U T A H   G E O L O G I C A L   S U R V E Y

SURVEY NOTES

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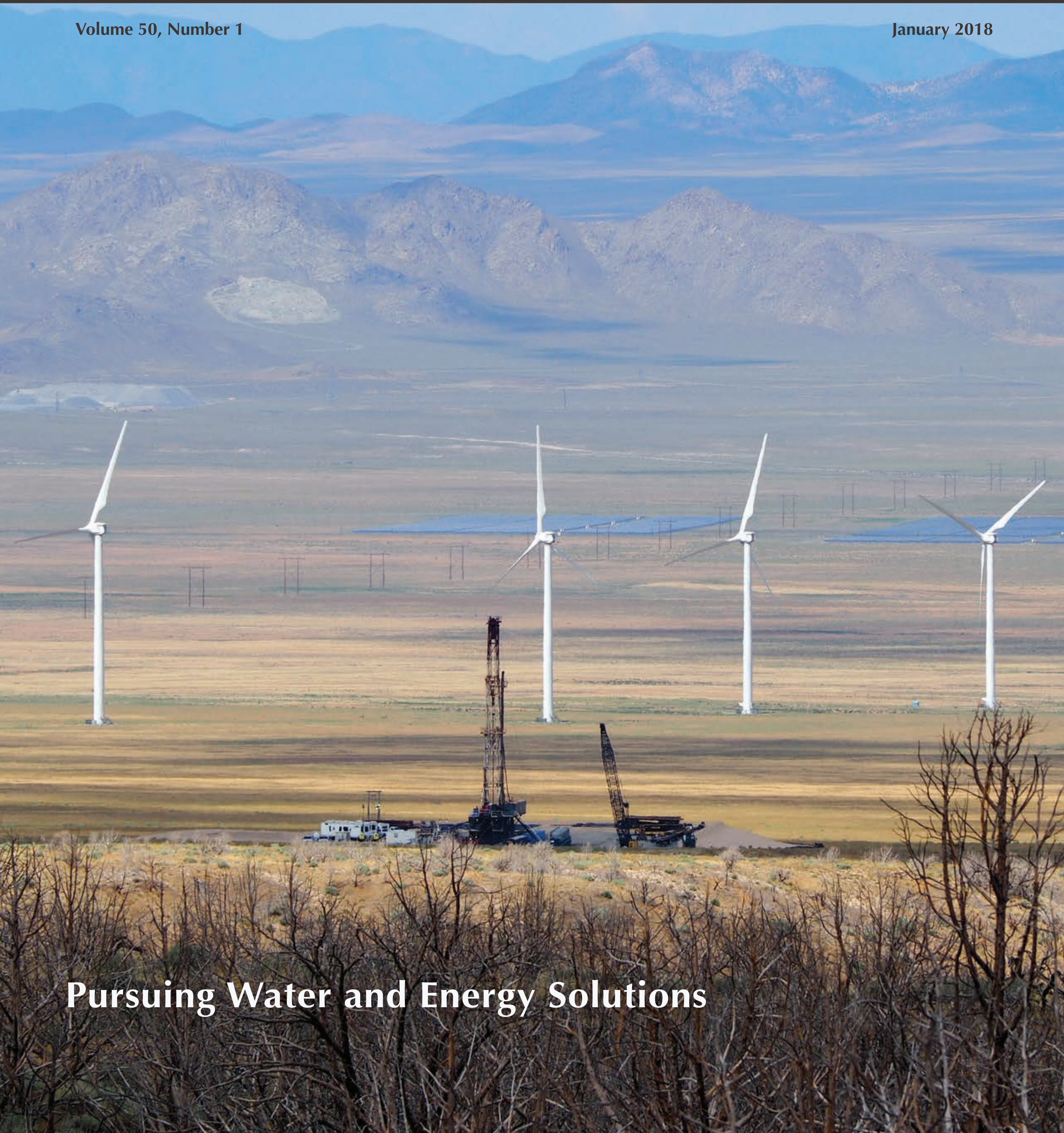

Pursuing Water and Energy Solutions

Contents

Design | *Jennifer Miller*

Cover | View to west across Milford-FORGE drill site. Longroad Energy wind farm and NRG-Dominion PV solar arrays visible in middle distance. Beaver Lake Mountains and quarries, San Francisco Mountains, and Wah Wah Mountains in far distance. Photo credit: Rick Allis

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THE DIRECTOR'S PERSPECTIVE

by Richard G. Allis

By far the largest project that the Utah Geological Survey (UGS) is involved in this year is characterizing the geological setting of the proposed FORGE (Frontier Observatory for Research in Geothermal Energy) site near Milford, Beaver County. The feature article in this issue of *Survey Notes* discusses the groundwater at this site. This project is funded by the U.S. Department of Energy (DOE) with a goal of establishing a field laboratory focused on advancing and developing new technologies for geothermal power generation. Existing geothermal power developments tap natural reservoirs which are fractured and contain high-temperature water (typically more than 150°C, 300°F). However, in many places, including the site near Milford and areas surrounding established geothermal fields, there are large volumes of hot, unfractured rock, and so far, no one has been able to create a fracture network in this "tight" rock. If the rock can be fractured, water can be circulated between injection and production wells, allowing the heat to be swept from the rock. Thermal calculations show that even if only a small fraction of the heat can be accessed, gigawatts of power potential are possible.

DOE has specified that the ideal FORGE site will have low-permeability, crystalline host rock at a temperature of 175°–225°C (350°–440°F) between 1.5 and 4 km depth (5000–13,000 feet). At the time of the last article about this project in *Survey Notes* (v. 48, no. 3), the Milford site was one of five chosen for a desk-top assessment of suitability to be the field laboratory. Since then, the project moved to Phase 2 with two sites selected for field characterization including the drilling of a deep well to prove temperature, depth, rock type, permeability, and stress regime. Milford is one of the sites, and Fallon, Nevada, is the other. The Milford team is led by Dr. Joseph Moore at the Energy & Geoscience Institute of the University of Utah, and the UGS is playing an important supporting role. The UGS has been directly involved in interpreting a new lidar survey revealing subtle faults; remapping the geology and hydrogeology of the Mineral Mountains and adjacent Quaternary deposits; and acquiring a variety of geophysical data from gravity, resistivity, and thermal mapping. The most exciting (and expensive) item was supporting the drilling of an investigation well which ended up going to 2300 m depth (7560 ft). Granitic rocks were encountered from 960 m (3150 ft) to the total depth. No drilling fluid losses occurred, indicating low permeability, as required by DOE. The hole is still recovering from the thermal disturbance caused by drilling, but the bottom-hole temperature 37 days after drilling and testing ceased is 197°C (387°F), and the deep thermal gradient is 70°C/km (3.8°F/100 ft). This site has an ideal thermal regime and rock characteristics to be the field laboratory envisaged by DOE.

DOE plans to announce the winning site in June 2018. The scale of the proposed activities at the winning site is expected to be about $150 million over five years, so this is important not only for the local economy, but also Utah. The UGS will continue to play a supporting role if Milford becomes the chosen site.

Drilling rig at the Milford site. The truck and boom on the left is running a cable down the well to measure temperature during a 24-hour shut-in to allow partial recovery of the thermal regime. Photo credit: Mark Gwynn

GROUNDWATER CONDITIONS

at the Utah FORGE site

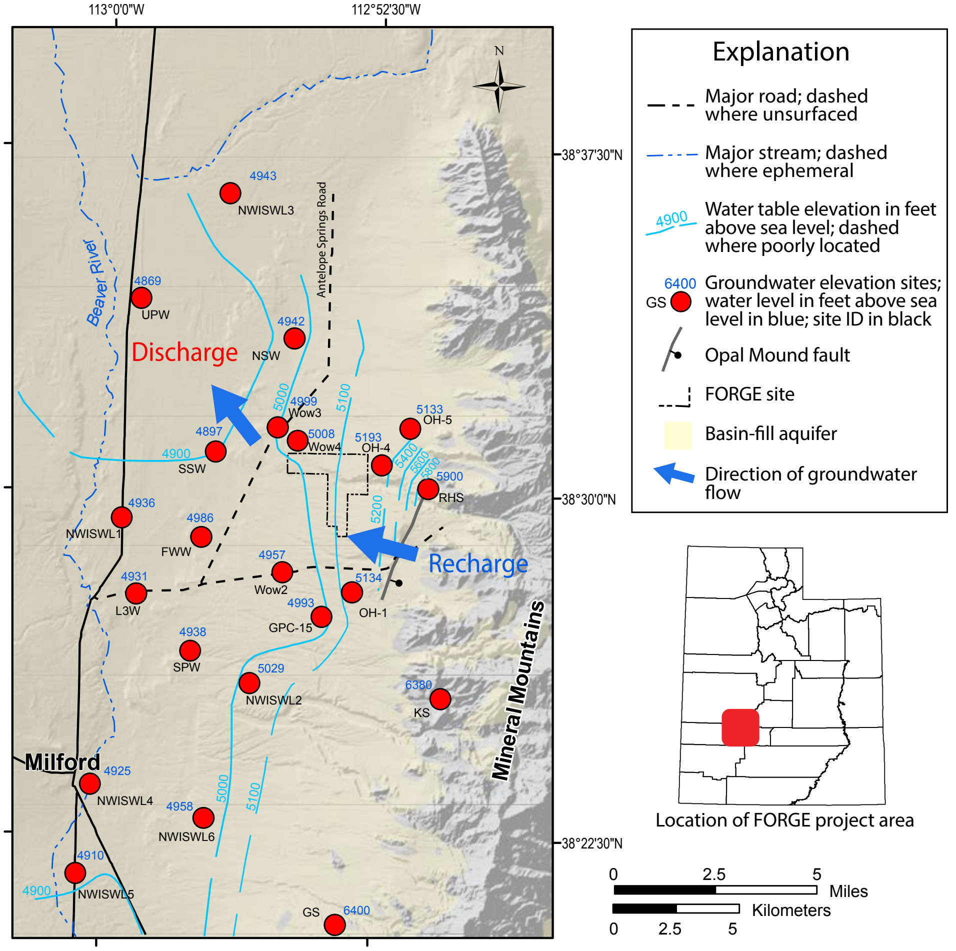
BY Stefan M. Kirby

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) project is a U.S. Department of Energy-funded geothermal energy research project aimed to design and test new techniques for stimulation and development of geothermal resources in hot crystalline rocks (see *Survey Notes*, v. 48, no. 3). These types of rocks (which include granite and various types of metamorphic rock) contain vast amounts of heat at depth throughout Utah and the U.S. Making use of this heat, for power generation or direct heating, has proven difficult because these rocks generally do not produce useable quantities of water to wells. The FORGE project aims to exploit these hot rocks by stimulating (fracturing) them and improving their ability to yield water to wells. For Utah, and particularly Beaver and Millard Counties, the FORGE project is an opportunity to tap into vast new energy and economic resources stored as heat in the earth's crust. The Utah Geological Survey is an important part of the FORGE project team, and work thus far has included characterization of the groundwater near the Utah FORGE site.

