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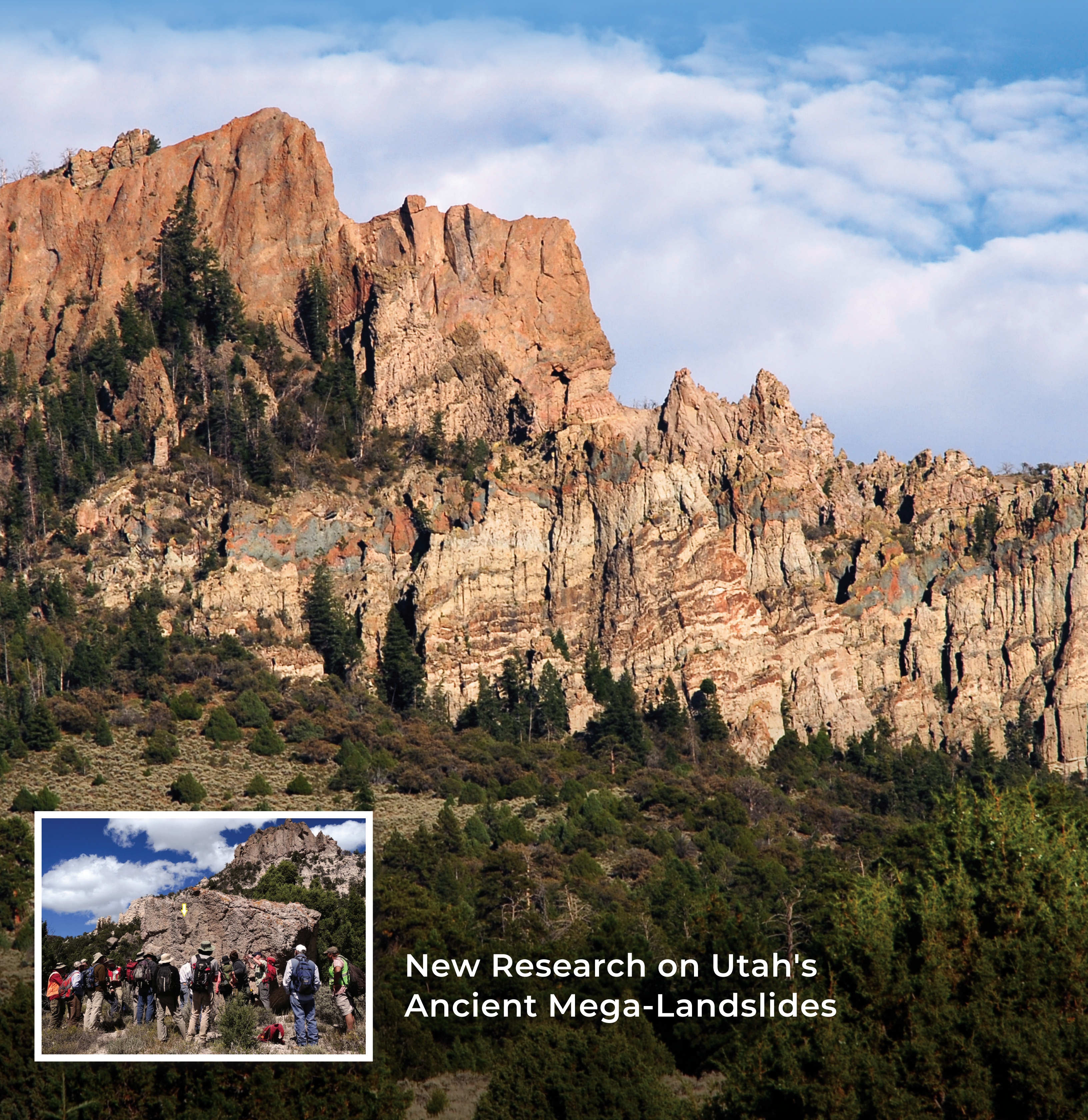

New Research on Utah's Ancient Mega-Landslides

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Design | Jackie DeWolfe

Cover | West-facing wall of the southern Sevier Plateau showing deformed volcanic rocks near the base of the Sevier mega-landslide. Inset: participants of the 2017 Geological Society of America-sponsored Thompson Field Forum examining the slide's base.

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Director's Perspective

by Bill Keach

January, February, and March were busy months for the Utah Geological Survey. When I started writing this article in late February, I had planned to talk about the move of the *Utahraptor* megablock from the Museum of Ancient Life at Thanksgiving Point to our facilities in Salt Lake City. The museum had been a wonderful host for five years and we thank them. However, it was time to bring 18,000 pounds of *Utahraptor* and other fossils closer to home. A great group of folks, including UGS employees, contractors, and volunteers, came together on February 26th to move the megablock into its new home at the Utah Core Research Center (UCRC).

Then, for the world, March certainly came in "like a lion" with the rapid spread of COVID-19. As of this writing (mid-March) I truly hope it goes "out like a lamb." Plans, schedules, and lives are changing, and many processes may have changed forever. Change is certainly happening for us at the UGS. In January of 2019, Utah Governor Herbert talked about the need for "*...increasing state employee use of transit and accountable telework*." The UGS has been on that path and had 29 percent of staff working from home at least one day a week as of the end of February. In March, this path to teleworking was accelerated to full implementation with our goal to protect our employees and the overall health of the state. We have asked our employees to telework when possible and we are employing remote conferencing. The need to telecommute may turn into a special blessing for me since my home is in Hurricane, in southern Utah. (As I write this, I'm looking out my window at the Virgin anticline in Washington County and, just beyond, my view is filled with the Quail Creek Reservoir.) However, not all of what we do at the UGS can be done from home. The UCRC needs staff on site since it is tough to prepare fossils and photograph rock core remotely. Also, many of our geologists must travel around the state to collect data from the field, which may be the ultimate telework that they love.

I am impressed with how fast the State, Department of Natural Resources, and the UGS came together with a singular goal of protecting the health of employees while finding ways to keep them productive. Each employee and team stepped up without complaint and work has progressed with little interruption. Looking forward, I am eager to see the long-term impact of finding new ways to deliver on our mission of providing "*timely scientific information about Utah's geologic environment, resources and hazards.*"

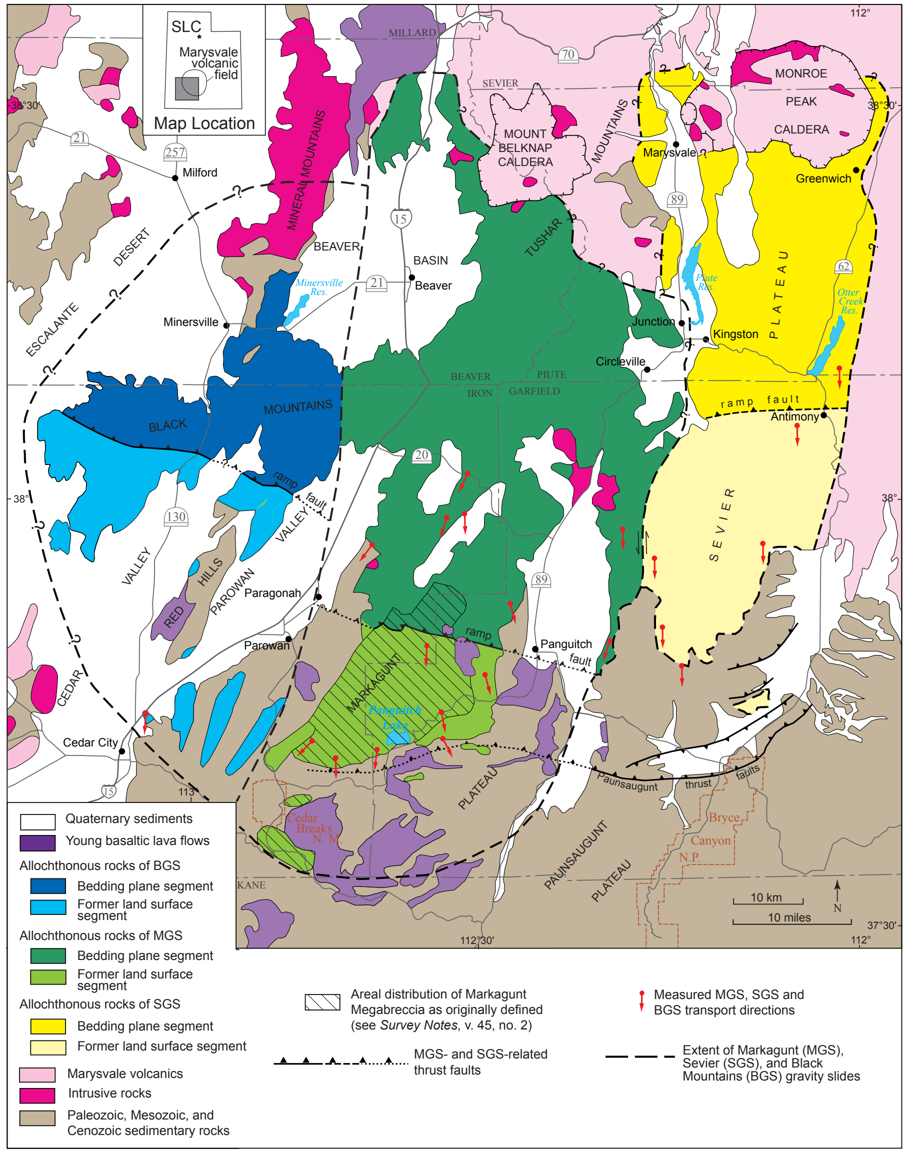
Just a few days after writing the above comments, another roar of the lion came at 7:09 a.m., March 18th with a magnitude 5.7 earthquake in Magna, Utah. The UGS office is just a few miles from the epicenter. We had a few staff in the office at the time. Fortunately, there were no injuries and only some minor damage. The UGS Hazards group responded quickly and did outstanding work assessing the situation and gathering data. See further comments in Survey News. An outcome of the event is a new website built by UGS staff that brings together information and resources from other state and federal agencies: earthquakes.utah.gov.

