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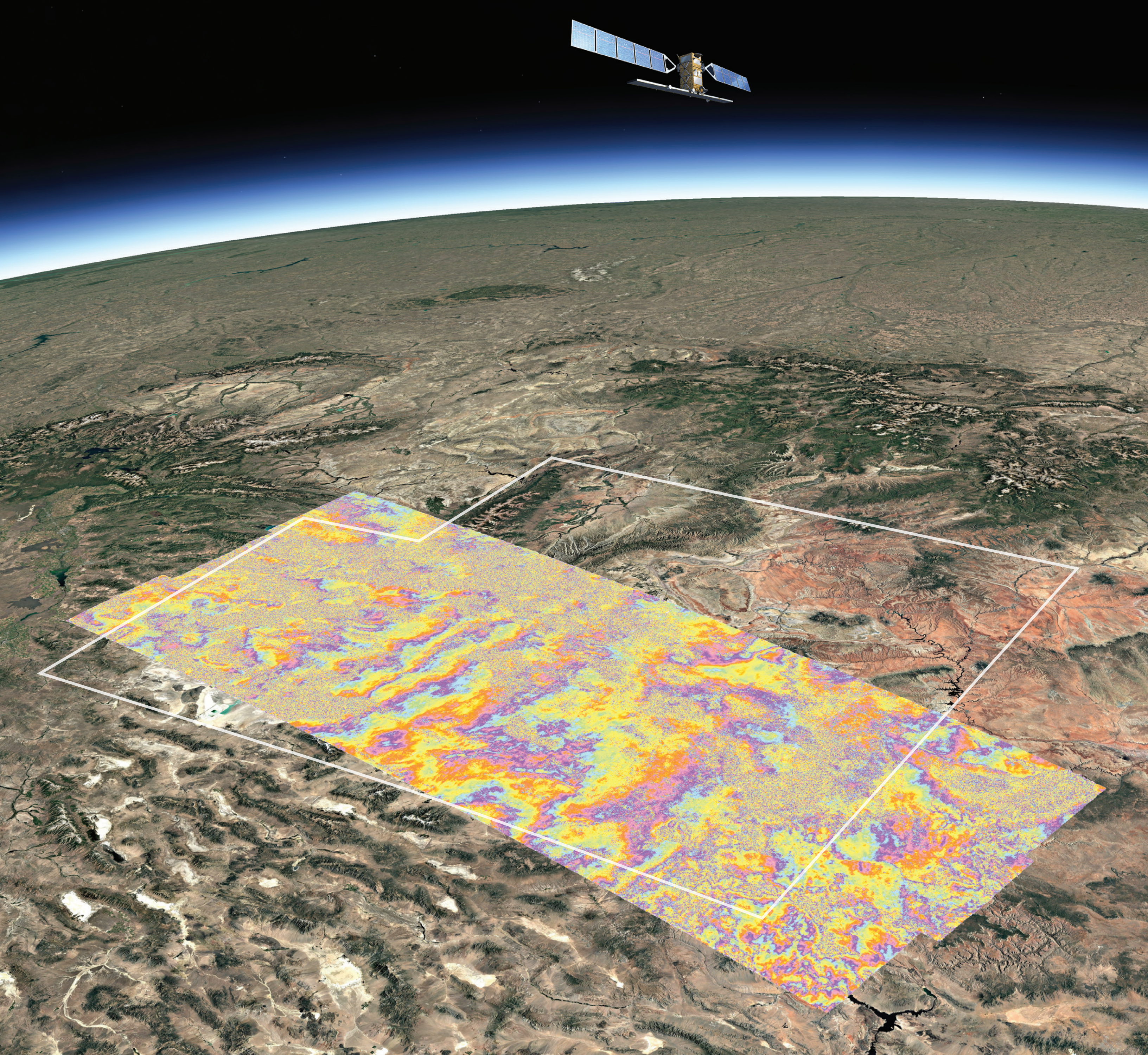

Tracking Utah's Ground Motion from Space Using InSAR

Google Earth; Data SIO, NOAA, U.S. Navy, NGA, GEBCO; Image Landsat/Copernicus

Contents

Design | *John Good*
Cover | An artist's impression of the European Space Agency's (ESA) SAR satellite Sentinel-1, with a wrapped synthetic aperture radar interferogram over Utah from 9/12/22 to 9/7/23. Each color cycle represents 2.8 cm of ground motion towards or away from the satellite, or phase delays due to noise sources such as variations in the atmosphere, ionosphere, or satellite orbits. Satellite rendering from the ESA; SAR data processed by ASF DAAC HyP3 2024. Contains modified Copernicus Sentinel data 2023, processed by the ESA.

DIRECTOR'S PERSPECTIVE

by Bill Keach

Ramblin' Man

What a ride! A little over six years ago I was privileged to take on the role and responsibilities of Director of the Utah Geological Survey and State Geologist. A major earthquake (2020), a pandemic (2020), a drought that took Great Salt Lake to an all-time historic low of 4,188.5 feet (2022) and the busiest landslide season since 2011 (2023) are just a few major events that occurred during my tenure.

Occasionally, as I sit down to write for this space, an oldie pops into my head that ultimately serves as a bit of a theme. This month, Ramblin' Man (1973) came to mind, for a whole lot of reasons. Travel for both work and pleasure has taken me to every county in Utah, most every state, six continents, and 40+ countries, and I've also had the opportunity to ramble in this column three times a year for the past six years. This will be my last ramble as I retired in April.

In this new world of AI, I asked an AI tool to summarize all the Director's Perspective articles I've written. It created an interesting list of key themes, including the **UGS's Role and Activities**, **Natural Resources and Energy**, **Natural Hazards**, **Water Resources**, **Technology's Impact**, **Challenges and Future Outlook**, and lastly **Personal Reflections**. AI's summary states "In essence, the articles provide a comprehensive overview of the UGS's work, priorities, and perspectives on key geological issues in Utah over a six-year period." I think that is a great summary.

My association with the UGS began many years before I became Director. I often brought field trip participants to study the rocks stored at the Utah Core Research Center (UCRC). The UGS was often our first stop before taking students and professionals alike on their first field trip in Utah. The cores reposited in the UCRC were the first glimpse for these participants of Utah's amazing geology.

My ramblings across the state have taken me to landslides, dinosaur footprints and fossils, river trips, oilfields, geothermal hot spots (pun intended), every national park and monument, and many state parks. It was a great opportunity to learn from the UGS staff who are passionate experts in all these and many other topics. Along the way it was also fun to share some insights with the public.

Lyrics from the song include:

"I was born a ramblin' man
Tryin' to make a livin' and doin' the best I can
And when it's time for leavin', I hope you'll understand
That I was born a ramblin' man"

In closing, my goal everyday was to give it my best. Now, *"it's time for leavin'."* It has been a wonderful ride. A heartfelt thanks to the folks I worked with. They do great science that matters to the well-being of the citizens of Utah. Equally amazing are all the citizens that work to make Utah a great place to live. In retirement, I can be found in Joseph (Sevier County). My first trip will be a ramble to Iceland to visit active volcanos and geothermal sites.

Keep *ramblin'*.

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TRACKING UTAH'S GROUND MOTION FROM SPACE USING INSAR: A NEW TOOL AT HAND

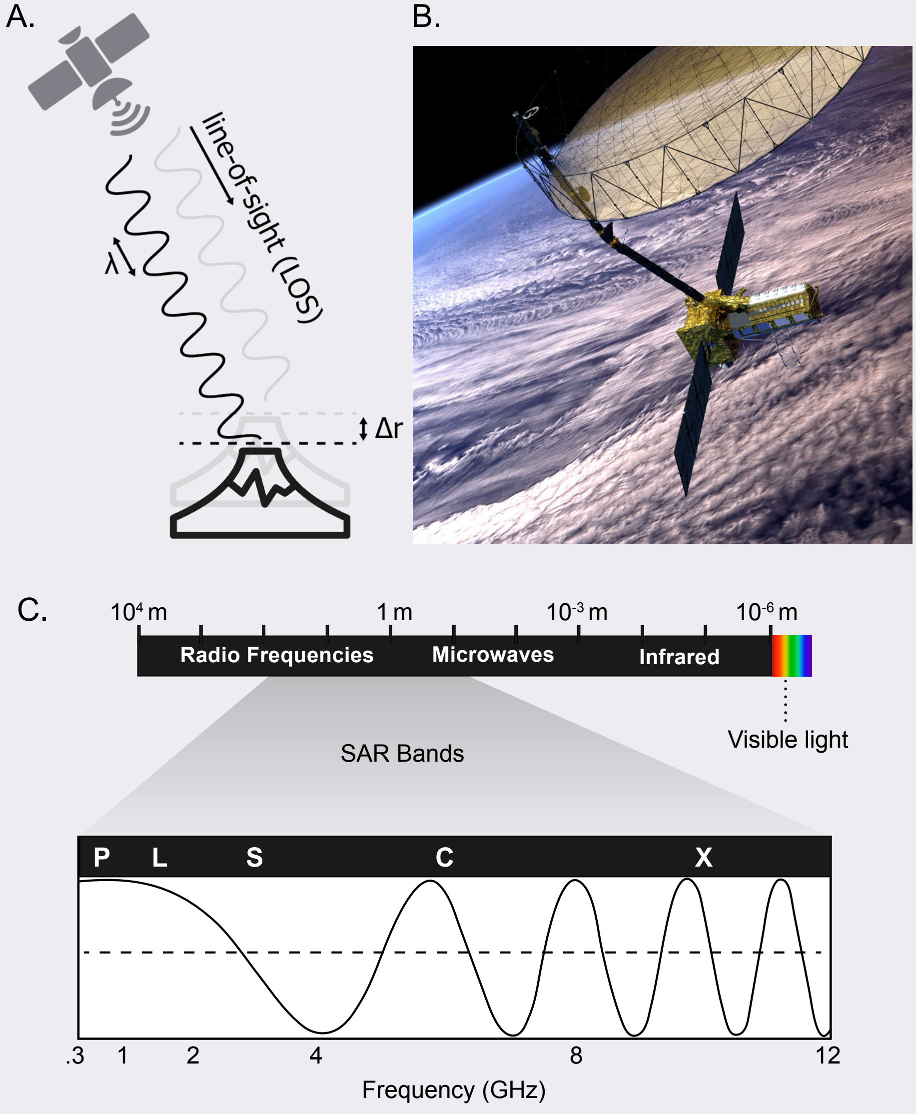
by Tara Shreve

In 2024, the UGS began to systematically use a satellite-based technique, called InSAR (Interferometric Synthetic Aperture Radar), to measure ground motion throughout Utah. To understand how InSAR works, imagine you're walking through a remote canyon. You may notice that the only sound to break the landscape's silence is the echo of each footstep. The delay between your steps and the echo conveys how far the sound has traveled before reflecting off the canyon wall back towards you. This delay, and the speed of sound, is all you need to figure out the distance to the canyon wall. Instead of using acoustic wave echoes, scientists can use electromagnetic wave "echoes" to measure ground motion from satellites orbiting more than 400 miles above our heads.

