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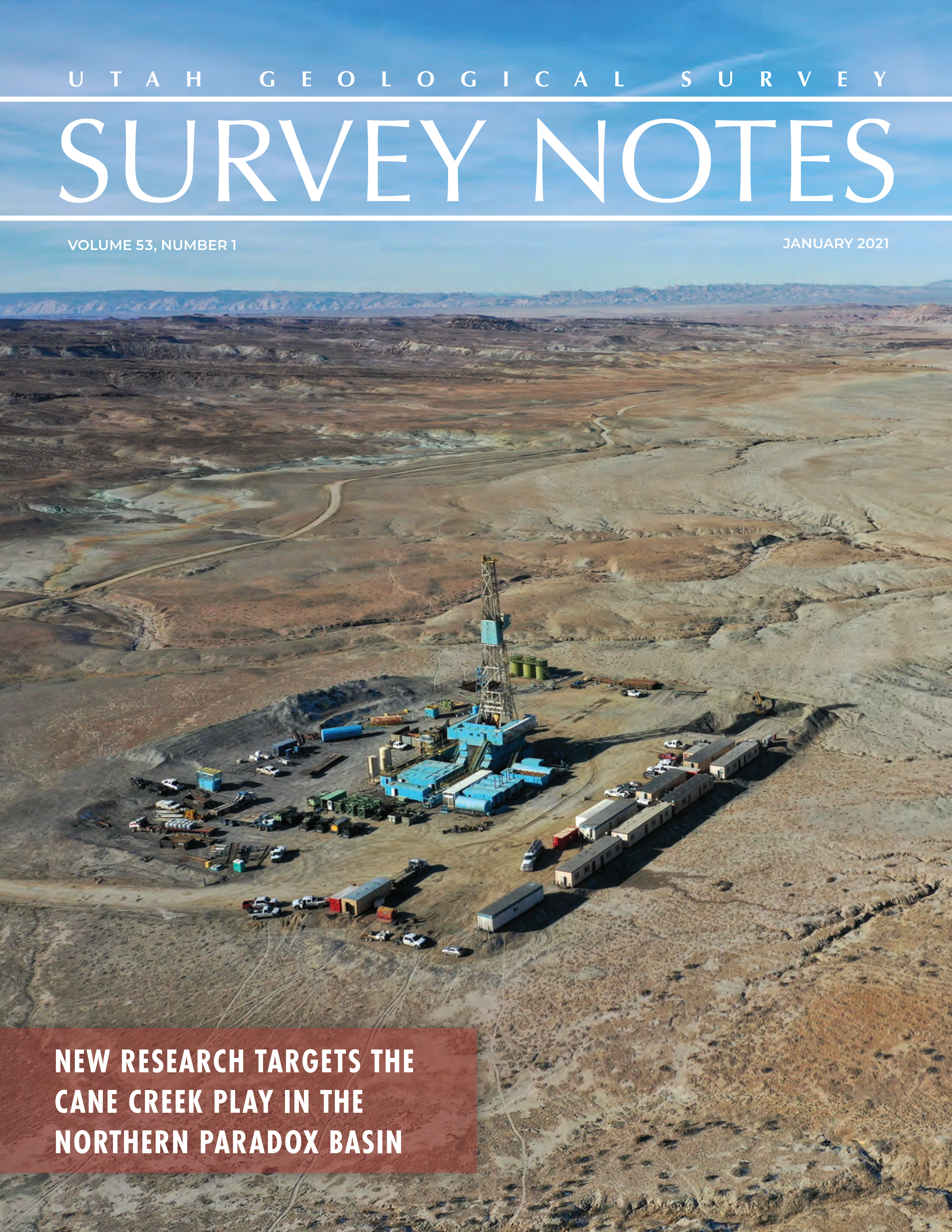

NEW RESEARCH TARGETS THE CANE CREEK PLAY IN THE NORTHERN PARADOX BASIN

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Design | Jackie DeWolfe

Cover | Drill rig getting ready to "spud" the State 16-2 research well, December 16, 2020. Drone photo by Christian Hardwick

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DIRECTOR'S PERSPECTIVE

by Bill Keach

Utah is an amazing geologic canvas with a wide range of geologic landforms that individually and collectively tell unique stories. Home to 5 national parks, 8 national monuments, and 44 state parks, most of which have geology as their centerpiece attraction, Utah attracts millions of visitors from around the world that come each year to behold its beauty.

This past fall, the UGS was invited to participate in a webinar series, "Celebrating America's Geoheritage." Organized by the U.S. National Committee for Geological Sciences (USNC-GS) and the National Academies of Sciences, Engineering, and Medicine (NASEM), it was a great forum to share what we love about geology in Utah with the rest of the country. Our presentation was also an opportunity to reflect on those who contributed to our understanding of and appreciation for our own backyard. Our talk, "Utah's Geoheritage, From the Iconic to the Unsung," explored many well-known and lesser-known places in Utah.

"The Mighty 5" national parks—Arches, Bryce Canyon, Canyonlands, Capitol Reef, and Zion—draw millions of visitors each year, and eight of Utah's nine national monuments are explicitly focused on geology or dinosaur fossils. Each is truly iconic in every geologic shape and form. Having led many field trips in Utah, one of my greatest pleasures is to simply watch people's faces when they see our magnificent geoheritage for the first time.

Appreciation for our geology did not start with the creation of iconic parks and monuments. For millennia (truly), people have visited these sites. Cultural insights can be learned from the thoughts and spiritual insights found in the form of pictographs and petroglyphs left by our indigenous ancestors at geologic sites across the state. A few of my favorites include Nine Mile Canyon (actually about 40 miles long), Buckhorn Wash Panel, Butler Wash, and the Parowan Gap.

Utah also has 44 state parks, many of which have amazing geology that serves as a backdrop to those who visit to recreate. During the pandemic, visitation to many of these parks has skyrocketed. The good news, depending on your perspective, is that many have come to know more about these amazing, even if "unsung," sites.

Over the past 20 years, *Survey Notes* has featured lesser known sites through our "GeoSights" article in each issue. This month's issue features an article on Raplee Ridge (San Juan County). If given the opportunity, I suggest doing the float trip on the San Juan River from Bluff to Mexican Hat. Here the river has eroded through the ridge providing a spectacular and up-close view of the feature. To learn more about the 60+ "GeoSights," please visit our webpage https://geology.utah.gov/apps/geosights/. Additionally, the Utah Geological Association (UGA) is about to release a guide to 40+ "Geosites" with full descriptions and directions.

Other great places that highlight Utah's geoheritage are geology parks, some of which came to be through efforts of local citizens. G.K. Gilbert Geologic View Park (Sandy), Springhill Geologic Park (North Salt Lake), and the Park City Sunrise Rotary Regional Geologic Park feature signage with clear explanations of the local geology. Stockton Bar (Stockton), a deposit of sand and gravel from ancient Lake Bonneville, was also preserved as a geoheritage site. Additionally, the UGA has identified 267 road signs throughout the state, each to help travelers better appreciate the geologic world around them (see https://utahgeology.org/resources/geologic-road-signs).

If you're looking for great places to visit, want to "social distance," be outdoors, and stay close to home, Utah's geoheritage is on display and waiting for you.