Utah's Ancient Mega-Landslides

by Robert F. Biek, Peter D. Rowley, and David B. Hacker

Southwestern Utah is home to what may be the largest terrestrial landslide complex known in the world. This is an exciting new discovery and much remains unknown, but the ancient Marysvale gravity slide complex (MGSC) is now the focus of new research to better understand its extent, age, and emplacement mechanics. By way of background, gravity slides are a special class of extremely large and geologically complex landslides several tens to thousands of square miles in extent. Here we refer to them as mega-landslides or slides for simplicity—they are larger and far more interesting than we ever imagined.

The history of this discovery reflects decades of work by dozens of geologists and is outlined in a new technical guide we published in 2019 through the Geological Society of America, *The Gigantic Markagunt and Sevier Gravity Slides Resulting from Mid-Cenozoic Catastrophic Mega-Scale Failure of the Marysvale Volcanic Field, Utah, USA*. As outlined in that report, we have learned a lot since sharing our initial understanding of these mega-landslides in 2013 and 2016 (see *Survey Notes,* v. 45, no. 2, and v. 48, no. 1).



The Sevier (SGS), Markagunt (MGS), and Black Mountains (BGS) gravity slides are each among Earth's largest terrestrial landslides. We continue to work to define the northern extent of the slides, and the strata that may post-date and thus bury their northern reaches. The Markagunt Megabreccia is what we now call the deposit of the MGS.

What is the Marysvale Gravity Slide Complex?

The Marysvale gravity slide complex comprises three ancient, gigantic landslides. Each slide is made up of volcanic rocks that erupted from Cascade-like stratavolcanoes of the Marysvale volcanic field, and distinctive, interbedded ash-flow tuffs erupted from Yellowstone-like calderas:

- the Markagunt slide, discovered in 2014
- the Sevier slide, discovered in 2016, and
- the Black Mountains slide, discovered in 2019.

Each mega-landslide exhibits the full range of structural features commonly seen in modern landslides, but on an enormous scale. These features include:

- extensional faulting in the upper parts of the slide,
- translational (horizontal) movement of the main body of the slide, which is characterized by mountain-size blocks jostled together,
- thrust faulting at the ramp fault and in the slide's toe area, and
- debris-avalanche deposits of the distal toe area, where the slide mass completely disaggregated into chaotic blocks.

All three mega-landslides remained undiscovered for so long precisely because of their gigantic size and initially confusing mix of extensional, translational, and compressional structures later modified by basin-range extensional faulting.

How Big is the MGSC?

The MGSC covers more than 3,000 square miles (>8,000 km^2), an area nearly the size of Yellowstone National Park, with a volume of slide debris that would nearly fill the Grand Canyon to its rim. The Markagunt slide is the largest among the three mega-slides having an overall length of about 60 miles (96 km) and breadth of 20 miles (32 km), making the deposit at least 1,350 square miles (>3,500 km^2) in extent. It is also over a mile (1.6 km) thick in its northern reaches at the breakaway zone in the modern-day Tushar Mountains, tapering southward to several hundred feet thick on the central Markagunt Plateau. Vital statistics of the Sevier and Black Mountains slides are similarly impressive, and runout over the former land surface of each slide was at least 20 miles (32 km).

When did the MGSC Form?

The timing of each mega-landslide emplacement is constrained by the age of the youngest rocks it overlies or deforms, and by the oldest undeformed rocks that overlie it. Currently, our evidence constrains emplacement of the:

- Sevier slide at about 25 Ma (million years ago),
- Markagunt slide at about 23 Ma, and
- Black Mountains slide after 21 Ma and likely about 18 Ma.

The slides thus get younger westward, mimicking the westward progression of volcanism in the volcanic field.

Evidence for Catastrophic Failure

Recognizing most modern landslides is straightforward given their telltale signs of raw scarps, open cracks, hummocky topography, and all-too-often damaged infrastructure. But the MGSC exhibits nothing so obvious. It is old. It is deeply eroded and partly buried by younger deposits and cut by later faults. The MGSC is, by any geologic standard, insanely big—so large that we cannot see it from any single vantage point. Still, key pieces of the puzzle remain, and the picture they paint is one of extraordinary calamity near the height of volcanism of the Marysvale field.

Diagnostic rock types produced by catastrophic collapse of the Marysvale volcanic field include:

- a thin bottom layer that consists of ground-up rock, which behaved as an overpressured fluid, reducing effective friction at the base of the mega-landslides, and which was injected under pressure into fractured landslide rocks, forming clastic dikes,
- rare, friction-generated melt rock (glass) known as pseudotachylyte, which demonstrates high-velocity movement of the mega-slides, perhaps as much as 200 miles per hour (100 m/sec), and
- deformed rocks, although not unique to mega-landslides, that demonstrate fracturing under high confining pressures.

These and other diagnostic rock types coupled with the uniformity of movement indicators (skid mark-like grooves and striations at the base of the slides), geologic structures within the slides, the overall geometry of the slides, and age and distribution of rocks involved or not involved, suggest that each mega-landslide represents a single catastrophic emplacement event.

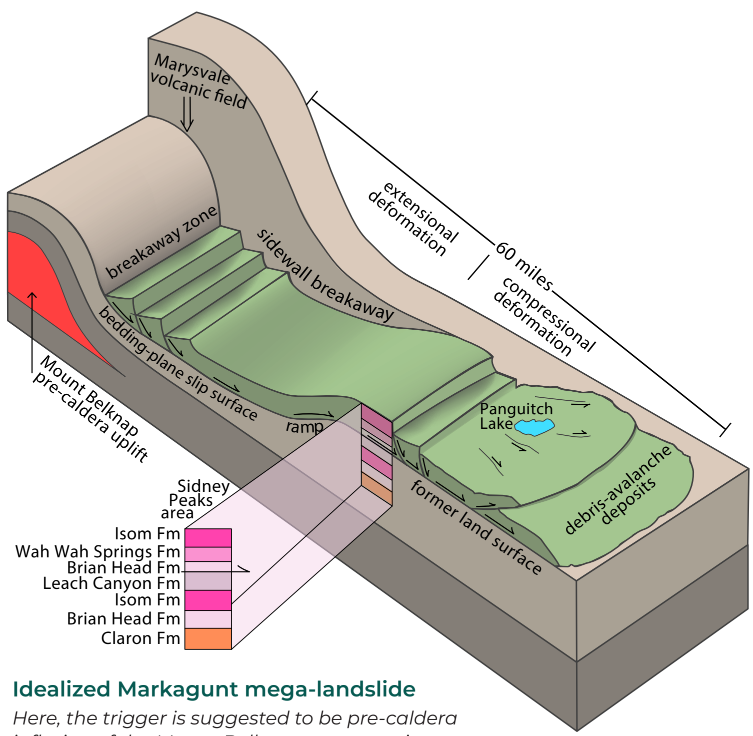
How did the MGSC Form?

Ongoing research will more fully answer when each mega-landslide occurred, what event may have precipitated catastrophic failure, and how such huge volumes of rock moved faster than freeway speeds more than 20 miles (32 km) across the landscape. But for now, we suspect several events came together to set the stage for catastrophic failure of the southern flank of the Marysvale volcanic field.

First, catastrophic failure was preceded by slow, radial spreading of the volcanic field, forming low-angle faults of the unusual Paunsaugunt thrust fault zone south of the field. The thrust faults formed because Earth's crust simply is not rigid enough to support massive volcanoes—slowly, over thousands to several million years, the volcanic field spread to a larger footprint and thus to a more stable profile.

