 7.6	750.2
Bonneville shore-line, vicinity of Milford (2d determination).	Milford Station	XXIII	+ 152.7	902.9
Fillmore sub-base barometer		XXIV		961.2
Bonneville shore-line, vicinity of Milford (3d determination).	Fillmore sub-base barometer	XIX	− 76.0	885.2
Fillmore sub-base barometer		XXIV		961.2
Bonneville shore-line, 7 miles south of Milford	Fillmore sub-base barometer	XIX	− 48.9	912.3
Bonneville shore-line, 2 miles east of Thermos	do	XIX	− 76.6	884.6
Bonneville shore-line, 4 miles south of Thermos	do	XIX	− 48.7	912.5
Bonneville shore-line, 7 miles south of Thermos	do	XIX	− 42.1	919.1
Bonneville shore-line, 1 mile west of Antelope Spring.	do	XIX	+ 38.7	999.9
Bonneville shore-line at Sulphur Springs	do	XIX	+ 45.2	1006.4
Bonneville shore-line, west of entrance to Pinto Canyon.	do	XIX	+ 214.1	1175.3
Bonneville shore-line, east of entrance to Meadow Creek Canyon.	do	XIX	+ 296.6	1257.8
Bonneville shore-line, west of entrance to Meadow Creek Canyon.	do	XIX	+ 294.5	1255.7
Bonneville shore-line, north of entrance to Shoal Creek Canyon.	do	XIX	+ 265.8	1227.0

ALTITUDES OF SHORE-LINES AND THEIR DIFFERENCES.

For convenience in comparison, all the determined altitudes of points on the Bonneville shore-line have been collected in Table XXV and arranged with reference to latitude, beginning with the most northerly. In addition to this a column has been prepared giving the "Inferred high-water level" of the Bonneville stage, with its probable error. The preparation of this column involves several considerations. In the first place, the shore record to which levels were run consisted in each case of a topographic feature which might or might not stand at the precise level of the corresponding water surface. In some cases there was reason to believe that it was higher, in other cases that it was lower, and in order to obtain the altitude given in the right-hand column, a correction was applied. To obtain the value of the probable error of this altitude, two sources of error had to be considered, the error of instrumentation, or error of the leveling proper, and the error of the estimated correction to the measured height.

In deciding upon the amount of allowance or correction to be applied to the determined altitudes in order to obtain the inferred high-water line, much attention was given to the local characteristics of the shore-line in the vicinity of each determined point. The effect of local conditions was the subject of special study by Mr. Gilbert, and the allowance for difference in altitude between the shore feature measured and the corresponding water surface was in each case based on his estimate.[1]

With reference to the error of instrumentation, the attempt was made to determine the general precision of each hypsometric method used. A probable error in accord with such determined precision was assigned to each separate measurement, and the probable error of each measured altitude was deduced from the combination of the errors of the several steps on which the measurement was based.

The probable error of the estimated allowance for the difference in altitude between the topographic feature measured and the high-water level was itself a matter of estimate only, being based upon considerations arising from Mr. Gilbert's general study of the subject.

The probable error of the corrected altitude was deduced by combining, in the usual manner, the probable error of instrumentation with the probable error of the "estimated allowance."

In ascertaining the precision of the barometric work, use was made of the long series of simultaneous observations at Fillmore and Salt Lake City. Sixty independent computations were made of the difference in altitude of the two stations, each computation being based on a single set of concurrent observations. A computation based on the discrepancies of the sixty results showed the probable error of a single determination to be ± 28 feet. The errors assigned to the barometric determinations were estimated on this basis, allowance being made for distance and other special conditions.

A part of the leveling work was duplicated, and an examination of the records of such duplicated work led to the belief that, as executed by us, a line of levels not exceeding five miles in length nor 1000 feet in vertical range, need not be assigned a

[1] A discussion of this subject will be found in Chapter III of this volume, under the headings "Embankment Series" and "Determination of Still-water Level," pp. 121–125. G. K. G.

greater probable error than one foot. Locke's hand level, when supported by a staff and used on a steep hillside, was found to have a probable error of about one foot in 800 feet of ascent.

The probable errors recorded in the following tables were obtained by combining the estimated probable errors of measurement with the estimated probable errors of identification of the plane of the ancient water surface. It is recognized that any individual determination, not duplicated, may involve some gross error for which no allowance is made, but if such errors exist their number is small.