A brief history of InSAR

Electromagnetic waves—radiant energy travelling close to the speed of light—also bounce off surfaces. In this case, the reflection is called *backscatter* and is the basis for radar systems. Radar stands for "RAdio Detection And Ranging," and is commonly used for weather monitoring. Weather radar emits radio waves (electromagnetic waves with wavelengths reaching up to miles), which bounce off ice or water droplets in the atmosphere. We can determine the distance to a storm (precipitation location), as well as the precipitation velocity and intensity, by recording the time it takes for the waves to travel back to the radar antenna and analyzing how the radio wave characteristics have changed over that time.

Since radar is a useful tool for locating and tracking objects like storms, why not use it to map features on the Earth's surface? This thought crossed scientists' minds in the first half of the 20th century. Initially, they encountered technical challenges, such as poor spatial resolution of these radar-generated images. To obtain resolution sufficient for distinguishing objects on the ground, a technique called synthetic aperture radar (SAR) was developed in the 1950s. The first SAR satellite, QUILL, was launched in 1964 by the United States National Reconnaissance Office, and it had a spatial resolution finer than 17 feet (~5 meters). One of the biggest advantages of a SAR satellite is that it provides its own illumination through a radar pulse. It can acquire images during the day, at night, or in cloudy conditions, as opposed to optical images from satellites or aircraft that rely on sunlight.

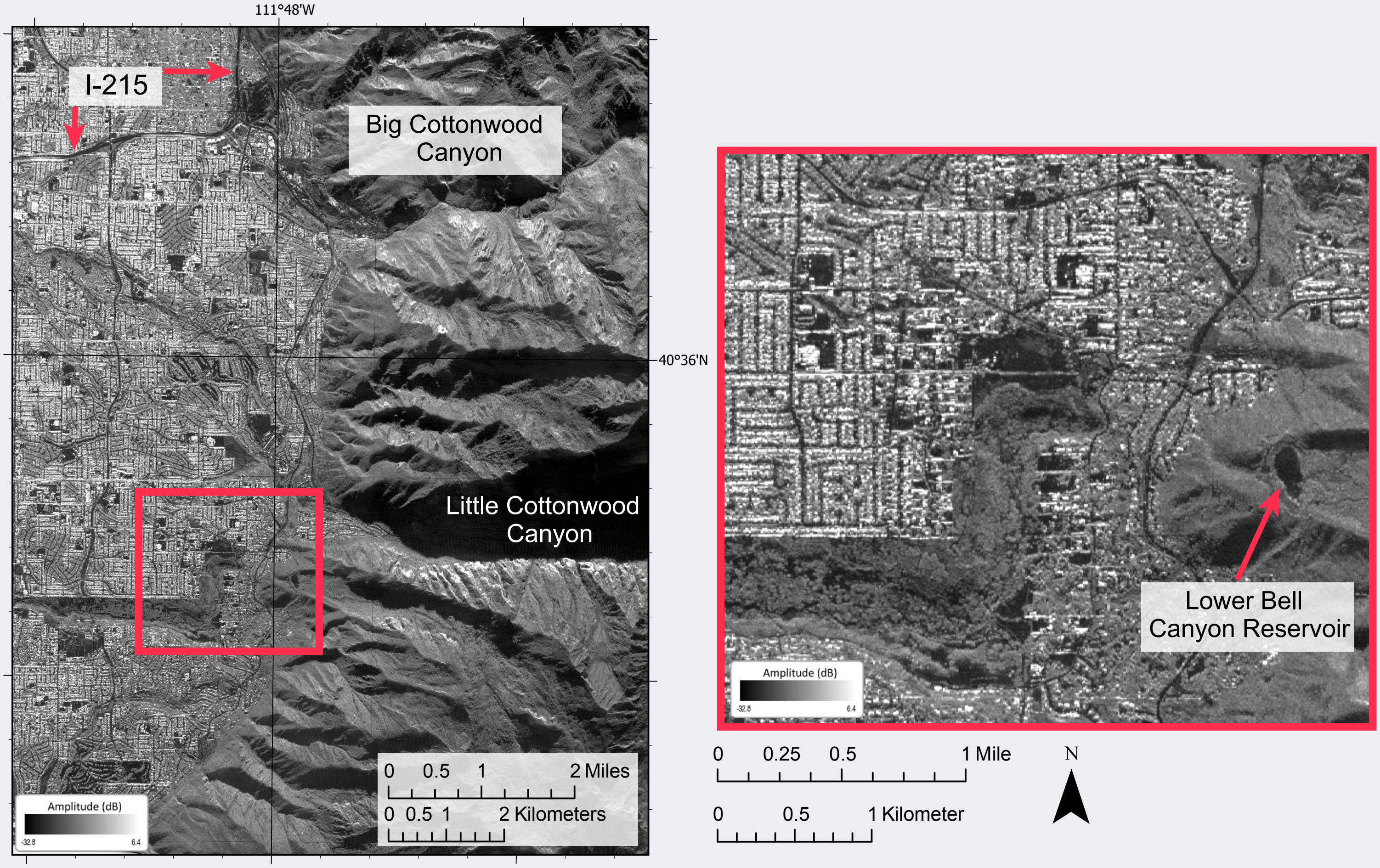


A. *Cartoon showing the satellite line-of-sight (LOS) and an emitted radio wave at two different times (black and gray). If the ground has moved between those times, a phase difference will correspond to a certain amount of motion towards or away from the satellite (LOS displacement). As a result, ground displacement measurements from InSAR are a combination of vertical and horizontal motion. The known wavelength (λ) of the radio wave helps convert the phase difference to a measure of length.* ***B.*** *An artist's depiction of the NASA-ISRO NISAR satellite. Credit: NASA/JPL-Caltech,* NISAR Satellite in Earth Orbit (Artist's Concept). ***C.*** *A chart of wavelength values, highlighting some of those used in SAR missions (L, S, C, and X-bands, with wavelengths of ~24 cm, 10 cm, 5 cm, and 3 cm, respectively). Longer wavelengths can penetrate through vegetation, but they are less sensitive to small ground displacements. Modified after* NASA Synthetic Aperture Radar (SAR) Data Basics.

With this new tool, scientists wanted to know if they could move beyond imaging the Earth's surface to measuring ground motion. A SAR image is created from an electromagnetic wave, and, as with any cyclic wave, at a given time, it has both an amplitude (the wave's energy) and a phase (the wave's position in its cycle). The phase changes with time as the wave travels towards the Earth. By comparing two SAR images acquired from nearly the same satellite position on different days, a change in phase can be related to ground motion, which results in a change in distance between the satellite and Earth. This change could be due to earthquakes, landslides, volcanic eruptions, or other geologic or human-related processes. Finding the phase difference between two days at any point in the SAR image will measure how far the Earth's surface has moved away from or towards the satellite "line-of-sight," or LOS. The proof-of-concept for this technique, called Interferometric SAR (InSAR), occurred in the 1970s and '80s. Applications of the technique were later expanded after the launch of the European Space Agency's ERS-1 satellite in 1991.

The golden age of (In)SAR

Since 1991, more than 15 civilian SAR satellite missions have been launched in collaboration with national space agencies, and at least 9 were still operational in 2024. These satellites provide global coverage at regular or semi-regular intervals (a few days to a few months between images at any given location). In many cases, the satellite images are freely available to the public. Spatial resolution varies from 3 feet to 10s of feet (a few meters), which is fine enough to distinguish buildings. There are also commercial SAR companies, which have launched groups of small SAR satellites to provide images more frequently and with higher spatial resolution (3 feet [1 meter] or less, which can distinguish between vehicles). SAR can also be mounted aboard planes, as is being done with the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR). This radar system, operated by NASA's Jet Propulsion Laboratory (JPL), is flown on an autopiloted Gulfstream-III (G3) jet. This approach provides more control over the flight path and finer detailed imaging (a few feet [meter-scale] spatial resolution).



SAR amplitude image of eastern Salt Lake Valley that demonstrates the ability to distinguish between buildings, roads, and small topographic features. Image acquired from the airplane-mounted UAVSAR on March 16, 2021. The spatial resolution is 7 by 5 meters (23 by 16 feet), and similar spatial resolution can be achieved by some civilian SAR satellites. Amplitude brightness depends on multiple factors, including material properties and surface roughness. As a result, grassy fields and bodies of water appear dark, whereas metallic surfaces such as building roofs are light gray or white. In the Wasatch Range, steep topography blocks radar waves emitted from the radar antenna, causing the shadowed regions. This shadow is due to the angle at which the antenna views the ground (side-looking). UAVSAR data courtesy NASA/JPL-Caltech and the SnowEx 2021 Western US campaign.