Buckhorn Wash Pictograph Panel photo by Bill Keach

UTAH'S EMERGING NORTHERN PARADOX BASIN UNCONVENTIONAL OIL PLAY

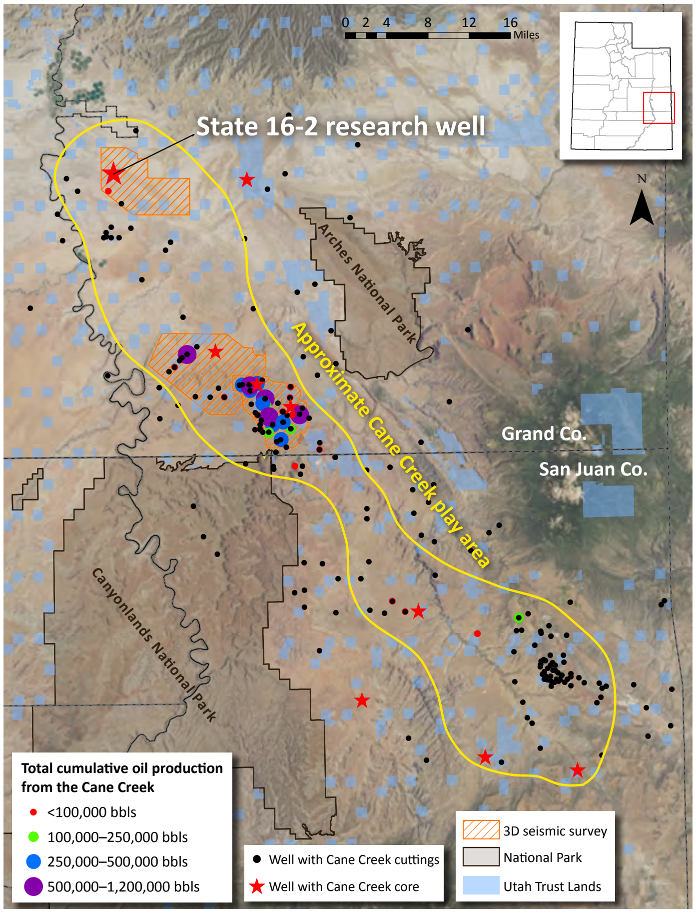
by Michael Vanden Berg

View (looking east) of the State 16-42 well pad and the proposed location of the State 16-2 research well.

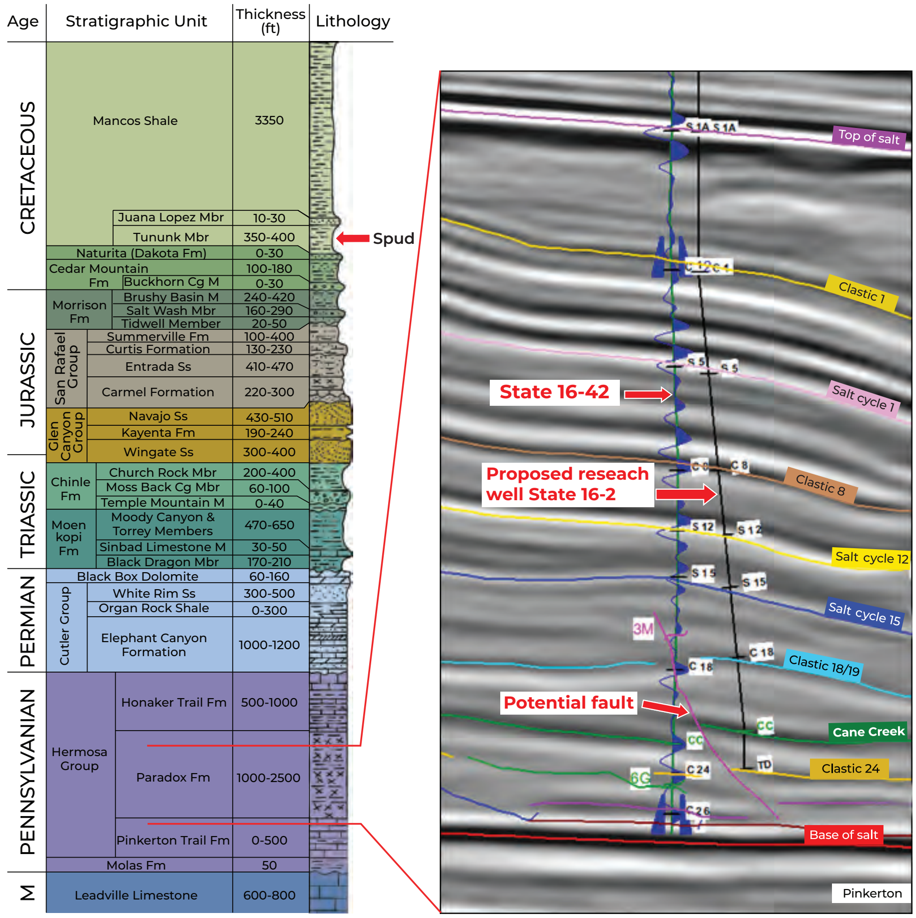
The Cane Creek interval within the Pennsylvanian-age Paradox Formation of the northern Paradox Basin, southeastern Utah, is touted by some as one of the last remaining emerging unconventional tight oil plays in the United States, with wells capable of producing up to 1,500 barrels of oil per day (initial production). However, the drilling history of the Cane Creek play has been fraught with challenges and disappointment. Nearly 100 years ago, one of the very first wells that targeted Paradox Formation reservoirs "blew-out"—the rig caught fire and was destroyed, a sinister omen for this troublesome target. Drilling activity increased in the 1950s and 1960s with the discovery of hydrocarbons in the underlying Leadville Formation. While drilling to the Leadville, several vertical wells encountered hydrocarbon shows in the overlying Cane Creek interval. In 1962, Long Canyon 1 was the first well to establish commercial production from the Cane Creek and has produced over one million barrels of oil (and is still producing). Despite the promise of the Long Canyon 1 well, it would not be until the early 1990s that significant exploration activity in the Cane Creek resumed; petroleum prospectors came armed with a new technology in the horizontal well. Although these new wells showed promise in the central part of the play, the prize of massive, play-wide production remained elusive. Fast forward two decades and armed with more advanced horizontal drilling technology plus new seismic data, the oil company Fidelity (which no longer exists) drilled several new wells around the central play area. Some of the new Fidelity horizontal wells were quite successful, but others were not. With the crash in oil prices in early 2015, the industry once again stepped back from this troublesome play to reevaluate and ask some fundamental questions. Can the mysteries of the Cane Creek be solved? Can the drilling challenges be overcome? Can the Cane Creek prove to be a commercially successful tight oil play?

As a way to help move the Cane Creek play needle in the direction of success, the U.S. Department of Energy (DOE) has awarded $8 million in federal funding to the Energy & Geoscience Institute (EGI) at the University of Utah and the Utah Geological Survey (UGS) to develop the tools and strategies necessary to more completely tap into this underutilized resource, while at the same time minimizing impact. The five-year project will utilize up to $3 million in state and private/industry cost-share funds to help accomplish its objectives.

Numerous factors currently impede the full production potential of the Paradox unconventional oil play. Current ex-



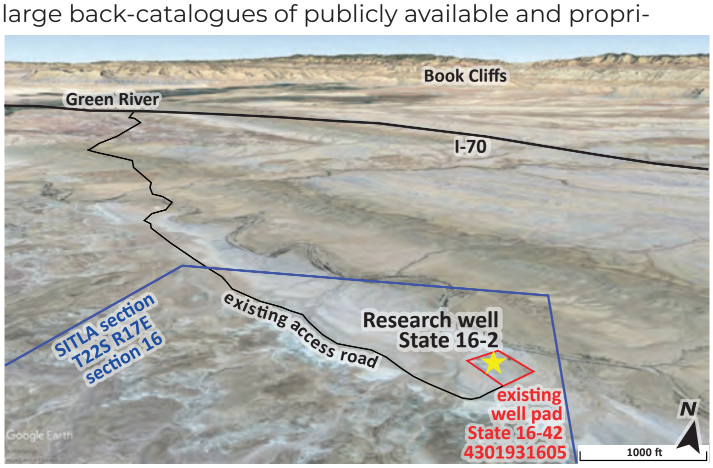
Map of Cane Creek play area showing available legacy data. bbls = barrels perience indicates that the Cane Creek can be a very successful fracture play, meaning the intersection of natural fractures with the wellbore can generate economic production (no hydraulic fracturing needed). However, the clastic (sandstone/shale/anhydrite) target zones are interbedded with several hundred feet of mechanically ductile salt layers. Over time, through the natural burial process, overburden pressure and regional stress regimes have caused the salt layers to flow like toothpaste, creating significant macro- and micro-structures within the reservoir zones. These heterogeneous structures make it difficult to predict natural fracture networks, fracture orientations, and subsequent horizontal well paths.



