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Great Salt Lake's SALT CRUST

Contents

Design | *Jennifer Miller*

Cover | *Salt crust exposed near Little Valley Harbor along the north arm of Great Salt Lake. Microbialite mounds are visible above the pink-colored salt crust, and many are capped with a partially dissolved salt layer. Photo by Andrew Rupke.*

THE DIRECTOR'S PERSPECTIVE

by Richard G. Allis

The Utah Geological Survey has just published the 4th edition of *Utah's Energy Landscape* (UGS Circular 121; http://ugspub.nr.utah.gov/publications/circular/c-121.pdf), a summary of energy production and consumption trends compiled by Michael Vanden Berg. Tables and graphs in the report were created from data in the Utah Energy and Mineral Statistics online data repository on our website (http://geology.utah.gov/resources/energy/utah-energy-and-mineral-statistics). The report highlights major short- and long-term energy transitions that are occurring in Utah. Perhaps the most dramatic change is that caused by the downturn in oil and natural gas prices. This caused the total value of Utah's energy production in 2015 to be less than half that of peaks recorded in 2014 and 2008 of over $6 billion per year. With prices still depressed, and only a small number of drilling rigs operating in the state, production of oil and gas is declining, and reduced revenue from oil and gas production is expected to continue. Utah has had three peaks in production since oil was discovered in the late 1940s (1959, 1975, 1985) and it is presently defining the fourth (2014). All four peaks have been close to 40 million barrels per year. A big difference from the past is that oil reserves are now 50 percent larger (800 million barrels) compared to past peak oil reserves of 600 million barrels in the late 1980s.

Utah's coal production is now close to half of its maximum value reached in 2000. However, consumption of coal within Utah has been roughly constant over that time, being largely used for power generation. The decrease in coal demand has been mostly caused by decreased shipments out of state as several utilities and industrial users in California and Nevada have switched to natural gas. Although coal-fired power generation in Utah has been roughly constant for the past 20 years, total power demand increased to a peak in 2008, followed by a slightly reduced demand due to the economic downturn and relatively mild winter and summer temperatures. The 30 percent growth in power demand in Utah over the past 20 years has mostly been supplied by natural gas-fired power plants, decreasing coal's share from 94 percent to 76 percent of the power mix.

Another interesting trend is the current boom in utility-scale solar photovoltaic (PV) generation. By 2017, Utah's utility-scale solar capacity will be 847 megawatts, more than all the other renewable generation combined (wind, geothermal, biomass, and hydroelectricity). In 2015, these renewables generated 4 percent of total electricity generation, so although still a small part of the power mix, this percentage will increase significantly. A new table in Circular 121 shows Utah solar PV generating at 20 percent of installed capacity, compared to wind at 23 percent, natural gas at 37 percent (used as peaking plants), coal at 73 percent, and geothermal at 83 percent (based on 2014 statistics). This highlights the increasing complexities Rocky Mountain Power has balancing traditional baseload power generation with a growing, more diverse mix of variable power generation.

For those thinking about the challenges facing Utah over the next few decades due to population and economic growth, increasing energy demand, and a changing regulatory environment, the latest edition of *Utah's Energy Landscape* is a valuable summary of critical trends.

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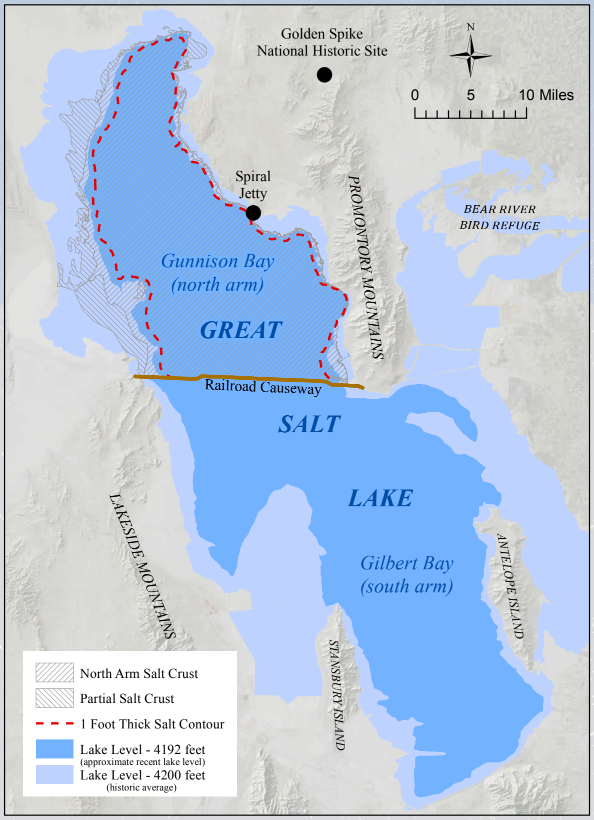
MORE THAN A GRAIN OF SALT: THE SALT CRUST ON GREAT SALT LAKE'S NORTH ARM

BY **Andrew Rupke and Taylor Boden**



The saltiness of Great Salt Lake (GSL) is its defining characteristic, but many people do not realize that some areas of the lake are saltier than others. Prior to the construction of the rock-fill railroad causeway that now separates the north and south parts (arms) of GSL, the lake had, more or less, one salinity level. Since the causeway was completed in 1959, Gilbert and Gunnison Bays (the south and north arms of the lake, respectively) have had distinctly different salinity levels. Because flow of brine through the causeway is restricted and because GSL receives most of its fresh water into the south arm, the north arm of the lake has become much saltier than the south arm (see *Survey Notes*, v. 34, no. 1, p. 1–4, 2002, and v. 47, no. 1, p. 8–9, 2015, for more information on the causeway). Shortly after these salinity differences began to manifest, the Utah Geological Survey (UGS) started to systematically sample and analyze the lake brine, and we continue to do so. Nearly 50 years of data show an average salinity of 12 percent in Gilbert Bay, but Gunnison Bay's average is much higher, about 25 percent. To put those numbers in context, ocean water salinity is about 3.5 percent.

For much of the past 50 years, Gunnison Bay has been salty enough to cause the formation of a salt crust on the floor of the lake. Modeling of past salinity levels in GSL by scientists at the U.S. Geological Survey (USGS) and Utah State University suggests that a salt crust has been present in Gunnison Bay since the mid-1960s with the exception of a short time period from the late 1980s to early 1990s when lake levels were exceptionally high and, as a result, salinity levels were low. Formation of a salt crust over hundreds of square miles is significant because it reduces the overall saltiness of the lake by confining hundreds of millions of tons of salt to the north-arm lake bed that would normally be all or partially dissolved in the lake brine. And, of course, the salinity levels of the lake have an impact on its ecology and industry. For instance, brine shrimp thrive in a certain range of salinity levels, and a reduced salinity in the south arm can have negative impacts on the mineral industry that operates in that part of the lake. While estimates indicate that the amount of salt in the crust fluctuates, at times the crust has probably stored about 20 percent of the salt in the GSL system.

Given the significance and volume of salt in the crust, surprisingly little research has focused on the crust itself (as mentioned, previous work relied on modeling salinity data—not direct observations of the salt crust). However, in the early 1970s the UGS conducted a core-drilling program across Gunnison Bay to gain information on the thickness, extent, and composition of the salt crust, but the data from that study were never published. Other studies occasionally included some limited information on the salt crust. In 2015, with the help of funding from the Utah Division of Forestry, Fire and State Lands, we began a study that combines old data and new information on the salt crust. One objective of our work is to provide an updated overview of what is known about the salt crust and make that information more broadly available in a single report, and another aspect is to generate some new data on the salt crust from field observations.