In 2025, NASA and ISRO (Indian Space Research Organisation) plan to jointly launch the NISAR satellite that will provide yet another opportunity to expand the already extensive archive of freely available SAR images.

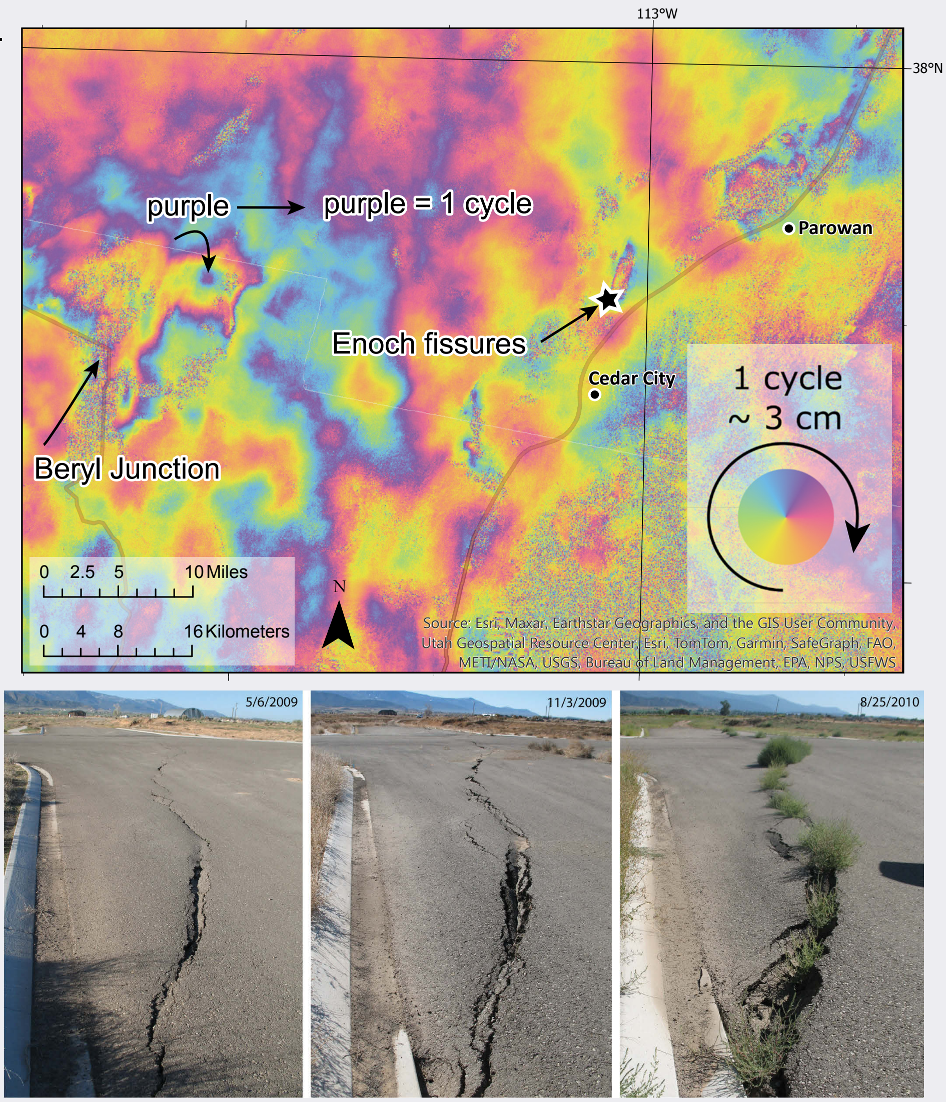
SAR sensors, complementary to other earth observation satellites and imaging techniques, have a plethora of applications. They have improved disaster response and hazard mitigation, advanced scientific understanding of earthquakes and volcanoes, and inspired governments, academia, and private companies to continually improve and apply this technology in the future.

InSAR applications at the UGS

Recently, the Utah Geological Survey (UGS) received federal and state funding to apply InSAR to monitor ground motion throughout Utah. The main focus is to identify potential areas of land subsidence, or sinking, caused by excessive groundwater withdrawal due to human activities. If more groundwater is pumped from an aquifer than is recharged by surface water, the water pressure in the underground pore space is reduced, allowing the aquifer sediments to compact. This sediment compaction causes land subsidence and, in addition to potentially causing damage to buildings and infrastructure, may permanently decrease the amount of water an aquifer can store. In turn, this results in lower water availability when surface water becomes scarce. In the U.S., 38% of water usage comes from groundwater. This number increases during periods of drought, such as the 2021–2023 extreme drought in Utah, which affected most of the state. A previous UGS study focused on measuring subsidence in southwestern Utah due to excessive groundwater pumping. This study found that subsidence in Cedar City Valley produced more than 8 miles of ground cracks, or fissures. According to historical aerial photographs, the first fissures began appearing in the 1960s. To help preserve the physical integrity of the aquifer, the Utah Division of Water Rights developed and adopted the Cedar City Valley groundwater management plan in 2021 to gradually reduce groundwater withdrawals. Moving forward, the increase in SAR data and improved processing techniques will allow for a systematic, semi-automatic analysis of InSAR data for monitoring land subsidence in Utah. Similar to Arizona and California, the UGS will routinely utilize and interpret InSAR data and provide the results to the public.

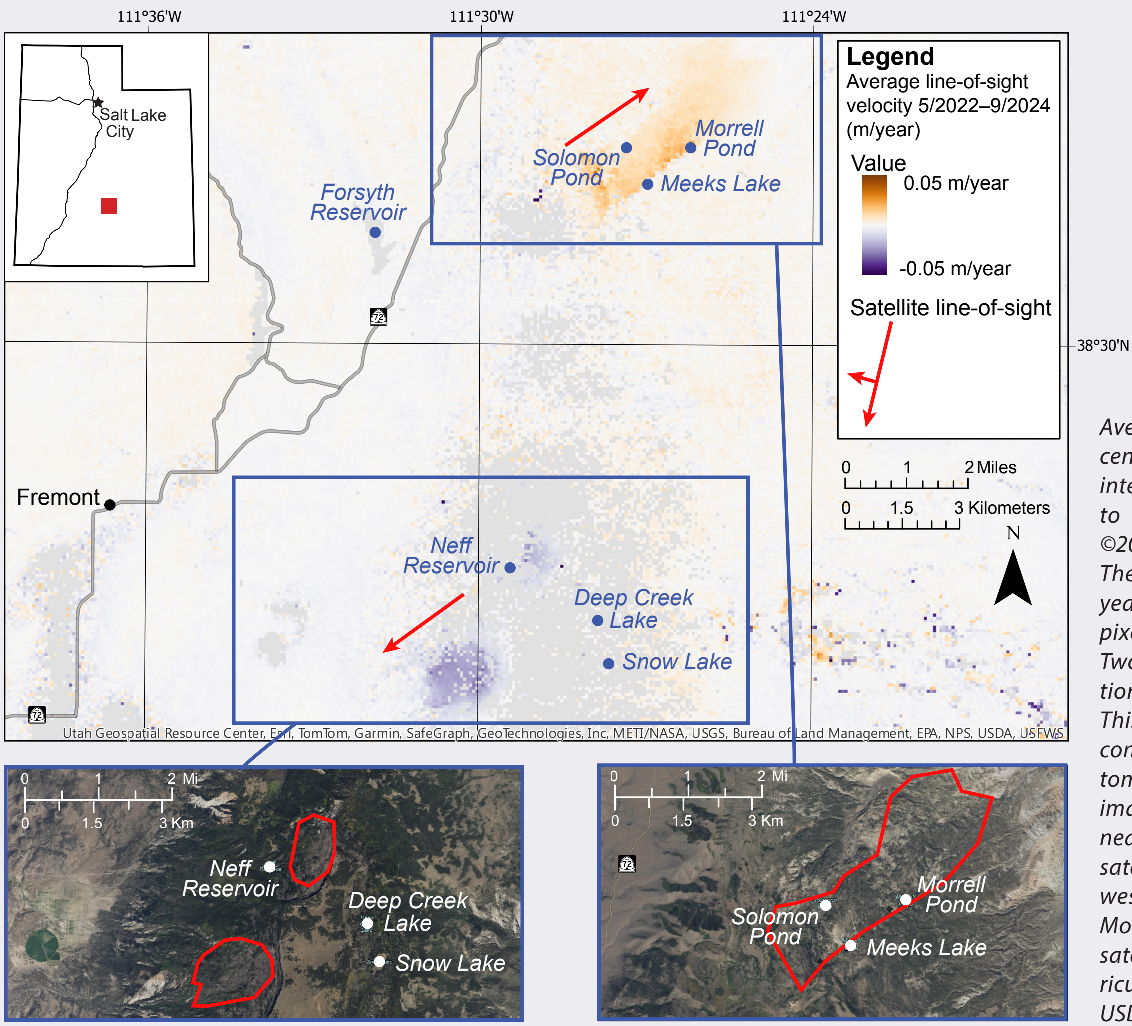
A.

B.