The Utah FORGE site is in Utah's arid west desert, eight miles northeast of Milford, near the Beaver-Millard County line. Groundwater in this part of Utah is the primary source for agriculture and drinking water. The FORGE project will also use this groundwater for various phases of drilling, completion, stimulation, and circulation testing. Because the groundwater is important to the local community and agricultural economy and as a supply for the FORGE project, understanding the conditions and chemistry of the groundwater is imperative.

The FORGE project area lies just west of the Mineral Mountains and the Roosevelt Hot Springs geothermal area. The Mineral Mountains are primarily Tertiary-age granitic intrusive rocks, Precambrian-age metamorphic rocks, and Quaternary-age volcanic rocks. Along the western margin of the range, the granitic rocks intrude the metamorphic rocks. The volcanic rocks occur west of the crest of the Mineral Mountains. Unconsolidated basin fill covers the remainder of the study area and consists of alluvial, lacustrine, and fluvial deposits.

Shallow groundwater in the study area resides in an unconsolidated basin-fill aquifer that blankets older rock units including the crystalline basement rocks that host the FORGE reservoir. Based on well logs, unconsolidated basin fill exists in both unconfined and confined conditions in the study area. Unconfined conditions generally exist across the broad alluvial fans that slope westward from the Mineral Mountains. Farther west along the valley floor, the unconsolidated basin fill includes thick layers of clay, which are just over 100 feet thick and may be laterally extensive along the valley axis. The total thickness of the unconsolidated basin-fill aquifer varies from more than 500 feet west of the Roosevelt Hot Springs hydrothermal system to 100 to 600 feet thick along the valley floor.

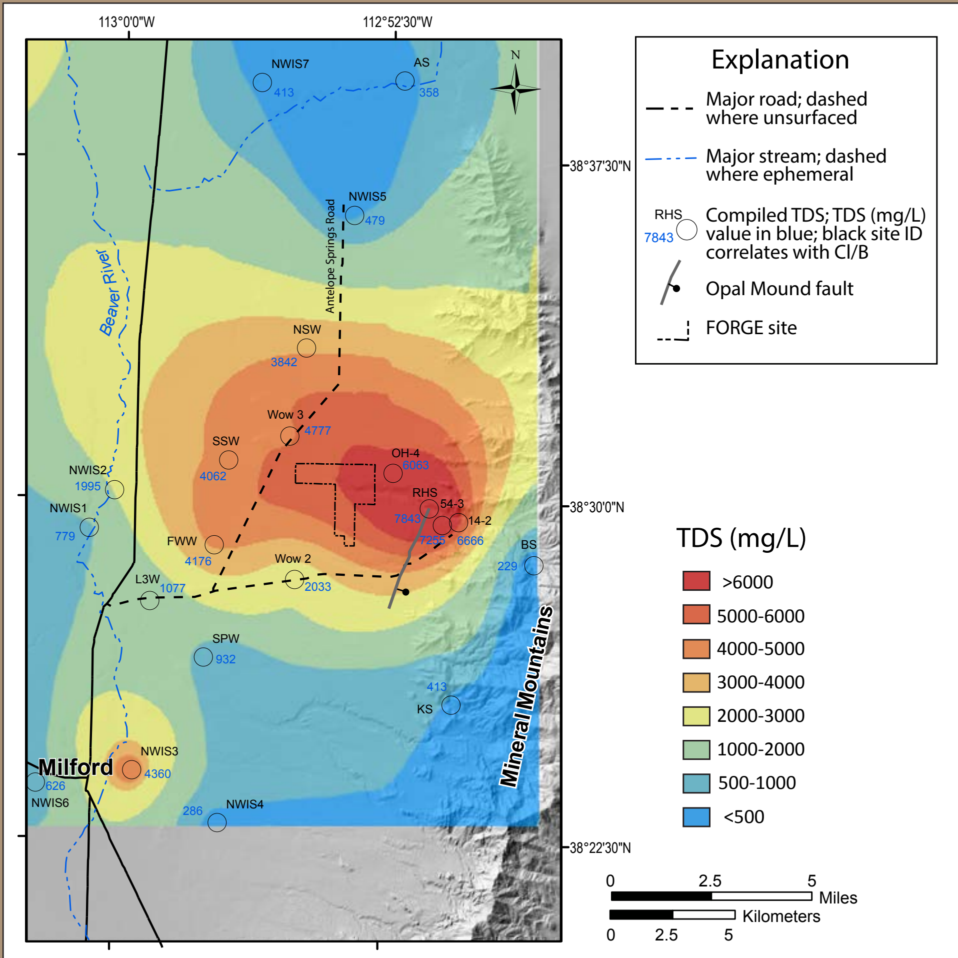


Potentiometric surface map for the Utah FORGE site. Groundwater elevation is highest west of the Mineral Mountains where the basin-fill aquifer receives recharge. Groundwater elevation decreases to the west towards areas of discharge near the Beaver River channel.

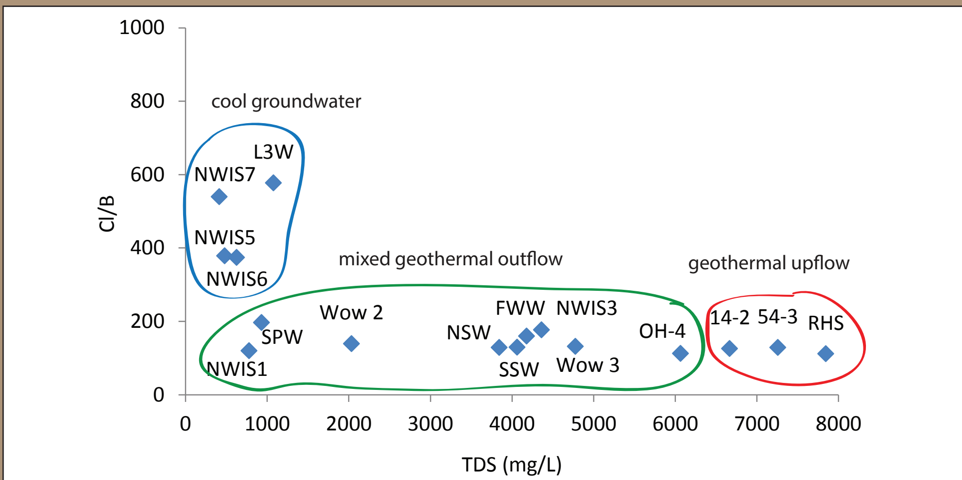
Groundwater generally moves from areas of recharge along the flanks of the Mineral Mountains to areas of discharge along the valley floor. Groundwater elevations decrease to the west away from the Mineral Mountains. Just west of the Opal Mound fault and Mineral Mountains, the potentiometric surface (or groundwater elevation) dips steeply westward and then flattens out towards the center of the valley. The depth to groundwater in the unconsolidated aquifer varies sharply across the study area, decreasing west from the Opal Mound fault. Beneath the FORGE deep drill site, the groundwater elevation is approximately 5100 feet and the depth to water is between 500 and 600 feet.

Groundwater chemistry provides basic information for groundwater quality and fluid flow through the shallow basin-fill aquifer. In the study area, groundwater chemistry indicates both calcium-bicarbonate to sodium-chloride water types. Samples of geothermal fluids from Roosevelt Hot Springs and geothermal production wells at the Blundell power plant are sodium-chloride water type. Nearly all samples, downgradient and to the west of these geothermal samples, share this sodium-chloride chemistry. Two samples from springs in the Mineral Mountains, upgradient of the geothermal samples, are calcium-bicarbonate type, representing non-thermal water. Other calcium-bicarbonate samples are located north of the project area near Antelope Springs and to the south near Milford.

A plume of thermal water having high total dissolved solids (TDS) concentration emanates from the north end of the Opal Mound fault and Roosevelt Hot Springs. This plume broadly defines the area of thermal outflow in which TDS concentrations decrease to the west, north, and south as the plume disperses in the unconsolidated basin-fill aquifer across the FORGE deep drill site. The ratio of chloride to boron (Cl/B) in groundwater beneath the FORGE site, which is uniformly ~100, also indicates the water originates from the active geothermal system at Roosevelt Hot Springs. As TDS decreases due to dilution from east to west, the groundwater Cl/B value remains consistent. The Cl/B ratio rises to 200–700 on the periphery of the outflow plume as the geothermal outflow mixes with cool basinal groundwater. TDS in groundwater beneath and adjoining the FORGE site ranges from 4000 to 6000 mg/L, exceeding the U.S. Environmental Protection Agency's primary and secondary drinking water standard. Therefore, potential use of groundwater in this area for drinking water and agriculture is limited. However, the groundwater is suitable and accessible for use in the FORGE project, and this use will have little impact on agricultural and drinking water used in the valley around Milford.



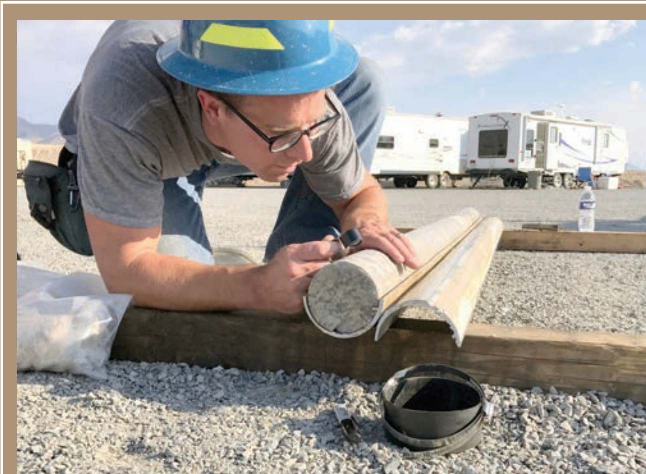
A high-TDS plume extends to the west from Roosevelt Hot Springs (RHS).



