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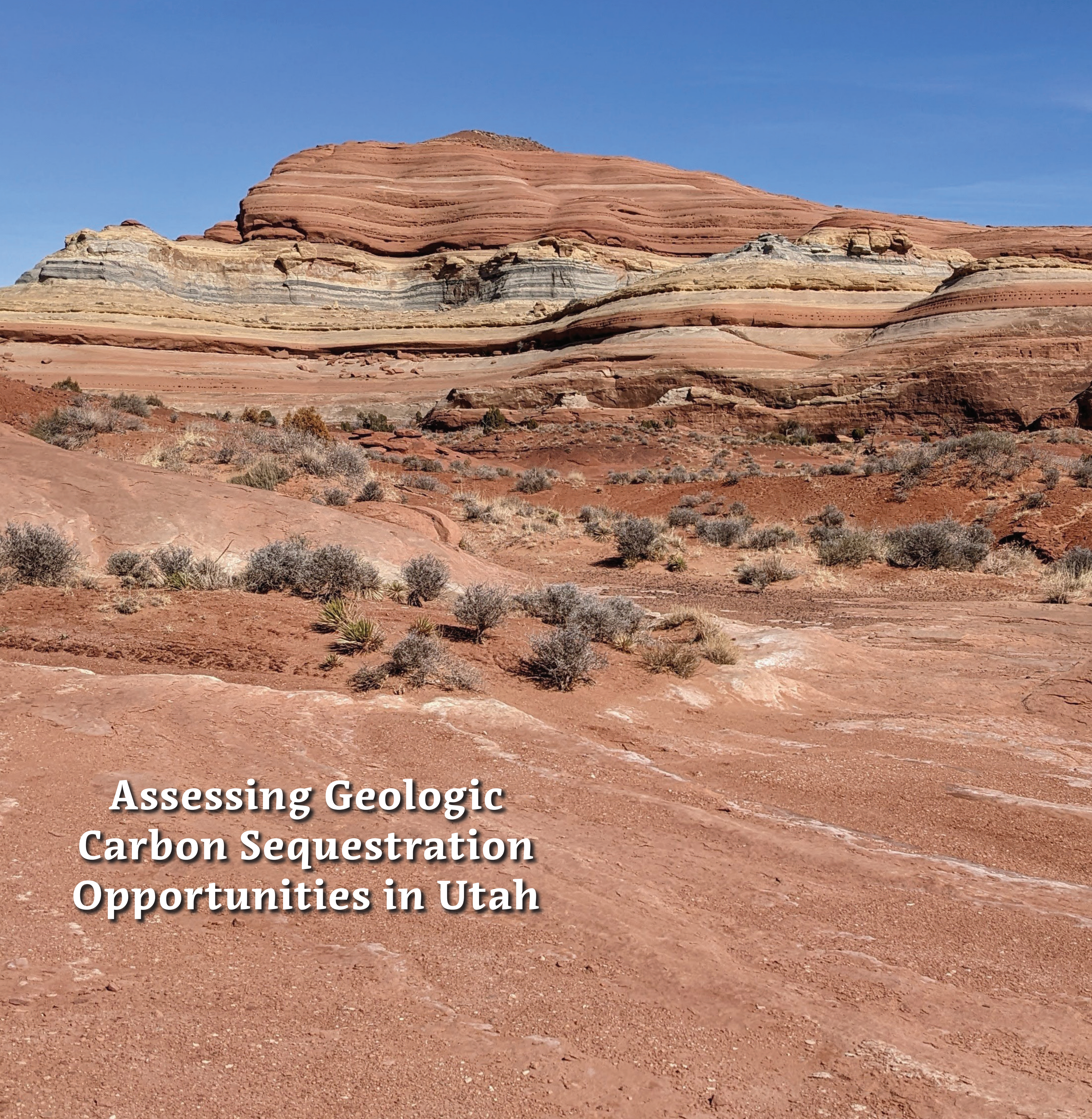

Assessing Geologic Carbon Sequestration Opportunities in Utah

Contents

Design | *John Good*
Cover | Bleached and bitumen-stained layers reveal the outline of an ancient petroleum reservoir in Middle Jurassic-age Entrada Sandstone, Grand County, Utah. These exhumed rocks provide a field-based, natural laboratory to study the CO_2 storage potential of similar rocks in the modern subsurface. Photo by Eugene Szymanski.

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DIRECTOR'S PERSPECTIVE

by Bill Keach

The earth is a bountiful resource, both above and below the surface. As with any resource, the earth must be managed carefully and responsibly, but the challenge is understanding what "best use" and "best management" practices are. Understanding and knowing what is best for today may not be a good predictor of what is best for tomorrow. What we do know is we live in an age of rapidly evolving technology, and technology demands resources. Think about the phone you use today. It is far different from the one I grew up with. Recently, while doing a crossword puzzle, I came across the clue "old way to make a call," the answer, "dial." Today, the answer would be "touchscreen." What resource from the earth makes this possible? Indium, as indium tin oxide, conducts electricity, bonds strongly to glass and is transparent—perfect for a touchscreen. Indium is a by-product of the refinement of zinc sulfide ores. Another resource needed for today's technology is lithium, one source of which is a by-product in the processing of magnesium here in Utah.

Creativity and societal needs work hand in hand to find uses for by-products created from processes focused on other uses. The main article in this issue of *Survey Notes* discusses Carbon Capture Utilization and Sequestration (CCUS) and focuses on the *Sequestration* aspect, wherein geology plays a key role. In Mona, Utah, Houweling's Tomatoes leverages the *Utilization* of carbon dioxide (CO_2). Rocky Mountain Power's Currant Creek plant uses natural gas to generate steam to drive turbines for power generation. By-products of the combustion process are heat and CO_2 (a greenhouse gas). Seeing an opportunity for both their company and the environment, Houweling's Tomatoes built a 28-acre greenhouse facility next door to the power plant. There they capture the heat and CO_2 from the burning of natural gas to grow tomatoes year-round. The tomatoes thrive on the optimum levels of CO_2 inside the greenhouse. Truly a better way to *utilize* a "greenhouse" gas, while keeping it out of our atmosphere.

Another article in this issue discusses a research project to find high-value rare earth elements in coal-related environments, which are also a source of methane gas and associated CO_2 gas. In the Drunkards Wash coalbed methane field just south of Price in Carbon County, , about 500 wells tap into unmined coal seams and produce gas. The gas is gathered and processed to remove any associated water and then moves through a pipeline to another plant. In this plant, amine (an ammonia derivative) is used to extract CO_2 from the gas, purifying it before it makes its way for use in our homes and elsewhere. In years past the CO_2 might have been released into the atmosphere. Today, the CO_2 by-product is cleaned and sold to an industrial gas company, which is located a few hundred feet from the amine facility. Eventually the CO_2 is *utilized* in various manufacturing processes. Some CO_2 even finds its way into your favorite carbonated beverage. Who knew a by-product could be so *utilized* (enjoyed)?

Fremont River, just east of Capitol Reef National Park, Hwy 24.

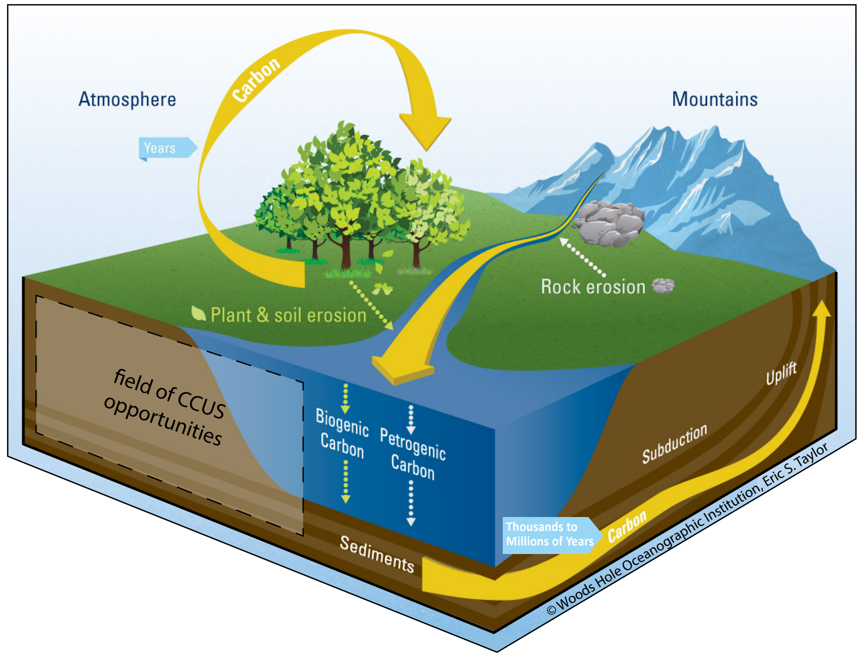
Assessing Geologic Carbon Sequestration Opportunities in Utah

by Eugene Szymanski, PhD

Introduction

As the primary component of all life on Earth, carbon (C) is all around us: in the air as carbon dioxide gas (CO_2), in plants and animals as drivers of cellular growth and respiration, including animal waste products like methane gas (CH_4), and as a building block of carbonate rocks like limestone ($CaCO_3$). Earth has two primary natural carbon cycles—the biogenic and geologic cycles—which use, exchange, and recycle elemental carbon over vastly different timescales. Carbon can be weathered from rocks, belched from volcanoes, integrated into living organisms of the biosphere, released into the atmosphere, soils, and oceans from decaying plant and animal material, and sequestered naturally as rocks and minerals in geological formations for thousands to millions of years.

These natural cycles have been disrupted since the start of the Industrial Revolution as significant volumes of CO_2 have been building disproportionately in the atmosphere from the combustion of fossil fuels and output from industrial processes. This is problematic because, as a greenhouse gas, CO_2 traps heat in the atmosphere which, in turn, affects global climate on geologic and human timescales. Commercial-scale carbon sequestration (a.k.a. "storage") is billed as a primary tool for combating anthropogenic climate impacts by redirecting harmful volumes of produced carbon from the atmosphere into less impactful storage options.