A. *Wrapped interferogram of southwestern Utah, near Cedar City, from ESA's SAR satellite Sentinel-1. This interferogram spans October 13, 2023, to July 27, 2024. One full cycle of color (e.g., purple → pink → yellow → blue → purple) is about 1.1 inches (2.8 cm) of ground motion away from the satellite during that time. The visible cycles near Beryl Junction, Enoch City, and Parowan are related to land subsidence due to excessive groundwater withdrawal. Continued land subsidence can result in earth fissures, as shown in the bottom panel. Pixelated areas indicate no reliable data. Sentinel-1 data ©2023, 2024 European Space Agency.* ***B.*** *Time sequence photo comparison showing progressive damage to pavement in the Parkview subdivision in Enoch City, Utah, due to land subsidence.*

InSAR can also be used to monitor other geologic hazards, such as earthquakes and landslides, that are prevalent in Utah. The 2020 Magna earthquake caused more than $62 million in damages, and the Wasatch Front has greater than a one in two chance (coin toss) of a magnitude 6.0+ earthquake in the next 50 years. If another earthquake with a magnitude 5 or above were to occur in Utah, comparing SAR images acquired before and after the event could quickly identify ground ruptures or disturbances and inform damage assessments. In addition, landslides can cost Utah millions of dollars in damages per year. To assist in mapping and tracking landslide motion, which often occurs at rates as slow as a few inches per year, we can use InSAR to identify and monitor moving slopes over the course of weeks or years. This dataset will complement field mapping and ground-based measurements using GNSS (Global Navigation Satellite System). Other sources of ground deformation in Utah that have rates well-suited for InSAR (a few tenths of an inch to a few inches per year) include ground deformation from mining, oil and gas extraction, geothermal-related subsurface changes, and motion of rock glaciers (masses of ice covered in rocks that move downhill). The UGS plans to leverage SAR datasets through collaborative projects across its programs to monitor ground surface changes throughout the state.



Average LOS ground motion velocity in central Utah estimated from Sentinel-1 interferograms spanning May 2022 to September 2024 (Sentinel-1 data ©2023, 2024 European Space Agency). The colorbar ranges from -5 to 5 cm/year (about -2 to 2 inches/year), and pixels with low reliability are masked. Two distinct regions of LOS ground motion are shown with blue rectangles. This motion is related to two landslide complexes, outlined in red in the bottom panels, showing optical satellite images. The northernmost landslide, near Meeks Lake, is moving toward the satellite, while the bottom landslides, west and northwest of Thousand Lakes Mountain, are moving away from the satellite. Imagery from the National Agriculture Imagery Program (NAIP), Esri, USDA Farm Service Agency.

ABOUT THE AUTHOR

Tara Shreve is an Interferometric Synthetic Aperture Radar (InSAR) Specialist who joined the Utah Geological Survey in 2024. She has a B.S. in mathematics and graduated with a Ph.D. in geophysics from the Institut de Physique du Globe de Paris in 2020, with a focus on InSAR geodesy. She has applied InSAR to identify, interpret and model ground deformation at remote volcanoes in Alaska, Vanuatu, Democratic Republic of Congo, and the Galápagos. Her work with the UGS is to monitor different geologic processes that drive ground displacement throughout Utah, such as land subsidence, landslides, and earthquakes.

Mapping and Modeling Phragmites at the Bear River Migratory Bird Refuge

by Pete Goodwin and Rebecca Molinari

Phragmites (*Phragmites australis* ssp. *australis*) threatens Great Salt Lake wetlands by readily invading shallowly flooded areas to form dense stands extending tens of thousands of acres. These stands replace native vegetation communities, degrade wildlife habitats, and consume additional water through greater evapotranspiration (the water evaporating from leaves during photosynthesis). Understandably, land managers around Great Salt Lake consider phragmites control a top priority and invest significant resources in treatment and eradication.

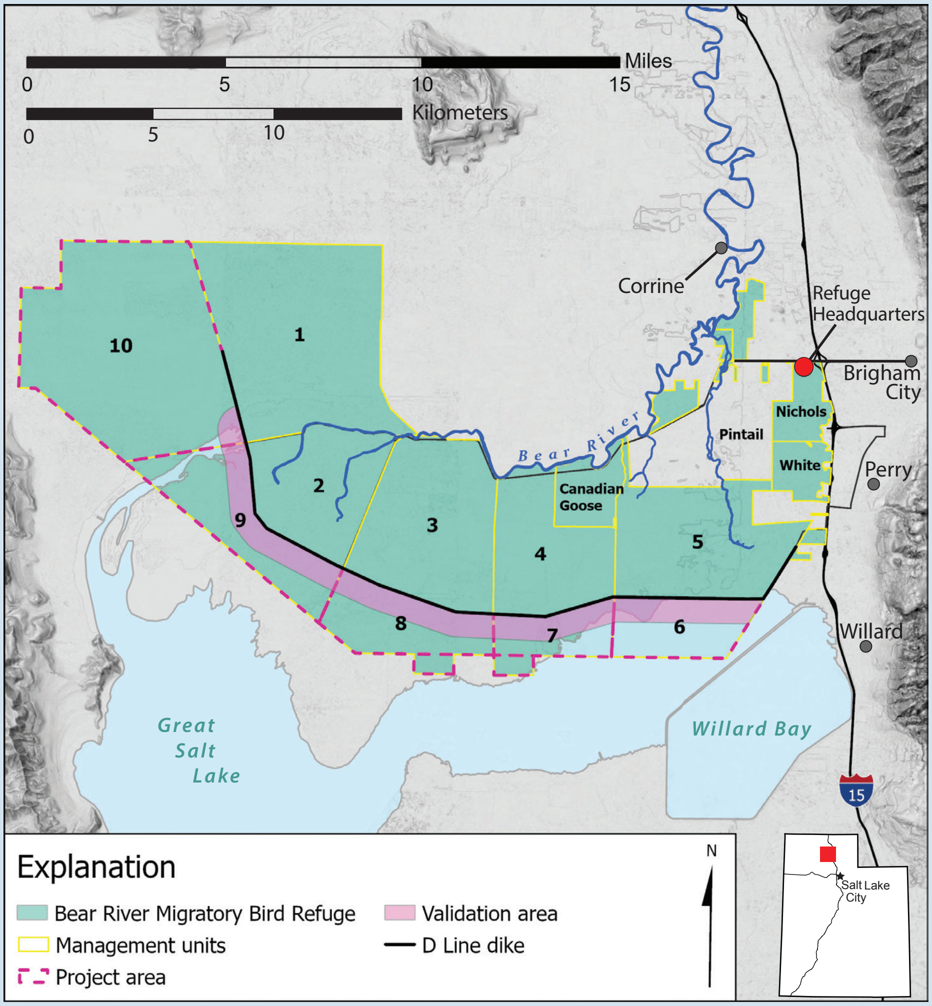
Effective phragmites control requires accurate vegetation mapping to identify new phragmites stands while clearly distinguishing native vegetation and to delineate possible treatment areas. The Utah Geological Survey (UGS) completed the most recent large-scale phragmites mapping effort as part of a 2014 National Wetland Inventory mapping project, but that mapping is over ten years old. Now, managers need new maps that reflect the current phragmites extent but that also can be easily updatable to keep pace with continuing phragmites expansion and control.

The Utah Division of Forestry, Fire & State Lands (FFSL) recognized this need for updated mapping and is working to develop computer models that identify phragmites across the entire Great Salt Lake watershed. To be successful, these models need to "learn" how to correctly map phragmites. The UGS, in collaboration with FFSL and the U.S. Fish and Wildlife Service (FWS), mapped and modeled vegetation at the Bear River Migratory Bird Refuge (Refuge) to map phragmites for FFSL models and test modeling workflows.

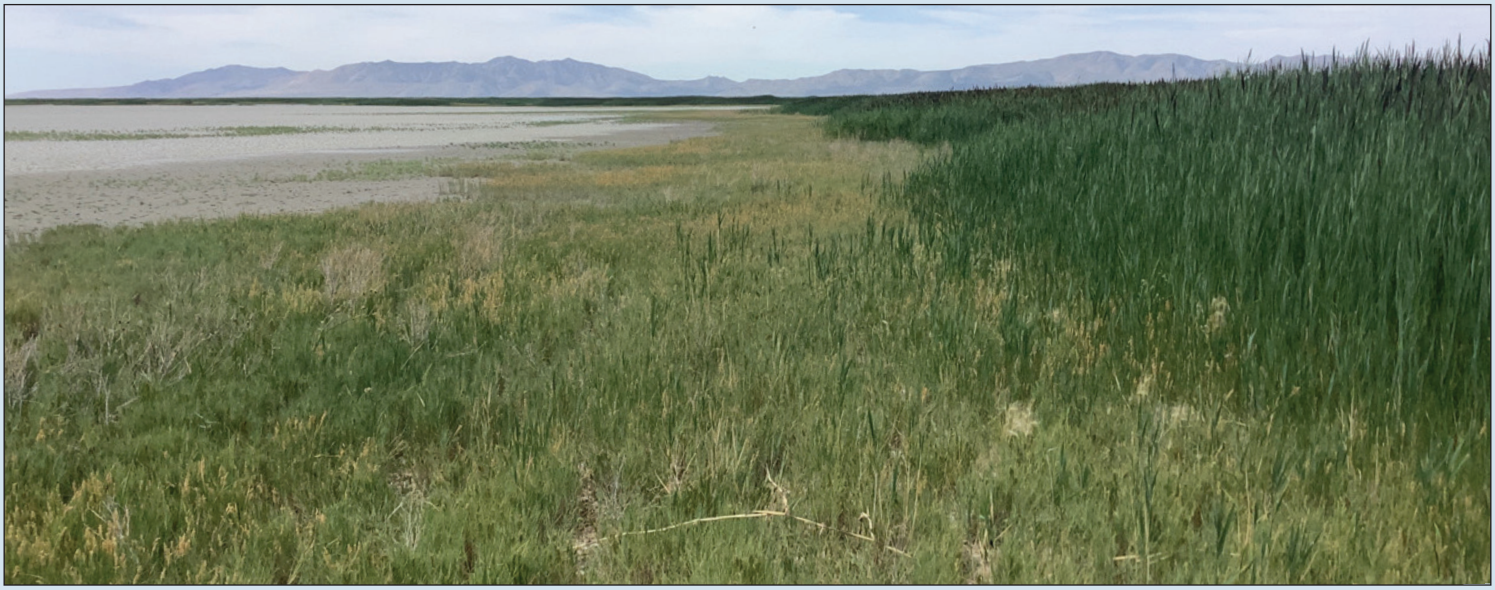
We mapped vegetation on the Refuge using two approaches—a manual photo interpretation using high-resolution imagery collected in July 2023, and an automated approach that developed several models using Random Forest (RF) algorithms classifying satellite imagery. Both approaches classified vegetation into four vegetation communities (dense phragmites, treated phragmites, shoreline, and other vegetation) and completely mapped those communities across the lower part of the Refuge (management units 6, 7, 8, 9, and 10). The manual approach relied on skilled ecologists to delineate each community across the entire project area, whereas the RF models required only a small set of representative mapping, typically referred to as training data. The RF models used the training data to "learn" how to correctly classify individual pixels of satellite imagery to our four vegetation communities.