Cl/B versus Total Dissolved Solids for groundwater samples near the FORGE site. Most groundwater samples surrounding the FORGE deep drill site have uniform Cl/B values of ~100 (indicative of geothermal upflow) with decreasing TDS resulting from mixing and dilution.

ABOUT THE AUTHOR

Stefan Kirby joined the UGS in 2004 and is a Senior Geologist in the Groundwater Program. He has worked on a wide range of projects that include basin-scale groundwater studies, geologic mapping, oil and gas produced water, and various aspects of geothermal investigations.



The Utah FORGE project took a big leap forward with the drilling of a deep geothermal scientific well. The FORGE team collected two intervals of core, at 6800 and 7440 feet, and cuttings at 10-foot intervals starting at 200 feet through the bottom of the well. These samples will be subjected to an extensive suite of analytical testing to asses the mechanical and thermal properties of the granitic reservoir. Top photo, UGS geologist Stefan Kirby has a close look at the recently collected core. Bottom photo, geologists discuss plans for testing the core.

Monroe's *"Sweet"* Groundwater Points to Contamination Source

BY J. Lucy Jordan

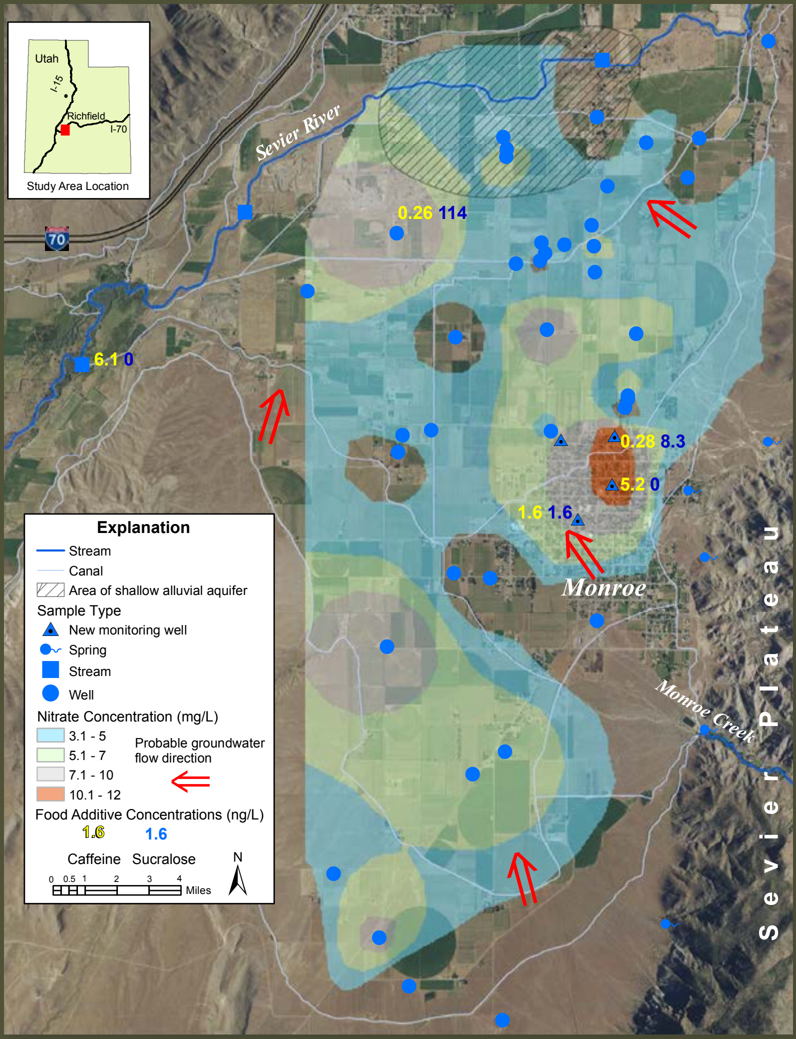
The Utah Geological Survey Groundwater Program recently used a multi-tracer approach that included caffeine and artificial sweeteners to identify sources of elevated nitrate in groundwater near the central Utah community of Monroe City. The U.S. Environmental Protection Agency warns that drinking water having nitrate concentrations greater than 10 milligrams per liter (mg/L) can be hazardous to human health. Previous work had revealed nitrate concentrations as high as 8 mg/L in domestic wells north of Monroe. Agriculture and septic tank leachate are the top two suspected sources for nitrate since most land in the Monroe basin is used for agriculture, which includes a sizeable dairy operation, and all rural and city residents (approximately 2300 people in a one-square-mile area of town) use septic tanks for wastewater disposal.

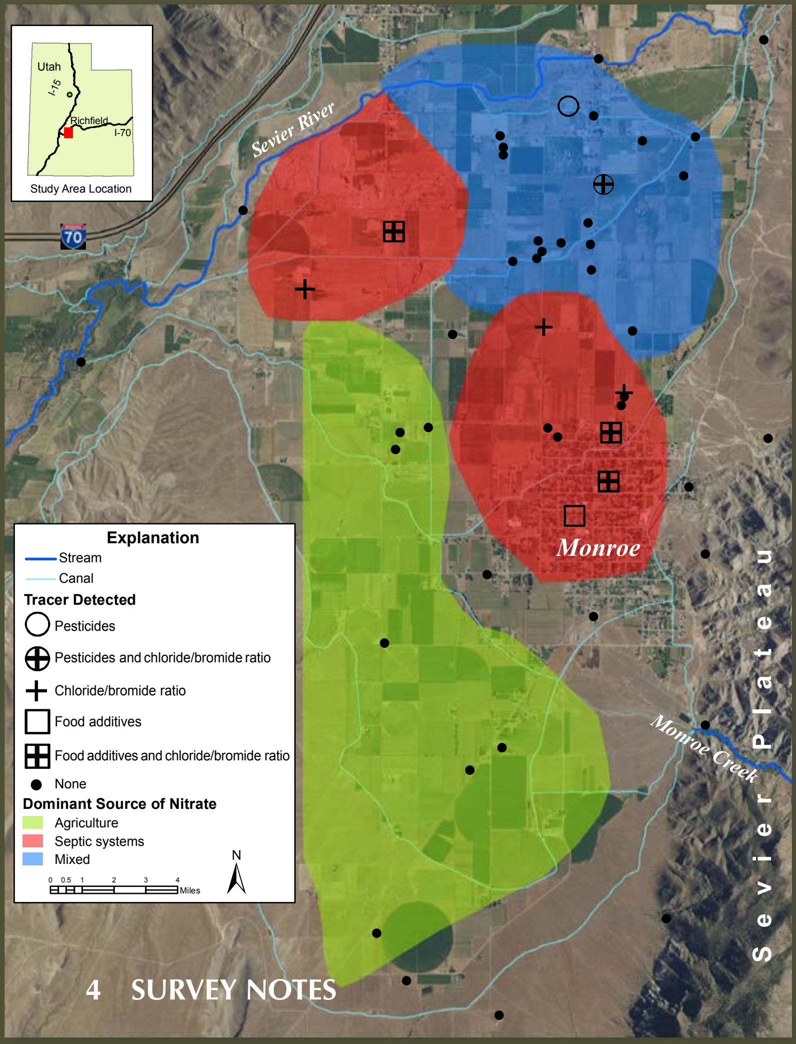
Most wells in the valley pump water from an unconfined aquifer composed of interbedded valley-fill sediments. Depth to the aquifer is generally between 40 and 200 feet. A sequence of coarse-grained alluvium up to about 120 feet thick near the Sevier River contains a separate shallow aquifer, in which the depth to water is commonly less than 15 feet. Recharge from the Monroe Creek alluvial fan, leakage from canals and irrigation ditches, and irrigation infiltration drive the generally northward-flowing groundwater system.

To pinpoint the source of nitrate, we drilled and installed four new monitoring wells into the top of the valley-fill aquifer underlying Monroe City. We found no evidence of perched groundwater underlying Monroe in the new wellbores, despite the presence of a seemingly continuous silty clay identified in each wellbore. Lack of perched water at the end of the irrigation season likely indicates that surface recharge and infiltration can travel downward 60 to 80 feet to the valley-fill aquifer.

We sampled the new wells, plus existing wells, springs, and surface water sources for general chemistry and a suite of human-derived markers. Our approach combined nitrate distribution with chloride distribution; the occurrence of coliform bacteria (an indicator of surface influence), agricultural pesticides, caffeine, sucralose (an artificial food sweetener), and common human and livestock pharmaceuticals; and chloride-to-bromide mass ratios to trace nitrate to its source. Chloride-to-bromide ratios can be used as a tracer because

UGS oversees drilling on one of four new monitoring wells in Monroe City.





the ratio in septic-tank leachate is higher than in livestock waste or fresh water due to salt in the human diet.

The best quality groundwater is near the mouth of Monroe Canyon and south of irrigated cropland; conversely, water quality is poorest under Monroe City. The low level of nitrate in mountain springs and wells upgradient from developed areas indicates that nitrate from geologic sources is not a contributor to nitrate in Monroe basin groundwater. The two primary irrigation water sources for agriculture are the Sevier River and Monroe Creek, both of which have lower levels of total dissolved solids and nitrate than most of the groundwater in the basin.

Groundwater quality in most wells in the Monroe basin shows impact from human activities. The average nitrate concentration in wells sampled for this study, excluding background wells, is 6.5 mg/L, a level indicating an average of 3.5 mg/L impairment above background due to human activities. The presence of coliform in some wells, all of which have elevated nitrate, suggests that surface influence, whether from septic tanks or agriculture, may be reaching the aquifer.

Septic tanks are the most likely source of water-quality degradation underlying and northwest of Monroe City based on (1) nitrate near and above the primary drinking water standard (concentrations from 7.0 to 11.8 mg/L); (2) the occurrence of caffeine and sucralose at the top of the aquifer; (3) chloride-to-bromide mass ratios that are suggestive of human sewage; and (4) trace amounts of ammonia and nitrite, common in systems where ammonia in septic-tank leachate is converting to nitrate. Although present in quantities that are over a million times less than those needed to give Monroe's water that "sweet caffeine kick," caffeine and artificial sweetener at the top of the water table underlying Monroe is a strong indication that the high density of septic tanks is impacting groundwater quality.