Second, catastrophic failure was near the end of peak local volcanism. Stratovolcanoes are inherently unstable features—large, steep, massive piles of hydrothermally altered and thus weakened volcanic rock—perched above actively inflating and deflating magma chambers, so it is no wonder that growth and subsequent collapse are typical features of so many stratovolcanoes worldwide (see the new U.S. Geological Survey publication *When Volcanoes Fall Down,* http://doi.org/10.3133/fs20193023).

Third, the volcanic field was built on a weak foundation of ash-rich sedimentary strata. We surmise that inflation of the volcanic field by intrusion of partially molten rock into



Idealized Markagunt mega-landslide

Here, the trigger is suggested to be pre-caldera inflation of the Mount Belknap area, causing arching of overlying strata and consequent failure on oversteepened slopes. The ramp is where the basal detachment angled upward and "daylighted" as the slide mass moved up and over the former land surface at least 20 miles (32 km). Attenuated strata thinned like a partially spread-out deck of cards, and older-on-younger rock relationships characterize the slide mass in the former land surface area, preserving a stratigraphy inherited from the source area. The Sidney Peaks area is where remnants of the mega-landslides were discovered—note repeated, older-on-younger strata.

the center of the field may have tilted these strata on the southern flank gently southward, providing gently dipping planes in underlying weak strata that would be ideal for sliding.

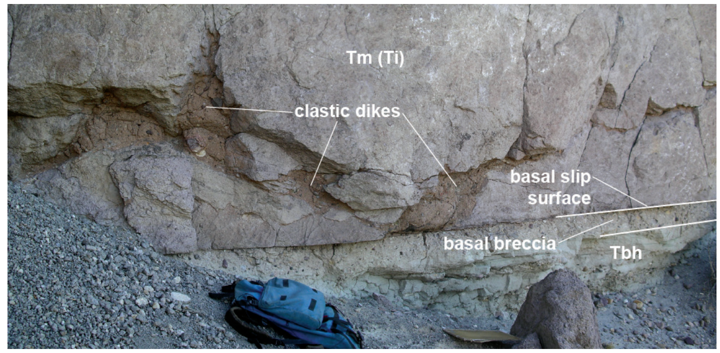
Finally, multiple volcanoes of the volcanic field failed catastrophically three separate times when its weak foundation could no longer support the growing volcanic mass. Possibly, an earthquake or eruption triggered each of the slides.

Why is the MGSC Important?

The MGSC may be the largest terrestrial landslide complex on Earth and exhibits exceptional evidence of catastrophic emplacement. Only the 49 Ma Heart Mountain mega-landslide in Wyoming is a terrestrial slide of comparable size and it was considered unique until discovery of the MGSC. The MGSC produced mega-landslide structures so large that they may be mistaken for tectonic features—this discovery thus opens the door to re-evaluate other, similar ancient and modern volcanic fields elsewhere in the world that may contain as-yet unrecognized gigantic landslides. Perhaps such mega-slides are more common than geologists once believed? The MGSC also contains the first reported occurrence of landslide-generated pseudotachylyte in North America and one of the few examples known in the world, which shows that emplacement was extremely rapid.

New Research on the MGSC

There is much we do not know about the Marysvale gravity slide complex. Yet our model of gigantic landslides—a holistic view of three types of geologic deformation (extension, simple translation or horizontal movement, and compression) not otherwise directly related to one another in most geologic environments—is a valuable tool to focus efforts to better understand these mega-landslides. Future research will focus on (1) new age and isotopic data to better constrain development of the volcanic field and its repeated partial collapse by catastrophic mega-landslides, (2) geologic mapping to tease out important details about each mega-landslide's characteristics and history, and (3) analog and computer models to understand the mechanics of sliding such large masses long distances over low slopes.



Basal layer and injectites (clastic dikes) at Haycock Mountain near the southern end of the Markagunt mega-landslide. Tm (Ti) = Tertiary Markagunt slide (Isom Formation) and Tbh = Tertiary Brian Head Formation.

Crushed and rehealed quartzite pebble.

Grooves and striations at the base of the Markagunt mega-landslide.

Slide surface lined with friction-generated melt rock (pseudotachylyte), also injected as a dike; GPS receiver is about 5 inches (13 cm) long.

About the Author

Bob Biek is a Senior Scientist with the UGS's Geologic Mapping Program, having joined the group in 1996 after four years with the North Dakota Geological Survey. Most of his geologic mapping is in southwestern Utah and along the Wasatch Front, where he has authored over 40 7.5' geologic maps and the St. George, Panguitch, and west half of the Loa 30' x 60' geologic maps. He is continually amazed at what one can learn simply by going outdoors and making a geologic map, and the discovery of Utah's mega-landslides, with colleagues Rowley and Hacker, is a classic case in point. Bob received his B.A. in Geology from the University of California at Berkeley in 1983 and a M.S. in Geology from Northern Illinois University in 1987. Photo by Steve Ruth.

The Uinta-Tooele structural zone–what's in a name?

by Donald L. Clark

Lying beneath our feet near the latitude of Salt Lake City is a long-lived and important east-west-trending structural zone and associated igneous and mineral belt that crosses Utah. This zone of crustal weakness allowed igneous rocks to migrate to the Earth's surface along with important metallic mineral resources. Recognized for nearly a century, this linear crustal feature has been assigned a litany of names, including the Bingham–Park City uplift, Uinta axis, Cortez–Uinta axis, Uinta–Gold Hill trend, Uinta arch, Uinta–Cottonwood arch, Bingham–Gold Hill mineral trend, Oquirrh–Uinta mineral belt, and Oquirrh–Uinta transverse zone. The proliferation of names may be due to which part of the proverbial elephant a geologist was studying. Decades of geologic mapping and research have clarified parts of the Uinta–Tooele structural zone (UTSZ)—our preferred name.

Location

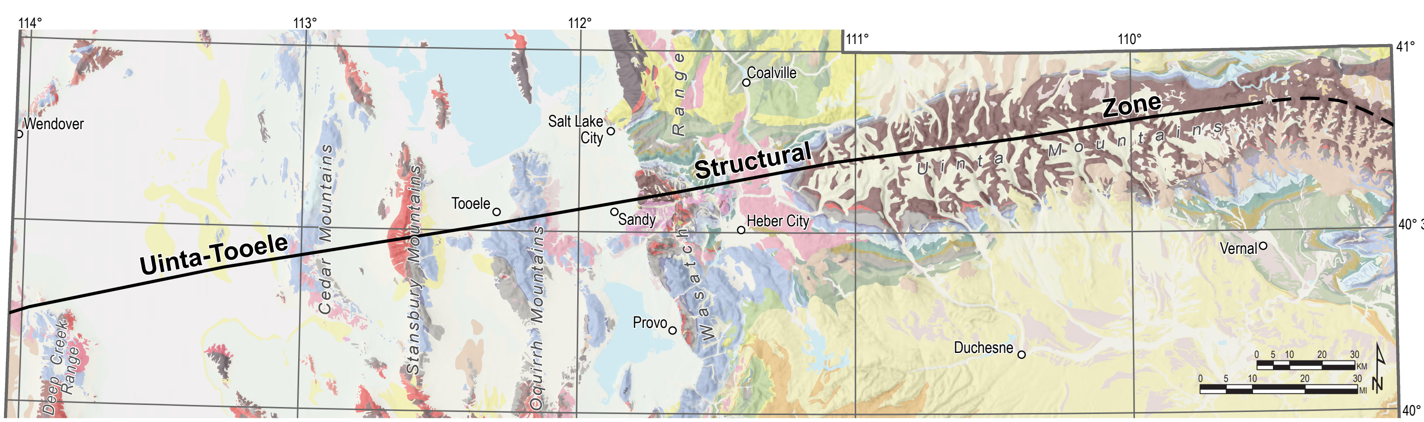
From east to west, the UTSZ stretches across the Middle Rocky Mountain and eastern Basin and Range Provinces. The zone likely begins in northwestern Colorado, includes Utah's Uinta Mountains (see *Survey Notes*, v. 50, no. 3, p. 1–3), and extends westward through the Park City and Cottonwood areas of the Wasatch Range (see *Survey Notes*, v. 50, no. 3, p. 4–5). Astute geologists recognized that the zone traverses across Salt Lake Valley to the Oquirrh Mountains and Bingham mining district. West of Bingham the zone continues across Tooele County and the Stansbury and Cedar Mountains (see *Survey Notes*, v. 49, no. 2, p. 1–3) to Gold Hill of the northern Deep Creek Range. The UTSZ likely trends into eastern Nevada (Ferber Hills and Kinsley Mountains area) where it is obscured by younger deposits and rocks and older structural features before dying out near the edge of the ancient Precambrian continent.

Lines of Evidence

Geologists were able to piece together the story of the UTSZ using several lines of evidence as follows.