We developed several RF models from several imagery datasets to test how model accuracy might vary by image resolution or collection date. For the resolution comparison, we developed three RF models from three satellite imagery datasets across a quality and availability spectrum. We used Sentinel (a free and widely available coarse [10 meter] resolution dataset) for a low-cost option, tasked Worldview (a high [2 meter] resolution dataset collected specifically for this project) for a high-cost option, and commercial Planet imagery (moderate resolution [3 meter] available for purchase from several vendors) for a moderate cost option. We selected Planet and Sentinel images closest to the July 20, 2023, WorldView collection date to minimize image variability.

We assessed the accuracy of each approach by evaluating the manual mapping and RF models against reference locations with known vegetation communities, typically referred to as validation data.



Overview of project area and Bear River Migratory Bird Refuge.



Typical vegetation on the Bear River Migratory Bird Refuge.

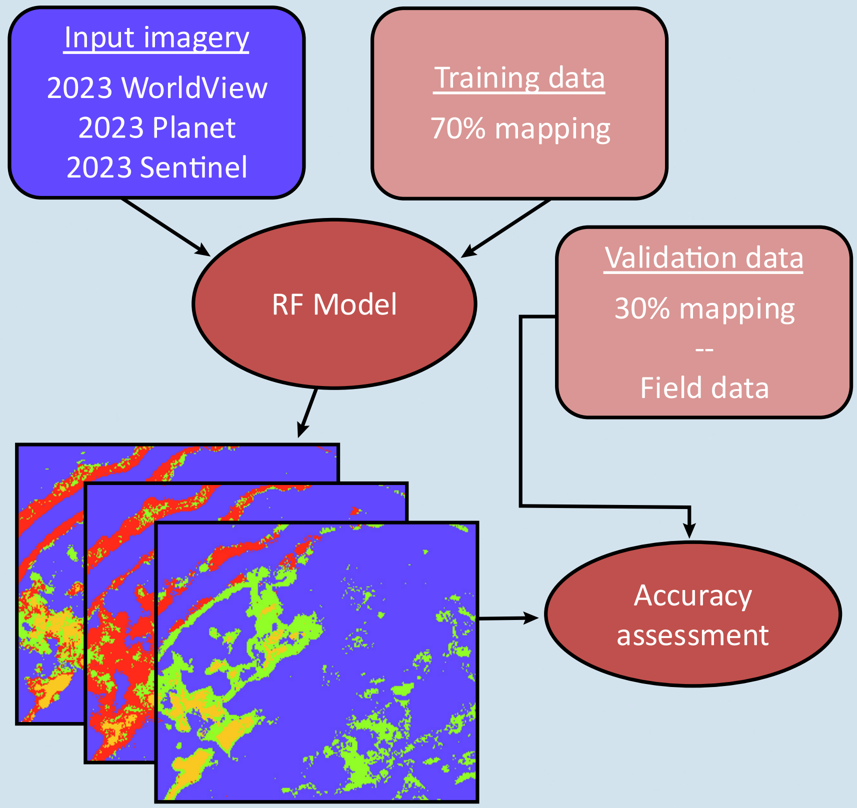
From the validation data, we determined overall accuracy and specific accuracies for dense phragmites and treated phragmites which we reported as user accuracy and producer accuracy. User accuracy measures how likely a mapped or modeled phragmites stand exists in the field; conversely, producer accuracy measures how likely an existing phragmites stand is included in the mapping or modeling. Useful phragmites mapping must be reliable (high user accuracy) to prevent unneeded effort attempting to treat incorrectly mapped phragmites but also complete (high producer accuracy) to provide managers with accurate estimates of total phragmites extent.

We found varying accuracies between the manual mapping and RF models produced by the manual and automated approaches, but each identified the dense phragmites community with over 80% user and producer accuracies. Some RF models approached 100% user and producer accuracies but had reduced accuracies when validated similarly to the manual mapping. Both approaches mapped treated phragmites less accurately and the RF models mapped this community with substantially lower producer accuracy, i.e., many existing phragmites treatments areas were not mapped as a treated phragmites community. Our RF models and manual mapping differ in several ways. Manual mapping depicted native vegetation communities with more nuance and identified treated phragmites communities more intuitively as impacted phragmites (e.g., dead thatch, mowed tracts, sparse regrowth) within a treatment boundary. RF models require vastly less time and effort and can consistently identify small (less than 400 ft^2) phragmites patches. Despite these differences, both approaches accurately identified phragmites stands with very similar boundaries.

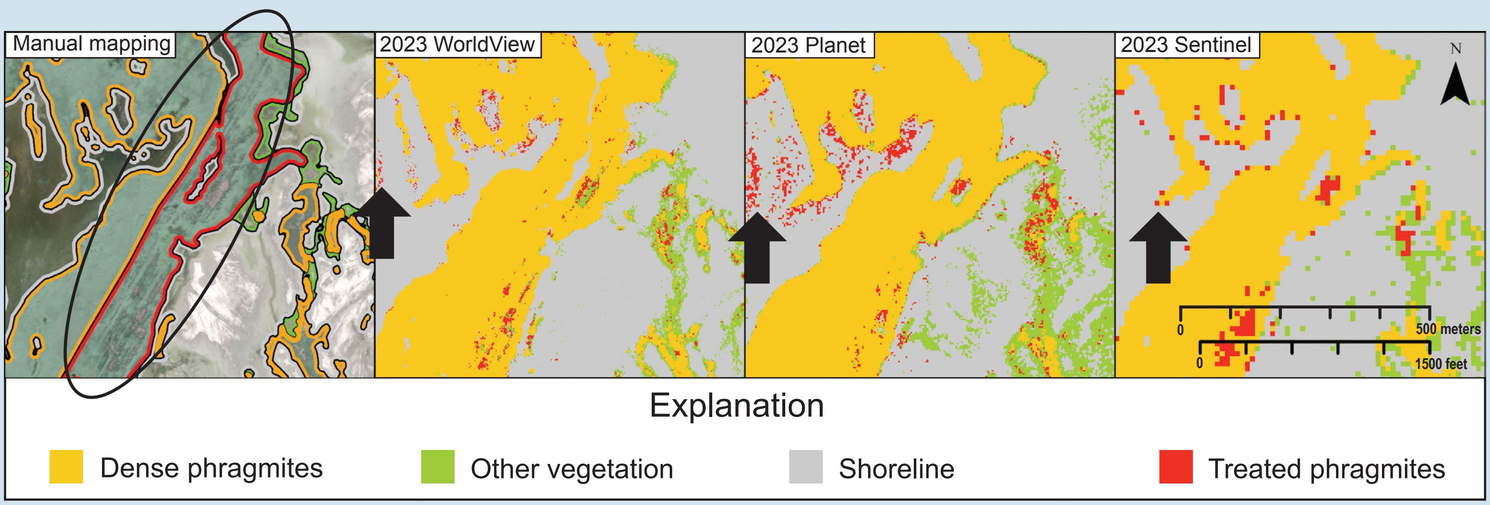
*Examples of typical vegetation communities (from left to right). Dense phragmites, treated phragmites, shoreline which included shallow water, barren playas, and sparse pickleweed (*Salicornia *spp.), and other vegetation which included all native marsh and meadow vegetation.*

Our best RF models relied on high-resolution (2 meter) satellite imagery trained on ample and diverse training data. We noticed accuracy decreased in areas with mixed signatures or those farther from our validation data. For instance, the RF models struggled to classify phragmites intermixed with native marsh vegetation or dense algae because we created training data by mapping very distinct phragmites patches. Additionally, these intermixed areas frequently exist at the southeastern edge of the project area, an area well outside our limited field validation area. Our project area did not include irrigated fields whose dense, green appearance would likely confuse phragmites models. We recommend future studies to examine model effectiveness across a project area containing both phragmites and irrigated fields. We also recommend that annual phragmites models be produced from easily available imagery like Planet or Sentinel to track changes in phragmites location and extent.

Our manual mapping and all RF models identified substantial phragmites infestations on the Refuge, with the dense phragmites vegetation community covering 2,000 to 2,300 acres, or 7% to 8% of the 30,125-acre project area. Within several individual management units (units 7 and 8), phragmites cover exceeded the 10% threshold USFWS set in recent habitat management plans. Although exploratory and highly specific to our project area, we were able to rapidly and accurately model obvious phragmites stands. These results bolstered Refuge staff efforts to fund and complete phragmites treatments in less intensively managed areas on the Refuge. Data produced by this project enabled more specific phragmites control on Refuge lands and laid groundwork for future large-scale phragmites modeling efforts.



Conceptual diagram of RF model development and assessment for imagery resolution comparisons. Models were trained using 70% of the representative mapping and the remaining 30% used as validation data in accuracy assessments. We also assessed each RF model using field data collected in fall 2023.