Our field study focused on nearshore investigation of the salt crust, and we examined it at several locations around the perimeter of the north arm. The recent low lake levels have exposed wide stretches of salt crust around the lake—ideal for scientific observation. The crust is generally a solid mass of coarse salt crystals that can be up to about half an inch long. The salt crystals are primarily halite, a mineral composed of sodium chloride—more popularly known as table salt. Chemical analyses indicate that the salt crust is about 99 percent sodium chloride with minor amounts of calcium, magnesium, potassium, and sulfur. The salt crystals typically grow in place on the bed of the lake, but delicate "rafts" of salt crystals also form on the surface of the water during the hot, dry summer months, which eventually sink and accumulate on the lake bottom. As part of the project, we developed a method for measuring the salt crust thickness, and we found crust up to 1.9 feet thick not far from the shore. Our data, in conjunction with past data and aerial photography, indicate that the salt crust covers nearly the entire lake bed of the north arm. Recent aerial photography shows a white rim of salt all the way around the north arm of the lake, and past data show thick salt in the central part of the lake. Although the scope of our project did not allow for measuring the crust thickness in the central parts of Gunnison Bay, the core drilling conducted by the UGS across Gunnison Bay in 1970 and 1972 showed salt crust up to 4.6 feet thick in more central parts of the lake, and boreholes completed during oil and gas exploration of the lake in 1974 showed salt crust locally up to 8 feet thick.

Using aerial photography, we mapped the outer extent of the salt crust and estimate that during late summer 2014 it covered a minimum area of 414 square miles. Where we measured the thickness of the salt crust, the salt was generally about one foot thick within a short distance from the water's edge. Using our data and published bathymetry from the USGS, we developed a contour around the north arm estimating where the salt is one foot thick. From the area within the 1-foot contour (349 square miles), we estimate that at least 436 million (short) tons of salt was present on the floor of the north arm during the late summer and fall of 2015. We estimate that another 20 million tons is present between the edge of the crust and our 1-foot contour for a total of 456 million tons of precipitated salt. Our estimate represents a minimum tonnage for the salt crust, because past data strongly suggest that the crust is much thicker in the central part of the lake where we were unable to measure it. Estimates for the total amount of salt in the GSL system are around 4.5 billion tons, so at least 10 percent, but likely much more, of that is sitting at the bottom of the north arm.

An important aspect of our work is that we have established a set of baseline data that we can use to monitor the salt crust and see if it is precipitating or dissolving. Over time we can reoccupy various sites that we have previously measured and determine if the crust is getting thicker or thinner. Our baseline data collection is timely because a bridge in the railroad causeway is scheduled to open during the second half of this year (it may be open by the time this article is published). This new bridge will allow increased flow of brine through the causeway, and will almost certainly affect salinity and water levels in both Gilbert and Gunnison Bays. If enough lower-salinity water flows into the north arm, the salt crust could begin to dissolve. If this happens, we hope to detect it when we perform periodic measurements of the salt crust. Monitoring the salt crust, coupled with continued brine sampling and salinity measurements, will help us and the broader scientific community to better understand how salt cycles through the lake. Ultimately, this improved understanding will allow us to be more prepared to help the various entities that manage the lake to make informed and prudent decisions.

If you are interested in checking out the salt crust for yourself, the easiest place to access it is at the Spiral Jetty (see *Survey Notes*, v. 35, no. 1, p. 10–11, 2003), which is south of the Golden Spike National Historic Site. The area is remote and requires driving several miles down an unpaved road, so be prepared. Once at the Spiral Jetty you may need to walk several hundred yards to reach the water's edge if water levels are very low, as they currently are. You will know you are on the salt crust once you are walking on a very solid surface. During the summer and fall you should be able to observe the coarse crystalline salt in the shallow water, and if you are there during the right conditions you may see some salt rafts forming on the surface of the water.

An above-water, exposed area of the salt crust provided a good location to extract a large crust sample. The gray material is oolitic sand and mud from below the salt crust. The pink color in the sample is a result of cyanobacteria that live in the north arm brine.

Salt rafts often form on the surface of the lake's brine and, in this case, have accumulated on the water's edge.

Coarse, intricate salt crystals form just below the brine surface on the floor of Gunnison Bay.

The Other Salt Crust: Another salt crust in Utah, famous as a racing surface and a movie setting, is also currently being studied. The racing community is concerned that the Bonneville Salt Flats (BSF), where many land speed records have been set, are deteriorating, and Dr. Brenda Bowen and some graduate students from the University of Utah have begun evaluating the area to understand what factors are affecting the salt surface. Cancellation of racing events at the BSF in 2014 and 2015 have heightened these concerns. The BSF began as a remnant of Pleistocene Lake Bonneville, but the salt crust is currently sustained as shallow, briny groundwater wicks to the surface and evaporates, leaving the salts behind. The BSF represent a complex and dynamic geologic system, and both natural and anthropogenic (human-caused) forces may play a role in changes being observed on the raceway. The study will investigate potential effects caused by a potash mining operation located south of the BSF that uses some of the shallow brine as their feedstock, as well as climatic and other natural factors. Hopefully, the results of the University of Utah's detailed study will provide some definitive conclusions on what factors are affecting the salt crust and what steps might help preserve the raceway.

ABOUT THE AUTHORS

Taylor Boden joined the Utah Geological Survey in 2004, working as a geologist for the Energy and Minerals Program. He has worked on a wide range of projects involving Utah's industrial and metallic mineral resources.

Andrew Rupke joined the Utah Geological Survey in 2010 as an industrial minerals geologist after working in the mining industry for 6 years. His research primarily focuses on Utah's industrial minerals, including potash, limestone, phosphate, and others. This work often leads him to Great Salt Lake, an important mineral resource for Utah, and he also coordinates the Survey's Great Salt Lake brine sampling program.

Utah Geological Survey is
Major Partner in Large Geothermal Project near Milford, Utah

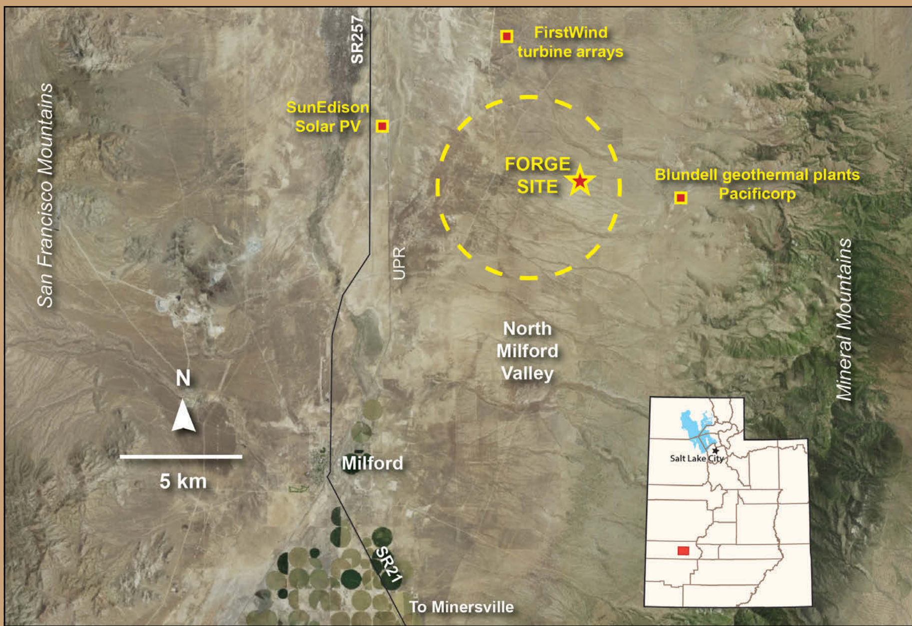
By Rick Allis

The U.S. Department of Energy (DOE) has begun a large geothermal project, known as FORGE (Frontier Observatory for Research in Geothermal Energy), to establish a field laboratory aimed at advancing and developing new technologies for geothermal power generation. Traditional geothermal power plants have wells that tap hot water or steam in naturally fractured rock (that is, a reservoir), and this fluid generates power as it is cooled at the surface in the plant before being injected back into the underlying reservoir rock. Utah has three such plants, all in Beaver County: Blundell (34 megawatts [MW] gross, owned by PacifiCorp Energy), Thermo No. 1 (10 MW, Cyrq Energy), and Cove Fort (25 MW, Enel Green Power). It has long been recognized that both the size of existing geothermal developments and opportunities for new developments are limited by a lack of well productivity. We can find large areas with hot rock at drillable depth, but frequently the volume that is naturally fractured and "productive" is much smaller.