Suture in Precambrian Basement: Geologists have long recognized that Salt Lake City lies near the "sutures" of several Precambrian basement provinces. About 1.7 billion years ago (Ga) two continental blocks from the south called the Mojave and Yavapai Provinces collided with parts of the Archean (older than 2.5 Ga) North American continental core called the Wyoming Province and Grouse Creek block (with a messy younger zone between called the Farmington zone). This east-west suture zone is named the Cheyenne belt. In the Utah area, the western part of this belt became a zone of structural weakness that strongly influenced future tectonic events.

Structural Basins and Uplifts: The rocks that now make up the Uinta Mountains formed when an immense amount of Neoproterozoic-age (750 million years [Ma]) sediment from rivers collected in a failed rift (tectonic spreading center) and gradually lithified. In the later Neoproterozoic, these basin rocks were uplifted and mostly eroded prior to deposition of Cambrian-age rocks. Mapping and stratigraphic studies have shown that this structural zone appears to have been intermittently active as tectonic upwarps, including the Ordovician-age Tooele arch (Tooele County area, 465 Ma) and later as the Devonian-age Stansbury uplift (Stansbury Mountains area, 370 Ma). The tectonism is indicated by key unconformities and coarse clastic rocks. The Uinta Mountains may preserve evidence of uplift as part of the ancestral Rocky Mountains (300 Ma). Evidence also shows that much later some of the large eastward-directed thrust sheets of the Sevier orogeny were bent and rotated as they slammed into the uplifted Oquirrh and Uinta Mountains in the Cretaceous–early Tertiary (100–50 Ma) (see for example, 30' x 60' geologic maps of the region and specifically the Mt. Raymond thrust area



Geologic map of Utah between 41° and 40° north latitude showing topography and location of the Uinta–Tooele structural zone (UTSZ). The pink and red polygons along the UTSZ are the igneous centers and associated mining districts. From Hintze and others (2000), UGS Map 179DM; for explanation of map units see https://doi.org/10.34191/M-179dm.

depicted on the Park City West quadrangle, UGS OFR-697DM). As deformation proceeded eastward during the Laramide orogeny (70–35 Ma), the Uinta Mountains were uplifted again as evidenced by thinning in Mesozoic rocks, forming the mountains we love today. More recent tectonic activity may be associated with Tertiary extension and lowering of the eastern Uinta Mountains (25 Ma to present).

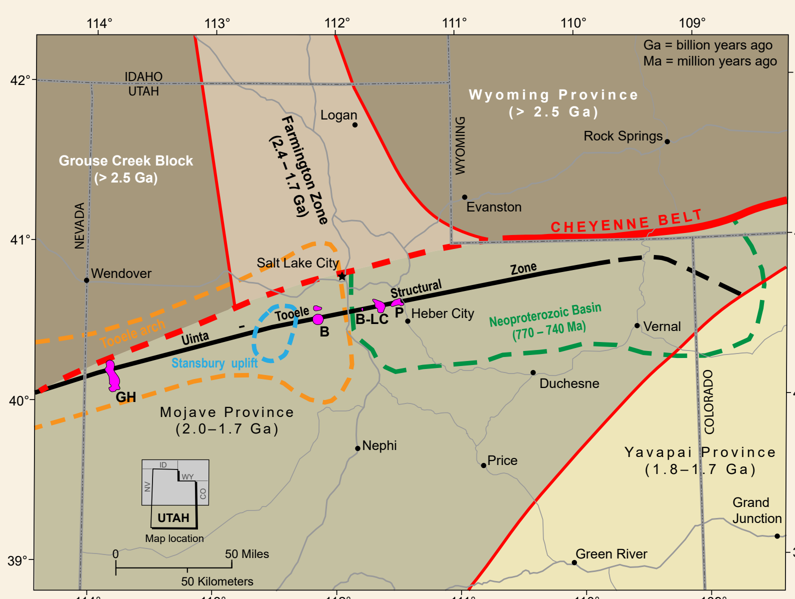
Igneous Activity: Crustal weakness in the UTSZ was a conduit for igneous rocks. Although intrusive igneous rocks are rare in the Uinta Mountains, a number of intrusive centers occur westward along the linear trend. The Park City porphyries, Park Premier porphyry, and Indian Hollow plug are in the Park City area. Farther west, the Alta, Clayton Peak, and Little Cottonwood stocks are in the Wasatch Range. The Bingham and Last Chance stocks are in the Oquirrh Mountains. Stockton has the Spring Gulch and Soldier Canyon stocks. South Mountain contains a few small basaltic dikes. The Stansbury Mountains have small rhyolitic intrusions and rhyolitic to intermediate extrusive rocks. The Cedar Mountains have rhyolitic to intermediate extrusive rocks and a small rhyolitic plug. An Eocene intrusion occurs at Gold Hill, along with an older Jurassic-age stock. Quartz monzonite stocks are noted in the Ferber-Kinsley area of eastern Nevada. These igneous rocks are associated with the wave of volcanism that swept north to south through Utah in Eocene to Oligocene time (about 40 to 23 Ma). Associated with the intrusives are the major mining districts of Park City (metal resources of silver, lead, gold, zinc) and Bingham (copper, gold, molybdenum), as well as the smaller districts of Big and Little Cottonwood (silver, lead), American Fork (gold, lead, silver), Stockton (lead, silver, gold, zinc), Gold Hill (arsenic, gold, silver), and several others.

Geophysical Data: In further support of the influence of the UTSZ, an alignment of magnetic rocks associated with the UTSZ is shown through aeromagnetic geophysical data obtained by airplane. This alignment is indicated by a patchy narrow magnetic high with several individual smaller highs, some elongated, that overlie exposed intrusive igneous rocks or postulated buried intrusive masses.

Topography: The UTSZ is readily apparent as the elevated spine of the Uinta Mountains, with numerous peaks exceeding 13,000 feet, one of the few east-west-oriented ranges in Utah. The zone continues through the Cottonwood area of the Wasatch Range (10,000–11,000-foot peaks). In the Basin and Range it follows elevated points of the Oquirrh and Stansbury Mountains (10,000–11,000-foot peaks) and crosses the dogleg of the lower-elevation Cedar Mountains and northernmost Deep Creek Range.

Summary

The Uinta–Tooele structural zone, previously known by several names, impacted the northern Utah area in several ways. Together, lines of evidence point to the existence of a substantial, weak, linear crustal feature that has been intermittently active over about 2 billion years of geologic time. This structural zone has been the location for both uplifts and basins. Key metallic mineral resources are associated with igneous rock masses brought to the Earth's surface through this zone of crustal weakness. Ongoing work by UGS and other geologists is helping to clarify the story of the UTSZ. This work provides insights into the area's geologic history and occurrence of valuable mineral resources.