Big picture perspective of the natural biogenic and geologic carbon cycles. Commercial opportunities for Carbon Capture Utilization and Sequestration (CCUS) often exist below ground within the dashed line region. Image modified from the Woods Hole Oceanographic Institution, 23 Nov. 2015 (https://www.whoi.edu/oceanus/feature/carbon-cycle/); used with permission.

The phrase Carbon Capture Utilization and Sequestration (CCUS) is typically used to describe the full range of techniques employed in the commercial carbon sector. Addressing each term individually: **capture** is the first step wherein elemental carbon, typically in the form of CO_2, is either captured directly from the atmosphere or concentrated from industrial waste streams; **utilization** can follow where the carbon, in many forms, is recycled for use in industrial processes or as feedstock for the manufacture of consumer goods like concrete, steel, and plastics; and **sequestration** is intended as a solution to keep produced carbon out of Earth's atmosphere, part of a greater initiative known as transitioning to "net zero" wherein a balance is achieved between the total volume of carbon stored versus emitted into the atmosphere. CCUS helps accomplish this in four key ways:

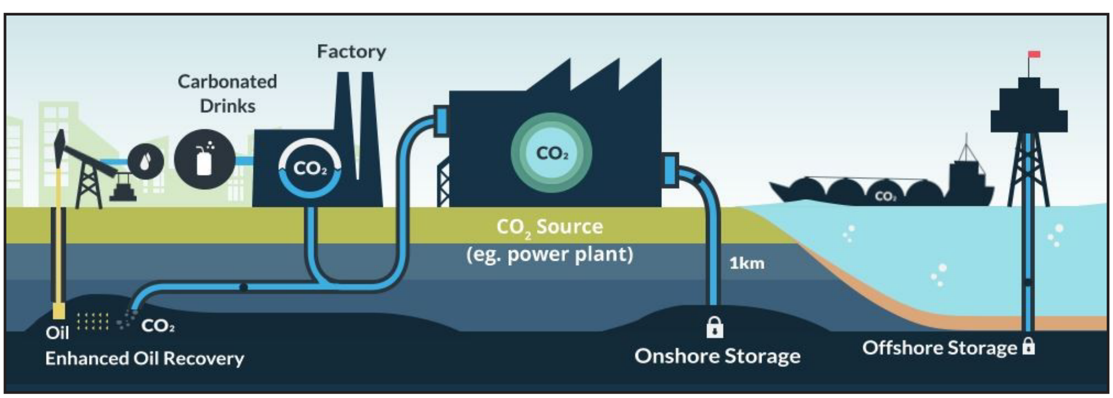
(1) it can be retrofitted to existing power and industrial plants to reduce emissions;

(2) it can support rapid upscaling of low-carbon hydrogen production;

(3) it can capture and store CO_2 directly from the air and bioenergy—energy that is derived from the breakdown of recently living organic materials; and

(4) it is often the most cost-effective approach to curb emissions in cement, iron, steel, and chemicals manufacturing.

CCUS also complements nature-based solutions, such as afforestation, reforestation, and restoration of native plant habitats along coastlines.

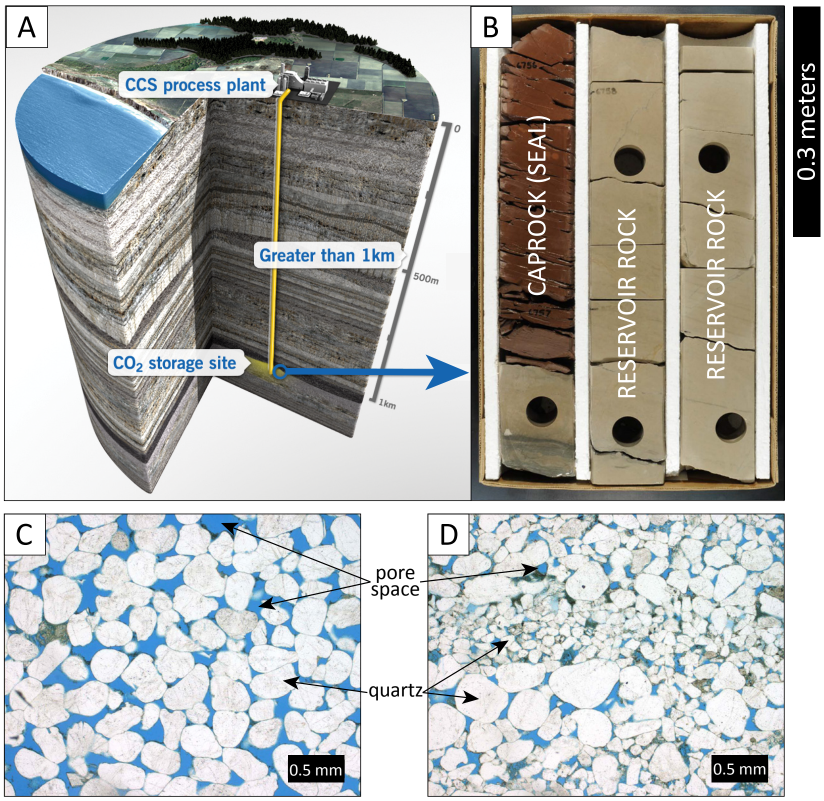


Instead of being vented into the atmosphere, CO_2 produced from sources like power plants can be redirected either for industrial and commercial uses like Enhanced Oil Recovery (EOR) and manufacturing or into geological storage, whether onshore or offshore. Figure modified from imagery provided by Global CCS Institute (https://www.globalccsinstitute.com/resources/ccs-image-library/).

Value Proposition

Apart from myriad environmental benefits, the economic value proposition for private sector carbon capture lies in tax incentives and carbon offset credits. Passed by the U.S. Congress in 2018, the FUTURE Act amends the Internal Revenue Code to extend and modify the tax credit for carbon dioxide sequestration and increases incentives for the capture and storage of CO_2. Specifically, Section 45Q provides a credit for every ton of captured CO_2 for secure geological storage within either enhanced oil recovery (EOR) processes or deep saline aquifers.

The University of Utah's Energy & Geoscience Institute (EGI) has led the way on CCUS research and projects in Utah for over 20 years, often partnering with the Utah Geological Survey (UGS) to leverage geologic knowledge and share technical project tasks related to assessing the potential for geologic CO_2 sequestration in Utah. Previous CO_2 projects in Utah include a large-scale CO_2 injection demonstration for storage and EOR in the Aneth oil field of southeastern Utah and a detailed geologic characterization of potential CO_2 storage reservoirs in saline aquifers in the northern San Rafael Swell of Emery County—more information about the CarbonSafe project can be found on the UGS website at https://geology.utah.gov/map-pub/survey-notes/energy-news/carbonsafe/. Most recently, EGI and the UGS are active members of the Carbon Utilization Storage Partnership (CUSP), a U.S. Department of Energy-funded research consortium consisting of academia, government agencies, national laboratories, and industry that was established in 2019 to accelerate onshore CCUS technology deployment in 13 western states.



The opportunity for Carbon Capture Utilization and Sequestration (CCUS)—sometimes abbreviated to CCS—depends considerably on the type of rock present in the subsurface. ***(A)*** *CO_2 storage can occur by injecting gas deep underground into rock strata deemed unsuitable for other purposes. Modified from imagery provided by Global CCS Institute (https://www.globalccsinstitute.com/resources/ccs-image-library/).* ***(B)*** *A 4-inch-wide slabbed rock core from the Covenant oil field, Sevier County, Utah. The sandstone (buff-colored) is a good reservoir rock due to its porous and often permeable grains. The mudstone (red) is a good geological seal because it has low permeability and prohibits fluid and gas from escaping upwards. The sharp color contrast indicates the boundary between the seal and reservoir rock. The five holes in the rock core are where plugs were drilled into the rock and removed for analysis.* ***(C)*** *and* ***(D)*** *are photomicrographs of Jurassic-age Navajo Sandstone (reservoir rock) from the Covenant oil field that illustrate pore space availability (blue areas) for CO_2 storage between quartz grains (white areas). Images B, C, and D modified from Chidsey and others (2020) (https://doi.org/10.34191/ss-167). Note the significant difference in scale from the well (kilometers) to the core (meters) to the rock grain and pore space (millimeters).*

Geological Assessment Work

The basic premise of sequestration is that compressed and liquified CO_2 is pumped via injection wells into underground porous rock formations (reservoirs) where it can invade pore space and either become trapped beneath impermeable strata (a.k.a. seal rock), dissolve within saline groundwater, or react with reservoir rock to form carbonate minerals, thus becoming stored for relatively long periods of time (thousands of years or more). A lot of scientific, technical, legal, and administrative work is required to rate the suitability of storage sites. Fortunately, Utah has many potentially viable geologic formations suitable as large-scale CO_2 sequestration reservoirs including, but not limited to: 1) the Leadville Limestone and Paradox Formation salts in the Paradox Basin, 2) the Mesaverde Group in the Uinta Basin and Mesozoic-age sandstone units in the south and east (e.g., the Navajo, Weber, and Entrada Sandstones), 3) the Navajo Sandstone in the northern San Rafael Swell, and 4) the Navajo Sandstone or deeper Kaibab Limestone in the southwest part of the state.