Over the past decade, horizontal drilling and the development of fracturing technologies that improve connection between wellbores and adjacent rock have transformed oil and gas production from tight (low-productivity) shale rock. The goal of the FORGE project is to apply these hydrocarbon technologies to hot, tight rock to create fractured zones around geothermal wells. Cold water can be injected into one well so that it moves through the fractures and becomes heated before being intercepted by an adjacent well (the production well), releasing its heat at the surface in a power plant. This technology is sometimes called Enhanced, or Engineered, Geothermal Systems (EGS). Modern power plants typically use a binary (secondary) system where a working fluid absorbs the heat energy of the hot water, flows through turbines to generate electrical power, and is air-cooled with large fans before repeating the process. The cooled water exiting the power plant is reinjected creating, in effect, a closed-loop circulation system where loss of water and environmental impacts are minimized.

DOE has specified that the ideal FORGE site will have crystalline host rock at a temperature of 175–225°C (350–440°F) between 1.5 and 4 kilometers depth (5,000–13,000 feet). Of the numerous sites that were initially proposed, DOE selected five for Phase 1, a desk-top assessment of the available data. A site near Milford, Utah, about 3 miles west of the Blundell power plant, was one of the Phase 1 sites. The team investigating the Milford site is led by the Energy & Geoscience Institute at the University of Utah, with the Utah Geological Survey (UGS) being a major partner. At the time of writing this article, the Phase 1 reports have been written, and the teams have presented their findings to DOE in Washington, D.C. Later in 2016, the best two or three sites will be selected to proceed to Phase 2, which allows completion of environmental clearances and fieldwork to improve site characterization. Announcement of the winning site is expected in early 2018, with less than a year to set up the facilities, and then five additional years to drill the deep wells, test stimulation

The FORGE site is in a renewable energy hub. This view shows the SunEdison photovoltaic array under construction in the foreground, a FirstWind turbine array in the middle distance, and PacifiCorp's Blundell geothermal power plant in front of the Mineral Mountains in the far distance. Photo by Mark Milligan.



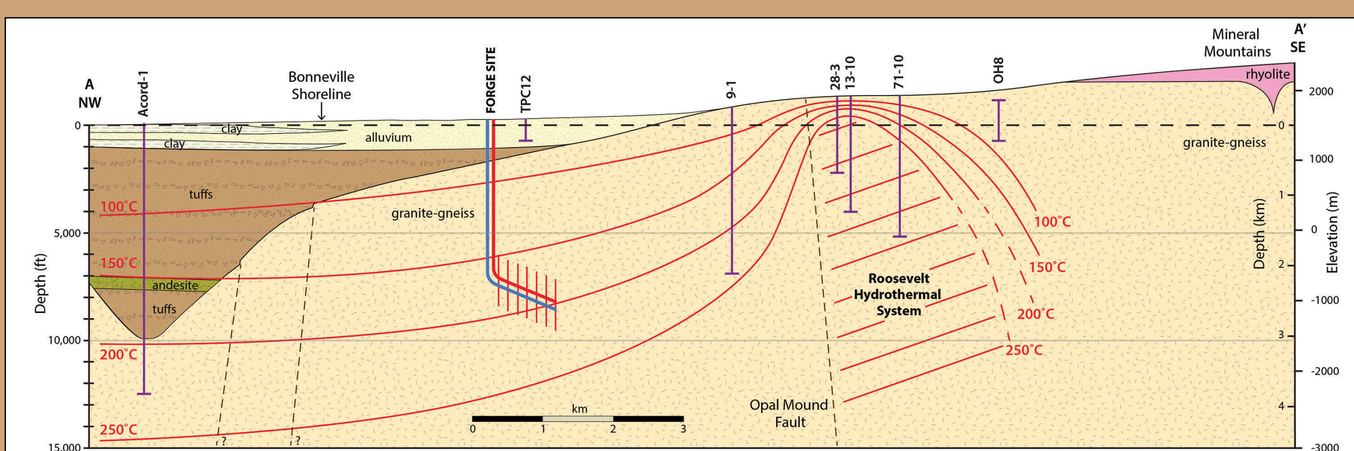
and monitoring technologies, and carry out circulation experiments to optimize techniques for extracting the heat from the hot rock. The site will be decommissioned at the end of the five-year technology testing period. If the technology advances have been successful it is hoped that geothermal industry participants will look to develop and expand the site for commercial power generation. It is also hoped that the new technologies can be replicated at many other places around the U.S.

Phase 1 work found that the Milford site has many positive attributes that make it an ideal site for the FORGE field laboratory. The site is unusually rich in exploration data because during the late 1970s there were at least five companies drilling wells around Roosevelt Hot Springs (RHS) trying to locate the best area for geothermal power generation. Also, DOE at that time funded researchers at the University of Utah to study RHS so that more could be learned about this type of hydrothermal system. Over 80 thermal gradient wells (typically to about 500 feet depth) and over 20 deep wells (to 13,000 feet depth) were drilled and had data available for analysis. The characteristics of RHS were documented in over 20 theses, ensuring that the exploration data were preserved. Reinterpretation of these data shows a 2-square-mile area on non-federal, undeveloped land has the required thermal regime for FORGE in a granitic host rock, with temperatures of around 200°C (400°F) at a depth of 2.5 kilometers (8,000 feet). The granite surface is between 0.5 and 1 kilometer (1,600–3,300 feet) depth, and the minimum temperature threshold of 175°C (350°F) for the engineered reservoir is at 2 kilometers (6,600 feet) depth.

An attractive feature of the Milford site is the easy access with several county-maintained roads leading to our preferred deep drill site, and the city of Milford with its accommodations, eating establishments, and supporting infrastructure just 10 miles away. DOE considers outreach to the public important, as well as the possibilities of educational opportunities demonstrating the role of geothermal power in future power generation. Adjacent to the proposed FORGE site is the Blundell geothermal plant, the FirstWind facility (306 MW capacity), and the SunEdison solar photovoltaic array (240 MW capacity). North Milford valley is also a major energy corridor to southern California with the IPP DC transmission line (2,400 MW), the Sigurd–Red Butte line (600 MW), and the Kern River natural gas line (2.3 bcf/day). FirstWind has set up a kiosk with educational displays, which could be expanded to include explanations on how other renewables such as geothermal and solar power can be integrated into the power grid. This area could become a place where visitors can get close to wind turbines, solar arrays, and geothermal facilities and learn about renewable power generation.

If the Milford site is selected for Phase 2, the UGS will have a major role participating in the site characterization fieldwork, overseeing the environmental permitting process, assisting with the FORGE website, and coordinating outreach initiatives. The Utah Core Research Center will also be the main repository for core and cuttings retrieved from the site, and will be available for visiting researchers to later study this material. If the Milford site is finally chosen as the field laboratory, the UGS will be involved in geothermal research at this site for at least the next six years, and will be making a major contribution to Utah's renewable power resources.

For more information, see the FORGE website at http://energy.gov/eere/forge/forge-home.