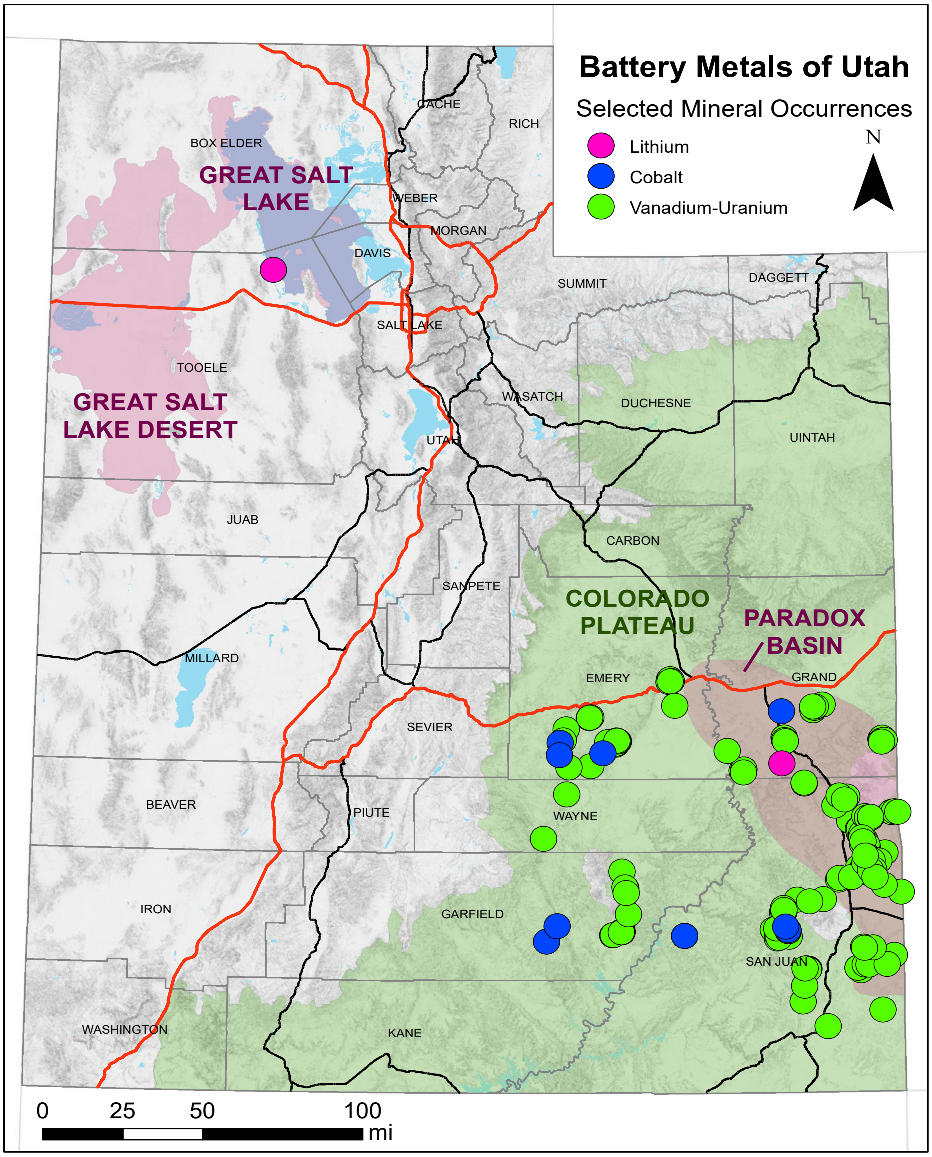
Precambrian basement provinces across northern Utah (note sedimentary cover rocks and surficial deposits are stripped away). Younger provinces (Mojave and Yavapai) were accreted (sutured) to the older continental core (Wyoming Province and Grouse Creek Block) across the Cheyenne Belt and a poorly defined westward extension through Salt Lake City. The resulting Uinta–Tooele structural zone (UTSZ) lies along this ancient area of weakness. The Farmington zone represents complications in the Precambrian accretionary tectonics of this area. The eastern part of the UTSZ contained a Neoproterozoic basin that was uplifted in the later Neoproterozoic and again in the late Paleozoic and early to middle Tertiary. The western part of the UTSZ contained uplifts called the Tooele arch and the Stansbury uplift, and igneous intrusions and related mining districts including Gold Hill (GH), Bingham (B), Big and Little Cottonwood (B-LC), and Park City (P).

Increased battery demand spurs interest in Utah's metallic resources

by Stephanie Mills

The term "battery metals" has come to prominence rapidly over the past five years, and refers to a category of resources that have become essential to powering our increasingly electrical world. Battery metals power our cell phones, laptops, and a growing fleet of electric vehicles, and play a role in bringing renewable energy into our homes. The International Energy Agency reports that in 2018 the global stock of electric passenger vehicles passed 5 million and is projected to exceed 130 million in 2030. The U.S. Energy Information Administration projects that renewables will account for a quarter of global energy consumption by 2040 and nearly half of electricity generation by 2050. Despite fluctuating prices, the case for increased demand of battery metals is strong, and explorers for these metals are active globally, including in Utah.

Lithium is perhaps the best known battery metal, as it is the essential component to the lithium-ion batteries that power everything from cell phones to electric vehicles. The leading global producer of lithium is Australia, mining lithium from hardrock sources such as igneous pegmatites. Chile is the second largest producer and has the largest reserves of lithium globally. Chile's reserves are found in brines, and, in fact, the Salar de Atacama alone accounts for over 35 percent of global lithium reserves ("salar" is Spanish for salt flat). Utah is known for Great Salt Lake (GSL) and extensive salt flats (e.g., Great Salt Lake Desert), so it may seem intuitive that there is lithium-producing potential similar to the Chilean salars. In actuality, GSL brines and the salt flats have lower concentrations of lithium and a higher ratio of magnesium to lithium than found in Chile, making the economics of lithium processing more costly. Lithium produced as a byproduct of magnesium recovery, such as U.S. Magnesium's operation on the GSL south arm, is the most likely source of lithium production

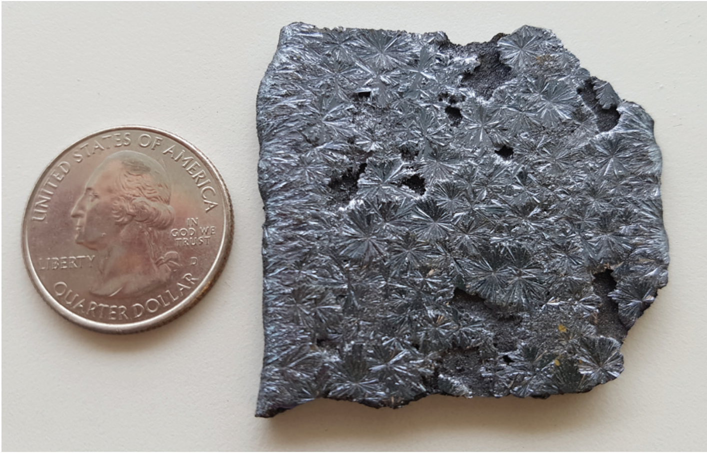


Significant lithium, cobalt, and vanadium-uranium occurrences in Utah.

from surface and shallow subsurface brines and salts in Utah. In the Paradox Basin in southeastern Utah, Anson Resources is testing the lithium potential of deep brines extracted from historical oil and gas wells. The current resource estimate for the Paradox Basin Brine Project is about 397 million brine tons at 98 ppm lithium, which equates to 205,500 recoverable tons of lithium carbonate equivalent plus byproduct bromine, boron, and iodine.

Cobalt is another battery metal that has received increasing attention over the past three years. Cobalt is used as a cathode in many types of batteries, including lithium-ion batteries. Currently, the majority of cobalt is mined in the Democratic Republic of Congo (DRC), which accounts for 60 percent of global cobalt production. The responsible sourcing of cobalt has received significant attention in recent years, with particular focus on the health consequences and child labor associated with cobalt mining in the DRC. The pressure for modern companies to have a transparent and ethical supply chain has led to greater interest in cobalt in other parts of the world. In Utah, cobalt is not a primary exploration target but is considered a valuable byproduct, occurring mainly in sediment-hosted copper and uranium deposits. The Copper Ridge project in Grand County is a sediment-hosted copper project targeting shallow oxide copper occurrences, and samples from the project have returned cobalt values up to 0.83 weight percent. Though copper is the main commodity, the cobalt could add significantly to the economic potential of the project.

Vanadium is an increasingly recognized battery metal. Whereas lithium and cobalt are linked more closely with the electric vehicle industry, vanadium is associated with the renewable energy movement. Vanadium redox-flow batteries (VRBs) are high-capacity batteries meant for large-scale energy storage applications, such as ensuring constant baseload energy during periods of low energy generation from renewables like wind and solar (e.g., on still or cloudy days). Although the majority of vanadium is still used for metallurgical purposes such as high-strength low-alloy steel, VRBs are poised to become a significant element in the modern energy landscape. Globally, the largest source of vanadium is from titaniferous magnetite deposits in China, Russia,



Refined vanadium ("black flake") from the White Mesa Mill in Blanding, Utah.

and South Africa, but the Colorado Plateau has been an important producer of vanadium from sediment-hosted uranium deposits since the early 1900s. During the Atomic Energy Commission's procurement program from 1947 to 1970, Utah produced approximately 12.5 million tons of ore averaging 0.65 percent V_2O_5, the equivalent of almost 62.5 million lbs V_2O_5. Energy Fuels' White Mesa Mill in Blanding remains the only operating conventional uranium and vanadium mill in the United States, though there is no current uranium or vanadium mining in Utah. In 2018, the mill upgraded its vanadium production capabilities and has been producing vanadium from stockpiles and alternate feeds since early 2019. The Beaver and Pandora uranium-vanadium mines, also owned by Energy Fuels, operated as recently as 2012, and increased demand for vanadium (and/or uranium) would likely see active mining resume.

As the battery industry matures, other metals, such as manganese and graphite, may become increasingly important. Utah remains one of the most favorable exploration and mining jurisdictions in the United States, and as host to three distinct physiographic provinces (Basin and Range Province, Colorado Plateau, Middle Rocky Mountains) is prospective for a wide variety of metallic resources.

For more information on battery metal mining and potential in Utah, see the Utah mining reports and the upcoming *Critical Minerals of Utah* publication, which can be found through the UGS publication page (https://geology.utah.gov/map-pub/publications/).

Glad You Asked

Mirabilite crystals on terraced mound.