The State 16-2 research well will "spud" in the Tununk Member of the Mancos Shale and drill down about 9,700 feet to the base of the Paradox Formation. The cross section on the right shows an image from the 3D seismic survey and provides a detailed glimpse into the subsurface, vital for well planning and drilling (lithologic column from Hintze and Kowallis, 2009).

Typical unconventional plays, such as in the Permian Basin of West Texas or the Williston Basin in North Dakota, are targeted with horizontal wells that are then hydraulically fractured to open pathways for hydrocarbons to travel to the wellbore (as opposed to targeting natural fractures). Could the Cane Creek be targeted in a similar way, basically bypassing the hunt for natural fractures, and instead artificially create them via hydraulic fracturing? The challenge in the Cane Creek is the limited thickness of the clastic zones, often only about 100 feet or less, and their bounding by salt. Typical hydraulic fracturing techniques would send fractures into the over- and underlying salt layers, which would mobilize the salt and clog any existing or created fractures, shutting down production.

The objectives of this research project aim to help solve these dueling scenarios. The project team will leverage large back-catalogues of publicly available and proprietary data—including rock cores, geophysical logs, and 3D seismic—to develop new geologic and geomechanical models that will help with natural fracture prediction and optimal well placement. At the same time, experiments will be conducted to refine novel stimulation techniques (e.g., hydraulic fracturing) that could be used in areas without natural fractures and that will avoid interaction with the salt.



Google Earth image showing the location of the State 16-2 research well.

One major step forward for this project will take place in late fall 2020 (this article was written before the well was drilled). The project team is partnering with Zephyr Energy to drill a scientific research well in the northern part of the play area, not far from the town of Green River, Utah. This exciting partnership creates a win-win situation for both the project team and the company. Zephyr Energy and their very experienced team of geologists and engineers will be the owner/operator of the well. The project team will assist Zephyr Energy with logistics, planning, and the acquisition of the scientific data from the research well. Two-thirds of the well cost will be paid by DOE funds, while up to one-third will be cost-share expenses paid by Zephyr. The project team can also take full advantage of Zephyr's already-collected exceptional 3D seismic survey collected in the area surrounding the research well to greatly reduce drilling risks (e.g., the well location was chosen to specifically avoid subsurface faults, the presence of which would not have been known without the 3D seismic data). The research well will also act as an important ground truth to further calibrate the seismic interpretations.

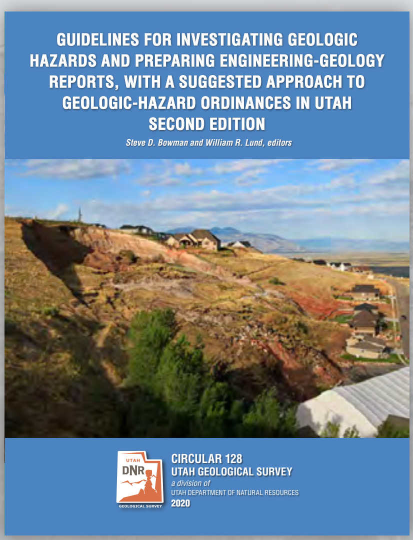
The research well, named State 16-2, will be drilled on the existing well pad used for the State 16-42 well, which was drilled in 2009, thereby eliminating the need for further land disturbance. This well is also located on a section of land owned by the Utah School and Institutional Trust Lands Administration. The well will "spud" (start of drilling) in the surface-outcropping Cretaceous-age Tununk Member of the Mancos Shale and will be drilled to a depth of approximately 9,700 feet, through Jurassic, Triassic, Permian, and Pennsylvanian deposits, in order to collect 100 feet of rock core from the Cane Creek interval in the lower Paradox Formation. In addition, the team will drill and collect sidewall cores (small core plugs, 1.5 by 3 inches in size, drilled from the side of the well bore with a special downhole drilling tool) from several of the overlying clastic zones that show petroleum production potential. This research well will provide geologists their first look at actual rock from the Cane Creek in the northern part of this play and will be the first time rock is collected from the other clastic zones. This information will fill important information gaps in our understanding of the geology of the area, the maturity of the source rocks, and the natural fractures. Finally, the team will collect additional petrophysical data via sophisticated downhole geophysical logs, including advanced borehole imaging tools. After the drilling is complete and all data have been gathered, the well will be temporarily abandoned in the hope that Zephyr can re-use a portion of the well bore to drill a horizontal test well in the Cane Creek at some point in the future.

The Cane Creek play has experienced some success over the years, with production totaling over 10 million barrels of oil since the first wells were drilled. However, there is an estimated 1.2 billion barrels of potential oil (barrels of oil equivalent, which includes natural gas) in the Cane Creek, meaning that 99.2 percent of the oil in the Cane Creek remains in-place. These numbers do not include all the other overlying clastic zones that also have petroleum production potential. So far, the challenges of this play have overshadowed the significant successes. This DOE-funded project seeks to provide multiple paths forward for the development of a commercially successful tight oil play (Cane Creek and other clastic zones) by reducing drilling risks and uncertainty.

For more information, visit the project website at http://paradox.unconventional.rocks.

ABOUT THE AUTHOR

***Michael Vanden Berg** has worked for the Utah Geological Survey for 17 years and is currently the Energy and Minerals Program Manager. In addition to his managerial duties, Michael researches the lacustrine deposits of the Green River Formation, including their hydrocarbon potential, as well as modern lacustrine systems such as Great Salt Lake. Michael is also co-PI of the DOE-funded Cane Creek project.*



The Geologic Hazards Program has released the second edition of the ***Guidelines for Investigating Geologic Hazards and Preparing Engineering-Geology Reports with a Suggested Approach to Geologic-Hazard Ordinances in Utah*** (UGS Circular 128). These updated guidelines provide recommendations for appropriate, minimum investigative techniques, standards, and report content to ensure adequate geologic site characterization and geologic-hazard investigations to protect public safety and facilitate risk reduction. The accompanying suggested approach to geologic-hazard ordinances and school-site investigation guidelines are intended as an aid for land-use planning and regulation by local Utah jurisdictions and school districts, respectively. Circular 128 is available at https://doi.org/10.34191/C-128.