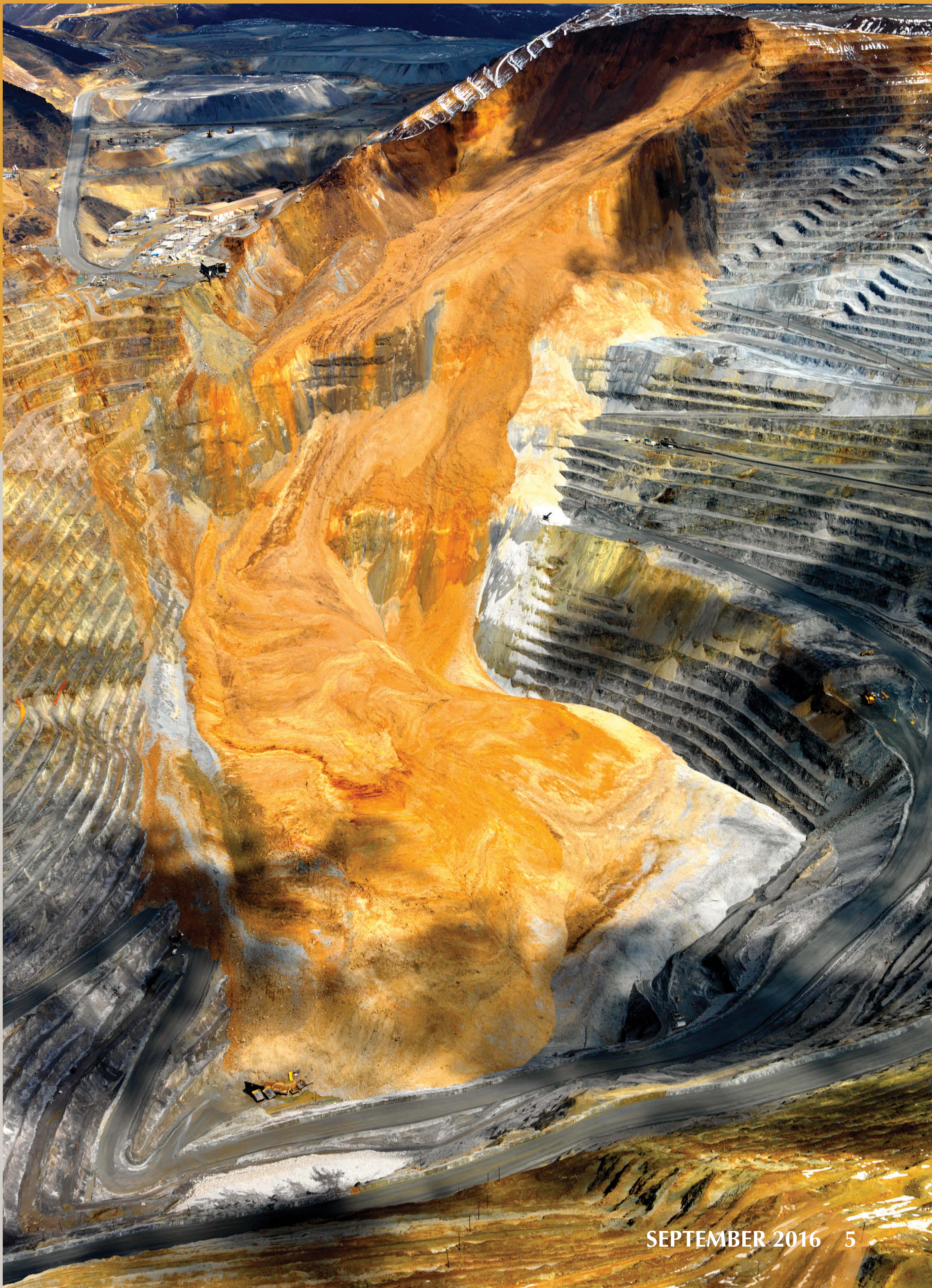


Cross section through the proposed FORGE site showing a pair of wells deviated towards the southeast. These wells will be hydraulically fractured so that water can circulate between the two lateral legs and sweep heat from the surrounding hot granite.

Bingham Canyon's Manefay Landslides AND THE FUTURE OF THE MINE

By Ken Krahulec

On April 10, 2013, two massive landslides carried about 145 million tons of waste rock into the bottom of the open pit at Bingham Canyon, the largest copper mine in the U.S. These are the largest mining-induced landslides in history. The two slides, named the Manefay landslides by Kennecott Utah Copper (KUC), started in the northeast corner of the open pit—the first at 9:30 p.m. was larger (nearly 100 million tons), and the second followed a little over an hour and a half later. The second slide was followed 11 minutes later by a small, shallow earthquake (about magnitude 2.5) beneath the mine, induced by the rapid shifting weight of the slides. Notably, the Manefay slides resulted in no injuries or deaths, but they significantly changed the face of the mine and caused hundreds of millions of dollars of damage to the operation.



The Manefay landslide at the Bingham Canyon open-pit copper mine on April 11, 2013. This view, toward the northeast, shows the landslide in its entirety with the main failure plane angling downward from the right side of the headwall scarp toward the buildings in the middle left. The slip plane is in the Manefay series beds of the Bingham Mine Formation. Also notable are the two different slides—the earlier light-gray slide of pyritized Bingham Mine Formation quartz sandstones overlain by the yellow-brown, oxidized dump material which slid about 1.5 hours later. Also apparent is the fluidity of the slide as shown by the layering in the foot of the deposit in the pit bottom. Multiple pieces of mining equipment caught up in the slide are barely visible at the toe of the slide in the lower left. Photo courtesy of Kennecott Utah Copper.

Fortunately, KUC was prepared and had a sophisticated network of geotechnical monitors in place at the mine. These monitors showed instability in the area of the slide beginning in November 2012, but becoming more threatening in early 2013. The area of the slide showed increasing movement, and when it reached a rate of about 2 inches per day on April 10 all employees were evacuated from the mine at 11 a.m. and a press release was issued at 2:38 p.m. warning that a slide was imminent.

Despite these efforts, the slides resulted in significant damage to both the mine's fixed infrastructure, including the main haul road, and somewhat surprisingly, to its fleet of mobile equipment, which had been moved to the far side of the pit. Damage to the fleet included 3 of the 13 shovels, 14 of the 100 haul trucks, and some other ancillary equipment including drills, bulldozers, and graders (haul trucks cost approximately $5 million and shovels about $45 million each). Some of the equipment was recovered, repaired, and returned to service, but most was a total loss.

The headwall of Bingham's Manefay slides was 1,150 feet high, and the slide was 9,840 feet long with a total drop of about 2,975 feet. The slides failed mainly along the Manefay series beds at the base of the Upper Pennsylvanian Bingham Mine Formation that dipped moderately northwest into the pit. The slide was somewhat larger than KUC anticipated, but more importantly, instead of acting like a rockfall or slump as previous small pit-wall failures had, this slide acted more fluidly and is properly termed a rock avalanche. This fluidity resulted in the slide reaching speeds in excess of 70 mph and advancing considerably farther to the southwest across the pit bottom than anticipated, resulting in the damage to the equipment.

Initial work after the slides consisted of assessing the situation and developing a plan to stabilize the headwall of the slide so that it would be safe to work below. Because the in-pit crusher and underground ore conveyor were not damaged, ore production resumed just 17 days after the slide. The other priority was to re-establish the main haul road into the pit. The new haul road is about ¾ mile long, 150 feet wide, and required the removal of about 6 million tons of landslide debris. The road was completed in just 7 months, largely as a result of the rapid innovative development and implementation of over 20 pieces of remote-controlled heavy equipment in areas that were still not safe for employees to work.

Remarkably, Bingham continued to produce moderate amounts of ore following the slides in 2013 and 2014, but in 2015 a reappraisal of the overall stability of the east side of the open pit mandated a massive waste rock stripping (removal) program to reduce the pit slopes and the risk of future landslides. This required nearly all of the mine equipment to be used in this waste stripping operation, resulting in little new ore production and the highest stripping ratio (5:1 waste:ore) in the 110-year history of Bingham's open-pit mining operations. Consequently, most of the material processed through the Copperton concentrator in 2015 was from a large, low-grade stockpile of previously mined material. Copper production from this low-grade material reduced the mine's output in 2015 by nearly 55 percent from the already modest 2014 production. This made Bingham's 2015 production the lowest since the mine was closed in 1986 due to low metal prices. Despite these considerable difficulties, Bingham still realized a slight profit in 2015.

Moving forward, there is another year of stripping planned for safety's sake on the east side of the pit along with gradually increasing copper production. After this, Bingham will still have about 700 million tons of ore primarily hosted in and under the south wall of the pit. Mining this reserve will push the south wall of the pit about 1,000 feet farther south and the bottom of the pit 300 feet deeper. This gives the mine a remaining life of 13 years, through 2028, with improved copper and molybdenum grades, which should return Bingham to the position of one of the largest annual copper and molybdenum producers in the U.S. by 2018.

For more detailed information on the Manefay slides please see: Pankow, K.L., Moore, J.R., Hale, J.M., Koper, K.D., Kubacki, T., Whidden, K.M., and McCarter, M.K., 2014, Geological Society of America GSA Today, v. 24, no. 1, p. 4–9.

“core center news”

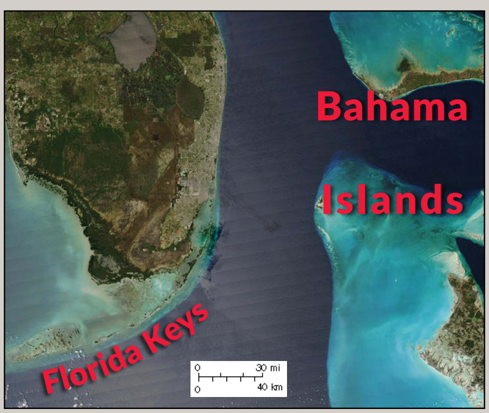
Cores from Greater Aneth Oil Field: A Trip Back in Time to Utah’s “Bahama Islands” and “Florida Keys”

By Thomas C. Chidsey, Jr.