What were those strange white mounds along the shores of Great Salt Lake?

by Mark Milligan and Elliot Jagniecki

Last fall Great Salt Lake State Park Ranger Allison Thompson noticed some very unusual white mounds growing on the south shore of Great Salt Lake just east of the Great Salt Lake Marina. She documented and photographed the growth of the mounds for several weeks before curiosity led her to seek a geologist to find out what they were. Utah Geological Survey (UGS) geologists determined the mounds were crystalline terraced spring deposits composed of the evaporite mineral mirabilite. The rarity and beauty of these spring mounds, enthusiasm of Utah State Park officials, and a possible connection to Mars research created a flurry of local, national, and international media attention that included on-air television interviews, as well as web and print articles. The second week of January had maximum media exposure and resulted in the Great Salt Lake Marina reporting 1,870 visitors, compared to 537 in 2019. Below are the most asked questions from the public.

What were the white mounds and when did they form?

In late October 2019, as air temperatures started to cool to near freezing, unique mineral mounds began forming on the south shore of Great Salt Lake. They were not composed of common table salt (sodium chloride—NaCl), but mirabilite (hydrated sodium sulfate—$Na_2SO_4{\cdot}10H_2O$), also known as Glauber's salt.

How did the mirabilite mounds form?

When sodium-sulfate-saturated spring water emerged at the surface and came into contact with the cold winter air, the mirabilite crystals formed and built up into mounds. Spring water that slowly flowed and cascaded down the slope of the mound formed a collection of small mirabilite crystal terraces, similar in appearance to the travertine rimstone and dam terraces that form at Mammoth Hot Springs in Yellowstone National Park.

What conditions were needed for the mounds to form?

In the 1940s, researchers investigated this area and reported finding a 3- to 6-foot-thick mirabilite layer 30 inches down in the subsurface. Groundwater may have partially dissolved this mirabilite layer, which was then reprecipitated at the surface as the spring water emerged. It is also possible that sulfate-saturated shallow aquifers occur in the area, and, at times, discharge to the surface and precipitate mirabilite. Temperature and relative humidity mainly control the stability of mirabilite crystals. Mirabilite will precipitate and be stable at sub-freezing temperatures in dry environments but will dehydrate as temperatures increase; with high humidity/moisture the mineral can be stable until about 90°F. Because of Utah's dry climate, the impressive clear mirabilite crystals that formed the mounds tend to dehydrate to form a white, powdery, easily erodible mineral called thenardite (Na_2SO_4). Furthermore, the mounds can only form if the area, at an elevation of about 4,194 feet, is above lake level, a rare occurrence until the past few years.

Why were there multiple mounds?

It is hypothesized that as the mounds grew, they eventually sealed off their spring water sources, causing the groundwater to find a new pathway to the surface, and thus, a new mound formed a few dozen yards away. As of January 2020, the beach immediately east of Great Salt Lake marina had as many as five mounds that grew up to 3 feet tall and several yards wide.

How rare are mirabilite mounds?

The mineral mirabilite is quite common and found in saline lakes around the world, including in the north arm of Great Salt Lake, in great abundance. In certain saline lakes, mirabilite crystals form in the water column, float to the surface, and are washed ashore to form a slushy slurry or dune-like accumulations of crystals. Additionally, mirabilite crystals can grow in shallow depressions along the shores of the south arm of Great Salt Lake. However, terraced crystalline mirabilite mounds formed by flowing spring waters are more rare—they have never before been

Drone view of mirabilite mounds on the south shore of Great Sale Lake. Great Sale Lake Marina at top middle of photo. View to the west.

Terraces of a mirabilite mound, south shore Great Salt Lake.

scientifically documented at Great Salt Lake, though we have received reports of casual observers spotting them in the past. Mirabilite-precipitating springs and the formation of terraced mounds have been documented in a few locations such as the Canadian Arctic, central Spain, and the Antarctic. The flurry of media attention around the mounds on the south shore of Great Salt Lake spurred public reports of additional mound sites elsewhere on the shore of Great Salt Lake that UGS geologists are actively investigating. Wherever they are found around the lake, the features are ephemeral; warmer seasonal temperatures turn the mirabilite to the powdery mineral thenardite. Higher lake levels also inundate and destroy them. These features may or may not reform again next winter depending on lake level and spring flow.

Is there a Mars connection?

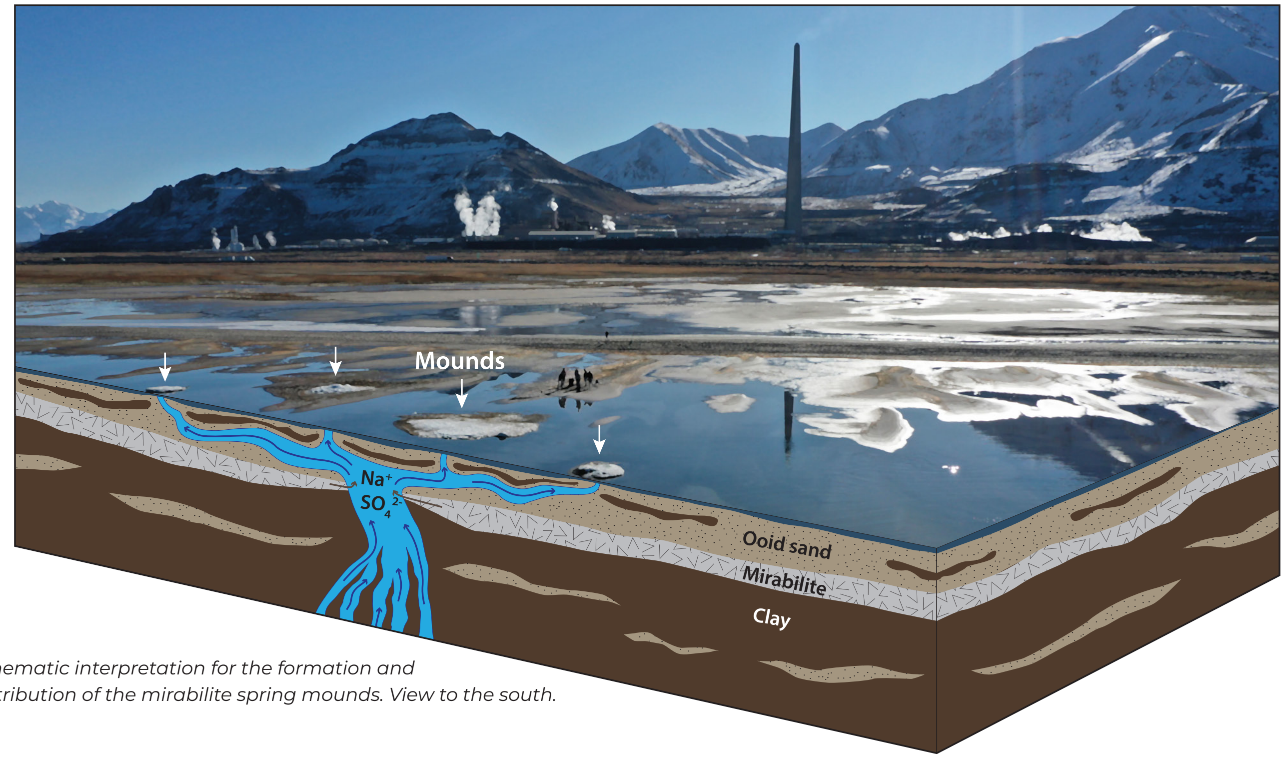
While Mars has conditions conducive to the formation of mirabilite (dry, cold, etc.), the mineral has not yet been documented there. Mars does have topographic mounds that some researchers believe may be related to saline groundwater. In addition, orbital spectrometers have suggested the presence of sulfates on the surface. Because of these similarities, some researchers are interested in the growth of mirabilite mounds on Earth because they may serve as analogues for understanding geologic processes on Mars. Additionally, modern mirabilite mounds are associated with microbial activity, making them especially interesting to researchers looking for evidence of life on Mars.

Don't tread on me.

Mirabilite mounds are fragile. If you find any, please report them to the UGS and do not walk on them or collect samples. Besides, mirabilite is unstable at temperatures above freezing and dehydrates to form a white powder (thenardite), so the samples would not last more than a day.

Want to know more?

UGS geologists are actively studying this phenomenon and our understanding of the mirabilite spring mounds continues to evolve. For more information visit https://geology.utah.gov/popular/general-geology/great-salt-lake/mirabilite-spring-mounds/.



Schematic interpretation for the formation and distribution of the mirabilite spring mounds. View to the south.