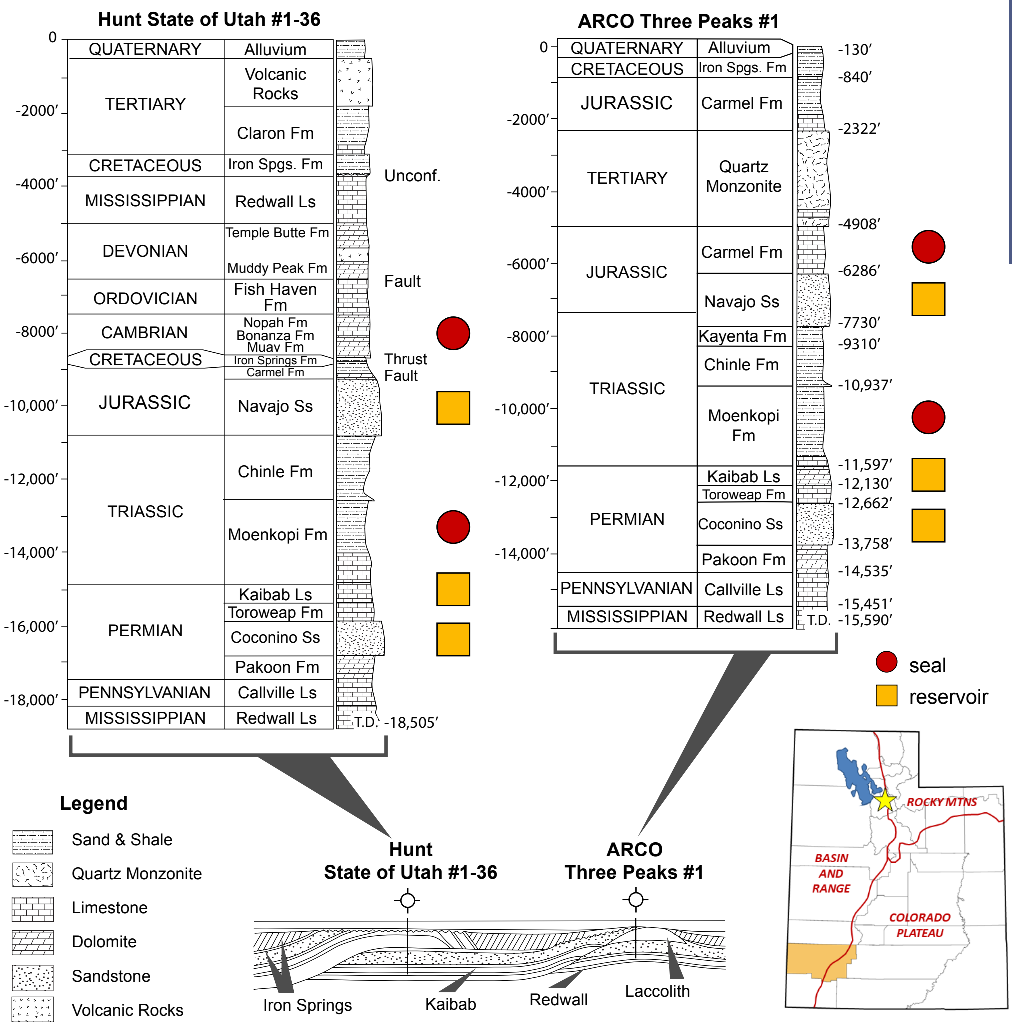
One interesting area of study is Iron County, Utah, where the UGS and EGI are performing rigorous site characterization including subsurface geological CO_2 storage viability and capacity, environmental risk assessment, and economic feasibility options. This region in Utah's Basin and Range Province—expressed topographically as low, broad valleys punctuated by tall, north-south-oriented mountain ranges—was selected for several reasons including accessible outcroppings of key geologic strata, existing public datasets, and wells that provide strong control on subsurface geology potentially favorable for CO_2 injection.

In southwest Utah, wildcat oil and gas exploration has had very few economic successes, but those efforts demonstrated the presence of thick sequences of Paleozoic- and Mesozoic-age sandstone and limestone strata in the subsurface that could potentially store vast volumes of CO_2 gas. Several world-class reservoir/seal pairs are present in the area, providing multiple injection targets, and the absence of working petroleum systems lowers the risk of unavailable pore space and overpressure. Additionally, relatively low drilling and injection costs are anticipated since some reservoirs lie at relatively shallow depths (less than 7,000 feet) still acceptable for proper storage.

The UGS and its partners use many techniques to study the local geology. Rock collected from wells provides important ground-truth information about groundwater conditions, pressure domains, and the range of rock types. Interpretations made from 2D (two-dimensional) seismic, gravity, and magnetics data allow us to create images of the subsurface for mapping structural controls and to develop models of fracture networks that control reservoir permeability and seal rock competency.

Future Direction

Utah has a natural wealth of subsurface geologic reservoirs suitable for carbon sequestration. Utah also has several major industrial carbon emitters within the state. Because the Iron County region can be used as a geologic analogue for other sites in the Basin and Range Province, characterization work by the UGS and its partners will reduce geologic uncertainty, allow prioritization of potentially viable CO_2 sequestration sites elsewhere, and set precedents for rigorous site characterization reports, data, and products in other western states.



In central Iron County, exploration wells drilled by the Hunt Oil Company and Atlantic Richfield Company (ARCO) in the 1980s evaluated the hydrocarbon potential of subsurface strata. Though they did not result in economic discoveries, their data may be used to characterize potential CO_2 injection targets. The State of Utah map shows the three major physiographic provinces and the location of Iron County (colored orange) where these wells were drilled. Schematic illustrations of the geologic layers encountered by the Hunt State of Utah #1-36 and ARCO Three Peaks #1 wells show the subsurface stratigraphy with several potential reservoir (orange square) and seal (red circle) injection targets. Prominent geologic features include the Three Peaks quartz monzonite intrusive body (called a "laccolith"), layered packages of Paleozoic- and Mesozoic-age sedimentary strata, and thrust faults that placed older rocks above younger and duplicated the stratigraphy in some places—for example, see Cambrian-aged rocks (approx. 485-540 million years old) overlying Cretaceous strata (approx. 70-140 million years old) in the Hunt State of Utah #1-36 well. The ARCO Three Peaks #1 well yielded several sets of well cuttings and some cores that are currently held in the Utah Core Research Center. Figures modified from van Kooten (1988) with permission (https://doi.org/10.1130/0016-7606(1988)100%3C1533:SAHPBT%3E2.3.CO;2).

See the following publications for more information:

1. **U.S. launches net-zero world initiative to accelerate global energy system decarbonization**: Energy.gov, November 3 2021, https://www.energy.gov/articles/us-launches-net-zero-world-initiative-accelerate-global-energy-system-decarbonization.
2. **IEAGlobal Energy Review 2021**: IEA, Paris, https://www.iea.org/reports/global-energy-review-2021.
3. **S.1535–115th Congress (2017–2018)**: FUTURE Act. (2017, July 12), https://www.congress.gov/bill/115th-congress/senate-bill/1535.
4. **Carbon Utilization Storage Partnership (CUSP)**, https://cuspwest.org/.

ABOUT THE AUTHOR

Eugene Szymanski is a Senior Geologist in the UGS Energy and Minerals Program with research interests in landscape evolution, chronostratigraphy, and source-to-sink analysis of modern and ancient depositional systems. Prior to joining the UGS in 2021, Eugene worked at Chevron for 11+ years where he conducted hydrocarbon exploration, strategic geologic research, and applied technology development. He holds Adjunct Faculty appointments at The University of Kansas and The University of Arkansas where he co-advises students and collaborates on research projects. Eugene holds degrees from Bloomsburg University of Pennsylvania (2000, B.S. Geology), Boston College (2005, M.Sc. Geophysics), and The University of Kansas (2013, Ph.D. Geology). He is a Licensed Professional Geologist in Utah.