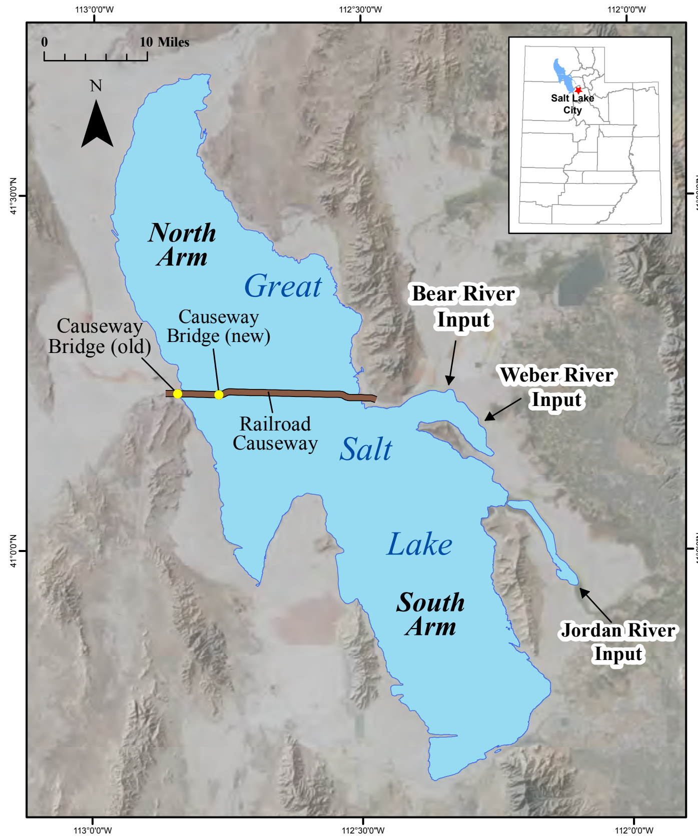
THE SIGNIFICANCE OF GREAT SALT LAKE'S NORTH ARM ON LAKE SALINITY

by Andrew Rupke and Elliot Jagniecki

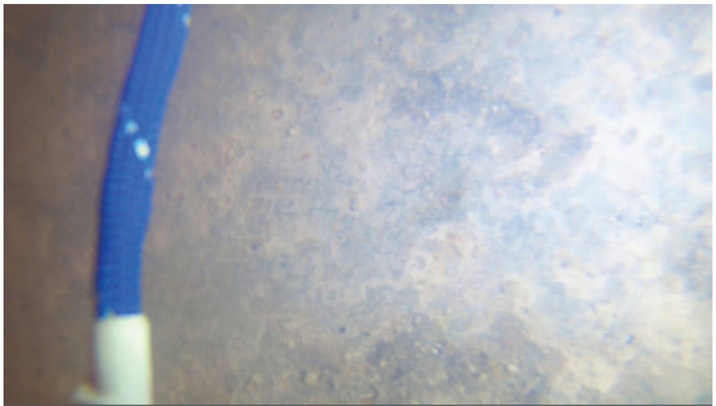
Yes, Great Salt Lake is salty, but some parts of the lake are saltier than others. Human activity has altered the natural environment of Great Salt Lake, with the most noteworthy modification being the roughly 20-mile-long railroad causeway that separates the lake into north and south arms. The causeway, in its current form, is primarily constructed of rock and only allows limited water flow between the two arms of the lake. This constriction of flow, as well as the fact that the rivers delivering fresh water to the lake only enter the south arm, has caused the north arm of the lake to become much saltier than the south arm.

Water flows through the causeway primarily via two bridge openings. The bridges are located on the west side of the causeway and are about 4 miles apart. The eastern bridge is relatively new and was constructed to replace the flow of two culverts that were closed in 2012 and 2013 due to structural integrity issues. The new bridge, opened in December 2016, was built with a control berm on the north side of the causeway that can be modified to control and change water flow through the opening. With this new ability to adjust flow between the two arms of the lake, the Utah Division of Forestry, Fire and State Lands and the Utah Department of Environmental Quality (both of which are charged with managing Great Salt Lake) are seeking to understand how salt cycles through the lake system and how salinity is affected by water flow through the causeway openings. Salinity levels are important because they affect the lake's ecosystem and the viability of the lake's mineral industry. For example, brine shrimp thrive within certain salinity thresholds and declining salinity in the south arm of the lake has been a concern for mineral producers operating in that part of the lake.

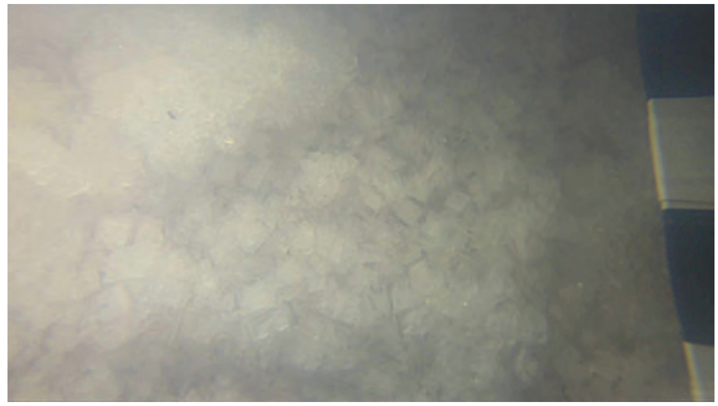
Since the completion of the railroad causeway in 1959, the north arm of Great Salt Lake has typically been at or near saturation with respect to halite, the mineral form of sodium chloride (with the exception of a high water period during the 1980s and early 1990s). In other words, water in the north arm is often at a state where it cannot hold any more dissolved salt so solid salt forms (or precipitates) from the water. In fact, past research by the Utah Geological Survey (UGS) and others has shown that a salt (or halite) crust is often present on the floor of the north arm and can be several feet thick in some areas. However, the extent and thickness of the salt crust varies due to changes in north arm salinity brought about by lake level changes, changes in flow through the causeway, and seasonality. The salt crust is an important salinity control for the entire lake system because it stores salt that might otherwise be in solution (or dissolved) and able to move into the less saline south arm. In the years preceding the new bridge opening in late 2016, the north arm was often saturated with respect to halite and an extensive salt crust formed, particularly during the dry months of late summer and early fall when evaporation is high. However, following the bridge opening, a large amount of fresher south arm water flowed into the north arm, thereby lowering its salinity. This large influx of water from south to north was, in part, due to the south arm lake level being several feet higher than the north arm at the time of opening, but this difference has since reduced to only about a half a foot. In the first couple of years following the new bridge opening, only minor salt precipitation occurred in the north arm and most of the nearshore salt crust dissolved. In 2019, the UGS began a concerted research effort to observe how the overall salt crust is responding to the new bridge opening and what conditions are required for north arm water to begin precipitating salt.



The roughly 20-mile-long railroad causeway separates the north and south arms of Great Salt Lake.



The salt crust on the floor of the north arm at a water depth of 10 feet in August 2019. The relatively smooth surface indicates that the crust is dissolving. The white segment of the cord is about 1 inch long.



The salt crust on the floor of the north arm at water depths of about 20 feet (top) and 15 feet (bottom) in September 2020. Coarsely crystalline bottom-growth halite indicates that salt is precipitating and the salt crust is growing. Scale is in inches.

One innovative approach used was to take photographs of the lake floor in deeper parts of the north arm to observe the texture and characteristics of the ever-changing salt crust. This approach has been a challenge due to the turbid (or cloudy) conditions of the water, but we have managed to capture some scientifically significant images. In late summer 2019, we observed salt crust at water depths of 10 feet, but its appearance was flat and smooth, indicating that the crust was actively dissolving rather than growing. In deeper areas (about 25 feet) we observed a flat surface with a thin accumulation of fine sediment (we remain uncertain about the significance of this sediment). However, images taken at the same and other locations in late summer of 2020 showed something much different: coarse, newly formed salt crystals. This coarse texture of salt crystals is consistent with what we had observed in past research in the nearshore environment when salt was forming and the salt crust was growing. We are also attempting to pinpoint the conditions of the north arm water at which this salt starts to form. We routinely sample north arm water and measure its density in parallel with making observations of the salt crust. With some of our samples, we add more salt to see if it can be dissolved in the water or if the water is already holding as much salt as possible (i.e., at halite saturation). If the water can hold more salt, the density will be higher in the "spiked" sample than the sample to which no salt has been added (the "control" sample). Geochemical modeling of the chemistry of the north arm water has also allowed us to estimate the density at which the water is saturated and ready to precipitate salt. Based on our field observations, experimentation, and geochemical modeling, the north arm becomes salt saturated at a density of about 1.22 grams per cubic centimeter at room temperature. For comparison, fresh water has a density of 1.00 grams per cubic centimeter and seawater has a density of 1.02 grams per cubic centimeter.

This new information provides a piece of the puzzle that we and other researchers can use to understand and predict when the north arm salt crust will be growing and sequestering salt from the overall Great Salt Lake system or when the salt crust is dissolving and returning salt to the system. We can also look at past records of density measurements and infer, to some degree, when the salt crust was growing or dissolving. If the salt crust is returning salt to the system, the salinity of the south arm should increase, which, as previously mentioned, can impact the ecosystem and mineral industry at the lake. Our observations and conclusions should lead to a better understanding of how salt cycles through the Great Salt Lake system so that those who manage the lake can make more informed decisions on how or if the salinity of the lake should be adjusted by future modifications to the control berm or causeway.