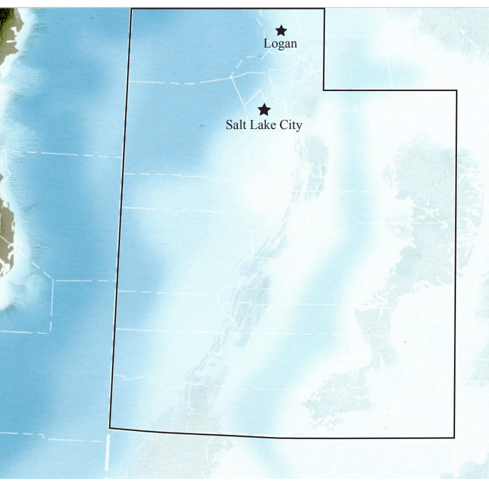
Geosights

Wind Cave, Logan, Utah

Wind Cave, considered an arch, has a "skylight" in the roof. Note person inside cave for scale. View to the northwest.

by Stephanie Carney

Contrary to its name, Wind Cave (sometimes Caves) was formed by water, not wind. This popular hiking destination, also referred to as the Witch's Castle, is in Logan Canyon just east of the city of Logan in Cache County. The cave developed below ground over thousands of years before being exposed along the north side of the canyon. The hiking trail meanders through rocks of the Lodgepole Limestone to where the cave is exposed mid-mountain. A brief journey through the geologic history of the area will shed light on the creation of this well-known landform.

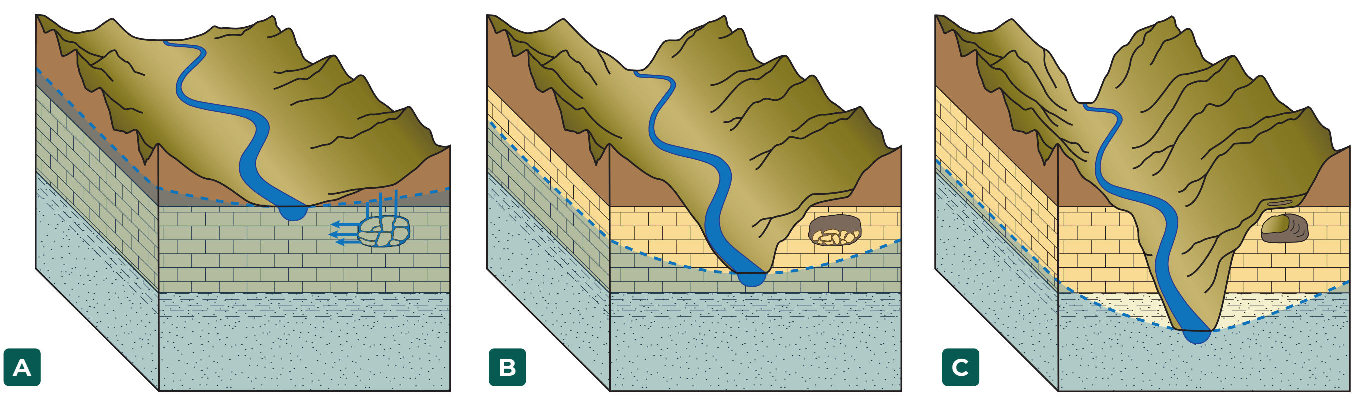


Paleogeographic map of Utah during the Early Mississippian when most of Utah was covered by a warm, shallow sea. map modified from Ancient Landscapes of the Colorado Plateau by Ron Blakey and Wayne Ranney).

The Early Mississippian-age Lodgepole Limestone is a gray, cliff-forming, fossiliferous limestone deposited about 350 million years ago. During this time, Utah was covered by a warm tropical sea and limestone deposition was ubiquitous across the state. Northern Utah was the site of a shallow marine platform home to various creatures like horn coral, crinoids, and brachiopods that are now fossilized in the Lodgepole Limestone.

Long after deposition, burial, and cementation of the Lodgepole, the area underwent tectonic compressional events resulting from the subduction of the Farallon plate (made of thin oceanic crust) beneath the western margin of the North American plate (made of thick continental crust). The Sevier orogeny (i.e., mountain-building event), which began in the Middle Jurassic (about 170 million years ago [Ma]) and lasted into the Eocene (about 40 Ma), deformed and moved Paleozoic through Late Cretaceous-age strata in northern Utah over 30 miles eastward along thrust faults. Rocks in northeastern Utah were further deformed during the Laramide orogeny, beginning in the Late Cretaceous (about 70 Ma) and lasting into the Oligocene epoch (about 20 Ma), which overlapped with the late stages of the Sevier orogeny (for more information on the Sevier and Laramide orogenies see *Survey Notes*, v. 32, no. 1, p. 1–4).

At the future site of Wind Cave, the Lodgepole Limestone and strata above and below were gently uplifted and folded into the broad Logan Peak syncline (trough), the axis of which trends roughly north to south, parallel to the western front of the Bear River Range. When the long-lasting compressional forces abated, the area underwent a westward-



Exhumation of Wind Cave.

A – *The cave develops slowly below the water table (area below dashed blue line) where the rock interacts with flowing groundwater (blue arrows).*

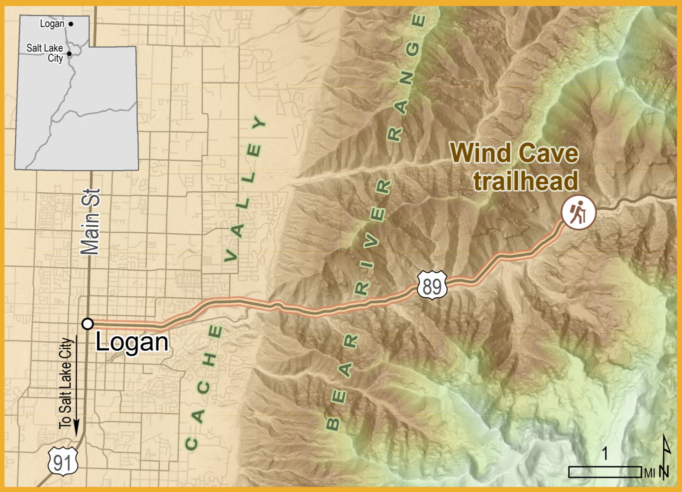
B – *The Logan River erodes down into the valley and the water table lowers.*

C – *Erosion of the canyon walls keeps time with incision of the river and the cave is gradually exposed.*

directed "relaxation," or extension, accommodated by normal faults. This extension caused the crust to "pull apart" resulting in the development of the Basin and Range Province, which is characterized by the repeating ranges and valleys present in the western U.S. today. The Bear River Range, bounded on the west by the East Cache fault zone, began to uplift relative to Cache Valley during this extensional event that started approximately 17 Ma.

Through a combination of tectonic uplift and erosion of overlying strata, the Lodgepole Limestone ended up at shallow depths below the ground surface where it could interact with groundwater, which can dissolve limestone. As rain falls, it absorbs carbon dioxide from the air and as it percolates into the ground, it mixes with carbon in the soil creating carbonic acid, a weak acid. The carbonic acid slowly dissolves the limestone along joints and fractures and between bedding planes. Given enough time, large caverns can form. Once the water table drops below the level of the cavern, stalactites and stalagmites can begin to grow. These speleothems can be dated to gain an idea of when a cave formed.

Although no speleothems are preserved in Wind Cave, a speleothem from a nearby cave in the Tony Grove area was dated at 100,000 years old. Because speleothems develop in a cavern open to air, the caves around Tony Grove, and likely Wind Cave, were above the water table 100,000 years ago and therefore began to form prior to that time. Exhumation and exposure of Wind Cave occurred gradually as the Logan River incised into the canyon and the canyon walls eroded.



HOW TO GET THERE:

From Main Street in Logan, Utah, head east into Logan Canyon on 400 North/U.S. Route 89 for about 7.5 miles. Turn left into the Wind Cave trailhead parking area on the north side of the highway. The trail is 1.8 miles to the cave and gains about 1,000 feet elevation. The climb is moderate to very steep in places and has limited shade. Sturdy walking shoes are essential as are water and sun protection. There are no restrooms at the trailhead, but the Guinavah-Malibu Campground, directly south across the highway, has flush toilets. Dogs are allowed on the trail but must be kept on a leash. The trail is open all year, but is best accessed in March through November.

GPS coordinates: 41°45'44" N., 111°42'13" W

Teacher's Corner

UGA Teacher of the Year

Ms. Rhoda Perkes of Lone Peak High School in Alpine School District is this year's recipient of the Utah Geological Association's (UGA) Utah Earth Science Teacher of the Year Award. Ms. Perkes has taught science for the past five years and uses her role as a facilitator to engage students. She provides ample opportunities for groups of students to conduct research, work with provided data, work through laboratory exercises, and perform other goal-oriented hands-on activities.

Ms. Perkes was awarded $1,500 plus $300 in reimbursements for procuring resources related to earth science education. The science department at Lone Peak High will also receive $300 in reimbursements for procuring resources related to earth science teaching (e.g., materials, field trips, etc.) Additionally, Ms. Perkes is UGA's nominee for the Rocky Mountain Section of the American Association of Petroleum Geologists (AAPG) Teacher of the Year Award. Congratulations Rhoda!

Survey News

Damage to commercial buildings in Magna from the 2020 M 5.7 Magna, Utah, earthquake.