Nitrate in groundwater south and west of Monroe is elevated above background levels. Here, septic tanks are widely dispersed and irrigated farming and livestock management are widespread. Chloride-to-bromide mass ratios in groundwater in this area are not indicative of human sewage, and food additives and pharmaceuticals that may be present in human waste were absent. The most likely source of elevated nitrate in this area is runoff and infiltration of irrigation water from fields fertilized with manure or chemical fertilizer, and/or infiltration and runoff from livestock pens and waste containment pits.

Chemical signatures in groundwater north of Monroe point to mixed sources of water-quality degradation. Indicators of septic-tank influence (chloride-to-bromide mass ratios) and agricultural influence (pesticides) do occur, but most wells show neither of these markers. Groundwater flow in the valley-fill aquifer likely carries contaminants northward from the agriculture-dominated south and west areas and the septic-system-dominated Monroe area to mix with local septic-system and agricultural contaminants in this area.

Water managers and residents can use the information provided by this study to protect the area's groundwater resources from further water-quality degradation.

Upper Map: *Groundwater flow direction, sample locations, nitrate distribution, and food additive concentrations in the Monroe basin. Median caffeine and sucralose concentrations in septic-tank effluent are typically around 50,000 ng/L.*

Lower Map: *Multi-tracer "hits" and likely sources of nitrate contamination in the Monroe basin.*

MONITORING GROUNDWATER RESPONSE
to Large-Scale Juniper Treatments

BY Hugh Hurlow, J. Lucy Jordan, Stan Smith, and Emily Keller

Beginning in the late 1800s in the Great Basin and east-central Utah, pinyon-juniper forests encroached downward from their original extent in the mountain ranges to cover much of the mountain front areas. The encroachment has been attributed to fire suppression, climate change, and land-use practices. Effects of these extra trees include increased wildfire hazard, reduced grazing forage, reduced sage-grouse habitat, reduced spring flow, and deeper groundwater tables. To mitigate these environmental problems, federal, state, and private cooperators in Utah and other Intermountain West states are conducting extensive pinyon-juniper treatment (i.e., cutting) projects. The treatments aim to increase sage-grouse habitat, reduce wildfire risk, and improve grazing for wildlife and livestock. Project proposals commonly cite increased shallow groundwater and spring flow as additional benefits. The Utah Geological Survey Groundwater Program has begun a five-year project, funded by Utah's Watershed Restoration Initiative, to monitor the response of groundwater and wetland vegetation to pinyon-juniper treatments.

In spring 2017, we began the project in northwestern Tintic Valley, about 50 miles south of Tooele and 10 miles north of Little Sahara Recreation Area. The area includes a 1-mile reach of perennial flow along Death Creek, and four springs. We will monitor spring flow, surface water flow, groundwater levels, groundwater chemistry, soil moisture, aquatic vegetation, and upland vegetation in two planned treatment areas and two control areas. The basic hypothesis is that groundwater recharge and resultant soil moisture, spring flow, and stream flow will increase in the treatment area due to succession of sage and grass having lower water use than the juniper forests, whereas similar changes will not be observed outside the treatment area. Vegetation monitoring will be conducted to test the hypothesis of increased wetland extent and to provide habitat data to compare with sage-grouse monitoring data collected by Utah State University. Monitoring in control areas having similar topography and hydrology to the treatment areas will enable us to distinguish variations in spring flow, groundwater levels, and soil moisture due to climatic variation from those resulting from the treatment. Climate will be monitored using data from an existing station operated by the U.S. Bureau of Land Management. Pre-treatment monitoring will establish baseline conditions and the hydrological response to climatic variations. Post-treatment monitoring will quantify changes that result from the treatment. Vegetation monitoring will focus on possible expansion of current wetlands adjacent to springs and Death Creek, and on succession of pinyon-juniper forest by sage and grasses. Chemical and isotopic sampling of springs and wells will help detect possible changes in local recharge rates.

Monitoring of spring and stream flow by hand began in spring 2017, as did chemical and isotope sampling. We have identified gaining and losing reaches along the stream and an abrupt change in stream chemistry that likely corresponds to groundwater inflow. Spring flow decreased slightly over the summer, suggesting seasonal variation and, therefore, sensitivity to climatic fluctuations and annual recharge. Installation of piezometers, soil moisture-monitoring sites, flumes, and vegetation transects occurred in fall 2017. During the next few years, we anticipate learning how seasonal and annual precipitation and climate variations affect the groundwater system, and how the surface water–groundwater system functions. After the treatment in 2020, we will look for changes in these patterns that reflect increased recharge in the treatment areas.

Newly installed monitor well near the Mud Spring 1. This well is in a control area and will be used to determine if changes in groundwater are related to pinyon-juniper treatment or climate variation.

TEACHER'S CORNER

FREE PROFESSIONAL DEVELOPMENT OPPORTUNITY FOR UTAH TEACHERS

In conjunction with the American Association of Petroleum Geologists' (AAPG) Annual Convention and Exhibition in Salt Lake City, the AAPG presents a free Earth Science Educator Program highlighting the rocks, landforms, and geologic history of Utah by way of a workshop and field trip along the foot of the central Wasatch Range. Participants will receive 8 hours of relicensure credit, a classroom-ready rock kit with large specimens of each rock type, and locally-oriented supplementary educational materials.

The program is directed toward the 4th, 5th, and 7th grade Utah Science Core Standards for Earth science and will be led by Utah Geological Survey geologists. Space is limited and will be filled on a first-come, first-served basis for actively employed school teachers and specialists. Educators from grade levels not specified will be placed on a waiting list and contacted as space is available. Stipends for long-distance travel may be available.

Date: Saturday, May 19, 2018
Time: 8:30 a.m. to 4:30 p.m.
Location: Utah Department of Natural Resources Bldg,1594 W. North Temple, SLC, UT
Registration deadline: April 5th, 2018

For registration information and other questions, please contact Jim Davis at the Utah Geological Survey (jmdavis@utah.gov; 801-537-3306).

AAPG 20-23 May 2018 • Salt Lake City, Utah ACE 2018 ANNUAL CONVENTION & EXHIBITION

EARTH SCIENCE WEEK 2017

This past October, 785 students participated in the Utah Geological Survey's 16th annual Earth Science Week (ESW) celebration. Students from 14 schools visited the Utah Core Research Center to learn about geology and paleontology through fun hands-on activities. To our 28 volunteers from professional associations, universities (instructors and students), public- and private-sector institutions, and individual geology enthusiasts who helped make ESW 2017 possible—thank you!

Since its creation in 1998 by the American Geosciences Institute (AGI), ESW has encouraged people everywhere to explore the natural world; promote Earth science understanding, application, and relevance in our daily lives; and encourage stewardship of the planet. For more information on ESW, see the AGI web page at www.earthsciweek.org; for information on next year's ESW activities at the Utah Geological Survey, see our web page at https://geology.utah.gov/teachers/earth-science-week/.

Utah Hosts Field Conference on GIGANTIC LANDSLIDES

BY Robert F. Biek

The southern flank of the Marysvale volcanic field, in south-central Utah, played host to an international gathering of geologists assembled to investigate two of the largest terrestrial landslides on Earth, the newly discovered Markagunt (MGS) and Sevier (SGS) gravity slides (see *Survey Notes*, v. 48, no. 1). This six-day Thompson Field Forum, *Catastrophic Mega-scale Landslide Failure of Large Volcanic Fields* held September 16–22, 2017, was sponsored by the Geological Society of America and brought together 27 participants representing four countries. Co-sponsorship of the conference was by the Utah Geological Association, Utah Geological Survey, Kent State University, Geologic Mapping Inc., and over a dozen Panguitch ATV enthusiasts (who transported participants to remote outcrops). The conference was convened by myself and colleagues David Hacker (Kent State University) and Pete Rowley (Geologic Mapping Inc.).

Large landslides are known from hundreds of volcanoes around the world, yet the mega-scale failure of volcanic fields themselves, producing gravity slide structures so large that they blur the boundary between gravitational and tectonic processes, has not received widespread attention. This was a transformative week of (1) redefining the physical limits of what is possible, (2) investigating evidence—on the outcrop—to identify unique characteristics of structures and deposits indicative of mega-slide deformation and of fast versus slow processes, and (3) planning for future collaborative studies.

The forum gathered together experts in rock mechanics, landslides, volcanology, petrography, paleomagnetism, sedimentology, isotope geochemistry, structure, and tectonics, with the intent of studying these landslides from a variety of perspectives. The conference emphasized many points, including the following:

- Different lines of evidence diagnostic of large to small catastrophic gravity slides.
- Cross-disciplinary assessment of extreme deformation recorded by basal layers and associated injectites (clastic dikes), shear zones, pseudotachylyte (friction-generated melt rock), deformed clasts, and main and sidewall breakaways.
- Factors contributing to volcanic landslide initiation and transport—why and how did these slides happen?
- The role of magmatic intrusions in inflation of volcanic fields and slope destabilization.
- Gravitational basement spreading of volcanic fields prior to catastrophic failure.
- Relationship to other large landslides and volcanic provinces throughout the world and on other planets.
- Public education opportunities highlighting unique features of the slides and evolution of the Marysvale volcanic field, which are adjacent to several of Utah's national and state parks and monuments.

Importantly, there was significant debate about structures and features diagnostic of catastrophic failure versus those produced by (1) slow, episodic tectonic processes, or (2) volcanic processes, distinctions that are critical in identifying mega-scale landslides in volcanic fields elsewhere. The MGS and SGS provide significant research opportunities on these and other questions. Already, research by several of the nine students who participated in the conference is underway, as is preliminary laboratory work to support future funding proposals. Early next year, the conveners will submit a field guide and participant abstracts for publication in the Geological Society of America Field Guide Series.

Participants on the 2017 Thompson Field Forum "Catastrophic Mega-scale Landslide Failure of Large Volcanic Fields," here gathered at the base of the 22 million-year-old Harmony Hills Tuff, one of the regionally extensive ash-flow tuffs that constrain emplacement parameters and timing of the MGS and SGS. From left to right: Shannon Hunter, Bill Lund, Chris Rowan, Julia Morgan, Grant Willis, Nic Barth, Lee Siebert, Jay Melosh, Eric Ferré, Bob Biek, Kevin Rafferty, Sam Thiele, Mike Hozik, Mark Anders, Zach Smith, Ashley Griffith, Scott Giorgis, Majie Fan, Troy Barber, Melanie Ray, Jeff Keith, Dave Malone, Pete Rowley, Mike Braunagel, David Hacker, Collin Jensen; Amy Hughes (not pictured). Photo courtesy Lance Weaver, Utah Geological Survey.