Comparison of results from manual mapping and random forest models. All approaches generally agree on dense phragmites but disagree on treated phragmites with the RF models mapping only parts of a known treatment area (black oval) but identifying patches outside treatment boundaries (black arrows).

Further reading:

Report of Investigation 287: https://ugspub.nr.utah.gov/publications/reports_of_investigations/ri-287/ri-287.pdf

Utah Lake Phragmites Control/FFSL Story Map: https://storymaps.arcgis.com/stories/4ba238d169f043f89e1eec1c37d066cd

How to restore Phragmites-invaded wetlands/restoration BMP: https://ffsl.utah.gov/wp-content/uploads/USU-Phragmites-Control-and-Restoration-BMP-whitepaper.pdf

WHAT IS THE STORY BEHIND LAKE POWELL'S ROCKS?

by Lance Weaver

Glad You Asked!

Nestled within the Glen Canyon National Recreation Area (GCNRA), Lake Powell is a testament to both human ingenuity and the enduring power of nature. The lake fills the entirety of the roughly 170-mile length of Glen Canyon. Sometimes referred to as Utah's "sixth national park," this vast reservoir offers a unique blend of recreation and stunning geological beauty. Its sheer size and intricate shoreline distinguish it from any of Utah's other lakes, while its geological story reveals a complex and fascinating past.

The first recorded European encounter with Glen Canyon comes from the Domínguez-Escalante Expedition of 1776. Just a few months after Thomas Jefferson signed the Declaration of Independence, the two Spanish explorers spent several weeks being led by Native American guides across a narrow passage through the canyon's nearly impenetrable walls. Almost one hundred years later in 1869, John Wesley Powell, the lake's namesake, explored the area by boating down the Colorado River and wrote the first known geologic investigation of the region.

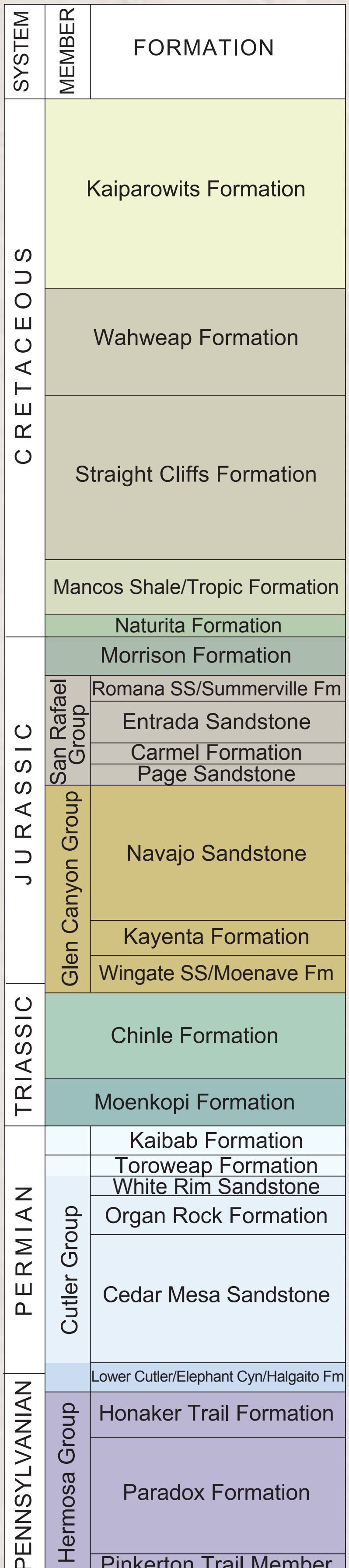
Almost another century later, in 1956, construction began for Glen Canyon Dam near the Utah-Arizona border. Designed to regulate and store water from the Colorado River Basin for six states—Utah, Colorado, Arizona, New Mexico, Nevada, and California—the dam also became a vital source of hydroelectric power. Its construction followed years of debate among government agencies, conservationists, and water resource planners, underscoring its enduring role in regional water management and the ongoing discussions surrounding its impact. The completion of the dam led to the formation of Lake Powell, one of the largest reservoirs in the United States.

Perhaps Lake Powell's most unique feature is its expansive cliff-lined shores. At full pool, its shoreline stretches greater than 1,900 miles, a figure that dwarfs the entire west coast of the continental United States. This remarkable length is a product of the flooding of Glen Canyon's intricate network of slot canyons and translates to a myriad of opportunities for exploration in the 96 major canyons and countless smaller coves and inlets. Adding to its allure are numerous natural features found within or near the recreation area, including iconic natural bridges and arches like Rainbow Bridge, Halls Creek Bridge, Broken Bow Arch, LaGorce Arch and many more in Glen Canyon's Escalante arm. These natural wonders, sculpted by millennia of erosion, punctuate the landscape and provide a glimpse into the canyon's ancient geological history.

Houseboats parked in Navajo Canyon, amidst towering cliffs of Navajo Sandstone.

The geology of Glen Canyon is a story spanning hundreds of millions of years, displaying a continuous sequence of rock layers that range from Pennsylvanian (~320 million years old) to Late Cretaceous (~66 million years old) age. The oldest exposed rock layer, the Pennsylvanian-age Hermosa Group, lies at the base of this geological sequence and is exposed on the flanks of the Monument Upwarp on the northeast end of the lake. Above the Pennsylvanian–Permian-age Cutler Group lies the Early Triassic-age (~250 million years old) Moenkopi Formation, which is visible on both the northernmost and southernmost areas of Glen Canyon National Recreation Area. Overlying the Moenkopi is the Middle to Late Triassic-age (~230 million years old) Chinle Formation, known for its vibrant colors and abundant petrified wood.

Perhaps the most impressive geologic unit in the region is the Early Jurassic-age (~200 to 190 million years old) Glen Canyon Group, a suite of sandstones that dominate the canyon's landscape and borrows its name. This group consists of the Wingate Sandstone, known for its deep red sheer cliffs; the Kayenta Formation, characterized by its ledges and slopes of interbedded



Simplified stratigraphic column.

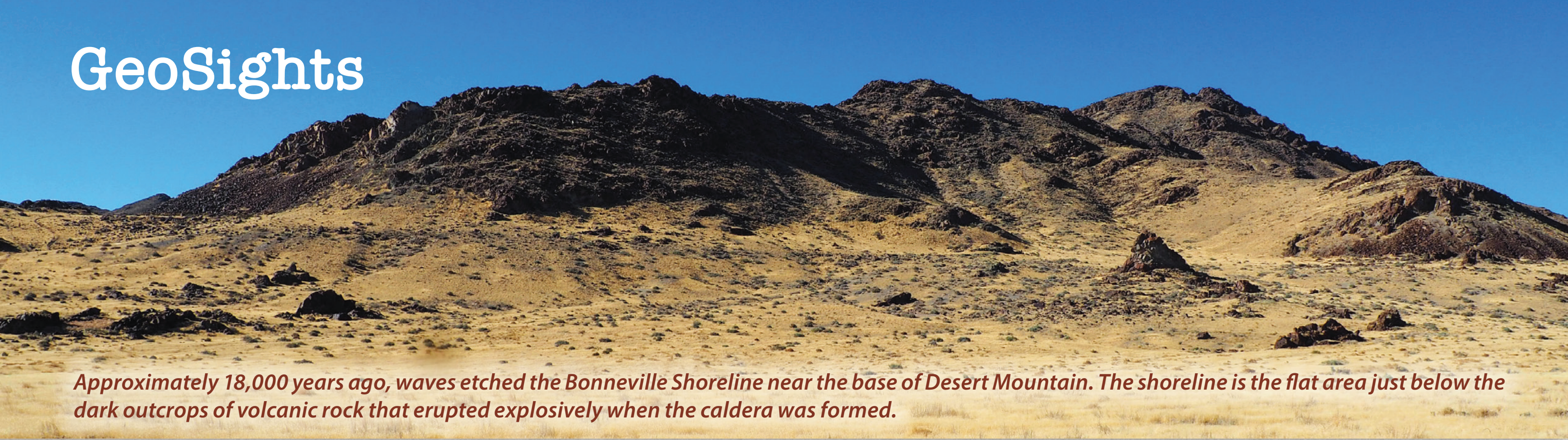
Broken Bow Arch, Escalante Canyons section of Glen Canyon National Recreation Area.

shale and sandstone; and the massive Navajo Sandstone, which forms tall cliffs and slickrock canyons. This sequence of sandstones tells a story of ancient deserts with shifting sand dunes in a setting not unlike that of the modern Sahara Desert (see *Survey Notes* v. 44, no. 3). The entirety of the southern Utah Cretaceous-age sequence (~145 to 66 million years ago) is also visible from the southern and central parts of the lake, offering a complete picture of the region's Mesozoic Era history.

Following deposition, burial, and lithification of these rock layers, the Colorado Plateau was uplifted, and the Colorado River and its tributaries began to incise or cut down into the rocks to form the impressive collection of canyons that compose the Glen Canyon National Recreation Area. The majority of modern Glen Canyon's incision occurred within the last 5.5 million years, during a pulse of rapid uplift on the Colorado Plateau.

Part of what makes the geology of Lake Powell so unique is the juxtaposition of the lake's completely level surface against the undulating regional geology. As one travels up lake from Glen Canyon dam, geologic rock formations of different ages take turns occupying the shorelines. This unique experience is caused by the regional folding of the Monument and Circle Cliffs upwarps that have uplifted the oldest layers to the surface in the northmost sections of the lake, exposing the Pennsylvanian- and Triassic-age units. Conversely, the Kaiparowits basin brings younger Cretaceous- and Late Jurassic-age layers to lake level. Adding to the geological intrigue are prominent geologic features visible from the lake, called laccoliths, caused by magma rising through the subsurface and bending the overlying rocks into unique dome-like structures seen at Navajo Mountain and the Henry Mountains.