ADDITIONAL INFORMATION

- **More Than a Grain of Salt: The Salt Crust on Great Salt Lake's North Arm**, *Survey Notes*, v. 48, no. 3, September 2016
- **What is the Boxcar Seawall?**, *Survey Notes*, v. 47, no. 1, January 2015
- **A Lake Divided–A History of the Southern Pacific Railroad Causeway and its Effect on Great Salt Lake, Utah**, *Survey Notes*, v. 34, no. 1, January 2002

CORE CENTER NEWS

MINING CORE AT THE UCRC— BOOSTING UTAH'S METAL EXPLORATION

by Stephanie Mills

The Utah Core Research Center (UCRC) houses an ever-growing treasure trove of geological material and information, representing $5 billion worth of investment in Utah's natural resources and including everything from core to cuttings and downhole logs to geochemical assays. In 2020, the UCRC received core from over 20 new boreholes and cuttings from more than 120 wells, including oil and gas, oil sand, and industrial mineral materials. These donations included over 6,000 feet of core from the Green River Formation in the Uinta Basin covering an area previously devoid of geologic data that will help answer long-standing questions about the evolution of ancient Lake Uinta and the Green River Formation petroleum system. Also in 2020, the UCRC repatriated Utah core from the Oklahoma Geological Survey, further consolidating Utah's geological record in one place.

Though many of the materials housed by the UCRC are related to the oil and gas industry, the importance of the UCRC's core repository to the metals exploration and mining community cannot be overstated. Districts often undergo several iterations of exploration and mining for metalliferous minerals, and access to this historical data and drill core can often save explorers significant time and money and can help reduce environmental impacts by minimizing the amount of duplicated fieldwork and drilling. The UCRC hosts cores from major mining districts across Utah, including the Stockton, Ophir, Mercur, Dugway, Drum Mountain, San Francisco, North Star, La Sal Mountain, and Lisbon Valley districts, and cuttings from a dozen more. The UCRC mining repository represents a substantial cross section through Utah's prolific mining history.

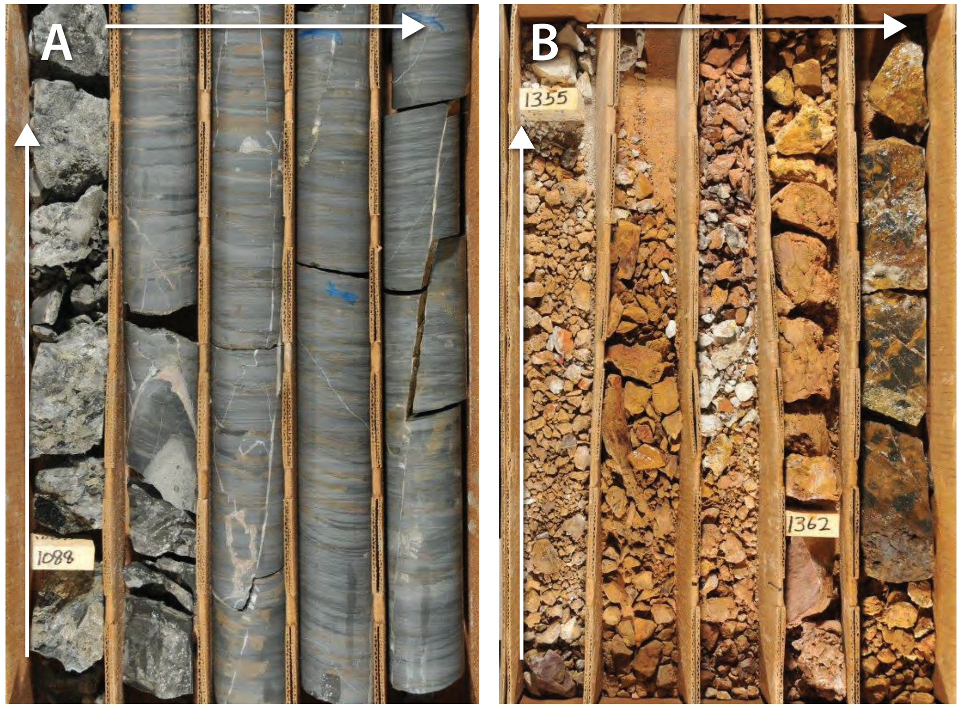
But why do mining districts undergo so many different phases of exploration and mining? The periodicity of the mining industry is due to either new geological information or new economic drivers. For example, the Mercur district in Tooele County had a major resurgence in gold mining after geologic understanding of "invisible gold" expanded in the 1960s, and uranium in southeastern Utah only became more economically desirable than radium

Mobilization of Freeport-McMoran's drill rig in 2015 to drill hole DM-15-01 in the Drum Mountain district; the core was ultimately donated to the UCRC.

and vanadium after discovery of nuclear fission in 1938. Sometimes both new geologic information and changes in the economics of a project can spur new life in a mining district, such as discovery of high-tonnage, low-grade porphyry mineralization coupled with first-in-the-world use of steam shovel stripping and open-pit mining methods, the combination of which made Bingham Canyon the most productive mining district in the United States.

The Drum Mountain (or Detroit) mining district, located in south-central Juab and north-central Millard Counties, is a recent example of a district with a new lease on life. The district began as a copper, gold, and silver producer in 1872, but by the time active mining ended in 1976 the district had become the state's largest manganese producer and produced minor amounts of halloysite clay, iron, and bismuth. Exploration evolved from targeting vein and replacement deposits in the early 1900s to targeting porphyry and sediment-hosted gold mineralization over several periods from the 1960s to present day. In 2012, the Drum Mountain district was the most competitive metal exploration area in Utah. Freeport-McMoRan was one of the companies active during this exploration frenzy. However, after drilling several holes they decided to drop their position in 2015. As good geological stewards, Freeport-McMoRan donated the entirety of one of their cores from the program, over 2,500 feet, to the UCRC.

Starting in 2019, the Drum Mountain district was back in the spotlight. Initially, interest in the district was related to critical mineral potential, specifically the significant manganese production from the district (see *Critical Minerals of Utah*, UGS Circular 129), which led to the donated



A) DM-15-01 core from 1,087.5 to 1,096.5 feet in the Whirlwind Formation showing a pebble dike in the top ~2.5 feet with quartzite, siltstone, and limestone clasts and minor disseminated pyrite. B) DM-15-01 core from 1,352 to 1,365.5 feet with strong brecciation, iron oxide and clay alteration, quartz and calcite veins, and 1,220 ppb gold at the faulted contact of the Dome Limestone and Chisholm Formation. Arrows show downhole direction.

Freeport-McMoRan core being photographed by UCRC staff through a data preservation grant from the U.S. Geological Survey. In 2020 Alderan Resources, an Australian-based junior explorer that has also been active in the San Francisco and Rocky mining districts of Beaver County, claimed ground in the Drum Mountain district in pursuit of sediment-hosted gold and porphyry copper targets. Although the UCRC was closed to public visits due to the COVID-19 pandemic during Alderan's early exploration planning, the photographs of the Freeport-McMoRan core gave Alderan preliminary information on stratigraphy, alteration, mineralization, and structure to inform their exploration and drill program planning. The drill hole extends through a Cambrian-age section from the Pierson Cove Formation through the Prospect Mountain Quartzite, and most minerals-related alteration occurs in zones of structural deformation (e.g., a pebble dike in the Whirlwind Formation). The highest concentration of gold in the hole, up to 1,220 ppb, is found at the faulted contact between the Dome Limestone and Chisholm Formation.

The Drum Mountain district is a perfect example of how the UCRC aids the minerals industry by housing and protecting historical materials, while also following modern exploration trends and working to make materials accessible to explorers, researchers, and the public. However, none of this would be possible without the donation of materials in the first place, and we encourage explorers to consider donating representative drill core from projects across Utah to help us grow the repository of Utah's geologic knowledge. If you are interested in donating core to the UCRC, please contact UCRC Curator Peter Nielsen at peternielsen@utah.gov or call (801) 537-3359.

Glad You Asked!

HOW DOES PLATE TECTONICS MAKE FOR GREAT SKIING?

by Jim Davis

Ecker Hill, February 17, 1935, was a world-class ski jump. Underlain by Triassic-age (~240 million years ago) Thaynes Limestone, Ecker Hill is 2 miles north-northwest of the 2002 Utah Olympic Park, near Park City. This area exhibits folding in the rock layers and many thrust faults caused by compressional tectonics between 100 and 50 million years ago. Photo courtesy of the Utah Division of State History.