ENERGY NEWS

BY Michael Vanden Berg

American Association of Petroleum Geologists ANNUAL CONVENTION & EXHIBITION is Coming to Salt Lake City!

The American Association of Petroleum Geologists (AAPG) is holding their Annual Convention and Exhibition (ACE) meeting in Salt Lake City on May 20–23, 2018. As many as 5000 geologists and other petroleum professionals from all over the world will descend on Salt Lake City to participate in this annual conference. This meeting will be a huge opportunity for the State of Utah to showcase its world-class geology to an international crowd. Several geologists from the Utah Geological Survey (UGS), as well as volunteers from the host society, the Utah Geological Association (UGA), are involved in the planning of this conference, including myself as General Chair.

The biggest attraction of any Utah-based geology-related meeting is of course the field trips. The local committee has organized 13 field trips which will take participants to every corner of the state. A highlight will be the geotourism trips planned for Utah's "Mighty 5," including trips to Arches and Canyonlands, Zion and Bryce, and Capital Reef National Parks. Several other trips will be more technical and include classic and geologically famous locales such as the Book Cliffs, San Rafael Swell, Henry Mountains, Uinta Basin, and the Wasatch Front.

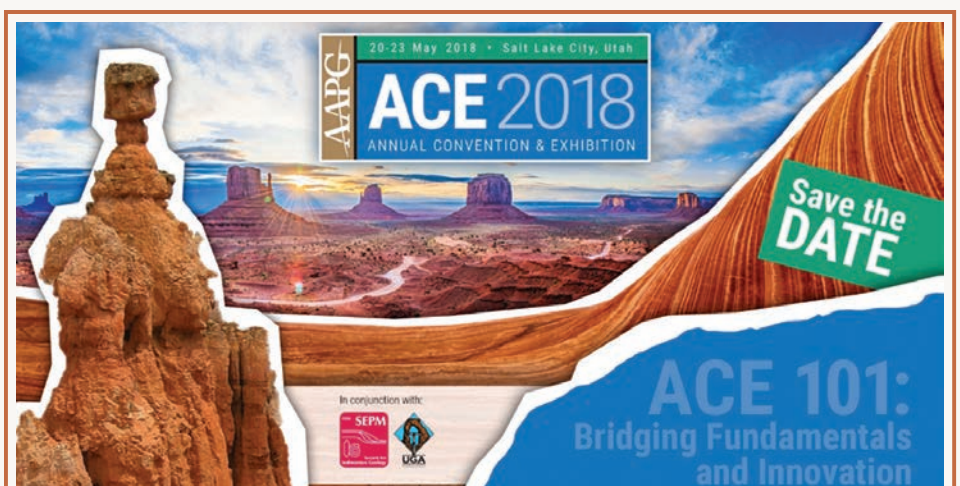
Having the 2018 AAPG ACE meeting in Salt Lake City provides a very unique opportunity to focus on the importance of lacustrine (lake) systems to the petroleum industry. Exploration in lacustrine systems has had a significant resurgence in the past decade with the discovery of massive oil deposits in the south Atlantic lacustrine pre-salt play. We plan to take full advantage of Salt Lake City's proximity to the most famous lacustrine rocks in the world, the Eocene Green River Formation. Two different field trips will highlight several aspects of this well-known formation: a trip to the Greater Green River Basin in southwestern Wyoming will feature the overall lacustrine depositional system and its controls, including the formation of microbialites; and a second trip will focus on the fluvial-deltaic deposition in the Uinta Basin in northeastern Utah and its importance to the basin's significant petroleum production. And of course, no visit to Utah can be complete without a trip to Great Salt Lake. The Great Salt Lake system provides a unique opportunity to study modern lacustrine processes and to investigate rare recent microbial carbonate development (see *Survey Notes*, v. 47, no. 2).

Make sure to keep an eye out for the 20-foot by 20-foot UGS/UGA exhibit space right near the entrance of the exhibition hall.

In addition, a special invited rock core session is being planned for the meeting. Confirmed cores include: (1) the public debut of the PR-15-7c core that captures nearly the entire Green River Formation in one continuous 1600-foot set of rock; (2) three lacustrine cores from the Kwanza Basin pre-salt play, offshore Angola; (3) core from the lacustrine Elko Formation in Nevada; (4) a sampling of Pennsylvanian carbonate cores from the Aneth oil field, the largest producing oil field in Utah (see *Survey Notes*, v. 48, no. 3, and v. 49, no. 2); and (5) cores from several different domestic unconventional basins. A second goal of the core session is to highlight the importance of regional core centers. State- and federal-run core centers are vital repositories of this priceless material. Their efforts are often overlooked, and yet these collections represent hundreds of billions of dollars' worth of investment. Several core centers, including the Utah Core Research Center, have already committed to show core and will be advertising their facilities.

The three-day technical program will consist of over 400 oral presentations and 600 poster presentations organized into 10 themes (siliciclastics, carbonates, geochemistry, geophysics, energy innovation, and more). Several other events will take place in conjunction with the main technical program including luncheons, special sessions, short courses, a teacher workshop, and numerous business meetings. Furthermore, a very large, 50,000 square-foot exhibition hall will host nearly 250 petroleum-related companies, universities, and nonprofits. Make sure to keep an eye out for the 20-foot by 20-foot UGS/UGA exhibit space right near the entrance of the exhibition hall.

The upcoming AAPG meeting will be an invaluable opportunity for the State of Utah to interact with a very large international group of petroleum professionals and will allow Utah to showcase its amazing geologic resources to the rest of the world. As General Chair, I hope you consider attending this important meeting; we want this event to be a success and leave AAPG with the desire to return for future ACE meetings.



Registration opens in January. Visit the website at ACE.AAPG.org/2018.

GLAD YOU ASKED

WHAT IS AN UNCONFORMITY?

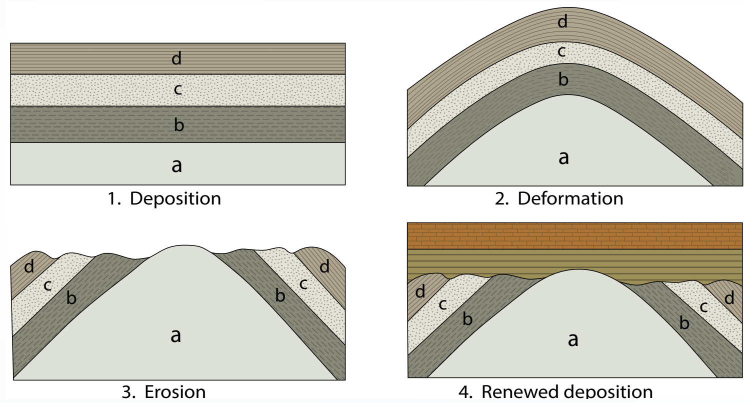
BY Jim Davis

Put simply, an unconformity is a break in time in an otherwise continuous rock record. Unconformities are a type of geologic contact—a boundary between rocks—caused by a period of erosion or a pause in sediment accumulation, followed by the deposition of sediments anew. Danish scientist Nicolas Steno first sketched an unconformity in the year 1669.

Unconformities, legendarily James Hutton's Unconformity at Siccar Point on the coast of Scotland, played a key role in advancing theories of geology at the end of the scientific revolution in the late 18th century. Hutton sought out, described, and exhibited unconformities as conclusive evidence of deep time, tectonic forces, and the recurrent cyclical processes shaping Earth's crust. Accordingly, Siccar Point is a geologic shrine, a destination for Earth science pilgrims, and has been christened "The Great Unconformity." That term also pertains to the famous unconformity in the Grand Canyon, also known as "Powell's Unconformity," where a quarter of Earth's history, more than a billion years, is omitted. In Utah, a still longer span of time is absent at the unconformity on the Colorado River at Westwater and Ruby Canyon in Grand County. Here one-and-a-half billion years is missing between a black, schistose Precambrian rock and the overlying Triassic Chinle Formation. Lesser known than the "Great" unconformities, the Salina Canyon unconformity in Sevier County, Utah, is an exemplary unconformity that is striking in appearance.

Sediments accumulate layer by layer in low-lying places such as the ocean floor, river deltas, wetlands, basins, lakes, and floodplains. An unconformity is created when these depositional environments change to a regime of no-net accumulation so that the deposition of sediments, which records time, ceases. In some cases, sediment accumulation simply stops, and more often erosion begins stripping rock layers away. Eventually, these static or erosional areas become depositional environments once again, typically through subsidence of the land or inundation by rising water. Thereafter sediment begins to accumulate and depositional history resumes in the rock record. What remains of this deposition-erosion-deposition sequence is an unconformity, a boundary between a group of older rocks below and the younger rocks above. The contact represents a span of missing time in the rock record, called a hiatus. This line in the rocks can be irregular or horizontal, depending on the topography of the original surface when deposition of sediments resumed after the hiatus.

The Salina Canyon unconformity in central Utah. The vertical strata of the Jurassic-age Twist Gulch Formation (lower part of exposure) are attributed to the Sevier Orogeny mountain-building event. Further warping of the Twist Gulch occurred by flow and doming of salt, gypsum, and mudstone in the underlying Arapien Shale. Erosion then beveled off the Twist Gulch and the Paleocene-Eocene-age Flagstaff Limestone was deposited over the vertical strata when an extensive lake, Lake Flagstaff, stretched over this region. The hiatus between these rock units is more than 100 million years.