Time machines—Homer Simpson made one out of a toaster and Mr. Peabody and his pet boy, Sherman, invented the “Wayback Machine.” If you were to take one of these time machines to southeastern Utah near the Four Corners area and set the dial to 308 million years ago—the middle of the Pennsylvanian Period—transporting you back in time, the region would look very different from the desert landscape of today. Back then, southeastern Utah was covered by a warm, shallow-marine sea that at times was very salty. Shoals of ooids—rounded sand-size grains composed of concentric layers of calcium carbonate—formed in a high-wave-energy environment on the shallow, lime-mud seafloor or along the beach swash zones. Banks of broken shells, corals, and other skeletal debris also accumulated as coarse sands in the shallows. Currents removed most of the mud from these skeletal and ooid deposits, leaving open pore space between the grains. Additionally, patches of leafy, seaweed-like algae, called *Ivanovia* and *Kansasphyllum*, built up from the sea bottom to the surface in well-circulated, moderate- to low-energy environments, and were occasionally exposed to the atmosphere. These algal buildups or “mounds” can be likened to giant piles of potato chips, each “chip” being an algal leaf or plate, and spaces between the chips being pores. These same types of deposits—ooid shoals, skeletal banks, and algal mounds—can be found today around the Bahama Islands and along the Florida Keys, no time machine required!

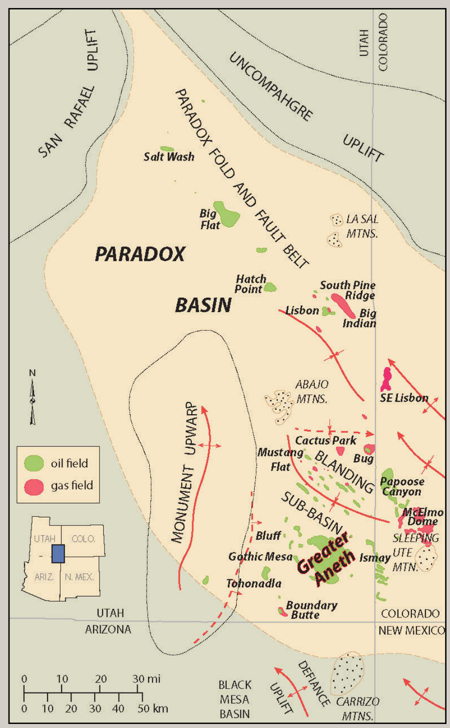
So what happened to these marine deposits in Utah since Pennsylvanian time? A lot! They were (1) sealed, top and bottom, by organic-rich marine muds and layers of evaporites (anhydrite and/or salt); (2) lithified (compressed and cemented into the carbonate rock *limestone*) and preserved as layers in southeastern Utah’s Paradox Formation; (3) buried thousands of feet below sea level and heated for millions of years, causing the contained organic material to “cook” into oil and migrate into the pores that still existed between the ooids, skeletal grains, and algal plates, where it became trapped and stored; and (4) uplifted back up thousands of feet to their current depth (from 7,000 feet below the ground to surface outcrops seen along the San Juan River Canyon). Along the way, some of the rocks and pores within them underwent changes called diagenesis. Mineral-bearing fluids altered some limestone to a rock called dolomite (a magnesium-calcium carbonate). In other instances, pores were plugged with various minerals and tar-like “dead” oil called bitumen, whereas new pores were created by fresh water dissolving ooids, skeletal grains, and algal plates.

Why is this all so important? Sixty years ago Texaco Inc. drilled a wildcat well in southeastern San Juan County, the No. 1 Navajo C, into the porous, marine limestone rocks of the Paradox Formation and discovered Greater Aneth oil field—the largest oil field ever found in Utah. Greater Aneth has produced over 479 million barrels of oil as of January 1, 2016. The field still has 445 active wells, which produce over 11,000 barrels of oil per day, and should continue to be a major contributor to Utah’s oil production for many years to come. Dozens of similar but smaller fields have since been discovered and produce oil throughout this region of Utah referred to as the Paradox Basin.



Landsat image of southern Florida and the Bahama Islands.

The Utah Core Research Center (UCRC) has an incredible collection of cores taken from wells in Greater Aneth and surrounding fields that produce from the Paradox Formation, generously donated by the various oil field operators and petroleum exploration companies over the years. Once slabbed (cut in half), these cores show, up close and personal, all the various environments of deposition (ooid shoals, skeletal banks, algal mounds, etc.) that existed during Pennsylvanian time in southeastern Utah. They also show the diagenetic changes that have occurred over the millions of years since and how those events affect oil production. Additionally, the rocks in cores indicate sea-level fluctuations and cyclicity, important factors in understanding differences in oil production from one well to another and identifying new drilling locations.



Location of Greater Aneth and other oil fields in the Paradox Basin, southeastern Utah.

Above left – ancient ooid shoal deposit shown in Greater Aneth core. Inset is a microscopic image of round ooids and porosity (shown in blue) capable of storing oil. Above right – Joulter's Cay ooid shoal complex, Andros Island, Bahamas. Ooid shoals as far as the eye can see (view to the north). Inset is close-up of typical Joulter's Cay ooids.

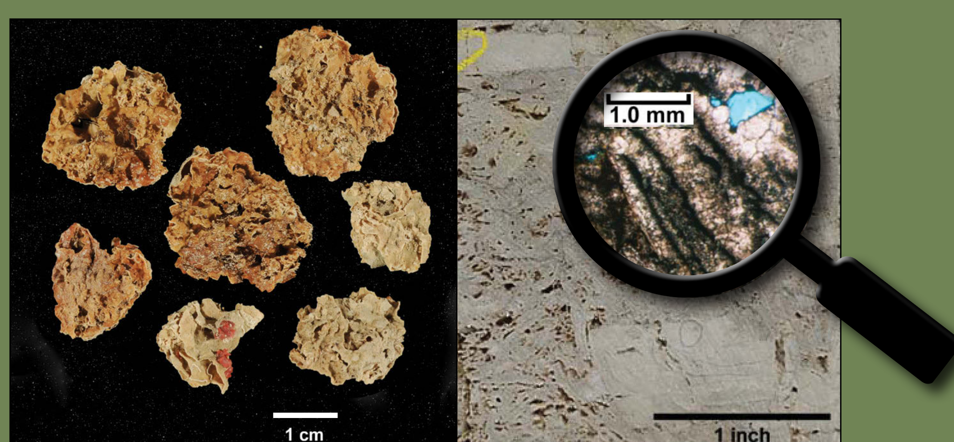
Above left – skeletal debris that accumulated in a shallow-water bank as preserved in a Greater Aneth core. Inset is a microscopic image of skeletal grains (dark) and excellent pore space (blue) between those grains. Above right – underwater photograph of "clean," rippled, calcareous sands of the White Bank sand shoal off Key Largo, Florida. Inset is close-up of coarse-grained, clean skeletal (primarily coral) sand grains from the White Bank sand shoal.

The characteristics of the Paradox Formation observed in the Aneth field cores provide outstanding teaching tools for geology students. Professional industry geologists also use these cores to help search for potential new oil fields in Utah or better understand how to recover more oil from existing fields. The cores are also used to help explore for similar fields elsewhere in the world, especially where cores are not available. For example, Greater Aneth cores have been used in several major Utah Geological Survey (UGS) studies designed to increase production from other nearby fields, reduce drilling risks, and lead to new discoveries. Greater Aneth was also a focus of a major UGS field characterization project to enhance oil production from this very mature field by injecting carbon dioxide gas into the porous rocks to force remaining oil out, thus extending the life of the field (see article titled "Geological Sequestration of Carbon Dioxide and Enhanced Oil Recovery—the Utah Geological Survey's Efforts to Reduce Global Warming While Increasing Oil Production," 2007 *Survey Notes*, v. 39, no. 2, p. 4–7).

The great British geologist, Sir Charles Lyell, in his three-volume *Principles of Geology*, published in 1830–33, popularized one of the first concepts of modern geologic thought, "The present is the key to the past." I would add that the Paradox Formation cores at the UCRC from Aneth and other fields are keys to understanding Utah's geological past.