TABLE XXV.—*Comparative Schedule of Altitudes of Points on the Bonneville Shore-line.*

Locality.	Description of Determined Point.	Determined Altitude above the Lake Shore Gauge Zero.	Inferred high-water level, above Lake Shore Gauge Zero.
		Feet.	*Feet.*
Red Rock Pass	Inner edge of a cut-terrace	897.7	906 ± 4
Franklin	do	933.7	940 ± 3
Logan	do	933.0	942 ± 4
Kelton Butte	Crest of an embankment	1024.3	1019 ± 3
Promontory	Inner edge of a cut-terrace	1044.2	1050 ± 3
Willard	do	976.6	985 ± 3
Tecoma	Middle of a cut-terrace	971.1	981 ± 5
Ogden		970.7	980 ± 5
Salt Lake City	Inner edge of a cut-terrace back of Fort Douglas. By first determination.	970.9	979 ± 5
Salt Lake City	Inner edge of a cut-terrace back of Fort Douglas. By second determination.	976.2	984 ± 5
Black Rock	Inner edge of a cut-terrace	1000.3	1008 ± 3
North end of Aqui Range	Inner edge of cut terrace. By first determination.	1060.1	1068 ± 3
North end of Aqui Range	Inner edge of a cut-terrace. By second determination.	1066.0	1074 ± 4
Point of the Mountain	Crest of an embankment	957.4	950 ± 3
Stockton	do	1019.0	1014 ± 5
Santaquin	Inner edge of a cut-terrace	899.4	902 ± 3
Lemington	do	894.0	902 ± 5
Fillmore	Crest of a bay bar	941.8	938 ± 8
Pavant Butte	Near outer edge of a cut-terrace	893.6	902 ± 15
Kanosh Butte	Middle of a cut-terrace	943.9	953 ± 15
Base of North Twin Peak	Outer edge of a cut-terrace	962.4	971 ± 20
Base of South Twin Peak	do	928.7	939 ± 20
Milford	End of a V-embankment. The elevation given in the third column is the general mean of the three determinations of the point given in Table XXIV, weighting the first at 5, the second at 3, and the third at 1.	906.3	904 ± 10
7 miles south of Milford	Outer edge of a cut-terrace	912.3	921 ± 20
2 miles east of Thermos	Middle of a narrow cut-terrace	884.6	893 ± 25
4 miles south of Thermos	Middle of a cut-terrace	912.5	921 ± 25
7 miles south of Thermos	do	919.1	927 ± 25

TABLE XXV.—*Comparative Schedule of Altitudes of Points on the Bonneville Shore-line*—Continued.

Locality.	Description of Determined Point.	Determined Altitude above the Lake Shore Gauge Zero.	Inferred high-water level, above Lake Shore Gauge Zero.
		Feet.	*Feet.*
Antelope Spring (Lower Escalante Desert).	Middle of a cut-terrace	999.9	1008 ± 30
Sulphur Springs	Outer edge of a narrow cut-terrace	1006.4	1015 ± 25
Pinto Canyon	Outer edge of a delta terrace	1175.4	1175 ± 35
Meadow Creek Canyon (East of entrance).	Outer edge of a delta terrace	1257.8	1258 ± 35
Meadow Creek Canyon (West of entrance).	Outer edge of a delta terrace	1255.7	1256 ± 35
Shoal Creek Canyon (North of entrance).	Near outer edge of a delta terrace	1227.0	1227 ± 35

Tables XXVI and XXVII present, in form similar to the arrangement of Table XXV, the determinations made on the Provo and Stansbury shore-lines.

TABLE XXVI.—*Comparative Schedule of Altitudes of Points on the Provo Shore-line.*

Locality.	Description of Determined Point.	Altitude above Lake Shore Gauge Zero.	Inferred water level, above Lake Shore Gauge Zero
		Feet.	*Feet.*
Franklin	Inner edge of a cut-terrace	568.7	569 ± 3
Logan	Crest of a bar on edge of a delta	576.9	577 ± 2
Kelton	Inner edge of a cut-terrace	663.2	663 ± 3
Promontory	......do	672.3	672 ± 3
Willard	......do	623.6	624 ± 5
Black Rock	......do	640.3	640 ± 4
North end of the Aqui Range	Inner edge of a cut-terrace, by first determination.	678.0	679 ± 3
North end of the Aqui Range	Inner edge of a cut-terrace, by second determination.	685.0	685 ± 4
Point of the Mountain	Crest of an embankment	581.9	580 ± 3
Stockton	Crest of a bar	644.0	640 ± 5
Pavant Butte	Inner edge of a cut-terrace—indistinct	564.5	
White Mountain Spring	Crest of an embankment	556.0	553 ± 10
Do	Line of calcareous tufa on lava outflow about Tabernacle Butte.	530.0	530 ± 15