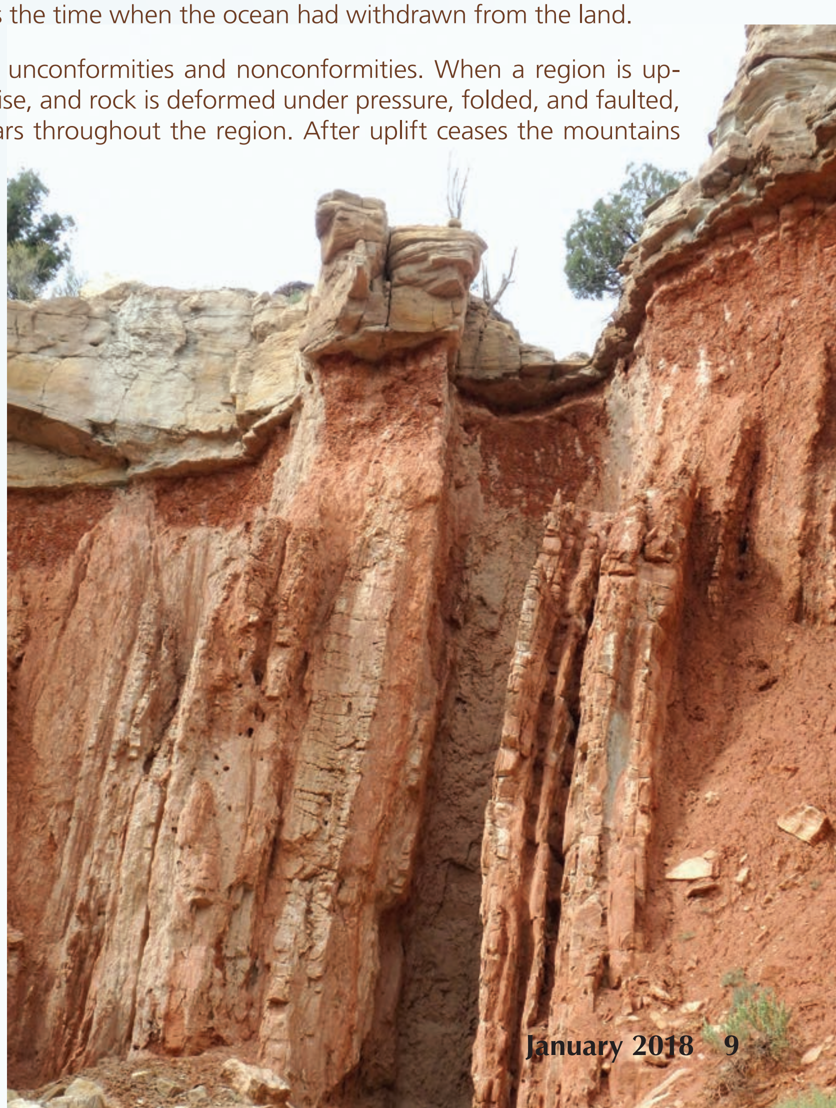
Above: *Evolution of an angular unconformity.* ***Left***: *The Great (angular) Unconformity at Siccar Point, Scotland. Devonian-age "Old Red Sandstone" caps tilted Silurian-age greywacke (a clay-rich sandstone) representing a time gap of around 60 million years. The Siccar Point unconformity has become the symbol of James Hutton's Theory of the Earth. UGS geologist Tom Chidsey (right) and Brigham Young University geologist Tom Morris stand just above the contact between the two rock units during the History of Geology in Great Britain Field Course. Photo courtesy of Scott Ritter, BYU.*

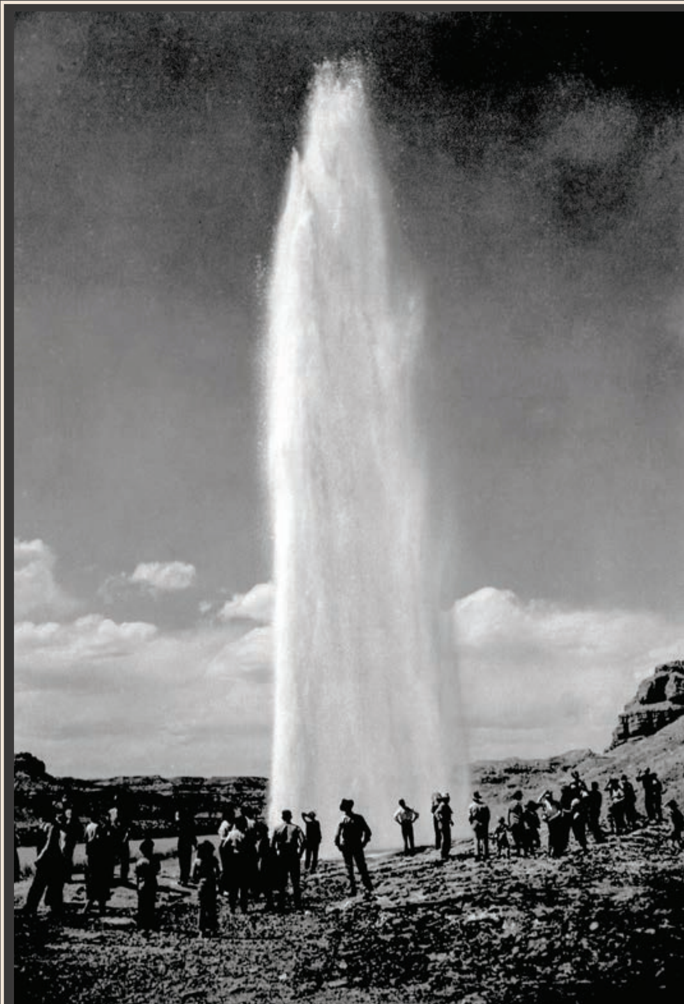
Unconformities are classified according to their genesis as either angular unconformities, paraconformities, disconformities, or nonconformities. The most obvious are angular unconformities where there is a change in the configuration of rock layering. In this case, horizontal sedimentary layers overlie tilted or contorted sediments, such as at Hutton's Unconformity, the Grand Canyon unconformity, and the Salina Canyon unconformity where the rock layers below the hiatus are nearly vertical. The most difficult to recognize is the paraconformity where horizontal sedimentary rocks are above and below the contact—there can be scant visible evidence of a hiatus when identical rocks are above and below. Disconformities are akin to paraconformities, but are usually easier to recognize because of irregular topography at the contact between sedimentary rocks. Nonconformities are the only type where the rock below the hiatus is not sedimentary rock, but rather igneous or metamorphic rock that has been planed-off before sediments were deposited over them.

Sea-level fluctuations commonly produce paraconformities and disconformities. When sea level drops, erosion begins on the newly exposed land. When sea level rises and covers the land, deposition recommences. The time recorded in the sediments is equivalent to when the land was submerged, and the hiatus represents the time when the ocean had withdrawn from the land.

Tectonic forces also produce unconformities, especially angular unconformities and nonconformities. When a region is uplifted, deposition usually ceases and erosion begins. Mountains rise, and rock is deformed under pressure, folded, and faulted, and erosion dominates over tens or hundreds of millions of years throughout the region. After uplift ceases the mountains are planed down to low-lying depositional environments once again. The time when deposition resumes is marked by unconformities. The passage of time at the hiatus encompassed the raising and dismantling of a mountain range.

Above: *UGS geologist Michael Vanden Berg marks the Salina Canyon unconformity that exhibits slight topographical irregularities; the uneven erosional surface was preserved when deposition resumed as the Flagstaff Limestone. Photo credit: Rebekah Stimpson.* ***Right***: *Close-up view of the contact between the vertically tilted Twist Gulch Formation and the Flagstaff Limestone of the Salina Canyon unconformity.*





Crystal Geyser post card, date uncertain. The caption reads, "No trip through Southeastern Utah is complete without a visit to the world's only cold-water geyser. This phenomenon of nature spouts a column of cold water to a height of 100 to 150 feet every hour. The absence of heated water in the geyser makes the eruptions one of the world's mysteries as to the source of the tremendous forces necessary to force a column of water to these heights…"

GEOSIGHTS

Crystal Geyser, Grand County, Utah

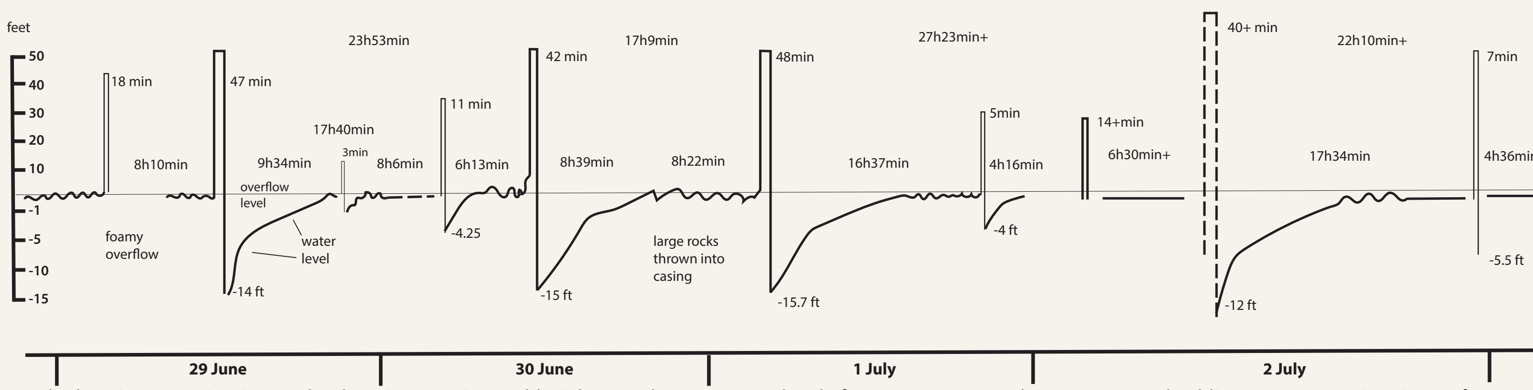
BY Lance Weaver

When most people think about geysers, they picture a Yellowstone-like hot spring where pressure from steam sends a tall column of water into the air. In Utah, however, several "geysers" erupt due to the same process that causes soda pop to shoot out of the can when you hold your finger over the lid and shake it. Although technically not true geysers, these cold-water eruptions look so much like hot-water geysers that they are referred to as "soda pop geysers." In Utah, the largest of these is Crystal Geyser.

Crystal Geyser is a partially human-made geyser located on the shore of the Green River, approximately 10 miles south of the town of Green River, Utah. The geyser originated in 1936 when an oil exploration well tapped into a groundwater system under immense pressure caused by a reservoir of trapped carbon dioxide (CO_2) gas. However, the high-pressure system that the well penetrated had previously created a series of ancient natural springs and tufa deposits which were first referenced by John Wesley Powell in 1869. On his way down from the present town site of Green River and the state park museum which now bears his name, he wrote, "an hour later, we run a long rapid, and stop at its foot to examine some curious rocks, deposited by mineral springs that at one time must have existed here, but are no longer flowing" (Powell, 1875, *Report on the Exploration of the Colorado River of the West and Its Tributaries*, p. 51–52).