Great snow and great skiing and snowboarding are ultimately the result of plate tectonics. Plate tectonic activity, the relative movement of independent pieces of Earth's exterior shell, involves the Earth's plates migrating (changing their relative position), splitting apart (allowing new crust to form where magma wells up), and colliding with each other (destroying old crust in subduction zones). This activity creates the planet's mountain ranges, volcanic chains, rift valleys, and ocean basins, ridges, and trenches. Snow conditions are a sum of topography, elevation, latitude, and distance to the ocean. These factors constrain climate and are shaped by a history of tectonics. Mountains govern the first two factors and all four factors govern snow—its quantity, quality, and duration.

TECTONIC HISTORY

Utah's ski resorts are located along the Wasatch hingeline, a northeast to southwest band of mountains that arcs through central Utah. The hingeline's origins stretch back nearly a billion years before the "Greatest Snow on Earth®." Once formed, the hingeline perpetuated an east-west division in Utah through geologic time. The hingeline commenced with the break-up of the supercontinent Rodinia. The land rifted (split apart) along the hingeline, fragmenting the landmass and allowing oceanic crust to form in the gap. As the rift widened, the region west of the hingeline subsided for a long period of time, ocean waters encroached, and Utah was at the edge of the continent.

Hundreds of millions of years of quiescence followed, with tropical beaches, coral-filled seas, mud flats, lakes, broad river plains, and vast expanses of sand dunes. Stream networks drained much of the continent through Utah to the western ocean. Then plate tectonic activity resumed with the break-up of the supercontinent Pangea. The Farallon Plate began subducting beneath the continent, forming a convergent plate boundary. By Middle Jurassic time, around 170 million years ago, volcanism began in western Utah and 70 million years later mountain building ramped up from compression from the west. West of and at the Wasatch hingeline, the crust thickened and mountains formed from thrust sheets—large bodies of rock shoved eastward and folded. Intense volcanism ensued over much of the state. Throughout this mountain building time, Utah became steadily more distant from the western ocean.

After a time the remains of these mountains underwent the next and current stage of tectonics. Basin and Range extension is stretching and thinning Earth's crust from the Wasatch hingeline to the Sierra Nevada. This deformation produced faulting that created long and repeating mountain ranges and valleys. Vertical movement on the Wasatch fault has resulted in the Wasatch Range abruptly rising thousands of feet above the adjacent valleys.

Yet how does this tectonic history make for favorable skiing and snowboarding? Here are a few factors that make skiing great in Utah, with focus on the central Wasatch Range and how plate tectonics fits in.

SNOW COVER THROUGH THE SEASON

Tectonic plate migration has taken Utah from the equatorial latitudes and landed it squarely in the mid-latitudes. In this zone extratropical cyclones, weather systems some thousand miles across, pass intermittently from the Pacific Ocean to the Rocky Mountains, delivering blizzards. In a normal year, frontal storms through the winter and spring bring fresh snow to the mountains every week or two. Abundant spring storms can extend the ski season until early summer for some resorts. High elevation keeps temperatures cold and precipitation frozen late into the year.

ACCESS TO THE SLOPES

The Wasatch fault has produced steep mountains without foothills. The physiography was beneficial for settlement and subsequent growth of the Wasatch Front urban corridor, a long, narrow strip of populated area where more than two million people now reside. The valleys have fertile soils and a long growing season with hot summers. The adjacent mountains provided timber, rangeland, metallic resources, and winter snowpack as a source of water for irrigation of valley crops. Consequently, an extensive metropolitan area is now located within minutes of the mountains. Nine premier ski resorts are within a one-hour drive of Salt Lake City.

TEMPERATURE RANGE

Skiers and snowboarders prefer that snow not melt or that temperatures are not too cold for comfort. Temperature is largely a function of latitude and elevation. The Cottonwood Canyon resorts, at 8,000 to 11,000 feet above sea level, have daily high temperatures in the winter months around 31°F, and daily lows around 9° to 14°F. Although the valleys are not much warmer in the winter than the mountains, springtime offers the opportunity to ski and bike on the same day.

HIGH-QUALITY SNOW

Utah's interior position and the presence of numerous mountain ranges between the state and the ocean make for quality snow. Utah is about 600 miles or more from the ocean. Storms driven by the prevailing Westerlies from the Pacific Ocean must track perpendicular across the Sierra Nevada or Cascade Range, then across a washboard pattern of Basin and Range mountains. Along the way, these storms drop a significant amount of their original moisture as precipitation so that Pacific air masses arrive in Utah relatively dry. Along with bitterly cold temperatures aloft due to elevation and interior location, these relatively dry storms produce a variety of snowflakes—columns, plates, needles and dendrites—typically having a moderately low density. Alta snow density averages 7.8 percent December through January and 8.5 percent for the whole snow year.

ABUNDANT SNOW

Western Utah's Great Salt Lake Desert receives as little as five inches of precipitation a year, whereas areas of the Wasatch Range average ten times as much precipitation, with hundreds of inches of winter snow. The upper Cottonwood Canyons are among the snowiest locations on Earth. Alta and Brighton have the 4th and 10th highest average annual snowfalls, respectively, in the United States. The steep relief of the Wasatch Range induces orographic lifting—air is forced to rise up and over the range. As air rises, it expands, cools, and its relative humidity increases leading to precipitation. Great Salt Lake, averaging 1,700 square miles and never freezing over, influences local weather. The lake is a product of Basin and Range tectonics and is the most prominent of the lakes of the Great Basin—the northern and internally drained area of the Basin and Range Province. Following the passage of a cold front, lake effect snow shower bands can stretch from the lake to the south, southeast, and east across the valleys and into the mountains, boosting snowfall.

VARYING TERRAIN AND BEAUTIFUL SCENERY

Latitude and elevation contributed to modest glacial growth in the Wasatch Range in the past. Recurring ice ages in the Quaternary Period, the last one peaking around 20,000 years ago, triggered alpine glaciation in Utah's mountains. Glaciers begin growing in the shade of the highest summits, etching out bowl-like amphitheaters and sculpting pointed peaks and jagged ridges. The streams of ice then course downslope, carving U-shaped canyons and hanging valleys from tributary glaciers. The result is ski areas with variable topography—both abrupt and gentle—and vertical relief that locally exceeds 3,000 feet.

Although glaciers have provided the finishing touches on the landscape, a composite of tectonic events have left their imprint on the Wasatch Range. Overthrust faulting, intrusions of igneous rock (plutons), and folds can be viewed and appreciated from resorts. Rock outcrops exhibit diverse chapters of tectonic history, including gneiss, schist, and quartzite from ancient continental crust, marine limestone and sandstone from the former edge of the continent, conglomerates shed from eroding mountains, and granite and tuff from volcanic activity.

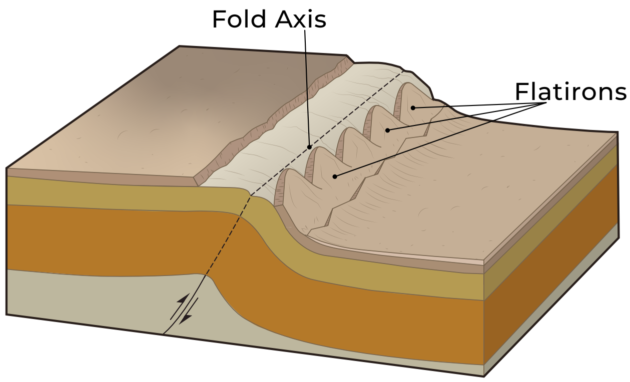
Structures such as faults, folds, and thrust sheets from prior mountain building episodes add attributes to the landscape and can be viewed from ski resorts, even under the snow cover of winter. The Hellgate Cliffs opposite the Snowbird resort exhibit a thrust fault where compressional forces from the west shoved rock eastward. The cliffs are a Mississippian-age limestone capped with older Mineral Fork Tillite and Tintic Quartzite. Photo courtesy of Mark Milligan.