TABLE XXVII.—*Comparative Schedule of Altitudes of Points on the Stansbury Shore-line.*

Black Rock	Cut-terrace	254.3	254 ± 3
North end of the Aqui Range		332.7	333 ± 3

Tables XXVIII and XXIX are in general compiled directly from Tables XXV, XXVI and XXVII, and give the differences in altitude of the high-water lines of the Bonneville and Provo stages, and Provo and Stansbury stages respectively. The Snowsville, Dove Creek, and Matlin results come direct from Table XVIII.

TABLE XXVIII.—*Differences in Altitude of the Bonneville and Provo Shore-lines at Various Localities.*

Locality.	Description of Point on Bonneville Shore.	Description of Point on Provo Shore.	Difference of Altitude.
			Feet.
Snowsville	Outer edge of a cut-terrace	Outer edge of a cut-terrace	365 ± 2
Franklin	Inner edge of a cut-terrace	Inner edge of a cut-terrace	371 ± 2
Logan	do	Crest of bar on edge of a delta terrace.	365 ± 3
Wellsville	Crest of an embankment	Crest of an embankment	382 ± 2
Kelton	do	Inner edge of a cut-terrace	356 ± 3
Promontory	Inner edge of a cut-terrace	do	374 ± 3
Dove Creek	Crest of a bar	Built terrace	413 ± 2
Matlin	Outer edge of a cut-terrace	Crest of a bar	411 ± 3
Willard	Inner edge of a cut-terrace	Inner edge of a cut-terrace	361 ± 3
Black Rock	do	do	360 ± 3
North end Aqui Range	do	do	389 ± 3
Grantsville	Crest of an embankment	Crest of a bay bar	380 ± 3
Stockton	do	do	374 ± 3
Point of the Mountain	do	Crest of an embankment	370 ± 3
Cup Butte	do	Inner edge of a cut-terrace	392 ± 3
Snowplow	do	Crest of an embankment	397 ± 2
Fish Spring	Outer edge of a cut-terrace	Outer edge of a cut-terrace	382 ± 5
Pavant Butte	Crest of a V-bar	Cut-terrace (indefinite)	339 ± 10
Fillmore	Crest of a bay bar	Crest of embankment on White Mountain Butte.	385 ± 8
Preuss Valley			
(Middle series)	Crest of an embankment	Crest of an embankment	345 ± 2
(South series)	do	do	341 ± 2

TABLE XXIX.—*Differences in Altitude of the Provo and Stansbury Shore-lines at various localities.*

Vicinity of	Nature of the Provo Shore.	Nature of the Stansbury Shore.	Difference of Altitude.
			Feet.
Matlin	Outer edge of a cut-terrace	Crest of a bar	310 ± 3
Black Rock	Inner edge of a cut-terrace	Cut-terrace	386 (?)
North end of the Aqui Range	do		346 ± 3

APPENDIX B.

ON THE DEFORMATION OF THE GEOID BY THE REMOVAL, THROUGH EVAPORATION, OF THE WATER OF LAKE BONNEVILLE.

BY R. S. WOODWARD.

The following paragraphs contain an outline, with special reference to the Lake Bonneville problem, of a general investigation of the form of the geoid as influenced by local attracting masses of certain determinate forms. The fullest publication constitutes Bulletin No. 48 of the U. S. Geological Survey, entitled On the Form and Position of the Sea-Level. Some of the mathematical work appears in the Annals of Mathematics, in Nos. 5 and 6 of Vol. 2 and No. 1 of Vol. 3; and the principal numerical results with reference to an ice cap are abstracted in the paper by Messrs. Chamberlin and Salisbury on The Driftless Area of the Upper Mississippi Valley, in the Sixth Annual report of the U. S. Geological Survey, pages 291–298.