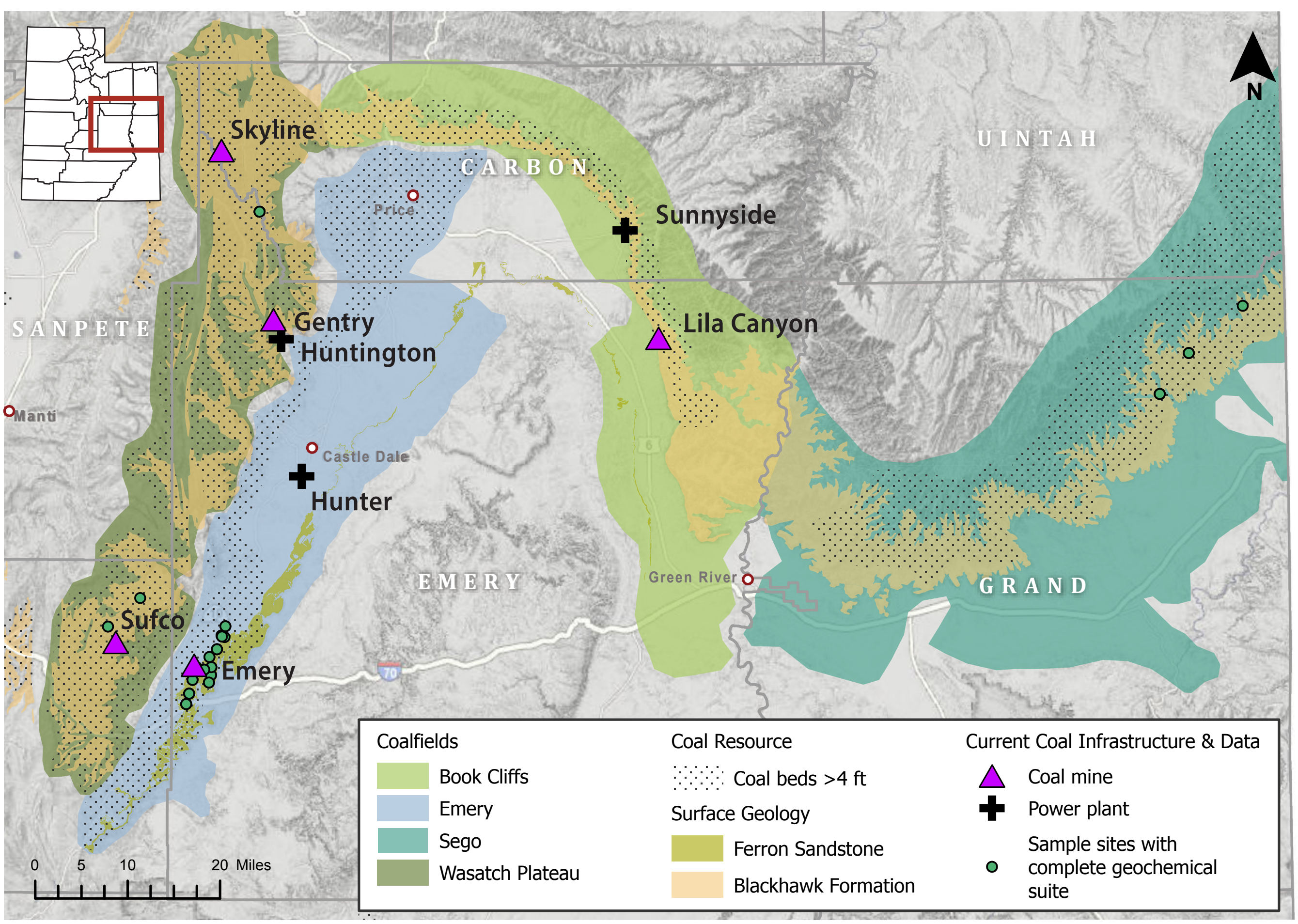
Coal for High Technology

by Ryan Gall

Utah is a fortunate state with ample opportunities to develop high-tech renewable energy. In the past decade, Utah has put itself on national and global green energy maps with rapid development of utility-scale solar farms (together contributing over 1,500 megawatts to the electric grid), three large windfarms (totaling 387 megawatts), the FORGE (Frontier Observatory for Research in Geothermal Energy) research station, and the novel Advanced Clean Energy Storage project which aims to use hydrogen to aid storage of renewable energy in subsurface salt domes. Remarkably, Utah may have another previously overlooked contribution to the green energy transition: coal! Yes, coal, the carbon-rich resource that most individuals emphatically consider *not* green. However, a new U.S. Department of Energy (DOE)-funded project, "Carbon Ore, Rare Earth and Critical Minerals" (CORE-CM), aims to demonstrate whether western U.S. coal and coal waste streams might have alternative uses that can support the development of carbon-neutral infrastructure and other high-technology industries. The study is led by the University of Utah, Department of Mining Engineering, and has 25 partnering institutions including the Utah Geological Survey.

Coal and coal-adjacent strata can be enriched in rare earth and other elements important to the development of high-tech products. Rare earth elements, or REEs, consist of the 15 lanthanide series elements as well as yttrium and scandium which exhibit similar geochemical properties. These elements are important components of cameras, LED lights, electronic displays (e.g., smart phones, televisions, and computer monitors), medical devices (e.g., MRIs and X-rays), and notably, magnets and batteries integral to the establishment of carbon-neutral infrastructure. Praseodymium (Pr), for example, is a common component of batteries used in electric bikes and automobiles. Neodymium (Nd) and dysprosium (Dy) are used in permanent magnets for industrial-scale wind turbines and electric vehicle motors.

The global demand and production of rare earth oxides (that can be refined into rare earth metal) has increased markedly over the past few years. From 2016 to 2021, rare earth oxide production more than doubled from 129,000 to 280,000 metric tons. Projections for the next decade indicate an additional *fivefold* increase in demand for REEs specific to the manufacturing of carbon-neutral technology (Nd, Dy, Pr, and Tb). The projected need and lack of domestic production has led the U.S. Geological Survey to classify REEs as "Critical Minerals" (defined as mineral commodities integral to our economic and national security, whose supply chains rely on foreign markets). Clearly, production of REEs will need to substantially increase to meet societal needs.



Utah coalfields and active coal infrastructure. Sample points represent data compiled by the U.S. Geological Survey CoalQual database and highlight the limited historical dataset of thorough geochemical sampling. CORE-CM will increase sampling across the region to add to this dataset and improve understanding of how critical minerals vary across coalfields.

The Utah and Colorado geological surveys are assisting the CORE-CM project via a detailed characterization of REEs and other critical minerals in coalfields of the Wasatch Plateau and Book Cliffs. These current and historical coal mining regions contain thick Cretaceous-age coal beds representing 85- to 75-million-year-old marshland deposits within the Blackhawk Formation and the Emery and Ferron Sandstone Members of the Mancos Shale. This regional characterization aims to define the elemental composition and variation of coal and adjacent rocks using samples collected from mines and drill cores. Partnering institutions will also assist in the geochemical characterization of select coal waste streams such as coal wash plant material (rock "washed" out of the run-of-mine coal production stream) and coal ash waste collected from power plants. Additional engineering teams are researching methods that can develop carbon fibers, graphene, and important polymers from coal's carbon. Thus, the comprehensive study aims to showcase how the entire commodity and associated waste streams can be used to produce multiple end products that each contribute to technological and economic success.

REEs are a particular high-value commodity because mineable rocks enriched in economic concentrations of REEs are exceptionally rare. Most REEs are currently mined from uncommon igneous deposits (carbonatites and alkaline rocks) and to a lesser degree, placer deposits (sedimentary deposits sourced from weathering of an REE-enriched rock). Though coal itself typically contains low REE concentrations, some coal contains interlaminated claystone and/or volcanic tuffs that are considerably REE enriched. Waste product from coal-fired power plants is another potential REE source, because burning coal removes carbon and concentrates heavier elements in the leftover ash. These potential sources of REEs, combined with an established coal supply chain, makes coal a contender to contribute to the growing REE market.

Geoscientists still have much to accomplish in the effort to characterize REEs and other critical minerals, although researching and identifying prospective resources is necessary to accommodate growing societal need. Utah is not alone in its study of coal as a potential contributor to new industries. More than a dozen other similar DOE-funded studies are assessing other coal resources across the nation while also developing novel coal product processing methods. Who would have thought that coal could be part of 21st century research as a potential contributor to new high-tech industries?

Rare earth elements and their common uses

REE	Common uses
Scandium (Sc)	Lighting, aluminum alloys
Yttrium (Y)	Lasers, cancer therapy, LED lights
Lanthanum (La)	Rechargeable batteries, camera lenses, refinery catalyst
Cerium (Ce)	Catalytic converters, LED lights, glass polishing
Praseodymium (Pr)	Magnets, electric vehicle batteries, ceramics
Neodymium (Nd)	Magnets, electric vehicle batteries, lasers, ceramics
Samarium (Sm)	Cancer therapy, magnets nuclear reactor control rods
Europium (Eu)	Color displays, lasers, nuclear reactor control rods, superconducting alloys
Gadolinium (Gd)	MRI contrast agent, nuclear reactor shielding
Terbium (Tb)	Color displays, magnetorestrictive alloys, solid-state devices
Dysprosium (Dy)	Magnets, lasers, nuclear reactor control rods
Holmium (Ho)	Magnets, artificial magnet fields
Erbium (Er)	Surgical lasers, fiber optics, nuclear reactor control rods
Thulium (Tm)	Portable X-ray source, lasers
Ytterbium (Yb)	Atomic clocks, stainless steel additive, lasers, cancer therapy
Lutetium (Lu)	PET scan detectors, refinery catalyst, refractive glass

Interbedded coal and sandstone in the Blackhawk Formation (just off SR-6, near Helper). Source : Mike Vanden Berg

Suggested reading:

- U.S. Geological Survey Rare Earths Statistics and Information
- Zhou, B., Li, Z., and Chen, C., 2017, Global potential of rare earth resources and rare earth demand from clean technologies: Minerals, v. 7 no. 11, p. 203.

PALEO NEWS

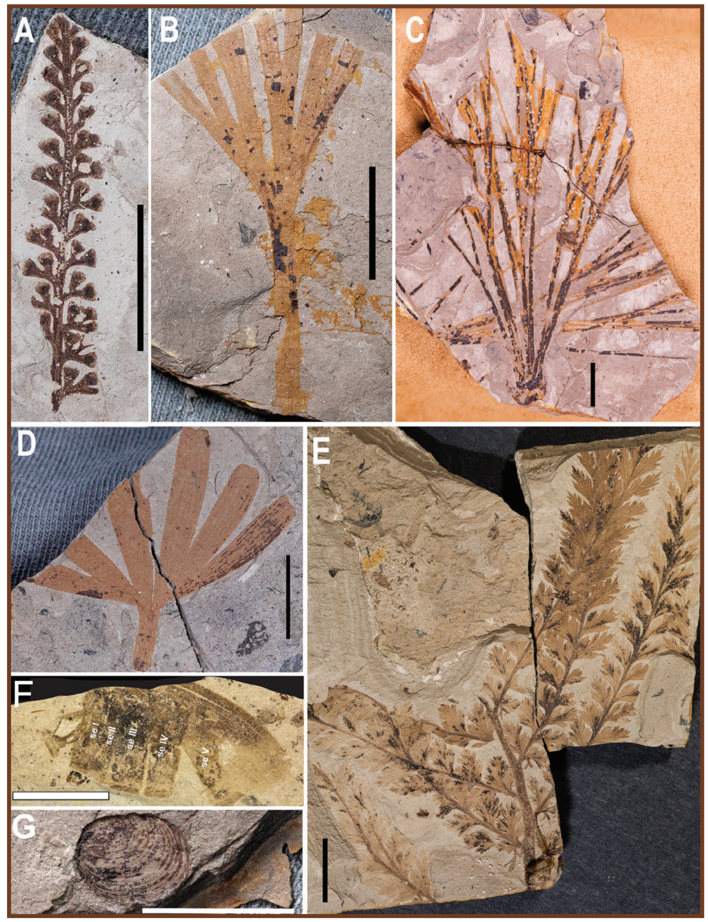
New Discoveries of Morrison Formation Plant Fossils Expand Our Knowledge of Jurassic Ecosystems

by

James Kirkland, Utah Geological Survey
John Foster, Utah Field House of Natural History State Park Museum
Don DeBlieux, Utah Geological Survey
ReBecca Hunt-Foster, Dinosaur National Monument

Utah's Jurassic-age Morrison Formation is world famous for its many dinosaur fossil sites such as Dinosaur National Monument, Cleveland-Lloyd Dinosaur Quarry, and the Hanksville-Burpee site. These sites attract visitors and researchers from all over the globe to see and study iconic dinosaurs such as *Allosaurus*, *Stegosaurus*, and *Diplodocus* among many others. Artistic museum reconstructions of these animals in their environment allow us to envision what it was like to be living in the distant past. These reconstructions are based on renderings of the plants that were living during the time of these dinosaurs. However, our knowledge of the plant communities that existed during the time of deposition of the Morrison Formation is limited because well-preserved plant fossils are quite rare. The discovery of a new fossil site in the Morrison Formation near Blanding, Utah, however, is greatly expanding our understanding of Utah's environment during the Jurassic.