Lake Powell stands as a significant testament to the interwoven forces of nature and human activity. It offers visitors a unique way to traverse Glen Canyon and explore the breathtaking landscapes of the canyon and its fascinating geologic history.



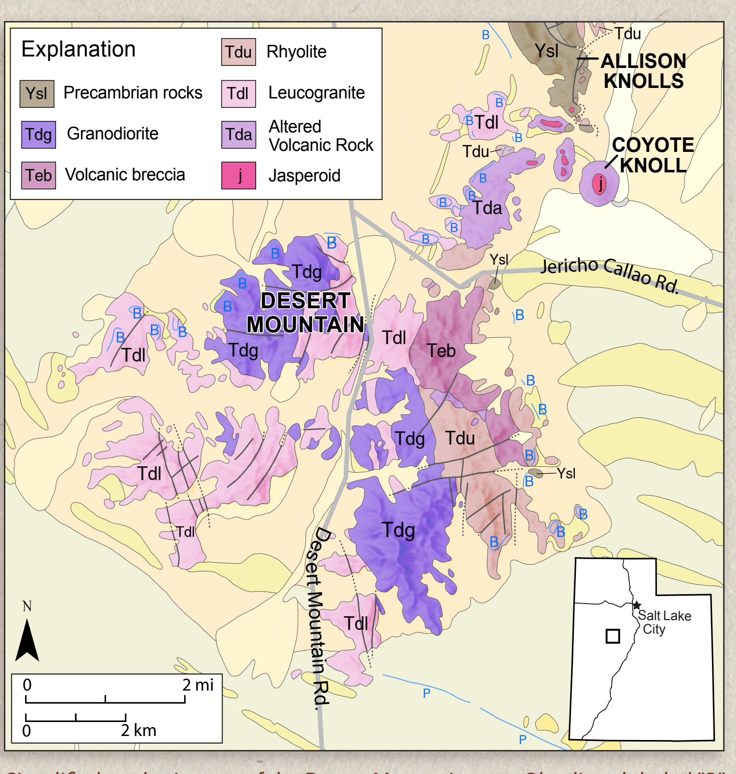
Approximately 18,000 years ago, waves etched the Bonneville Shoreline near the base of Desert Mountain. The shoreline is the flat area just below the dark outcrops of volcanic rock that erupted explosively when the caldera was formed.

Desert Mountain, Juab County, Utah *by Jackson Smith*

Desert Mountain is a cluster of isolated peaks in Juab County, roughly 25 miles north of Delta, Utah. Located in the Tintic-Deep Creek mineral belt of the Basin and Range Province, the area is known to rock climbers for its granitic outcrops, but most others are unaware of this fascinating and fantastic geologic site.

Desert Mountain is a small solitary range that echoes fiery volcanic eruptions and ancient magmatic upheaval from long ago and is now a quiet, remote monument of that geologically violent time. The range is composed of igneous rocks including granite, rhyolite, and tuff, as well as a few sparse outcrops of Precambrian-age sedimentary rocks. Only a few scientific research studies have been conducted on Desert Mountain, but based on the most recent studies, the area is believed to be the remnants of an ancient volcanic caldera. A caldera forms when a volcano empties a large amount of its magma chamber in an enormous eruption, causing the volcano to collapse inwardly and form a circular bowl-shaped depression.

About 30 to 40 million years ago during the Eocene to Oligocene Epochs, the Desert Mountain area became a center of magmatic activity when a large body of magma intruded into the Earth's crust. Crustal rocks in the area consisted of Precambrian-age sedimentary rocks and Eocene-age igneous rocks from a previous episode of intrusion that likely occurred just prior to the one that created the Desert Mountain caldera. The precise timing of this previous intrusion is not certain, but you can see it today as the dark-crystalline granitic rock (granodiorite) covering widespread areas of the Desert Mountain Range. The newer intrusion of magma erupted as a sticky, low-silica rhyolitic lava flow, some of which can now be seen just off the Jericho Callao Road before reaching Desert Mountain Pass. A nearby stratovolcano also erupted around this time expelling andesitic lava, as evidenced by andesitic rocks found at Desert Mountain today.



Simplified geologic map of the Desert Mountain area. Blue lines labeled "B" are Lake Bonneville shorelines and heavy black lines are faults. Modified from Pampeyan, 2005.

After emplacement of the magma chamber and the eruption of the rhyolitic lava, a huge, cataclysmic eruption occurred at Desert Mountain ejecting volcanic ash, blocks, and rock fragments. These deposits (pyroclastic rhyolite) can be seen today all over the eastern side of the Desert Mountain Range. At this point, the magma chamber had emptied so much of its contents in such an enormous eruption that its roof collapsed, forming a volcanic breccia, which is a thick chaotic assemblage of rocks consisting of fragments of the Precambrian-age sedimentary rock and igneous rocks within a matrix of volcanic material. This volcanic breccia is also prevalent on the eastern side of Desert Mountain Range.

Desert Mountain volcanic breccia, formed from the caldera collapse.

Following the collapse, the leftover magma rose upwards below the bottom of the caldera and cooled into a "resurgent dome" of light-colored granite, called leucogranite, that makes up most of Desert Mountain today. As the magma began to cool, fractures and fissures formed, allowing hotter, still molten, magma from below to rise and fill the voids. These thin vertical sheets cooled to create dikes containing an igneous rock called aplite. These sugary-textured, white aplite dikes locally contain cavities that feature large grains of quartz, feldspar, and mica. Juxtaposed with the older and much darker volcanic and granitic rocks, the leucogranite of Desert Mountain and the white aplite dikes are distinct and unmistakable.

Hot fluids associated with the resurgent magma circulated through the caldera and altered the volcanic rocks. This process helped to create clay and rocks enriched in silica, like jasperoid. This geothermal fluid also helped create small ore deposits of predominantly silver and copper that were last mined in the first half of the twentieth century, with a total value of under $20,000 (modern metal prices).

A final, comparatively small pulse of magma intruded the leucogranite of Desert Mountain, cutting through it in many places to form what appear to be very dark lamprophyre dikes that offer a striking contrast in color to the lighter granite that they cut through.

Over the past 17 million years, tectonic forces have been pulling apart the Earth's crust between Utah's Wasatch Range and California's Sierra Nevada Mountains, an area called the Basin and Range Physiographic Province. This westward-directed extension and thinning has led to dramatic changes in topography, creating north-south-trending, fault-bounded valleys and mountain ranges. The extension and movement along local faults have slowly exhumed and tilted the Desert Mountain area eastward so that the extruded volcanic rocks lie east of the once buried granitic intrusion.

Around 30,000 years ago, ancient Lake Bonneville covered much of western Utah and parts of Idaho and Nevada. By about 18,000 years ago, when the lake had grown to its largest size, the highest part of Desert Mountain would have appeared as a peninsula connected by a small isthmus to the higher land to the northwest near Coyote Knoll. The shorelines of Lake Bonneville are still visible around the mountain range's flanks at an elevation of approximately 5,170 feet.

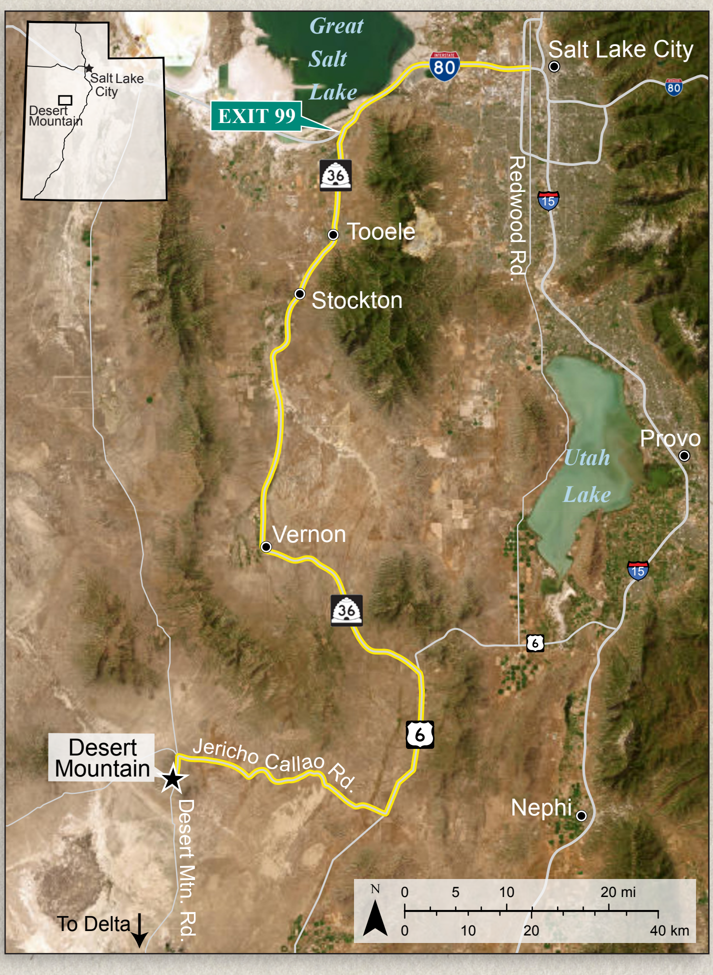
The leucogranite of Desert Mountain.

Lamprophyre dike cutting through the leucogranite of Desert Mountain.