The form and position assumed by the surface of the ocean or the surface of a lake at any time are determined by the contemporaneous distribution and velocity of rotation of the earth's mass. Any change in that distribution or in that velocity of rotation involves, in general, changes in both the form and position of the free surfaces of all terrestrial bodies of water. Such surfaces are called level surfaces, or now more commonly, equipotential surfaces. Mathematically they are always regarded as closed surfaces, or as encompassing the earth, however limited their visible portions presented by isolated bodies of water may be. Thus, the sea surface is imagined to extend through the continents, its position at any invisible point being the height to which water would rise if permitted to flow through a canal from the sea to that point.

Of the two factors which determine the form and position of the sea level at any epoch, the distribution of the earth's mass is the more important. Indeed, the rotation of the earth may be entirely ignored in computing the effects on the sea-level of such changes in the superficial distribution of matter as are here considered.

It will be convenient in what follows to distinguish between the relative attitudes of the surfaces of the sea or any similar equipotential surfaces at different epochs by referring to them as disturbed and undisturbed surfaces. Thus, according as we call the present sea surface undisturbed or disturbed the past and future surfaces are disturbed or undisturbed. It will also be convenient to call any mass producing such relative changes in sea level a disturbing mass.

In the paper referred to above it is shown that the effect of superficial masses of small magnitude in comparison with the earth's mass in distorting the sea-level is expressed by the formula

$$v = \frac{V - V_0}{g}, \tag{1}$$

in which v is the elevation or depression of the disturbed surface with respect to the undisturbed at the point where the potential of the disturbing mass is V;[1] V_0 is the potential of the disturbing mass along the line of intersection of the disturbed and undisturbed surfaces, or the value of V where $v = 0$; and g is the acceleration of gravity.

The application of the above formula presents no difficulty except in the calculation of the potentials V and V_0, which are in some cases quite complex quantities. For one of the most important classes of cases, namely that in which the disturbing mass is symmetrically disposed about a radius of the earth's surface, the potentials have been expressed in terms of integrals which may be readily evaluated for the characteristic points of the disturbed surface. In this class of cases the disturbed surface will evidently be equi-symmetrical with respect to the axis of the disturbing mass, and, disregarding the effect of the rearranged water, the amount of the disturbance is defined by the following formula:

$$v = \frac{3\rho}{\pi\rho_m} \int_0^{\beta_0} \frac{d(\mathrm{I} - \pi \sin \tfrac{1}{2}\beta)}{d\beta} \varphi(\beta) d\beta. \tag{2}$$

Herein v has the same meaning as in (1), ρ is the density of the disturbing mass, ρ_m the mean density of the earth, π the number 3.14159 +, β the angular distance of any point of the disturbing mass from its axis, and β_0 is the angular radius of the border of the mass or the limiting value of β. The quantity I is a definite integral which may be most briefly expressed thus—

$$\begin{aligned} \mathrm{I} &= \int_0^{\alpha} \left(\frac{\cos p - \cos \beta}{\cos p - \cos \alpha}\right)^{\frac{1}{2}} dp \text{ when } \alpha < \beta \\ &= \int_0^{\beta} \left(\frac{\cos p - \cos \beta}{\cos p - \cos \alpha}\right)^{\frac{1}{2}} dp \text{ when } \alpha > \beta, \end{aligned} \tag{3}$$

wherein α is the angular distance of any point of the disturbed surface from the axis of the disturbing mass. α and v are thus polar co-ordinates of the disturbed sea surface.

The effect of the rearranged sea-water, ignored above, is simply to produce an exaggeration of the type of surface defined by (2), and this exaggeration may be expressed by a series of rapidly converging terms (see §§ 20–24 of paper on Form and

[1] If m be an element of the disturbing mass and r its distance from the point in question, the potential of the mass is the sum of all the quotients $\frac{m}{r}$, or $V = \Sigma \frac{m}{r}$. The non mathematical reader should distinguish carefully between potential and attraction, the latter being a derivative of the former.

Position of the Sea Level), but for the small masses here considered the sum of these additional terms is insignificant. In all cases, indeed, the characteristic effects are expressed by equation (2).