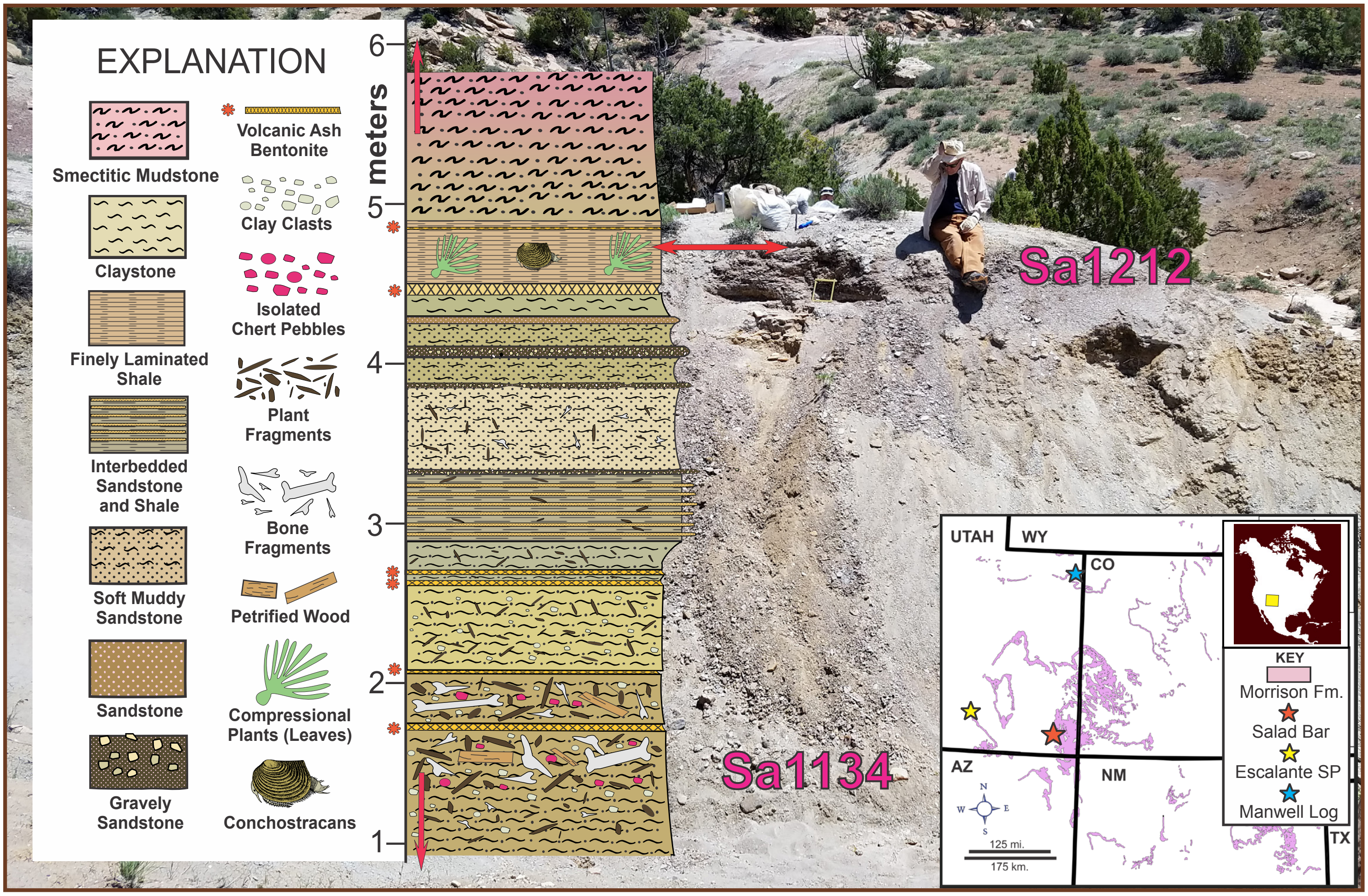
The most commonly preserved plant fossils in the Morrison are petrified conifer logs like those displayed at Escalante Petrified Forest State Park in south-central Utah. In 2015, the Utah Geological Survey (UGS) Paleontology Section helped move a large petrified log to a display near the park entrance, which allows visitors, especially those with limited mobility, to view the iconic fossils for which the park is named. Another extensive petrified forest in the Morrison Formation is located south of Dinosaur National Monument. The Utah Field House of Natural History State Park Museum (FHPR) in Vernal, Utah, led by Mary Beth Bennis and with the help of Utah Friends of Paleontology volunteers, collected a large petrified log from this area. This massive log, known as the "Manwell Log," is on display at the Field House's Jurassic Hall. Most of these Morrison Formation logs are from conifer trees and we sometimes find fossilized seeds and cones. Other less-common petrified woods include those of cycads, cycadeoids (an extinct group of cycad-like plants), and the stems of the enigmatic gymnosperm *Hermatophyton*.



A few of the species from the Jurassic Salad Bar site. ***A)*** *The reproductive organs of the fern* Coniopteris hymenophylloides. ***B)*** *Partial leaf of the ginkgophyte* Sphenobaiera *sp.* ***C)*** *Leaf bundles of the ginkgophyte* Czekanowskia turneri. ***D)*** *Partial leaf of the ginkgophyte* Ginkgoites *sp.* ***E)*** *Partial frond of the fern* Coniopteris hymenophylloides. ***F)*** *Abdominal segments and forewing of the giant water bug-like insect* Morrisonnepa jurassica *(Lara and others, 2020); abbreviation se = abdominal segment.* ***G)*** Conchostracans, *often called clam shrimp. All scale bars = 1 cm. Photos by Tom Howells, Utah Field House of Natural History State Park Museum.*

The Manwell Log on exhibit at the Utah Field House of Natural History State Park Museum (Vernal) with Ruby and Harrison Foster for scale. The log preserves wood grain and bark textures. Photo courtesy of John Foster.

Sites that preserve identifiable foliage, however, are rare in the Morrison Formation as most sites preserve only carbonaceous fragments. Out of the thousands of fossil sites documented in the Morrison Formation in the Rocky Mountain region, only nine sites yield an abundance of leafy plant material. In 2016, the UGS Paleontology Section was funded by the Bureau of Land Management (BLM) to survey for fossils in the Morrison Formation of San Juan County near Blanding. While surveying an area of Morrison badlands, Jim Kirkland found some bone eroding from a hill. He then noticed

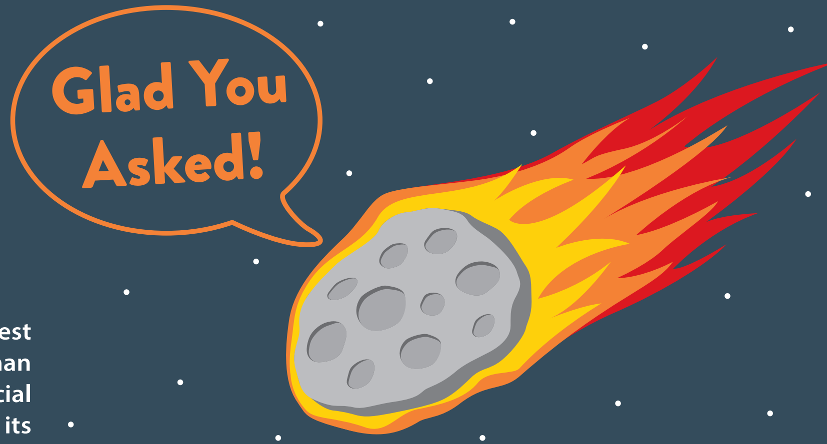


Simplified stratigraphy of the Jurassic Salad Bar site showing two prominent fossil levels: a lower level of pebbles with plant and bone fragments (Sa1134), and an upper finely laminated leaf level overlying a volcanic ash (Sa1212). This site has produced some of the best-preserved plant and invertebrate fossils ever found in the Morrison Formation.

that in addition to bone fragments, there was an abundance of macerated plant fragments and petrified driftwood. Based on extensive field experience, he knew these rocks might preserve a microsite, a site of very small animal and plant fossils. Microsites can typically only be identified by digging into fresh rock because the small fossils do not withstand surface weathering of the rock. Our UGS team later returned to the site along with fellow experts on Mesozoic-age microsites, Scott Madsen (retired UGS) and Jeff Eaton (retired Weber State University geologist). We noticed a band of dark-colored rock at the top of the hill overlying a volcanic ash. This dark layer was a finely laminated shale that contained well-preserved leaf fragments. We collaborated with John Foster (FHPR) and ReBecca Hunt-Foster (Dinosaur National Monument) to direct the investigations at this unique site. John is a leading expert on the paleontology of the Morrison Formation, and he enlisted the help of the late Sid Ash (Weber State University), an expert on Mesozoic plants, to help identify some of the many spectacular plant fossils that have been collected. Most sites are just known by their locality number, but when a site is special, we sometimes give it a name. This site has been dubbed the Jurassic Salad Bar. The fossils here belong to ferns, conifers, and relatives of modern ginkgos. A possible ginkgophyte, *Czekanowskia turneri*, occurs in dense mats, and the abundance of these fossils should lead to a much better understanding of this plant. Additionally, palynomorph samples first examined by the Smithsonian's Carol Hotton yield a well-preserved assemblage of pollen and spores.

The plants found at the Jurassic Salad Bar site are typical of wetland environments, potentially deposited in an oxbow lake or small pond. Work is ongoing with Carol Gee (University of Bonn, Germany) to better refine the stratigraphy and plant fossil assemblages. We expect that fossils from this site will greatly expand our knowledge of Jurassic-age plants. In addition to the exquisite plant fossils, this site has produced some other surprises. A giant water bug-like insect was described in 2020 with the help of an Argentinean colleague, Maria B. Lara (Centro de Ecología Aplicada del Litoral), and named *Morrisonnepa jurassica*. This insect is only the second documented in the Morrison Formation. Another interesting find is a rare crayfish that is one of the few ever found in the Morrison Formation. In addition, conchostracans (clam shrimps), insect eggs on leaves, fish, frogs, and salamanders have been found. We interpret one small splotch of tiny frog and salamander bones as a regurgitalite (fossil vomit) of a predatory amioid fish (based on scales found at the site). Although fossil plants may be more abundant at other sites, this locality has the best-preserved plant fossils ever found in the Morrison Formation. The fossils here are helping to expand our knowledge of Jurassic Period ecosystems and illustrate the importance of continuing fossil surveys even in formations that have been studied for well over a hundred years.