Perhaps because of a geologic investigation published in 1914 that reported a series of oil seeps in the area, an exploratory oil well, the Ruby No. 1, was drilled in 1935 on the margin of the ancient spring deposits. In November of that year, a Moab newspaper reported on the progress of the well stating that a significant flow of water had been encountered at a depth of 44 feet. By January 1936, the newspaper reported that drillers had encountered CO_2 gas at a depth of 360 feet at high enough pressures to shoot 105 pounds of drilling mud 60 feet into the air. The well was abandoned after drilling to a total depth of 2627 feet, but in its aftermath, a geyser was created that quickly became a regional attraction. The November 1936 front page of Moab's *Times-Independent* boasted of a new geyser that spouted an 80-foot column of water at regular intervals of about 15 minutes and a 150-foot column at intervals of about 9 hours.

The pressurized CO_2 gas that drives Crystal Geyser is likely derived from rocks close in age to those that have produced much of the oil and natural gas in the adjoining Paradox Basin of southeastern Utah—an ancient sedimentary basin containing oil-producing shale and evaporite rocks deposited more than 250 million years ago. The gas migrated upward into the Jurassic-age Navajo and Entrada Sandstones, where it became trapped and pressurized. The Little Grand Wash fault, which runs in an east-west direction adjacent to Crystal Geyser, served as a barrier to the upward migration of gas in these geologic units, trapping



Graph showing eruption intervals, durations, estimated heights, and some water levels from June 29 to July 4, 2000. Dashed lines are approximations of two major eruptions. h=hours, min=minutes. (From Crystal Geyser, Green River, Utah: A Summary of Observations from 1972–2008, *by Richard L. Powell.)*

it in an underground reservoir of permeable rock. Weakness in the fault also served as a conduit for fluids in this pressurized system to leak upward, creating carbonate-rich springs and oil seeps which early geologists reported in the immediate vicinity.

When the 1935 oil exploration company penetrated the cap on this gas reservoir, water from higher geologic units flowed down the hole to meet gas escaping from lower geologic units. The mixture of the gas and water continues between eruptions until a CO_2 saturation point is reached. As soon as the water becomes oversaturated, the CO_2 violently bursts out of solution and forcefully ejects the water from the borehole. Holes in the casing of the well allow much of the ejected water to flow back down the well and the whole process begins again.

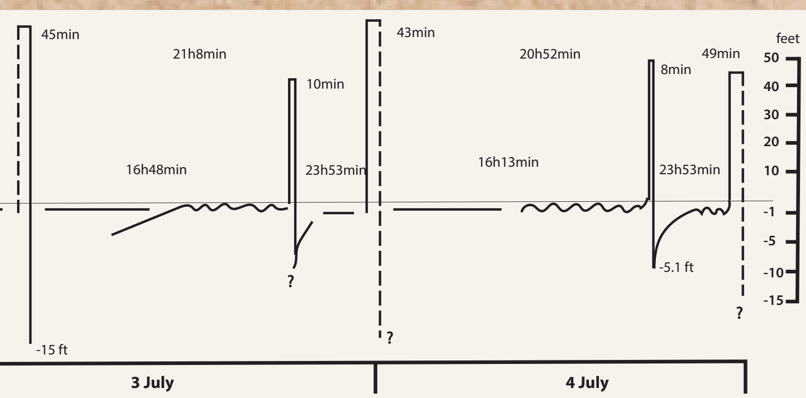
Crystal Geyser is not the only CO_2-driven geyser in this region of Utah. The same type of gas deposits in the northern Paradox Basin are responsible for several nearby springs and smaller but similar geysers around the town of Green River and Woodside. Other cold-water CO_2 geysers are known in California, Germany, France, Serbia, Slovakia, and New Zealand. At its highest historically documented eruption of around 200 feet, Crystal Geyser is certainly one of the largest in the world.

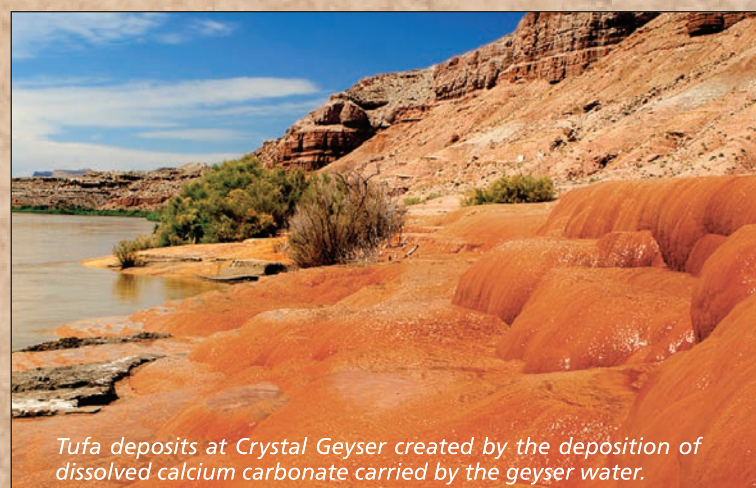
In recent years, Crystal Geyser appears to be decreasing in both its height and reliable frequency of eruptions. Much of this was likely caused by visitors dropping rocks down the borehole, creating a significant plug less than 50 feet down. Plans to clear the major obstructions have never materialized. Plans have also been made, but never carried out, to pressure cap the geyser in a way that might increase the frequency or reliability of the eruptions. Because major eruptions can often be more than 24 hours apart, and can often occur in the middle of the night, seeing them can be a difficult task and major time commitment. Studies carried out over the past two decades have used sensors to map the exact frequency and height of eruptions. These studies found that minor eruptions were somewhat unpredictable and ranged in height from 2 to 10 feet. Major eruptions attained heights of 40 to 80 feet and occurred on a schedule ranging from 17 to 27 hours apart. Eruption durations ranged from 3 to 49 minutes.

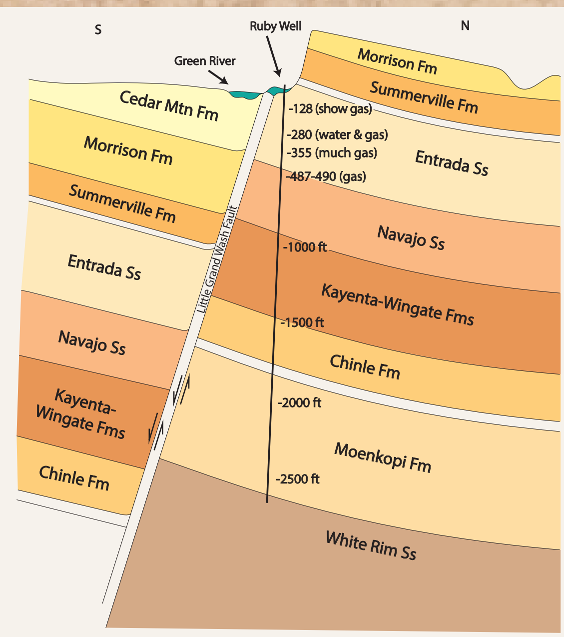
Crystal Geyser is a unique geologic feature that has fascinated tourists for decades. For those willing to wait around for its eruptions, Crystal Geyser can provide the unique experience of watching or even playing in one of the world's few large cold-water geysers.

HOW TO GET THERE

Access Crystal Geyser from I-70 exit 164, at the east end of the town of Green River, Utah. From there, head east for 2.4 miles on the frontage "New Area 51 Road" to the junction with "Crystal Geyser Safari Route." Follow this well-graded dirt road south then west for 4 miles until arriving at a parking lot adjacent to both Crystal Geyser and the Green River boat access. **Warning: Roads may be impassable in wet weather or winter conditions.**

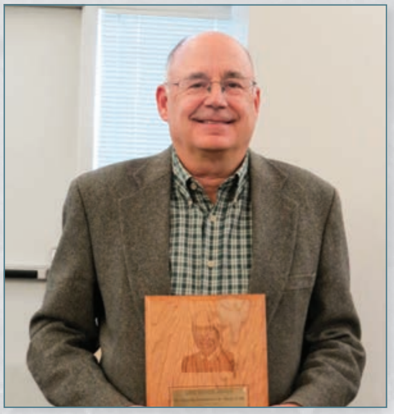



Tufa deposits at Crystal Geyser created by the deposition of dissolved calcium carbonate carried by the geyser water.



Idealized geologic cross section showing the rock units penetrated by the Ruby No. 1 well. (Modified from Crystal Geyser, Green River, Utah: A Summary of Observations from 1972–2008*, by Richard L. Powell.)*

2017 Lehi Hintze Award | THOMAS CHIDSEY



The Utah Geological Association (UGA) and the Utah Geological Survey (UGS) presented the 2017 Lehi Hintze Award to Thomas C. Chidsey, Jr., for his outstanding contributions to Utah geology. Tom is the 15th geologist to receive this award and the first Lehi Hintze student to be honored. Tom's contributions over his 40-year career include (1) completion of his M.S. thesis on the northern House Range of western Utah at Brigham Young University (BYU) in 1977 and published by the Utah Geological and Mineral Survey (now the UGS) and BYU Geology Studies in 1978, (2) petroleum exploration efforts with Celsius Energy Company in Utah from 1980 to 1989, and (3) research and numerous publications and presentations with the UGS since 1989.

Tom began his career with Exxon in Kingsville, Texas, but in 1980, he accepted a position at Celsius Energy Company that brought him back to Utah. But it is in his work for the past 28 years with the UGS Energy and Minerals Program where Tom has made his most significant contributions. He has conducted studies on oil and gas reservoirs, outcrop analogs, carbon capture and sequestration, modern and ancient microbial carbonates, groundwater aquifers, the geology of Utah parks, and the comparison of Utah ancient geologic landscapes to those on Mars. Tom has published 95 technical papers, 37 nontechnical articles, and 101 abstracts. He has co-edited a book published by the American Association of Petroleum Geologists (AAPG) on the Ferron Sandstone, edited three UGS Bulletins, co-edited seven UGA Publications, and is co-editor of UGA's online journal *Geology of the Intermountain West*. Of these publications, Tom regards his work on UGA Publication 28, *Geology of Utah's Park and Monuments* as one of his greatest contributions to Utah geology.