For lenticular masses of the type assumed in the text, the thickness is given by the expression

$$\varphi(\beta) = h_0 \left(1 - \frac{\sin^n \frac{1}{2}\beta}{\sin^n \frac{1}{2}\beta_0}\right). \tag{3}$$

Here h_0 is the thickness along the axis of the mass, β and β_0 have the meanings assigned above and n is any positive integer. This formula makes $\varphi(\beta) = h_0$, or the mass of uniform thickness when n is infinite. For other values of n the mass will be thickest along its axis and diminish in thickness more or less rapidly as we pass from the axis to the border, or as β increases from 0 to β_0. Some of the curves defined by (3) are shown in Figure 51. The scale for the sector A B C, representing a great circle of the earth through the axis of a lenticular lake basin, is 1 : 125,000,000 and the radial scale for the curves $n = 1, 3, 7$ is exaggerated about 5,000 times, the assumed value of h_0 being 1,000 feet.

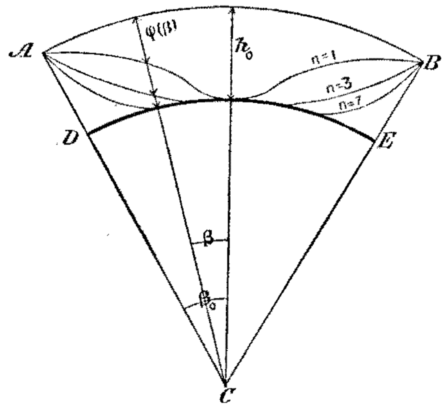

FIG. 51.—Cross-section of Ideal Lenticular Lake Basins.

Scale for section of terrestrial sphere $\frac{1}{125000000}$.

Radical scale for thickness of disturbing mass, or for $\phi\ (\beta) = \frac{1}{25000} = \frac{5000}{125000000}$

$\phi(\beta) = h_0 \left(1 - \frac{\sin^n \frac{1}{2}\beta}{\sin^n \frac{1}{2}\beta_0}\right)$, $h_0 = 1000$ feet.

For the particular value of $\varphi(\beta)$ given by (3), equation (2) becomes

$$v = 3\,\frac{h_0\rho}{\pi\rho_m}\left\{\int_0^{\beta_0} \mathrm{I}d\left(\frac{\sin\frac{1}{2}\beta}{\sin\frac{1}{2}\beta_0}\right)^n - \frac{n\pi}{n+2}\sin^2\tfrac{1}{2}\beta_0\right\}. \tag{4}$$

If we represent the values of the definite integral in this equation for points along the border and at the center of the mass by S_2 and S_1 respectively and denote the corresponding values of v by v_2 and v_1 respectively, we find

$$v_2 - v_1 = 3\,\frac{h_0\rho}{\pi\rho_m}\left\{S_2 - S_1\right\}. \tag{5}$$

This expresses the difference in altitude of the disturbed surface at the center and at the border of the disturbing mass. When, as in the present case, the disturbing mass is water in a lake basin, we must substitute for ρ the difference in density of water and superficial rocks. That is,

$$\rho = 1 - 2.8 = -1.8 \text{ approximately.}$$

Finally, if we wish to ascertain the separation at the center of the basin, due to a change in the density of its contents, of equipotential surfaces which intersect along the border, we have only to differentiate (5) regarding (v_2-v_1) and ρ as variables and substitute for $\Delta\rho$ the change in density of the contents of the basin. Thus, the separation is expressed by

$$\Delta(v_2 - v_1) = 3\,\frac{h_0\,\Delta\rho}{\pi\rho_m}\left(\mathrm{S}_2 - \mathrm{S}_1\right). \tag{6}$$

The values of S_1 and S_2 in (5) and (6) may be found from the following expressions:

$$\mathrm{S}_1 = \frac{n}{n+1}\,\pi \sin \tfrac{1}{2}\beta_0.$$

$$\mathrm{S}_2 = \pi \sin \tfrac{1}{2}\beta_0 \left\{ \frac{n}{2\,(n+2)} + \frac{n}{16\,(n+4)}\left(1 + \sin^2 \tfrac{1}{2}\beta_0\right) + \frac{n}{128\,(n+6)}\left(3 + 2\sin^2 \tfrac{1}{2}\beta_0 + 3\sin^4 \tfrac{1}{2}\beta_0\right) + \ldots\ldots\ldots \right\}$$

The march of the above functions S_1 and S_2 and the corresponding values of $(v_2 - v_1)$ and $\Delta\,(v_2 - v_1)$ is illustrated by the numerical results given in the table below. The data for these results are the following:

$$h_0 = 1000 \text{ feet}, \quad \beta_0 = \text{arc of } 1^\circ,$$
$$\rho_m = 5.5,$$
$$\rho = -1.8,$$
$$\Delta\rho = -1.$$

The results in the fifth column show how much nearer to the center of the earth the assumed lake surface is at the middle of the basin than at its border; and the results in the sixth column show how much a shore trace at the middle of the basin would be found to be above the contemporaneous trace at the border, by a line of spirit levels run after the removal of the water.