To see the Greater Aneth oil field core set or schedule a workshop at the UCRC, contact Peter Nielsen, Curator (801-537-3359, peternielsen@utah.gov).

Microscopic images and modern algal plate samples courtesy of David E. Eby, Eby Petrography & Consulting, Inc.



Above left – modern algal plates from Momma Rhoda Cay, Bahamas. Above right – algal buildup shown in Greater Aneth core with visible porosity. Inset of a microscopic image of long, flat algal plates of Ivanovia.

WHAT GEOLOGIC HAZARDS SHOULD I BE AWARE OF AS A HOMEOWNER IN UTAH?

BY ROBYN KEELING

GLAD YOU ASKED

Utah's scenic landscapes are the result of natural geologic processes, many of which are still active today and have the potential to damage homes and endanger lives. Not all geologic hazards can be avoided; however, you can significantly increase your safety and reduce your risk of property damage by identifying which geologic hazards may affect you, learning more about them, and then taking steps to lessen your risk. If you are buying, building, or selling a home in Utah, here are some geologic hazards that you should be aware of.

Earthquakes: Of all the geologic hazards present in Utah, earthquakes pose the greatest threat to human life and structural damage from a single event. The Wasatch fault zone is the longest and most active fault in the region, extending 240 miles from north of Malad City, Idaho, to near Fayette, Utah, but there are hundreds of other hazardous faults across the state that have the potential to generate large earthquakes.

<u>Ground shaking</u> is the most widespread earthquake hazard and typically causes the most damage, but other potential earthquake hazards include surface faulting, liquefaction, and earthquake-induced landslides and flooding.

<u>Surface faulting</u> occurs during large earthquakes (generally magnitude 6.5 or greater) when the fault rupture reaches the ground surface and creates a fault scarp (a vertical break or offset). Generally, homes that straddle or are very close to fault lines have the greatest risk of damage from surface faulting.

<u>Liquefaction</u> may occur when loose, water-saturated, sandy soil is subjected to strong ground shaking and the soil behaves more like a liquid than a solid, which can cause houses to settle or tilt. Liquefaction potential is typically higher on valley floors and near streams and other water bodies. Landslides (and especially rockfalls) can be triggered by ground shaking, and flooding can result from dam failure, stream obstruction, water-line or canal breaks, and tilting (subsidence) of the land near water bodies.

Landslides and Rockfalls: The very mountains and hillsides that provide the most enticing scenery often have the highest risk of hazards related to slope failure. Most landslides occur during periods of rising groundwater levels due to excessive rainfall, snowmelt, or irrigation, and rockfalls are common in spring and summer months due to snowmelt, freeze-thaw cycles, and cloudburst storms. Landslides can move very slowly or very rapidly and can damage homes above, on, or below the slide area.

House destroyed by movement at the toe of the Parkway Drive landslide in North Salt Lake, August 5, 2014. Photo by Gregg Beukelman.

Before and after pictures of a home demolished during a fatal rockfall in Rockville, Utah. Two people perished when their house was struck by the rockfall. Photos taken September 29, 2010, and December 13, 2013 by Tyler Knudsen.

Flooding and Debris Flows: Both heavy precipitation and rapid spring snowmelt can cause Utah's streams and lakes to swell, overflowing their banks and saturating nearby floodplains. In areas with shallow groundwater, increased precipitation may cause subsurface structures such as basements and septic-tank soil-absorption fields to flood. Cloudburst storms can generate devastating localized flooding, including flash floods. Localized flooding and debris flows (mudflows) can also occur on alluvial fans located on the valley floor at the mouths of canyons.

Flooding along State Street, Salt Lake City, Utah, June 1983. Photo by S. Thiriot.

Earth fissure in Enoch City which has vertically displaced the pavement about a foot since 2007. Photo taken July 1, 2015, by Tyler Knudsen.

Land Subsidence and Earth Fissures: Over the past decade, subsidence and earth fissures have become a more prominent and widely recognized geologic hazard, particularly in southwestern Utah. Subsidence and earth fissures in Utah are most often caused by aquifer compaction resulting from the permanent reduction in volume of fine-grained deposits within aquifers following groundwater withdrawal. If groundwater pumping and general water-level decline in Utah continue, then existing fissures are expected to lengthen and new fissures are projected to form. Subsidence and earth fissures may cause damage to roads, buildings, railroads, and underground utilities, and may cause changes in ground-surface slope and elevation.

Radon: The vast majority of geologic hazard fatalities in Utah to date have come from exposure to radon gas, which is a known cause of lung cancer. Radon gas has no smell, taste, or color. It is the product of radioactive decay of uranium, which is naturally occurring in most rock and soil types. While radon can be found both indoors and outdoors, only indoor radon levels reach dangerous concentrations because the gas can collect in enclosed spaces rather than dispersing into the atmosphere. Radon-hazard-potential maps are available both at the state scale and as detailed maps of more populous areas, and can help you determine if a radon test is necessary. Inexpensive radon testing kits are available through http://radon.utah.gov or at your local home improvement store.

GEOLOGIC HAZARDS

RESOURCES FOR HOMEOWNERS:

- Geologic hazard maps, by county: http://geology.utah.gov/map-pub/maps/geologic-hazard-maps
- *Putting Down Roots in Earthquake Country–Your Handbook for Earthquakes in Utah:* http://files.geology.utah.gov/online/RS1_roots_earthquake_low.pdf
- *Utah Quaternary Fault and Fold Database* (interactive web map): http://geology.utah.gov/resources/data-databases/qfaults/
- PI-38 *Homebuyers Guide to Earthquake Hazards in Utah:* http://ugspub.nr.utah.gov/publications/public_information/pi-38.pdf
- PI-40 *The Wasatch Fault:* http://ugspub.nr.utah.gov/publications/public_information/pi-40.pdf
- PI-48 *Earthquakes & Utah:* http://ugspub.nr.utah.gov/publications/public_information/pi-48.pdf
- PI-92 *The Wasatch Fault FlyBy Video:* http://geology.utah.gov/hazards/earthquakes-faults/utah-faults/
- Utah Seismic Safety Commission: http://ussc.utah.gov
- Be Ready Utah: http://www.utah.gov/beready/
- PI-58 *Homeowner's Guide to Recognizing and Reducing Landslide Damage on Their Property:* http://geology.utah.gov/hazards/homebuyers/guide-to-recognizing-and-reducing-landslide-damage/
- PI-98 *Landslide Hazards in Utah:* http://ugspub.nr.utah.gov/publications/public_information/pi-98.pdf
- PI-94 *Rock-fall Hazards in Utah:* http://ugspub.nr.utah.gov/publications/public_information/pi-94.pdf
- PI-70 *Debris-Flow Hazards:* http://ugspub.nr.utah.gov/publications/public_information/pi-70.pdf
- PI-90 *Wildfires and Debris Flows in Northern Utah:* http://ugspub.nr.utah.gov/publications/public_information/pi-90.pdf
- *Floods – What You Should Know when Living in Utah:* http://dem.utah.gov/wp-content/uploads/sites/18/2015/02/Flooding-Outreach.pdf
- Federal Emergency Management Agency Flood Insurance Rate Maps (FIRM): http://msc.fema.gov/portal
- State of Utah radon information, test results by zip code, and test kits: http://radon.utah.gov

It is important to remember that even when a local government approves a subdivision or building permit, that does not guarantee safety from geologic hazards, and these hazards are not covered by standard homeowner's insurance. Also, when buying a home, keep in mind that Utah law does not require previous owners or real estate agents to disclose geologic hazards. It is therefore prudent to conduct your own geologic-hazard research for your area by looking at published geologic hazard maps, along with any relevant site-specific investigations, if available.

The UGS Geologic Hazards Program helps protect Utah's public health and safety by investigating geologic hazards, providing state and local governments and the public with information and technical services, preparing geologic-hazard maps and publications, and responding to geologic-hazard emergencies. In order to document and better understand geologic hazards, the UGS encourages cities, counties, and the public to inform us of events when they occur so that we may investigate the hazard if warranted. For more information on geologic hazards, visit http://geology.utah.gov/hazards/.