What is Utah's Largest Meteorite?



by Jim Davis

Hands down, the Drum Mountains meteorite is the biggest meteorite from Utah. The iron-nickel meteorite is more than five times heavier than the collective weight of all 25 other official meteorites of Utah. At 1,164 pounds, it was at the time of its discovery the 9th largest meteorite to be recovered in the nation. The Drum Mountains meteorite has been held at the Smithsonian National Museum of Natural History since transfer from Topaz—the War Relocation Authority's (WRA) Central Utah Project—in October of 1944, three weeks after its discovery.

Akio Ujihara, of West Los Angeles, and Yoshio Nishimoto, of Stockton, California, found the meteorite on or before September 24, 1944, while rockhounding for chalcedony for a lesson at the Topaz Lapidary School. They at once recognized that the rock was out of place, the size of a "potato sack" and the color of "burnt sienna." Spectacular "thumbprints," called regmaglypts, patterned its surface. Upon striking it with a hammer they knew it was pure metal by the sound. They detached chips off the meteorite and sent one to the Smithsonian with a sketch and description.

The letter arrives on the desk of Edward P. Henderson, Associate Curator, Mineralogy and Petrology. Henderson was keen on finding out the location of the meteorite, if there were others nearby, if it was on public land, and if a crater was present. He requests a site visit from the U.S. Geological Survey (USGS) in Salt Lake City. Two weeks after the discovery, USGS geologist Arthur E. Granger is guided to the site. Henderson writes Granger, ". . . the sample is an iron meteorite, and if his [Nishimoto's] measurements are correct, it is a large one, and therefore an important new find." Granger reports, "The specimen was found in an area of low hills lying between the Drum Mountains and Little Drum Mountains" and "The country rock is entirely basic or basaltic lavas . . ." Granger finds no section corner markers, but concludes from "other observations" that the meteorite is in Township 15 South, Range 10 West, and "approximately" Section 29. This section is now geologically mapped as the Drum Mountains Rhyodacite, a dark-colored volcanic rock that spans the entirety of the broad saddle between the Drum and Little Drum Mountains. Section 29 is one square mile of federal public land.

"The present world war led to its discovery, along a complicated story trail."

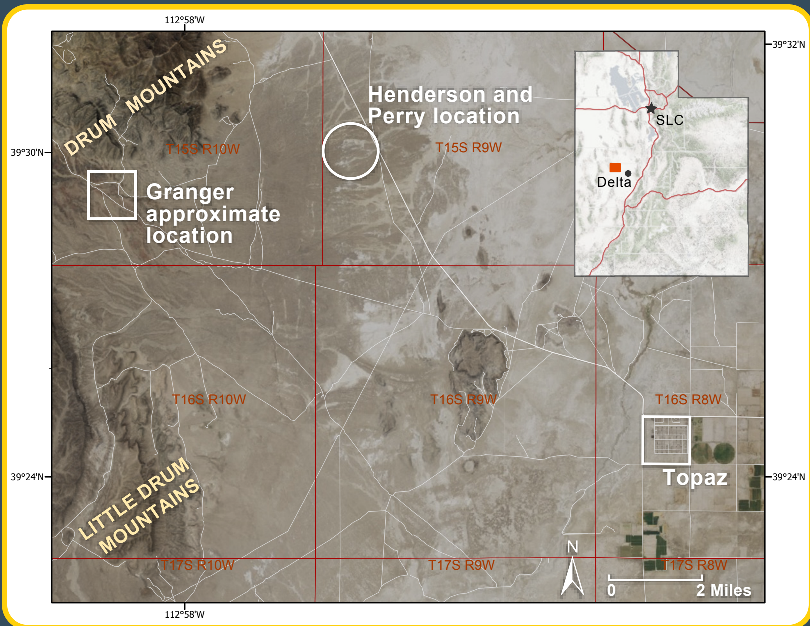
In "Topaz Internees Find Valuable Meteorite" by Frank Beckwith, *The Salt Lake Tribune*, July 29, 1945, and *The Utah Nippo*, August 3, 1945.

Inexplicably, Henderson's official report published four years later gives the location as 5 miles east-northeast of Section 29, at 39° 30′ N, 112° 54′ W. By excluding seconds in the latitude and longitude coordinates, the area cannot be defined more precisely than around one square mile and places the meteorite on gently sloping stream-deposited (alluvial) sediments—more than 2 miles from bedrock. Yet in reinforcement of the geologist's description, G.V. Morris, Evacuee Property Officer for the WRA at Topaz, recounts the journey with Granger, ". . . more or less extensive outcroppings of some black rock and the ground immediately thereabout more or less was covered by loose boulders." Granger and Morris are the only officials to see the meteorite in its original setting.

A meteorite this size might have produced a small crater, but none was found, perhaps erased by erosion. It lies in loose gravel, the bulk of it above ground. Mechanical weathering from wind-blown dust highlights the internal gridded crisscrossing fabric (called Widmanstätten) that stands in relief on the exterior. The buried portion is heavily weathered, corroded from continuous contact with soil moisture, the regmaglypts replaced by corrosion pits. Granger estimates it has sat in place for at least a century, but never sees the deteriorated underside. The weathering of the exposed section of the meteorite is minimal, a few hundredths of an inch, enough to remove any flow lines, or as Henderson writes to Ujihara, ". . . delicate flight markings . . . [which] differ a little from the big pits or depressions you noted (and said resembled Swiss cheese)." Oddly, when the story is finally released, newspapers quote Ujihara and omit the most descriptive word, "Swiss."

After Granger's site visit Nishimoto and Ujihara muster friends and hire "local boys" to load the meteorite and truck it back to Topaz where it was placed on display for residents to view. Nishimoto then arranges for the meteorite to be transported by rail from Delta, Utah, to the Smithsonian in Washington, D.C.

The Drum Mountains meteorite at the Smithsonian. Flat surface at top is where the meteorite was cut for sectioning. https://commons.wikimedia.org/wiki/File:Drum_Mountains_meteorite_in_Museum_of_Natural_History.jpg



Topaz and the Drum Mountains/Little Drum Mountains

The Drum Mountains meteorite reinforced and contributed to future court rulings on meteorite ownership, such as they are property of the federal government if found on federal lands and subject to the 1906 Antiquities Act and that meteorites cannot be acquired through mining claims on federal land. Nishimoto staked a claim, or attempted to, on the site, likely at the suggestion of Morris, who mentions this particular to Henderson in a letter. This letter prompts Henderson to write the U.S. Secretary of the Department of the Interior, Harold L. Ickes, as to whether this would be an issue obtaining the specimen. The Assistant Secretary responds to Henderson that meteorites, like caverns, are "crystalline deposits marketable as curiosities," and not patentable under mining laws. Regardless, no record of this claim seems to exist.

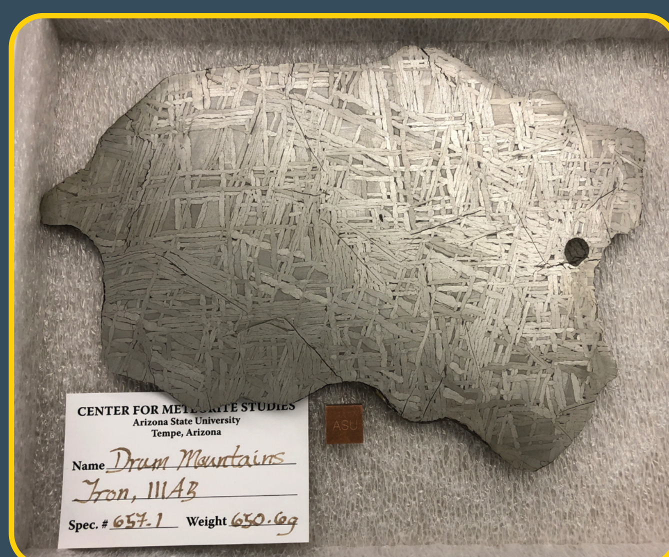
Legally, meteorites are the property of the landowner. Henderson states in his letter to Granger, "If the meteorite is now on public land it is the property of the U.S. government. . . " The meteorite's transfer to the Smithsonian is swift, before a news release. Morris writes Henderson, "As far as I know the knowledge of the discovery has been kept within the bounds of the immediate center, and no publicity has been released except in the residence's local paper [*Topaz Times*, October 11, 1944] which ran one story inviting the resident public here to inspect the specimen." Nishimoto and Ujihara write Henderson, "For your information, both the University of Utah and the State Government of Utah have discovered with regret that the specimen has left the State and is now in your hands."

Henderson writes Morris and requests specifics on Nishimoto and Ujihara and the circumstances of their discovery. Ujihara writes to Henderson on letterhead from the Topaz Lapidary School, stating, "The pleasure is mine to communicate with a great scientist like Mr. Henderson through our finding which was merely an accident. As for myself, I lost my home, business, and major part of my savings due to the evacuation. But it is only infinitesimal compared to the millions of people of war zones. My only desire is that by this incident it may benefit to the scientific world and in some way it may open a way to establish a better world for the coming generations. . . "

Although under no obligation, the Smithsonian, using funds from an endowment for obtaining specimens, allots a finder's fee to Ujihara and Nishimoto of $700 ($11,000 adjusted for inflation). Henderson writes Ickes, "We intend to reward these men for their discovery and have reason to believe they will accept it without hesitation." Newspapers at the time had such titles as "Utah Meteorite Purchased," though it was not a transaction because the meteorite was recovered on federal land; rather, it was an award for efforts and to more than cover moving and shipping expenses.