GeoSights

RAPLEE RIDGE, SAN JUAN COUNTY, UTAH

by Marshall Robinson

Raplee Ridge, a striking geographic feature in southeastern Utah, is commonly called “Raplee anticline,” or “Raplee monocline.” Geologically speaking, it is more accurate to call it a monocline, but on a map, you will only find the name Raplee Ridge. Regardless of the name, it is a beautiful feature that locals have described as resembling the design of a “Navajo blanket.” The multi-colored, zig-zagging triangular geometric shapes on Raplee Ridge’s steep western slope are shaped and colored like the patterns on beautiful blankets and rugs woven by members of the Navajo tribe. During the day, these colors tend to look washed out, but near sunset they become stunningly intensified. With approximately 1,600 feet of relief, the west-facing slope of Raplee Ridge can be seen from as far away as Goosenecks State Park and Mexican Hat Rock, which are ideal locations to take photos of the colorful hillside.



Block diagram of a monocline. Deep, compressional forces caused the rock layers to fold steeply upward along a relatively straight axis, creating a “step-up” in the ground. Flatirons are upward-facing rock formations that form along some monoclines (and other folds) when an upper layer of rock is more resistant to erosion than underlying layers.

GEOLOGIC INFORMATION

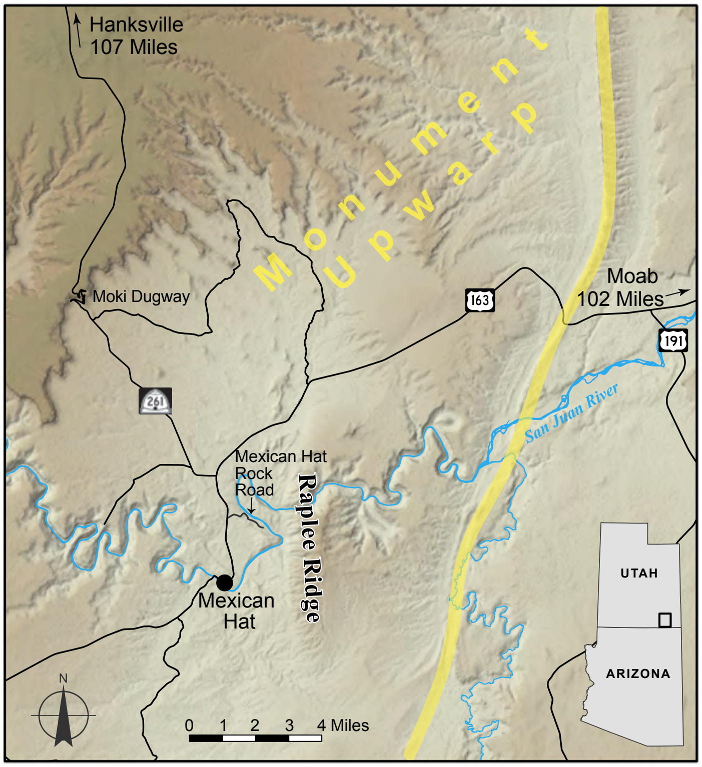
At the base of Raplee Ridge, before it juts sharply upward, buff-colored, Permian-age (251–299 million years ago) rocks called the Cedar Mesa Sandstone overlie older, Permian-age reddish-brown siltstone and sandstone known as the Halgaito Formation. The siltstone and sandstone of the Halgaito Formation fold upward as you move east and up the western slope of Raplee Ridge. Underlying the Halgaito Formation, steeply tilted, multi-colored layers of even older Pennsylvanian-age (299–323 million years ago) siltstone, shale, and limestone make up the majority of the surface of the western slope and are known as the Honaker Trail Formation. The zig-zag pattern within the Honaker Trail Formation is caused by runoff-induced differential erosion, cutting deep gouges and gullies that expose the many layers on the western slope. Some of the gullies are deep enough to expose even older Pennsylvanian-age layers of cherty limestone, sandstone, siltstone, and shale known as the Paradox Formation. Between these cut valleys are erosion-resistant, upward-pointing triangles of rock called “flatirons.” They line the face of Raplee Ridge’s western slope, exposing many colorful rock layers in between.

Eastern view of Raplee Ridge’s western slope from the dead end of Mexican Hat Rock Road. Geologic formation names and boundaries shown for reference.

Set amongst the flat, layer-cake geology of the Colorado Plateau, Raplee Ridge is the result of large-scale tectonic stresses that occurred during the Laramide mountain-building event (40–70 million years ago). During this time east-west-directed compressional forces buckled a region of present-day southeastern Utah known as the Monument Upwarp. Spanning between Comb Ridge to the east and approximately Lake Powell to the west, this buckle in Earth’s crust is a large anticline (or a fold that loosely resembles an inverted “V” shape). Within the Monument Upwarp, other north-to-south-trending structures (monoclines, synclines, and other anticlines) were created during the same period (see *Survey Notes*, v. 44, no. 2, p. 10). The shape and geometry of these structures within the Monument Upwarp are mainly a reflection of underlying structures created during the formation of the Ancestral Rockies (299–323 million years old) which are made up of Precambrian-age (greater than 541 million years old) rocks.

Raplee Ridge best fits the description of a monocline due to the rock layers getting tilted steeply up, then mostly flattening out at the peak of the ridge. Raplee Ridge is also called "Raplee anticline" because the rock layers to the east of its peak gradually extend down into the ground, loosely giving it the shape of an anticline; however, most geologists agree that it is better classified as a monocline. At the base of Raplee Ridge's western slope, the rock layers plunge into the ground and then fold back upwards west of the town of Mexican Hat creating a U-shaped syncline called the Mexican Hat Syncline.

HOW TO GET THERE:



Among many places to view Raplee Ridge, the iconic Mexican Hat Rock sits close to the base of Raplee Ridge and is an excellent viewpoint:

From Moab, drive south on U.S. Highway 191 for approximately 100 miles to Bluff. Roughly 3 miles west of Bluff, continue straight at the intersection onto U.S. Highway 163. Continue west on U.S. 163 for 18 miles and then turn left (east) onto Mexican Hat Rock Road (unpaved). There are multiple safe places to park along Mexican Hat Rock Road; however, it does dead end after approximately 1.5 miles.

From Hanksville, drive south and east on Utah State Route 95 for approximately 93 miles and then turn right (south) onto Utah State Route 261/County Road 235. Along Route 261, between 23 and 25.7 miles, an unpaved, difficult to traverse, and sometimes impassable (due to inclement weather) section of switchbacks known as Moki Dugway will be encountered. Approximately 7 miles after Moki Dugway, turn right (south) onto U.S. Highway 163 and continue for 1.5 miles then turn left (east) onto Mexican Hat Rock Road (unpaved).

The best time and place to view Raplee Ridge is near sunset from any location west of the Ridge.

Coordinates of suggested parking spot near Mexican Hat Rock: 37.17°N, 109.85°W

Teacher's Corner

UGS Offers Virtual Earth Science Week Activities

Earth Science Week is celebrated the second full week of October throughout the nation as well as in other countries. The purpose is to increase public understanding and appreciation of the Earth sciences. Launched in 1998 by the American Geosciences Institute (AGI), efforts have grown on local, national, and international levels to highlight the vital role Earth sciences play in society's use of resources and interaction with the environment.

Normally, the UGS hosts Earth Science Week activities for school groups, typically with around 700 students in attendance. However, due to the COVID-19 pandemic, on-site activities for Earth Science Week 2020 at the UGS were canceled. Instead, the UGS has created a self-guided virtual experience into Earth science topics where teachers, parents, students, and the public can learn about the Earth and its processes. Visit our web page at https://geology.utah.gov/2020-earth-science-week/.

SURVEY NEWS

2020 Employee of the Year | Starr Soliz

Congratulations to **Starr Soliz** who was selected by her peers as the 2020 UGS Employee of the Year. Starr has been with the UGS since 2005; she is currently an Executive Secretary, providing secretarial support for the Geologic Mapping and Groundwater programs and administrative support for the UGS as a whole. She also serves as the front desk representative, greeting all who contact the survey with a smile and kind voice. She consistently goes above and beyond her numerous duties and no task is ever too big or too small. During this unprecedented and difficult year, she was reliably in the office and kept the UGS running efficiently during the pandemic, allowing staff members to work remotely while maintaining a constant connection to the office. Whether we had issues with setting up our home offices or needed supplies, Starr was there to track down whatever we needed, keeping us safe and healthy and making our jobs and lives easier, and she has done it with strength, courage, and professionalism. Starr exceeds all expectations and has an incredible work ethic. She is a responsible, dependable, and giving co-worker. Starr is an outstanding employee and deserving recipient of this special award and recognition.