GeoSights

Salt Lake City Cemetery, Salt Lake County, Utah

By Jim Davis

Rock and Mineral Monuments in Salt Lake City Cemetery
(not inclusive)

Minerals and Fossil
Petrified Wood
Labradorite
Quartz

Igneous Rocks
Granodiorite—Flagstaff stock
Granitoids—assorted imported
Granite or quartz monzonite—Little Cottonwood stock

Sedimentary Rocks
Kyune Sandstone,Colton Formation
Nugget Sandstone

Metamorphic Rocks
Tintic Quartzite
Quartzite—assorted imported
Gneiss, Farmington Canyon Complex
Gneiss—assorted imported
Marble—assorted imported

Late nineteenth-century "oval with shoulders-style" headstone of reddish-orange Nugget Sandstone with toothed chisel marks along top and sides; date unknown. The sandstone is separating, or delaminating, along bedding planes, possibly from freeze-thaw cycles or expansion and contraction from temperature swings. Gray lichen can be seen growing on the stone.

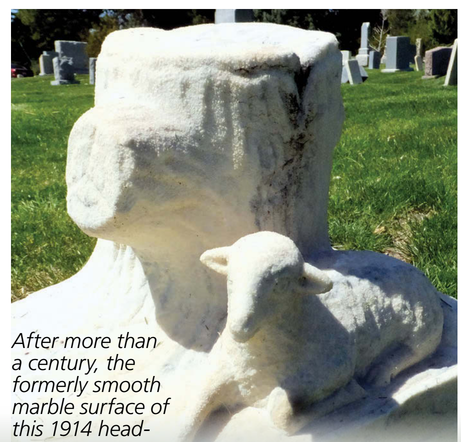
Nineteenth century American cemeteries were the forerunners of city parks. A solution to dwindling urban land availability, these burial grounds at the edge of town began to emulate the intensely groomed architectural landscapes popular in Europe that were crafted for aesthetics and pleasure. Cemeteries in America became open spaces, botanical grounds, and arboretums—places for leisure, reflection, and escape from the bustling, grungy city. By the turn of the century the Salt Lake City Cemetery was beheld as a Victorian-style park. As noted in a 1915 *Salt Lake Tribune* article titled "Cemetery Becomes City Beauty Spot," the cemetery was "…fast turning into a 'God's acre' that will rank for beauty with many of the finest cemeteries in the country."

The Salt Lake City Cemetery has the uncontested title of America's largest municipal cemetery, covering 120 acres (not counting other adjoining cemeteries, green spaces, and parks). Situated on a south-facing hillside in The Avenues neighborhood $1\frac{1}{3}$ miles due east of the Utah State Capitol, Utah's oldest enduring cemetery had its first burial just before the mid-nineteenth century, and today is a few thousand shy of reaching its full capacity of 130,000 graves.

> ***"A 'God's acre' that will rank for beauty with many of the finest cemeteries in the country."***

To geologists, cemeteries are rock gardens that offer an exclusive opportunity to see rock with a "manufactured on" date. The exact age of tombstone rock surfaces can be known and used to evaluate rates of weathering (the in-place breakdown of rock), types of weathering, and the effects of weathering on specific kinds of rock in particular environments. As such, a cemetery is a superb laboratory for weathering studies. By the mid-twentieth century most tombstones were carved from granite or other weather-resistant rock such as gneiss, coinciding with improved stone-cutting and polishing tools and low-cost transport. Prior to granite, fieldstones, slate (although absent in Salt Lake's cemetery), sandstone, and marble were often used and usually quarried nearby—today stone is imported from quarries all over the world. In 1900, more than three-quarters of Utah's dimension-stone industry value was from a dozen or so sandstone quarries that shipped as far as the Pacific Coast. Sandstone was a popular selection for early headstones in Salt Lake because in addition to being uniform, relatively soft, and easy to extract and carve, sandstone was local and inexpensive.

Rock weathering processes fall into three categories: biological, physical, and chemical. These processes can work alongside each other to enhance weathering, and particular rock types are more susceptible to particular processes. Organisms cause biological weathering—for example, lichens and mosses etching rock through organic acids or plant roots exploiting and enlarging cracks in rock. Physical weathering, such as freeze-thaw or salt crystal growth, pries rock apart. Chemical weathering preferentially attacks certain minerals through processes such as oxidation, carbonation, and hydrolysis—for example, disintegration of feldspar minerals in granite that leaves behind the more chemically resistant quartz crystals. Calcite in marble or limestone is highly susceptible to dissolution via acidic water—natural rainwater has an average pH of about 5.6 (moderately acidic) from carbonic acid, and rain in cities tends to be more acidic through the addition of sulfur dioxide and nitrogen oxide from combustion of fossil fuels.



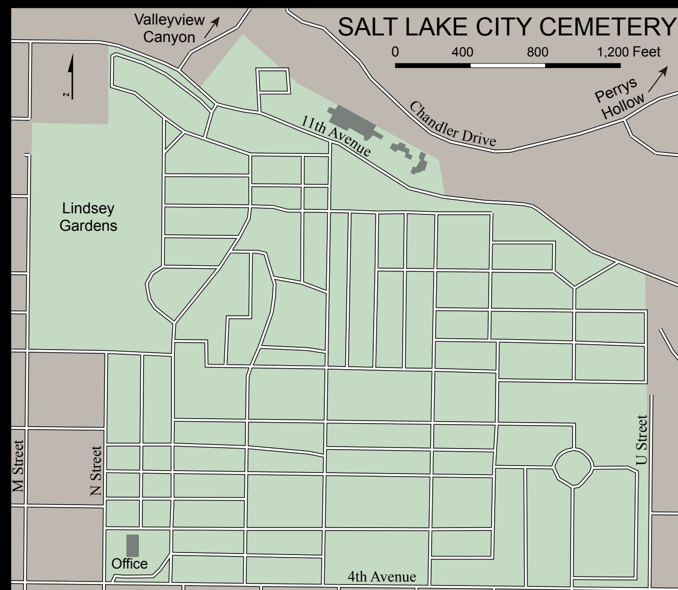
After more than a century, the formerly smooth marble surface of this 1914 headstone has taken on a rough, sugary appearance. Details carved into the sheep, a symbol typical of children's monuments in this period, have diminished due to the chemical weathering of the calcite minerals. Tree stump tombstones are commonly seen throughout America's cemeteries—dating to before the late 1920s, they were a membership benefit of the Woodmen of the World Life Insurance Society.

The Salt Lake City Cemetery shares in the history of one of the most notable natural disasters to strike the city. On Sunday, August 19, 1945, an extreme wind-rain-hail storm ripped through Salt Lake City at 10:30 p.m. Fifteen minutes later, there was a half-million dollars in property damage at the cemetery, Avenues neighborhood, and city airport. A 3-foot wall of water originating in Valleyview Canyon flowed across the western side of the cemetery to N Street, then jumped over to M Street. The flood tore through the cemetery, scouring flowerbeds, tearing up trees, dislodging tombstones, and carving deep gullies across plots. A second flood coming out of Perrys Hollow washed out roads and monuments in the middle of the cemetery, then broke through the boundary fence between O and P Streets, joining the flood out of Valleyview Canyon at M Street and 1st Avenue.

More than 120 homes in The Avenues were affected in the 1945 cemetery flood: basements flooded, yards were ripped out, and chunks of pavement, muck, and boulders "as big as bushel baskets," 300 to 400 pounds in weight, were deposited along South Temple in 5-foot drifts. Remarkably, there was no loss of life. The U.S. Forest Service cited the fire in the watershed the summer before as a major factor in the flood; the 15-minute deluge quickly ran off the unvegetated slopes. Since then, lower Valleyview Canyon has been urbanized and a flood-control retention basin was constructed in 1975 at 11th Avenue Park, and a dam and catchment with drain were constructed in Perrys Hollow at Chandler Drive.