The Smithsonian has a long history of meteorite collection and curation, scientific study, and collaboration with other meteoritical institutions and has been the traditional repository of meteorites found on federal land. The Smithsonian cut the Drum Mountains meteorite and sent samples, from largest to smallest, to Chicago, Moscow, Tempe, Ann Arbor, Calcutta, Madrid, and Harvard. Henderson also arranged, entirely unconventionally, for a slice to go to Ujihara and Nishimoto. Henderson writes Morris, "Most likely these men would appreciate a small polished slice as a memento of their discovery and I see no reason why we cannot present them each one." In February 1950, a 6-ounce polished and etched slice was sent to Nishimoto in Stockton, California, and presumably one was sent to Ujihara's address as well. Both discoverers of the Drum Mountains meteorite persisted in their zeal for rockhounding and lapidary, continuing in gem and Earth science clubs in California and appearing in magazines and articles for their techniques and notable finds.

*Correspondence from Smithsonian Accession 168531. Misspellings in quotations are corrected.



The Arizona State University (Tempe) slice of the Drum Mountains meteorite is one of several sent to meteoritic institutions around the world. This slice has been polished and treated with a nitric acid solution to reveal the Widmanstätten pattern—a latticework of ribbon-like crystals of iron-nickel alloys (kamacite and taenite) that differ in color and luster due to varying concentrations of nickel. The sample weighs about 1.4 pounds. Photo by Devin L. Schrader/Center for Meteorite Studies/ ASU. Courtesy of the ASU Center for Meteorite Studies.

GEO SIGHTS

Ice formations in the entrance room of LBCC. February 2022.

Big and Little Brush Creek "Ice" Caves, Uintah County, Utah

by Mark Milligan

Spaced nearly 5 miles apart, Big and Little Brush Creek Caves (BBCC and LBCC, respectively) are found high on the south slope of the Uinta Mountains, about 17 miles north of Vernal, Utah. Unlike better known caves with mineral formations of stalagmites and stalactites, these caves are filled with spectacular ice crystals and formations that vary seasonally and from year to year depending upon seasonal temperature and precipitation variations.

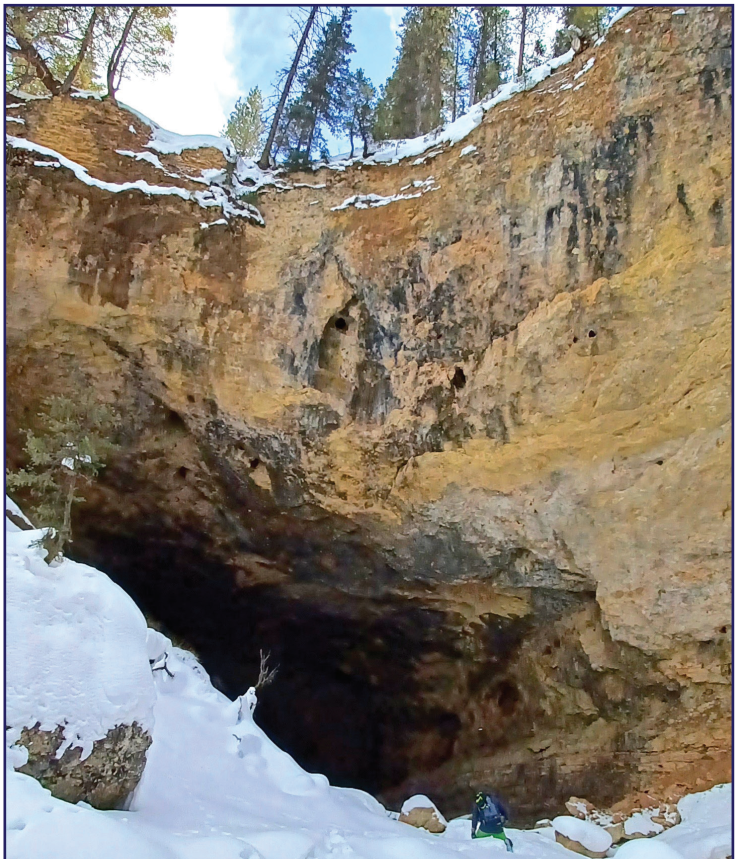
A substantial ice column in the entrance room of BBCC can persist into or throughout summer, and perennial ice is reportedly found a bit deeper in the cave. LBCC contains seasonal ice but no perennial ice; however, it is easier to access in winter, being near U.S. Route 191, which is plowed.

Large ice column in the entrance room of BBCC. February 2022.

The ability of BBCC to hold ice is due to multiple factors, including:

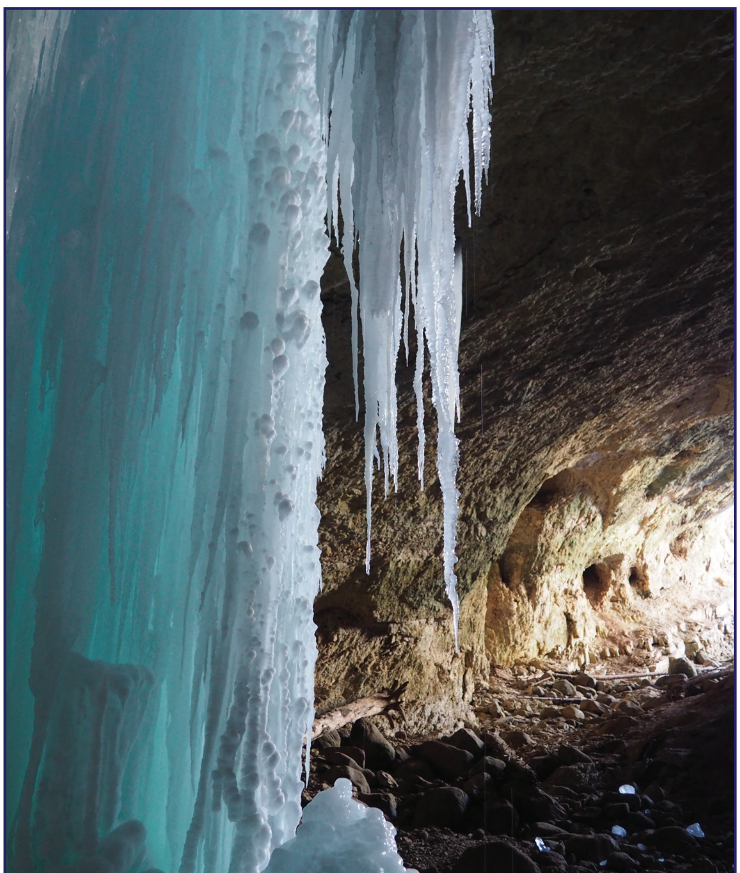
- High elevation—The cave is located at a chilly 8,160 feet above sea level.
- Cold trap—The entrance lies at the bottom of a dead-end canyon with a disappearing stream, causing dense cold air from higher up the mountain to settle and collect. Furthermore, the cave has no lower exit point so cold air cannot escape through the cave.
- No warming sun—The entrance faces north and is heavily shaded.
- Significant ice volume—When air temperatures drop below freezing, groundwater continues to drip into the cave, creating spectacular ice formations in winter. The larger they grow, the longer they take to melt away.
- Limited airflow—In the northeastern part of the cave, where perennial ice is found, a ridge of bedrock, sediment, collapse material, and ice itself constricts openings and thus airflow, keeping temperatures low during warm weather.
- Limited streamflow—Much of the water that would otherwise flow into the cave and melt ice, is lost to underground plumbing (karst) upstream of the cave.

"Hoarfrost" crystals on the ceiling of LBCC were formed by the direct condensation of water vapor to ice at subfreezing temperatures. Image is about 1 foot across. February 2022.



Entrance of BBCC. February 2022.

These 1- to 3-foot-long ice stalactites formed as groundwater dripped into BBCC during subfreezing air temperatures. February 2022.



Ice column in the entrance room of BBCC. February 2022.

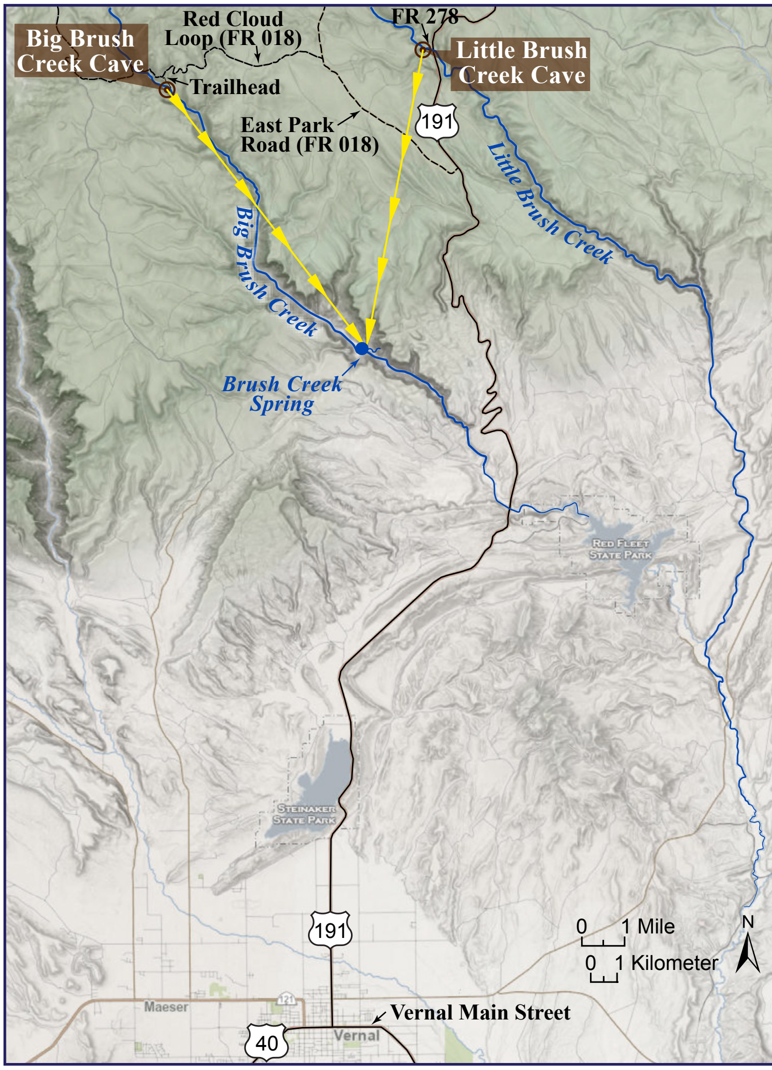
Both caves are located at the bottom of active though often dry stream channels within the Madison Limestone, which contains multiple caves and sinkholes in the greater area. These caves, like most caves, formed as acidic groundwater dissolved the limestone and carried it away in solution.