TABLE XXX.—*Values showing relative positions of Level Surfaces in a lake basin* 140 *miles in diameter and of* 1000 *feet maximum (axial) depth.*

n	S_1	S_2	$\mathrm{S}_2 - \mathrm{S}_1$	$v_2 - v_1$	$\Delta(v_2 - v_1)$
				Feet.	*Feet.*
1	0.00436	0.00161	0.00275	2.70	1.50
2	.00582	.00245	.00337	3.31	1.84
3	.00654	.00298	.00356	3.50	1.94
4	.00698	.00333	.00365	3.58	1.99
5	.00727	.00359	.00368	3.61	2.01
6	.00748	.00379	.00369	3.62	2.01
7	.00764	.00395	.00369	3.62	2.01
8	.00776	.00407	.00369	3.62	2.01
9	.00786	.00418	.00368	3.61	2.01
10	.00793	.00427	.00366	3.59	1.99
∞	.00873	.00556	.00317	3.11	1.73

APPENDIX C.

ON THE ELEVATION OF THE SURFACE OF THE BONNEVILLE BASIN BY EXPANSION DUE TO CHANGE OF CLIMATE.

By R. S. Woodward.

The following problems were submitted to me by Mr. Gilbert:

(1) Ten thousand years ago the surface (mean) temperature of the Bonneville basin, which had been long constant, was raised 10 F. and it has been since unchanged. The linear expansion of the subjacent material is .000,006 per degree F.; the cubic expansion .000,018. Horizontal dilatation being prevented by interference, the total cubic expansion was expressed in vertical dilatation. How many feet was the surface of the ground lifted?

(2) Same as above for period of 100,000 years.

(3) Same as above for period of 1,000,000 years.

The cooling by conduction of a large sphere like the earth from an initial uniform temperature, gives rise to cubical contraction whose amount is assigned approximately by the following formula:[1]

$$\Delta V = 8\pi r^2 uca \sqrt{\frac{t}{\pi}}, \tag{1}$$

in which

$r =$ the radius of the sphere,
$u =$ the initial uniform excess in temperature of the sphere over that of the surrounding medium,
$a^2 =$ the coefficient of diffusion, assumed constant for the whole sphere,
$e =$ the coefficient of cubical contraction, assumed constant,
$t =$ the time after the initial epoch,
$\pi = 3.1415+$.

This formula will apply to the earth for 1,000,000,000 years subsequent to the initial epoch without introducing errors greater than those involved in the assumption of constancy of a and e.

Conversely, the above formula will give the cubical expansion of a sphere, consequent upon being immersed in a medium which maintains a constant surface temperature u degrees higher than the initial temperature of the sphere.

[1] For complete formula see Annals of Mathematics Vol. III, No. 5.

If in the latter case we suppose the total volumetric expansion to result in vertical uplift, an effect which would follow from heating the earth's crust if it behaved under expansion like a liquid, the amount of the uplift will be expressed very closely by the quotient of equation (1) divided by the area of the surface of the sphere. Thus, calling the amount of the uplift Δr, we have

$$\begin{aligned} \Delta r &= \frac{8\pi r^2 uea \sqrt{\frac{t}{\pi}}}{4\pi r^2} \\ &= 2uea \sqrt{\frac{t}{\pi}}\,. \end{aligned} \tag{2}$$

Using the year and the British foot as units, Sir W. Thomson finds $a = 20$. With this value and with $u = 10°$ F. and $e = 0.000018$, (2) becomes

$$\Delta r \overset{\text{Foot.}}{=} 0.00406 \sqrt{t}.$$

This gives the following values of Δr corresponding to several values of t:

t.	Δr.
Years.	*Feet.*
10,000	0.41
100,000	1.28
1,000,000	4.06

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SCALE $\frac{1}{800,000}$ or 1 inch = 12.626 miles

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