Magna Quake

On the morning of Wednesday, March 18, 2020, northern Utah experienced a magnitude (M) 5.7 earthquake with an epicenter north of Magna, Utah. Field teams of geologists from the Utah Geological Survey (UGS) mobilized to look for evidence of liquefaction, lateral spread, rockfalls, and other geological effects from the earthquake. This was the largest earthquake in Utah since 1992, when a M 5.8 quake struck near St. George.

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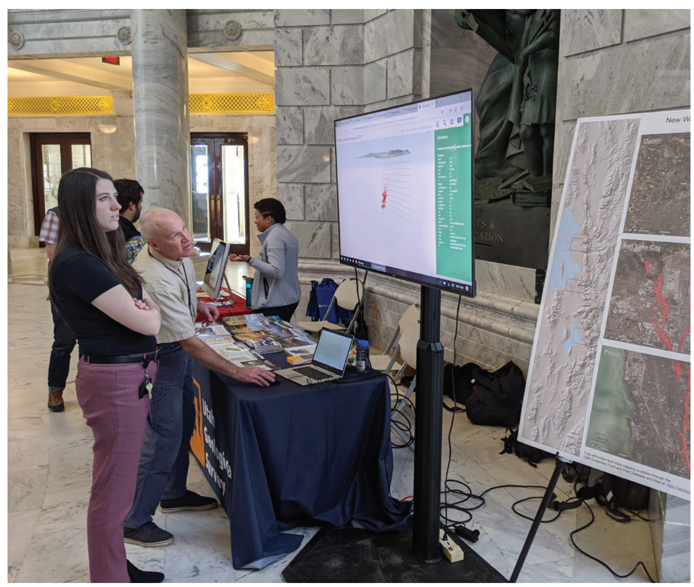
The UGS partnered with the Utah Seismic Safety Commission, Utah Division of Emergency Management, University of Utah Seismograph Stations, Be Ready Utah, and others to create a new website dedicated to providing earthquake information to the public. Earthquakes.utah.gov provides answers to frequently asked questions, important resources for homeowners, scientific information, and much more.

Preparedness on the Hill

UGS geologists from the Geologic Hazards Program were at the Utah Capitol Rotunda on February 27, 2020, participating in the Preparedness Day on the Hill event organized by the Utah Division of Emergency Management. The event highlighted a variety of emergency preparedness issues, including geologic hazards such as earthquakes and landslides.



(Above) GIS Manager Gordon Douglass displays a 3-D visualization of earthquake and aftershock hypocenters. (Left) Hazards Geologist Adam McKean talks about mapping earthquake hazards along the Wasatch Front.

Employee News

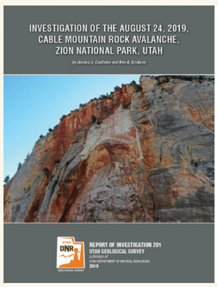
The Editorial Section welcomes **Jackie DeWolfe** as a new graphic and web designer. Jackie has a Bachelor of Fine Arts degree in Graphic Design from St. Cloud State University (SCSU) and over 10 years of experience in graphic and web design. Jackie replaces **Jenny Erickson** who accepted a position in the private sector. A warm welcome to Jackie and best wishes to Jenny!

New Publications

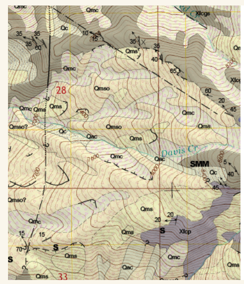
Available for download at ***geology.utah.gov***
or for purchase at ***utahmapstore.com****.*

Great Salt Lake North Arm Salt Crust Monitoring, Spring 2017 Update, by Andrew Rupke and Taylor Boden, 13 p., **OFR-714**, https://doi.org/10.34191/OFR-714

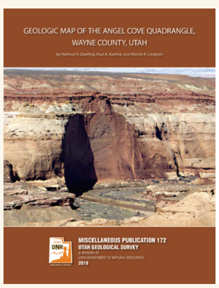
El Ciclo De Las Rocas (Spanish version of Rock Cycle—Always Changing), 27" x 32.5" poster, **PI-101,** https://doi.org/10.34191/PI-101



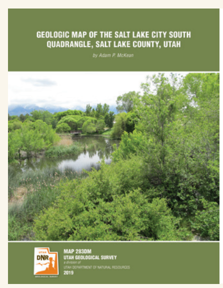
Investigation of the August 24, 2019, Cable Mountain Rock Avalanche, Zion National Park, Utah, by Jessica J. Castleton and Ben A. Erickson, 11 p., **RI-281**, https://doi.org/10.34191/RI-281



Interim Geologic Map of the Bountiful Peak Quadrangle, Davis and Morgan Counties, Utah, by Zachary W. Anderson, 19 p., 1 plate, scale 1:24,000, **OFR-703DM**, https://doi.org/10.34191/OFR-703DM



Geologic Map of the Angel Cove Quadrangle, Wayne County, Utah, by Hellmut H. Doelling, Paul A. Kuehne, and Martin R. Lindgren, 19 p., 2 plates, scale 1:24,000, **MP-172,** https://doi.org/10.34191/MP-172



Geologic Map of the Salt Lake City South Quadrangle, Salt Lake County, Utah, by Adam P. McKean, 13 p., 2 plates, scale 1:24,000, **M-283DM**, https://doi.org/10.34191/M-283DM

Recent Outside Publications by UGS Authors

Stratigraphic setting of fossil log sites in the Morrison Formation (Upper Jurassic) near Dinosaur National Monument, Uintah County, Utah, USA, by **D.A. Sprinkel**, M.B. Bennis, D.E. Gray, and C.T. Gee: Geology of the Intermountain West, v. 6, p. 61–76.

Is a linear or a walkabout protocol more efficient when using a rover to choose biologically relevant samples in a small region of interest?, by R.A. Yingst, J.K. Bartley, **T.C. Chidsey, Jr.**, B. A. Cohen, B.M. Hynek, L.C. Kah, M.E. Minitti, **M.D. Vanden Berg**, R.M.E. Williams, M. Adams, S. Black, M.R. El-Maarry, J. Gemperline, R. Kronyak, and M. Lotto: Astrobiology, v. 20, https://doi.org/10.1089/ast.2019.2095

Exploration in Utah—a look at the past, by **T.C. Chidsey, Jr.**: Rocky Mountain Association of Geologists, The Outcrop, v. 69, no. 2, p. 16–28.

Economic impacts of Utah's energy industry, 2017, by J.C. Downen, T. Holst, and **M.D. Vanden Berg**: Kem C. Gardner Policy Institute, The University of Utah, 26 p.

Biomarker similarities between the saline lacustrine Eocene Green River and the Paleoproterozoic Barney Creek Formations, by K.L. French, J.E. Birdwell, and **M.D. Vanden Berg**: Geochimica et Cosmochimica Acta, v. 274, p. 228–245.

The gigantic Markagunt and Sevier gravity slides resulting from mid-Cenozoic catastrophic mega-scale failure of the Marysvale volcanic field, Utah, USA, by **R.F. Biek**, P.D. Rowley, and D.B. Hacker: Geological Society of America Field Guide 56, 121 p., https://lccn.loc.gov/2019045272.

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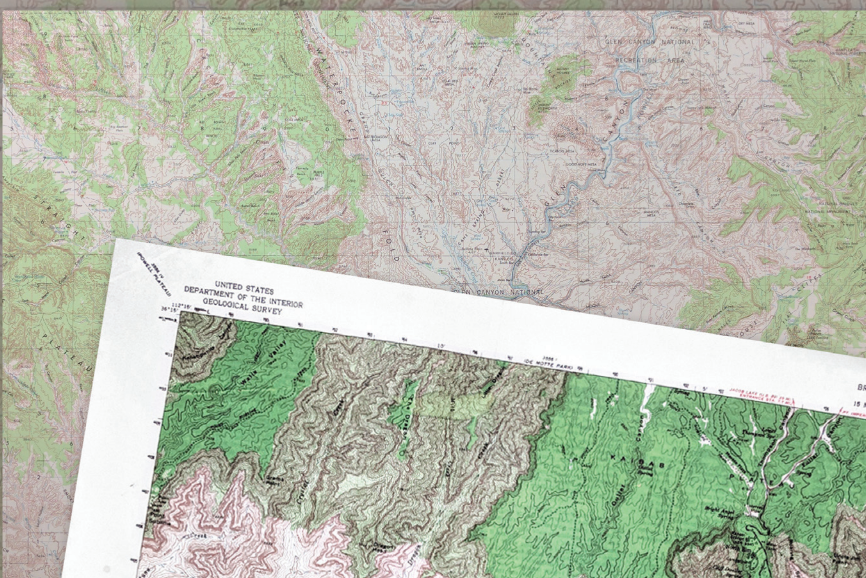

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