Tom Chidsey retired from the Utah Geological Survey (UGS) after 31 years of service. Tom joined the UGS in 1989 as a petroleum geologist in the Economic Geology Program (now the Energy and Minerals Program) where he became Petroleum Section Chief and later Senior Scientist. Tom worked on many UGS projects including several reservoir characterization/outcrop analog studies (Leadville Limestone, Paradox Formation, Weber Sandstone, Navajo Sandstone, Green River Formation, and Ferron Sandstone), Paleozoic shale-gas resources, CO_2 sequestration, Uinta Basin produced water, and microbial carbonates. Tom also worked with researchers from the Planetary Science Institute using Utah geology to help them interpret similar features on Mars and to develop protocols for current and future NASA rover missions. Tom authored/co-authored 105 technical publications, 108 abstracts, and 42 nontechnical articles. Tom also edited/co-edited four UGS Bulletins, a book for the American Association of Petroleum Geologists (AAPG), and seven Utah Geological Association (UGA) publications, including the award-winning *Geology of Utah's Parks and Monuments*. Tom served as UGA president in 2000, as General Chairman of the 2003 AAPG Annual Conference held in Salt Lake City, and received the prestigious UGS Crawford Award in 2002 and 2019 and the Lehi Hintze Award in 2017 for his outstanding contributions to the geology of Utah. Tom's expertise, institutional knowledge of Utah's geology, and humor will be greatly missed, and we wish him well in his retirement.

2020 Lehi Hintze Award | David Simon

The Utah Geological Association (UGA) and the Utah Geological Survey (UGS) presented the 2020 Lehi Hintze Award to **David Simon** for his contributions to Utah geology. Having over 40 years of experience as an engineering and environmental geologist, David has served as consultant to several municipalities in the Salt Lake Valley and is President of Simon Associates, LLC, a geologic and environmental consulting firm providing geologic services in Utah, Wyoming, and Idaho.

David's work has included general geologic consultation, application of standard-of-care, and implementation of geologic-hazards ordinances. In 2007, he was a member of the committee that drafted the Draper City Geologic Hazard Ordinance recommended by Governor Huntsman's 2008 Working Group on Geologic Hazards as the model ordinance for Utah municipalities. David has served on numerous boards and with organizations including the Utah Professional Geologist Licensing Board, the UGS State Mapping Advisory Committee, the UGS Liquefaction Advisory Group for the Wasatch Front, the UGS Board, and the Morgan County Geologic Peer Review Committee, as well as serving as the National President of the Association of Engineering and Environmental Geologists.

Named for the first recipient, the late Dr. Lehi F. Hintze of Brigham Young University, the Lehi Hintze Award was established in 2003 by the UGA and UGS to recognize outstanding contributions to the understanding of Utah geology.

Employee News

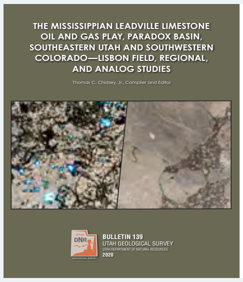
Congratulations to **Mark Milligan** who was promoted to manager of the Geologic Information & Outreach Program. Mark has worked with the UGS for over 20 years as a geologist and public information officer and replaces **Mike Hylland** who is taking time to focus on technical project work while continuing in his role as UGS deputy director. Congratulations to Mark and thank you to Mike for your many years of UGS leadership.

Anna Farb joins the Editorial Section as a new cartographer and GIS analyst. Anna has an M.S. degree in landscape architecture with an emphasis in GIS techniques from Utah State University. She replaces **Rosemary Fasselin** who accepted a senior GIS analyst position with the Geologic Mapping & Paleontology Program. **Eugene Szymanski** joins the Energy & Minerals Program replacing **Tom Chidsey** who retired in September. The Groundwater & Wetlands Program bids farewell to **Emily McDermott** who is moving to Alaska. Welcome to Anna and Eugene, congratulations to Rosemary, and best wishes to Tom and Emily.

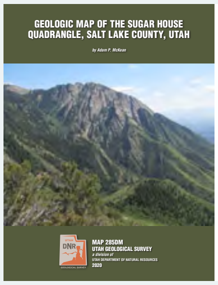
New Publications

Available for download at **geology.utah.gov** *or for purchase at* **utahmapstore.com**.

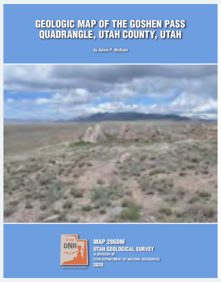
Utah Mining 2019: Metals, Industrial Minerals, Coal, Uranium, and Unconventional Fuels, by Stephanie E. Mills, Andrew Rupke, Michael D. Vanden Berg, and Taylor Boden, 37 p., **C-130,** https://doi.org/10.34191/C-130



The Mississippian Leadville Limestone Oil and Gas Play, Paradox Basin, Southeastern Utah and Southwestern Colorado—Lisbon Field, Regional, and Analog Studies, compiled and edited by Thomas C. Chidsey, Jr., 246 p., 9 appendices, **B-139,** https://doi.org/10.34191/B-139

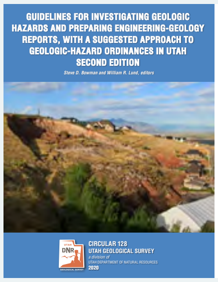


Geologic Map of the Sugar House Quadrangle, Salt Lake County, Utah, by Adam P. McKean, 27 p., 2 plates, scale 1:24,000, **M-285DM,** https://doi.org/10.34191/M-285DM



Geologic Map of the Goshen Pass Quadrangle, Utah County, Utah by Adam P. McKean, 14 p., 2 plates, scale 1:24,000, **M-286DM**, https://doi.org/10.34191/M-286DM

Surface to Subsurface Reservoir/Aquifer Characterization and Facies Analysis of the Jurassic Navajo Sandstone, Central Utah, by Thomas C. Chidsey, Jr., Thomas H. Morris, Stephanie M. Carney, Ashley D. Hansen, John H. McBride, and Craig D. Morgan, 102 p., 3 appendices, 1 plate, **SS-167,** https://doi.org/10.34191/SS-167



Guidelines for Investigating Geologic Hazards and Preparing Engineering-Geology Reports with a Suggested Approach to Geologic-Hazard Ordinances in Utah, Second Edition, edited by Steve D. Bowman and William R. Lund, 170 p., 5 appendices, **C-128**, https://doi.org/10.34191/C-128

Recent Outside Publications by UGS Authors

Groundwater Mixing in an Alkaline Paleolake—Eocene Green River Formation, Wyoming, by M. Baddough, A.R. Carroll, **E. Jagniecki**, B.L. Beard, T.K. Lowenstein, C.M. Johnson: Palaeogrography, Palaeoclimatology, Palaeoecology, v. 561, 18 p.

Characterization and Dynamic Analysis of the Devils Castle Rock Avalanche, Alta, Utah, by P. Pedersen, J.R. Moore, B.J. Quirk, **R.E. Giraud, G.N. Mcdonald**: Environmental and Engineering Geosciences, v. 26, no. 2, p. 201–215.

Invasive Plants of Great Salt Lake Wetlands—What, Where, When, How, and Why? by K.M. Kettering, C.R. Cranney, R. Downard, K.R. Hambrecht, E.E. Tarsa, **D.R. Menuz**, and C.B. Rohl, in B.K. Baxter and J.K. Butler, editors, Great Salt Lake Biology: Berlin, Springer, p. 397–434.

New Social Insect Nests from the Upper Jurassic Morrison Formation of Utah, by E. Armour Smith, M.A. Loewen, **J.I. Kirkland**: Geology of the Intermountain West, v. 7, p. 281–299.

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