How to Get There

From Salt Lake City, drive west on Interstate 80 to exit 99 and take State Route 36 south towards Tooele. Drive for 66 miles, passing through Tooele, Stockton, and Vernon. Turn right onto U.S. Route 6 and drive south for 15.3 miles. Turn right (west) onto Weiss Highway/Jericho Callao Road. Drive for 22.5 miles (the road will turn from pavement to dirt/gravel after about 6.5 to 7 miles). Take the left fork towards Desert Mountain Pass and drive for 1.5 miles to Desert Mountain.

Coordinates: 39.7815°N -112.5945°W



* Special thanks are owed to Professor Eric Christiansen from Brigham Young University, who aided my understanding of Desert Mountain's geology and is currently researching the Desert Mountain area.

• SURVEY NEWS •

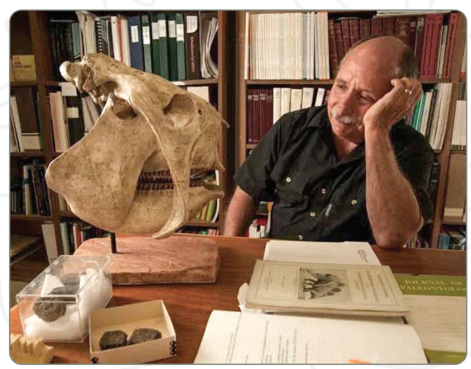
After six years of serving as State Geologist and Director of the Utah Geological Survey (UGS), **Bill Keach** retired in April. Before joining the UGS, Bill spent over 5 years in offshore hydrocarbon exploration in the Gulf of Mexico and with Sohio/BP in California and then 17 years with Landmark Graphics (now Halliburton), where he traveled the world developing 3D-visualization technology and its adoption. He then worked as a researcher for the Energy and Geoscience Institute at the University of Utah (U of U) while concurrently serving as an adjunct professor at both the U of U and Brigham Young University teaching courses on seismic interpretation and petroleum reservoir modeling. While at the UGS, Bill continued his adjunct positions with the U of U and BYU to satisfy his passion for teaching. One of his favorite roles in academia and as State Geologist has been the opportunity to develop and lead field courses taking students and professionals from around the world throughout Utah to see and learn its many geologic wonders.

Bill's calm and unwavering leadership held the UGS steady during the COVID-19 pandemic and concurrent emergency response to the 2020 Magna earthquake. His passion to share and ability to straightforwardly explain geology and the work of the UGS with the general public and Utah lawmakers led to the passage of legislation creating restricted accounts that will help stabilize UGS funding for decades to come. Furthermore, he has shepherded successful legislation requiring municipalities to share geotechnical reports for building permits with the UGS. This information is now publicly available and will serve to protect current and future Utahns.

Upon retirement Bill has immediate plans to travel to Iceland, and he will continue educating, leading field trips, and being involved in Utah geology in a myriad of ways. The UGS and citizens of Utah have benefited from Bill's ability to disseminate geologic information in a manner that helps us understand why it matters and how it affects our lives. Thank you, Bill, and we wish you well in your retirement!

In Memoriam

Former Utah State Paleontologist **Dr. David Gillette** passed away peacefully at his home in Flagstaff, Arizona, on February 10, 2025. Dr. Gillette was the first Curator of Paleontology at the New Mexico Museum of Natural History and served as Utah State Paleontologist at the Utah Geological Survey (UGS) before accepting the prestigious position of Colbert Curator of Paleontology at the Museum of Northern Arizona, where he remained until his retirement in 2020.



Dr. Gillette's work focused primarily on vertebrate paleontology, evolutionary biology, college-level and public education and outreach, and resource management. With over 220 publications during his career, he is recognized as a leading authority on Neogene glyptodonts. He made significant contributions to the understanding of Utah's paleontological resources including the discovery and excavation of the Huntington Mammoth and the founding of Utah Friends of Paleontology (UFOP), and helped move the paleontology program from the Utah Division of State History under the State Archaeologist to the UGS.

Dr. Gillette was a respected researcher, educator, and mentor who left a lasting legacy in the field of paleontology and inspired new generations of paleontologists. The UGS extends its condolences to his family, friends, and colleagues.

2025 Utah Legislative Session Events

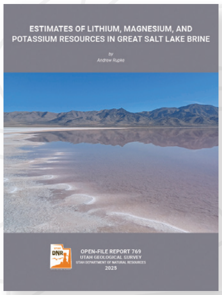
On January 31st the Natural Resources Map & Bookstore helped the Division of Outdoor Recreation and other local organizations celebrate the depth, uniqueness, and innovation of the outdoor recreation industry by attending Outdoor Recreation Day on the Hill at the Utah State Capitol. The event was well attended and gave our staff the opportunity to personally interact with multiple lawmakers and their staff. Then on March 5th the UGS participated in Maps on the Hill at the Capitol to present our various web applications and current mapping projects. This event showcases the diversity of mapping resources in Utah and demonstrates how mapping technology can support decision-makers.

Employee News

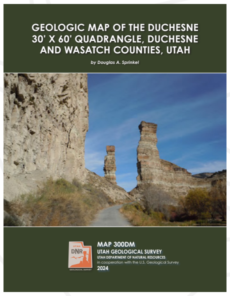
The Groundwater & Wetlands Program welcomes **Michael Herrman** as Wetland Ecologist and **Jessica Stern** as the Utah State Wetlands Coordinator. Michael recently moved to Utah from Northern Indiana and has a B.S. in biological sciences from Indiana University. His work at the UGS involves mapping wetlands and assisting with field work. Jessica has a M.S. in natural resources and environmental sciences from University of Illinois Urbana Champaign and a B.S. in environmental studies from Marlborough College. She will be responsible for updating Utah's Wetland Program Plan, researching wetland policies, and maintaining the Wetland Working Group. **Darlene Batatian** was named the new State Geologist and director for the UGS. Her professional experience is expansive, ranging from geologic field mapping to geologic hazards, groundwater site investigations, land development, and public policy. Darlene replaces Bill Keach, who retired in April. The Energy & Minerals Program bids farewell to **Jake Alexander** who accepted a job with the Utah Division of Forestry, Fire, and State Lands. **Lucy Jordan** retired in March after 21 years of service with the UGS. Lucy was a Senior Hydrogeologist with the Groundwater & Wetlands Program, and her work focused on water-resource assessments in Utah. **Tom Dempster** retired in January after 25 years of service as the Assistant Curator of the Utah Core Research Center (UCRC). A warm welcome to Michael and Jessica and congratulations to Darlene, Jake, Lucy, and Tom.

New Publications

Available at the Natural Resources Map & Bookstore—**utahmapstore.com** and for download at **geology.utah.gov**.



Estimates of Lithium, Magnesium, and Potassium Resources in Great Salt Lake Brine, by Andrew Rupke, 21 p., 1 plate, **OFR-769**, https://doi.org/10.34191/OFR-769



Geologic Map of the Duchesne 30' x 60' Quadrangle, Duchesne and Wasatch Counties, Utah, by Douglas A. Sprinkel, 62 p., 2 appendices, 2 plates, scale 1:62,500, **M-300DM**, https://doi.org/10.34191/M-300DM

Recent Outside Publications *by UGS Authors*

Detrital Thermochronology Histories Preserved in Paleogene Strata of Utah (USA) Provide Distant Records of Alleghanian Orogenesis and Sediment Dispersal, by A.L. Stevens Goddard, S.R. Black, E.A. Balgord, **Z.W. Anderson**, R.J. Leary, O.G. Thurston, and W.A. Yonkee: Geology, https://doi.org/10.1130/G52736.1

3D Characterization of Navajo Sandstone Cuttings Using Sub-Micron X-ray Computed Tomography for Permeability Simulated by Lattice Boltzmann Method, by R. Jaramillor, J. Jin, C-L, Lin, N. Moodie, E. Edleman, and **E. Szymanski**: Geoenergy Science and Engineering, v. 246, https://doi.org/10.1016/j.geoen.2025.213654

Following in the Footsteps of Dr. Martin G. Lockley—Another Ten Years of Paleontological Investigations in Glen Canyon National Recreation Area, Utah and Arizona, by A.R.C. Milner, V.L. Santucci, A.D., Marsh, M.R. King, J.D. Harris, A. DelGalvis, J.R. Wood, J.C. Buchwitz, H.A. Carter, **J.I. Kirkland**, D.L. Slauf, A.L. Charobee, C.J. Bennett, M. Rodriguez, J.S. Tweet and E.C. Clites: New Mexico Museum of Natural History and Science Bulletin 95

Sabkha Deposition on an Epicontinental-Foredeep: The Petroleum-Bearing Cane Creek Interval of the Pennsylvanian Paradox Formation, in the Paradox Basin, Utah, U.S.A., by **E.A. Jagniecki, M.D. Vanden Berg**, L.P. Birgenheier, S.M. Ritter, G. Maxwell, and D. List: Marine and Petroleum Geology, v. 174, https://doi.org/10.1016/j.marpetgeo.2025.107320

Cranial Anatomy and Stratigraphy of a New Specimen of the Tyrannosaurine Dinosaur Daspletosaurus from the Judith River Formation of Central Montana, U.S.A., by **E.W. Cowgill**, G.W. Storrs, R.R. Rogers, and A. E. Maltese: Acta Palaeontologica Polonica v. 70, no. 1, p. 159–174, https://doi.org/10.4202/app.01143.2024

Teacher's Corner

2025 UGA TEACHER OF THE YEAR

Congratulations to **Preston Croshaw** of DaVinci Academy who was presented the 2025 Utah Geological Association's (UGA) Utah Earth Science Teacher of the Year Award for his outstanding efforts in educating our youth on important earth science topics. In his current role of science teacher, Preston fosters curiosity and critical thinking in his 9–12 grade students through hands-on activities like building geologic models, exploring natural resources with maps, and developing real-life conservation plans. He is described by his students and colleagues as an inspiring and influential teacher and deserving recipient of this special recognition.

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