WARNING:

Beyond their initial cavernous openings both BBCC and LBCC have extensive cave systems that abound with hazards including vertical drop-offs and areas with bad air (high carbon dioxide levels). Spring snowmelt and/or rain can cause unexpected flooding. Do not explore these cave systems unless you are well prepared and have extensive spelunking experience. For more information on cave safety and spelunking, contact the National Speleological Society—https://caves.org/ or a local affiliate such as the Wasatch Grotto—https://caves.org/grotto/wasatch/.

Accessibility and Location:

The caves are accessed via U.S. Route 191, which is plowed and open through winter. However, secondary U.S. Forest Service roads are only open to automobiles when not covered by snow. During the winter the route from U.S. 191 to BBCC is a groomed snowmobile trail that is part of the Uintah Basin Snowmobile Complex. The route to LBCC is a dedicated cross-country ski trail during winter. Furthermore, high creek flow from spring snowmelt can seasonally flood BBCC making it inaccessible. Similarly, LBCC is often flooded in spring and summer. FOR ROAD CLOSURE DATES AND CREEK CONDITIONS, PLEASE CONTACT THE ASHLEY NATIONAL FOREST, VERNAL RANGER DISTRICT, 435-789-1181, https://www.fs.usda.gov/main/ashley/home.



Dye tracer tests by the UGS show that water entering BBCC and LBCC during high streamflow emerges at Brush Creek Spring, which is nearly 6 miles from the caves. Yellow arrowed lines are dye trace flow lines.

HOW TO GET THERE

The caves can be found using either GPS navigation or the indicated mileage below. Beginning on U.S. Route 191 at Main Street in Vernal headed north:

Big Brush Creek Cave coordinates—40.697169° N, 109.584026° W

19.7 miles	Turn LEFT onto East Park Road (FR 018).
3.3 miles	Turn LEFT onto Red Cloud Loop (FR 018).
3.5 miles	Trailhead is on the LEFT at a slight gap in the shoulder barrier with a "non-motorized" trail marker. Note: a roadside parking spot is about one-quarter of a mile farther on the road.
0.5 mile HIKE	Follow the double track trail for about one-half of a mile. At the fork, go right and then proceed down into the drainage bottom. The final descent is very steep and it may be easier to walk farther up the canyon and double back along the bottom. The cave mouth, which opens onto the creek bed and faces north, is easily spotted from above.

Little Brush Creek Cave coordinates—40.709144° N, 109.500585° W

22.0 miles	Turn LEFT onto FR 278.
0.4 miles	The cave mouth faces north and can be seen in the drainage bottom to the left. The final descent is very steep and it may be easier to drive farther up the canyon and double back along the bottom.

SURVEY NEWS

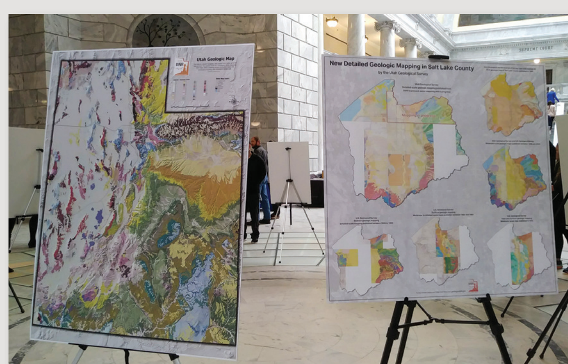
EMPLOYEE NEWS

Congratulations to **Stefan Kirby** who was promoted to manager of the Geologic Mapping & Paleontology Program. Stefan has worked with the UGS for over 18 years as a senior geologist with the Groundwater & Wetlands Program and replaces **Grant Willis** who will continue his work on mapping projects within the program. Congratulations to Stefan and thank you to Grant for your many years of UGS leadership.

Linda Bennett retired in April after 27 years of service with the UGS. Linda joined the UGS in 1995 as the front desk receptionist. She later became the accounting technician where she was responsible for accounts payable, accounts receivable, and procurement. Linda is looking forward to having more time to pursue new hobbies, traveling, and spending time with her family. We wish her well in her retirement!

MAPS ON THE HILL

In February the Utah Geological Survey participated in the 10th annual Maps on the Hill event at the Utah State Capitol to present several of our recent interactive mapping projects and showcase how they can be used to support important land-use decisions. Additionally, we presented posters highlighting the geologic mapping of Salt Lake County over time and a 3D shaded relief version of the state geologic map.

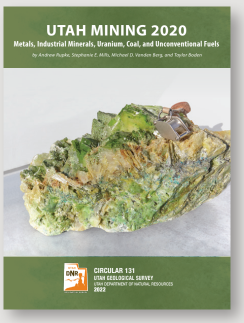


2022 UGA TEACHER OF THE YEAR

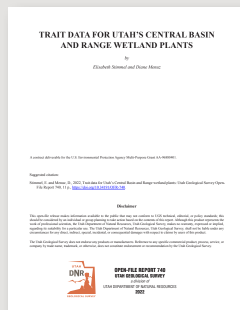
Ms. Kristy Coon of Naples Elementary in Vernal is this year's recipient of the Utah Geological Association's (UGA) Utah Earth Science Teacher of the Year Award. Ms. Coon is very passionate about teaching earth sciences to young people and does a great job of engaging her 5th grade students in the curriculum. Both Ms. Coon, personally, and Naples Elementary will receive monetary contributions for procuring resources related to earth science education. Additionally, Ms. Coon is UGA's nominee for the Rocky Mountain Section of the American Association of Petroleum Geologists (AAPG) Teacher of the Year Award. Congratulations Ms. Coon!

NEW PUBLICATIONS

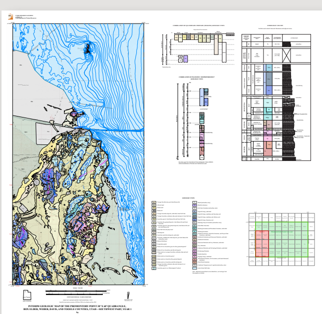
Available for download at geology.utah.gov *or for purchase at* utahmapstore.com.



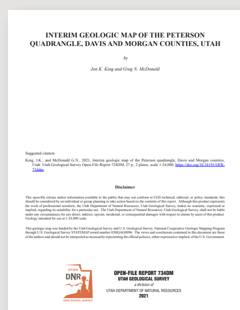
Utah Mining 2020—Metals, Industrial Minerals, Uranium, Coal and Unconventional Fuels, by Andrew Rupke, Stephanie E. Mills, Michael D. Vanden Berg, and Taylor Boden, 40 p., **C-131**, https://doi.org/10.34191/C-131



Trait Data for Utah's Central Basin and Range Wetland Plants, by Elisabeth Stimmel and Diane Menuz, 11 p., **OFR-740**, https://doi.org/10.34191/OFR-740



Interim Geologic Map of the Promontory Point 30' x 60' Quadrangle, Box Elder, Weber, Davis, and Tooele Counties, Utah—Southwest Part, Year 1, by Don Clark, 21 p., 1 plate, scale 1:62,500, **OFR-739**, https://doi.org/10.34191/OFR-739



Interim Geologic Map of the Peterson Quadrangle, Davis and Morgan Counties, Utah, by Jon K. King and Greg N. McDonald, 27 p., 2 plates scale 1:24,000, **OFR-734DM**, https://doi.org/10.34191/OFR-734DM

RECENT OUTSIDE PUBLICATIONS

BY UGS AUTHORS

A broad, distributed active fault zone lies beneath Salt Lake City, Utah, by L.M. Liberty, J. St. Clair, and **A.P. McKean**: The Seismic Record, v. 1, no. 1, p. 35–45, doi: 10.1785/0320210009

Organic geochemical evidence for the transition of Aptian-Albian hypersaline environments into marine restricted seas—The South Atlantic oceanic northern gateway and its implications for the pre-salt deposits, by L.P.H. Bastos, **E.A. Jagniecki**, W.H. dos Santos, D.C. Cavalcante, C.J. de Menezes, C.L.F. Alferes, D.B.N. da Silva, S. Bergamaschi, R. Rodrigues, and E. Pereira: Marine and Petroleum Geology, https://doi.org/10.1016/j.marpetgeo.2022.105632

Geologic Map of the Tent Mountain Quadrangle, Elko County, Nevada, by A.V. Zuza, S. Dee, **H.A. Hurlow**, A.W. Snoke, and B. Laabs: Nevada Bureau of Mines and Geology Open-File Report 21-03, 25 p., 1 plate

A 20-year partnership between the Utah Geological Survey and the National Park Service to inventory and monitor fossil resources in Utah's National Parks, by **D. DeBlieux**, **J. Kirkland**, and V. Santucci: Park Paleontology News, v. 15, no. 1, article 4

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TEACHER'S CORNER

Enhance Your Earth Science Educational Activities with a UGS Teaching Kit

Help your students learn about rocks, minerals, and fossils with a UGS teaching kit as part of your classroom earth science education activities. In addition to rocks, minerals, and fossils, other teaching kits provide interactive educational opportunities related to dinosaurs of Utah, plate tectonics, landforms, stream erosion and deposition, and the Ice Age.

Earth Science Week 2022

On-site activities for Earth Science Week 2022 at the UGS are tentatively scheduled for October 3–6 and 10–13. This popular annual event features hands-on activities that are particularly suited for the 4th and 5th grades, where earth science concepts are taught as outlined in the Utah Science Core Curriculum standards. Earth Science Week activities take place at the Utah Core Research Center in Salt Lake City and include panning for "gold," identifying rocks and minerals, experimenting with erosion and deposition on a stream table, examining dinosaur bones and other fossils, and new for this year, learning about earthquakes.

For more information on UGS teaching kits and and Earth Science Week activities, visit our Teacher Resources web page at :

geology.utah.gov/teachers

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