Tom has served as Rocky Mountain Section-AAPG President in 1993, UGA President in 1999–2000, and General Chair of the AAPG Annual Convention and Exhibition in 2003. Tom serves on several boards including the AAPG Rocky Mountain Section Foundation, BYU Geology Alumni Board (current Chairman), and the BYU College of Physical & Mathematics Volunteer Leadership Council. He is a member of several professional organizations including AAPG, UGA, Geological Society of America, Society for Sedimentary Geology, and Rocky Mountain Association of Petroleum 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. Tom's contributions to Utah geology, and his continued contributions, illustrate that he is very deserving of this honor. And as a former Hintze student, it seems quite appropriate.

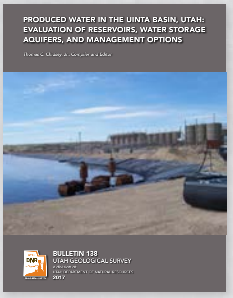
2017 Employee of the year | JOHN GOOD

Congratulations to John Good who was named the 2017 UGS Employee of the Year. John is a Graphic Arts Specialist with the Editorial Section and has worked for the Department of Natural Resources for 15 years, including the last three years with the UGS. His creative talent and commitment to produce high-quality publications has contributed to a positive UGS image to both the public and other government agencies. John has developed an excellent working relationship with authors and editors, understands their requests, and is always willing to research and find solutions to new and challenging publishing issues. His excellent work, productivity, positive attitude, and friendly sense of humor make John an outstanding employee and a deserving recipient of this special award and recognition.

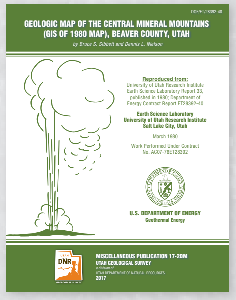
Gregg Beukelman retired in January this year after 7 years of service. Gregg joined the UGS in 2010 after a career in teaching, research, and geologic consulting. He worked in the Geologic Hazards Program as a Project Geologist where he concentrated on investigating, mapping, and reporting on landslides. Some of his major projects included landslide inventory, mapping on the Wasatch Plateau, and emergency response to several urban landslides along the Wasatch Front. As a geologist, Gregg combined his love of nature and passion for photography and captured many spectacular photographs that helped make the yearly *Calendar of Utah Geology* the major success it is today. Gregg's knowledge and expertise will be greatly missed, and we wish him well in his retirement!

NEW PUBLICATIONS

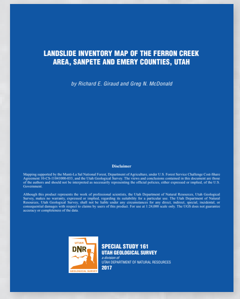
UGS publications are available for download at geology.utah.gov or for purchase at utahmapstore.com.



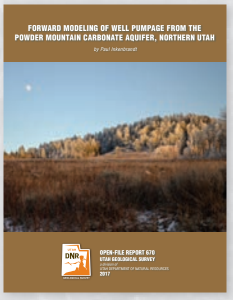
Produced water in the Uinta Basin, Utah–evaluation of reservoirs, water storage aquifers, and management options, compiled and edited by Thomas C. Chidsey, Jr., 279 p., 3 pl., + 7 appendices, ISBN 978-55791-939-7, **Bulletin 138**



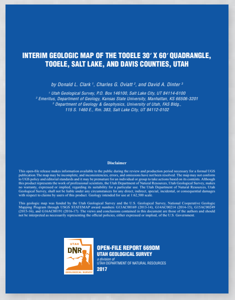
Geologic map of the central Mineral Mountains, Beaver County, Utah, by Bruce S. Sibbett and Dennis L. Nielson (GIS reproduction of 1980 map), 42 p., 2 pl., scale 1:24,000, ISBN 978-1-55791-942-7, **Miscellaneous Publication 17-2DM**



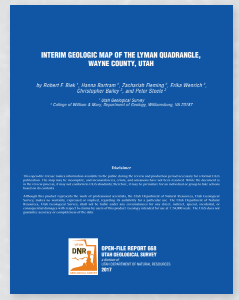
Landslide inventory map of the Ferron Creek area, Sanpete and Emery Counties, Utah, by Richard E. Giraud and Greg N. McDonald, scale 1:24,000, 1 plate, GIS data, ISBN 978-55791-941-0, **Special Study 161**



Forward modeling of well pumpage from the Powder Mountain carbonate aquifer, northern Utah, by Paul Inkenbrandt, 5 p. + 32 p. appendices, **Open-File Report 670**



Interim geologic map of the Tooele 30′ x 60′ quadrangle, Tooele, Salt Lake, and Davis Counties, Utah, by Donald L. Clark, Charles G. Oviatt, and David A. Dinter, 43 p., 3 pl., GIS data, scale 1:62,500, **Open-File Report 669DM**



Interim geologic map of the Lyman quadrangle, Wayne County, Utah, by Robert F. Biek, Hanna Bartram, Zachariah Fleming, Erika Wenrich, Christopher Bailey, and Peter Steele, 15 p., 2 pl., scale 1:24,000, **Open-File Report 668**

RECENT OUTSIDE PUBLICATIONS BY UGS AUTHORS

The history of late Holocene surface-faulting earthquakes on the central segments of the Wasatch fault zone, Utah, by C.B. DuRoss, S.F. Personius, S.S. Olig, A.J. Crone, **M.D. Hylland**, W.R. Lund, and D.P. Schwartz: Geology and resources of the Wasatch–Back to Front, Utah Geological Association Publication 46, p. 201–250.

Estimating the probabilities of future large earthquakes along the Wasatch Front, by Working Group on Utah Earthquake Probabilities (I. Wong, W. Lund, C. DuRoss, P. Thomas, W. Arabasz., A. Crone, **M. Hylland**, N. Luco, S. Olig, J. Pechmann, S. Personius, M. Petersen, D. Schwartz, R. Smith, and **S. Bowman**): Geology and resources of the Wasatch–Back to Front, Utah Geological Association Publication 46, p. 277–294.

Geologic tools for mapping in urban areas, with examples from the Salt Lake Valley, Utah, by **A.P. McKean**: Geology and resources of the Wasatch–back to front, Utah Geological Association Publication 46, p. 361–374.

Shorelines and vertebrate fauna of Pleistocene Lake Bonneville, Utah, Idaho, and Nevada, by **M. Milligan** and H.G. McDonald: Geology of the Intermountain West, v. 4, p. 181–214.

Upper Triassic lithostratigraphy, depositional systems, and vertebrate paleontology across southern Utah, by J.W. Matrz, **J.I. Kirkland**, A.R.C. Milner, W.G. Parker, and V.L. Santucci: Geology of the Intermountain West, v. 4, p. 99–180.

A chronostratigraphic assessment of the Moenave Formation, USA, using C-isotope chemostratigraphy and detrital zircon geochronology–Implications for the terrestrial end Triassic extinction, by C.A. Suarez, T.K. Knobbe, J.L. Crowley, **J.I. Kirkland**, and A.R.C. Milner: Earth and Planetary Science Letters, v. 475, p. 83–93, doi.org/10.1016/j.epsl.2017.07.028

Lower Cretaceous paleo-vertisols and sedimentary interrelationships in stacked alluvial sequences, Utah, USA, by R.M. Joeckel, G.A. Ludvigson, and **J.I. Kirkland**: Sedimentary Geology, v. 361, p. 1–24.

Descendants of the Jurassic turiasaurs from Iberia found refuge in the Early Cretaceous of western USA, by R. Royo-Torres, P. Upchurch, **J.I. Kirkland**, **D.D. DeBlieux**, J.R. Foster, A. Cobos, and L. Alcalá: Nature Scientific Reports, v. 7, 12 p. doi:10.1038/s41598-017-14677-2

Great Salt Lake (Utah) microbialite $\delta^{13}C$, $\delta^{18}O$, and $\delta^{15}N$ record fluctuations in paleolake geochemistry since the late Pleistocene, by D.L. Newell, J.L. Jensen, C.M. Frantz, and **M.D. Vanden Berg**: Geochemistry, Geophysics, Geosystems, v. 18, p. 3631–3645. doi.org/10.1002/2017GC007078.

Climatic control on fluvial deposition and architecture of the Douglas Creek and Parachute Creek Members, Green River Formation, southeastern Uinta Basin, Utah, by R.D. Gall, L.P. Birgenheier, and **M.D. Vanden Berg**: Journal of Sedimentary Research, v. 87, p. 1019–1047.

History and evolution of geologic mapping in Utah with emphasis on the Wasatch area, by **G.C. Willis**: Geology and resources of the Wasatch–front to back, Utah Geological Association Publication 46, p. 375–398.

Pressure trends at Cove Fort and Roosevelt Hot Springs geothermal systems provide insight to their flow regimes, by **R. Allis**, **M. Gwynn**, and **S. Kirby**: Geothermal Resources Council Transactions, v. 41.

Shallow thermal anomalies in west-central Utah, by **R. Allis**, **M. Gwynn**, and **S. Kirby**: Geothermal Resources Council Transactions, v. 41.

Assessment of the Quaternary faulting near the Utah FORGE site from airborne light detection and ranging (lidar) data, by **E. Kleber**, **A. Hiscock**, **S. Kirby**, and **R. Allis**: Geothermal Resources Council Transactions, v. 41.

Phase 2–updated geothermal Play Fairway Analysis of the Tularosa Basin, New Mexico, by G. Nash, A. Brandt, B. Pfaff, **C. Hardwick**, **M. Gwynn**, K. Blake, S. Simmons, and C. Bennet: Geothermal Resources Council Transactions, v. 41.

Update on the geochemistry and geohydrology of the FORGE deep well site, Milford Utah, by S. Simmons, **S. Kirby**, K. Rahilly, T. Fischer, and J. Moore: Geothermal Resources Council Transactions, v. 41.

Phase II of Play Fairway Analysis for the eastern Great Basin extensional regime, Utah–status of indications, by P. Wannamaker, J. Moore, K. Pankow, S. Simmons, G. Nash, V. Maris, A. Trow, and **C. Hardwick**: Geothermal Resources Council Transactions, v. 41.

Ground water levels of Round Valley, Utah, by **P. Inkenbrandt**, Geology and resources of the Wasatch–front to back, Utah Geological Association Publication 46.

Hydrogeology of the Powder Mountain area and evidence for Utah's only periodic spring, by **S.M. Kirby**, **P.C. Inkenbrandt**, and B. Dame, Geology and resources of the Wasatch–front to back, Utah Geological Association Publication 46.

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