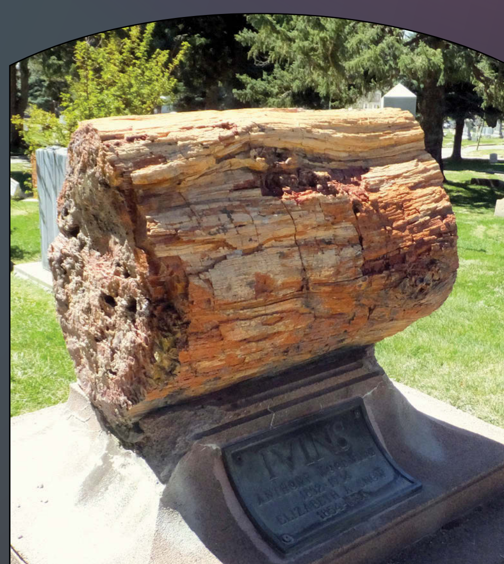
HOW TO GET THERE

Salt Lake City Cemetery is located in The Avenues neighborhood east of downtown and is bounded on the south by 4th Avenue, to the north by 11th Avenue (although a small parcel is north of 11th Avenue), on the west by M and N Streets, and on the east by U Street. Although there are several vehicle entrance points and a grid of streets within the cemetery, the main entrance is by the sexton's house/main office at the corner of 4th Avenue and N Street. The best examples of rock weathering and the greatest variety of rock types are found in the southwest section of the cemetery. Please drive carefully as there are deep roadside drains, narrow roads, and pedestrians. Always use proper cemetery etiquette.



Debris from the 1945 Perrys Hollow flood included vegetation, monuments, and slabs of pavement. Girl in white dress at far right for scale. Source: Earth Science Education Series No. 2, Utah Geological and Mineralogical Survey, 1971, B.N. Kaliser (compiler), available online at http://ugspub.nr.utah.gov/publications/earth_science_education/geol_hazards_utah/es-2.pdf.

Exfoliation and grain detachment, probably from freeze-thaw and acid-induced chemical attack of calcite cement between sand grains, is disintegrating this headstone of tan-gray Kyune Sandstone; date unknown. Note the miniature column formed in the sandstone at right. The Nugget Sandstone base shows little to no weathering and was likely adjoined to the headstone at a much later time.



A geologically elegant monument from 1936—a sizable perched bole of petrified wood.

Although chemically weathered with a gritty surface and rillen (small grooves), this fancy marble headstone from 1877 is still legible.

SURVEY NEWS

As this issue of *Survey Notes* was going to press, we received the sad news of **Lee Allison's** passing as the result of an accident. Lee was UGS Director and State Geologist from 1989 to 1999. A memorial will be included in the next issue of *Survey Notes*.

EMPLOYEE NEWS

The Editorial Section bid farewell to **Nikki Simon** who left to return to her home state of Montana. **Jen Miller** is our new graphic designer. She is a Utah native and previously worked in the health insurance industry. Welcome to Jen, and best of luck to Nikki.

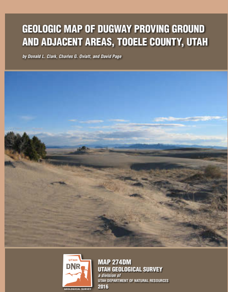
Former UGS administrative secretary **Cheryl Ostlund-Ward** passed away April 10, 2016. Cheryl was with the UGS from 1996 to 2002. We express our sincere condolences to Cheryl's family.

2016 CRAWFORD AWARD

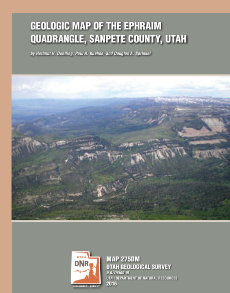
The prestigious 2016 Crawford Award was presented to UGS geologist **Bob Biek** in recognition of his work in mapping the Panguitch 30′ x 60′ quadrangle (UGS Map 270DM). Bob's mapping makes several significant contributions to our understanding of the geology of southwest Utah, including correcting significant aspects of Cretaceous and early Tertiary stratigraphy that have caused geologists problems for decades, and unraveling the enormous and complex Markagunt gravity slide. The Markagunt gravity slide study was initially published with co-authors Dave Hacker and Pete Rowley in *Geology*. Recognizing the significance of this work, the Geological Society of America recently agreed to fund a Thompson Field Forum on mega-gravity slides to be held in southern Utah in 2017. Additionally, UGS Map 270DM recently received the national Charles G. Mankin Award for geological mapping from the Association of American State Geologists.

The Crawford Award recognizes outstanding achievement, accomplishments, or contributions by a current UGS scientist to the understanding of some aspect of Utah geology or Earth science. The award is named in honor of Arthur L. Crawford, first director of the UGS.

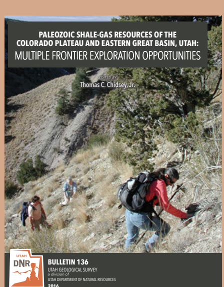
NEW PUBLICATIONS



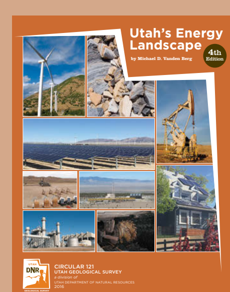
Geologic map of Dugway Proving Ground and adjacent areas, Tooele County, Utah, by Donald L. Clark, Charles G. Oviatt, and David Page, CD (31 p., 2 pl. [contains GIS data]), scale 1:75,000, ISBN 978-1-55791-912-0,
Map 274DM..............................$24.95



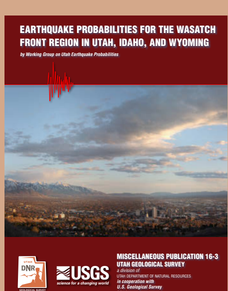
Geologic map of the Ephraim quadrangle, Sanpete County, Utah, by Hellmut H. Doelling, Paul A. Kuehne, and Douglas A. Sprinkel, CD (14 p., 2 pl. [contains GIS data]), scale 1:24,000, ISBN 978-1-55791-913-7,
Map 275DM...........................$24.95



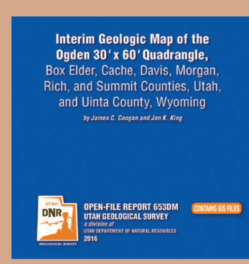
Paleozoic shale-gas resources of the Colorado Plateau and eastern Great Basin, Utah–multiple frontier exploration opportunities, edited by Thomas C. Chidsey, Jr., DVD (241 p. + appendices), ISBN 978-1-55791-909-0,
Bulletin 136........................$19.95



Utah's energy landscape–4th Edition, by Michael D. Vanden Berg, 41 p., ISBN 978-1-55791-924-3,
Circular 121..............................FREE



Earthquake probabilities for the Wasatch Front region in Utah, Idaho, and Wyoming, by Working Group on Utah Earthquake Probabilities, CD (164 p. + appendices), ISBN 978-1-55791-923-6,
Miscellaneous Publication 16-3.....$19.95



Interim geologic map of the Ogden 30' x 60' quadrangle, Box Elder, Cache, Davis, Morgan, Rich, and Summit Counties, Utah, and Uinta County, Wyoming, by James C. Coogan and Jon K. King, CD (147 p., 3 pl. [contains GIS data]), scale 1:62,500,
Open-File Report 653DM..........$19.95

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2017 CALENDAR OF UTAH GEOLOGY ORDER NOW!

Featuring scenic photographs highlighting Utah's geologic diversity. The photographs were taken by UGS employees who are often on assignment in some of the state's most interesting and unique locations. Pictures are accompanied by geologic descriptions and location information. The calendar is available at the Natural Resources Map & Bookstore, so order now and don't miss out.

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TEACHER'S CORNER

EARTH SCIENCE WEEK | OCTOBER 3–6, 2016

Hands-on Activities for School Groups

Come celebrate Earth Science Week with the Utah Geological Survey! This popular annual event features educational activities that are particularly suited for the 4th and 5th grades, where Earth science concepts are taught as outlined in the Utah Science Core Curriculum standards. Earth Science Week activities take place at the Utah Core Research Center in Salt Lake City and include panning for "gold," identifying rocks and minerals, experimenting with erosion and deposition on a stream table, and examining dinosaur bones and other fossils.

Groups are scheduled for 1½-hour sessions. Reservations typically fill early; to inquire about an available time slot for your group, contact Jim Davis at 801-537-3300.

Launched by the American Geosciences Institute (AGI) in 1998, Earth Science Week is an international event highlighting the vital role Earth sciences play in society's use of natural resources and interaction with the environment. For more information, please visit our web page at http://geology.utah.gov/teachers/earth-science-week/.

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