Hall of Giants at Carlsbad Caverns National Park, New Mexico. *Photo courtesy of Peter Jones*.

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In this issue...

Earth Briefs: The Detrital Zircon Revolution

Shari A. Kelley

The theme of this issue of Lite Geology is "Calcite in the Rock Cycle." In this Earth Brief, we are going to focus on a particular mineral, zircon ($ZrSiO^{4}$), that is found in most igneous, metamorphic, and sedimentary rocks in trace amounts. Zircon usually makes up much less than 1% of the volume of a rock and the grains are typically less than 0.25 mm across, the size of fine sand to silt grains. Zircon has two special properties. First, zircon is a very durable mineral. Consequently, after rocks weather and erode to release the zircon, these tiny crystals can survive a long journey as they are carried by streams, rivers, wind, and glaciers to distant lakes and oceans and other sites of deposition along the way. Second, zircon contains the element uranium, which changes slowly through a complex series of radioactive decay steps to the element lead. Thus the original crystallization age of zircon can be determined using the uranium-lead (U-Pb) dating technique.

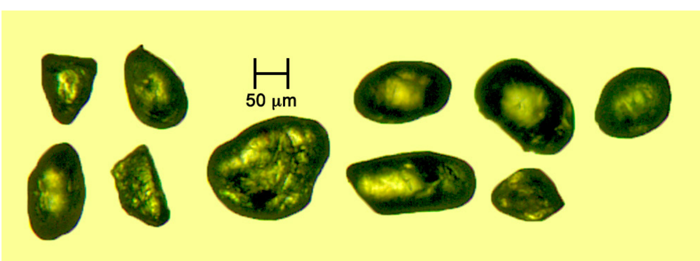
These two properties of zircon have led to the development of a revolutionary dating tool called detrital zircon U-Pb geochronology. The word "detrital" refers to the fact that the zircon grains are derived from the disintegration of pre-existing rocks. The disintegrated detritus is transported away from source rocks by water, wind, or ice and is deposited elsewhere. The term"geochronology" refers to the determination of the age of a mineral by measuring the relative ratios of radioactively unstable elements (U) to stable elements that result from radioactive decay (Pb). The method is considered revolutionary because of the explosion of research avenues that have been opened and explored using this technique. The number of scientific papers published on this topic has grown from a handful in the 1990s to more than 500 during 2015. The sudden increase of interest in this type of research is to due advances in sample processing and instrument design that allow for rapid, efficient, and relatively precise measurement of uranium and lead concentrations in individual zircon grains.

Detrital zircon geochronology has been applied to investigate a wide variety of scientific questions. The method is most commonly used to reconstruct the geologic history of eroded landscapes and to constrain the timing of deposition of sedimentary rocks that lack fossils or volcanic material. As you might expect, zircon grains from sandstone formed from an ancestral river deposit will have a broad range of U-Pb ages. If the headwaters of the ancient river were in a mountain range made up of Precambrian rocks, then some of the grains will be 1.6 to 1.7 billion years old. If that same river also flowed across rocks deposited during a time of heightened Jurassic volcanism, then a certain portion of the grains will record the Jurassic event. As many as 100 to 300 grains are analyzed to identify a variety of source areas. Statistics are then used to classify age populations that can then be tied to specific rock types or geologic events. That information is used to create paleogeographic maps of ancient mountain ranges and continental-scale rivers systems. The age of the youngest zircon population provides a maximum age of the deposit. The age is considered to be a maximum, because the timing of sandstone deposition is younger than the sand grains that make up the rock.

Bureau geologist Matthew Heizler has recently used the $^{40}Ar/^{39}Ar$ technique to date another detrital mineral, sanidine, derived from explosive caldera eruptions. For example, sanidine from eruptions at Yellowstone and other geologically youthful volcanic centers can be used to date river terraces and better constrain the evolution of large modern river systems like the Rio Grande and the Colorado River. Stay tuned for future developments on this front….

Additional reading

Detrital zircon U-Pb geochronology applied to tectonics, G. Gehrels, 2014, Annual Reviews of Earth and Planetary Science, v. 42, p. 127–149.



Detrital zircon grains from the Permian Glorieta Formation at a depth of 1753 feet in the Trans-Pecos Resources #1 Latigo Ranch C well in the Tucumcari Basin, east-central New Mexico. Note the different sizes and shapes of the zircon, which are indicative of the variety of sources and histories recorded by the grains. *Photo by Shari Kelley.*

Zircon Crystal. [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons. *Photo courtesy of Géry Parent.*

Calcite, the Crystalline Chameleon

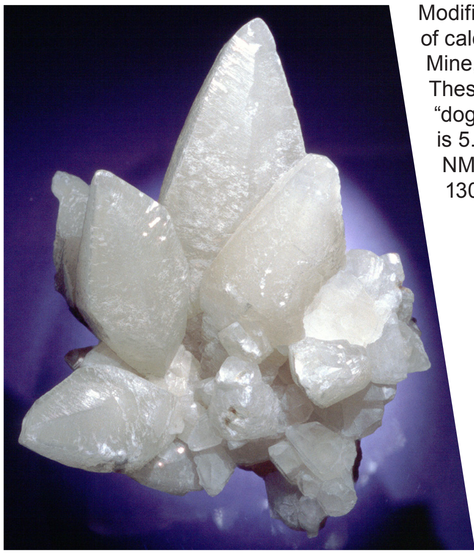
Calcite is notorious for its vast number of rhombohedral crystal forms (more than 300!). Crystals can vary from obtuse, acute, thin tablular or long prismatic rhombs and scalenohedrons. Many modifications of the crystal form are possible and crystal twinning is common. Other forms include fibrous, lamellar, granular, earthy, tuberose, nodular and pseudomorphs (false forms). Luckily, other physical properties help to identify this mineral, like its low hardness (Mohs Hardness equals 3) and diagnostic rhombohedral cleavage (3 planes at inclined angles). Calcite also displays some distinct optical properties in transparent to translucent crystals that produce double refraction and high birefringence (pastel colors, see marble microphotograph). The mineral also reacts with weak acid to form CO_2. The pure mineral is clear to white most commonly, but any color is possible due to impurities.

No mineral displays more external crystal forms than calcite. Victor Goldschmidt presented over 1,000 illustrations of calcite crystals in his monumental work, "Atlas der Krystallfomen" (Atlas of Crystal Forms) originally published in 1913. Because of the wide diversity of form and color, some mineral collectors choose only to collect calcite. Why does this mineral display so much variety?

Part of the answer lies in the abundance of the mineral, and the wide range of temperature and pressure conditions in which it can form. Certain forms are favored under particular conditions of temperature, pressure and chemical environment. Experiments have shown that the presence of foreign ions (ions that do not enter the calcite structure) can affect crystal form by inhibiting growth on certain faces and favoring others. Animals accomplish this same feat in engineering their shells. They are able to influence nucleation and crystal growth to produce the morphology of their living structures. Essentially the wide variety of calcite crystal forms reflect the diversity of the environments in which it can crystallize.

Typical rhombohedral calcite crystals, note the slight pink color (due to manganese) from the Empire Mine, Grant County, New Mexico. The "scalloped" crystal surface suggests a different form of the crystal is trying to emerge. This specimen measures 1.9 inches. Located at the NMBGMR Mineral Museum (No. 13162). *Photo courtesy of Jerry Scovil.*

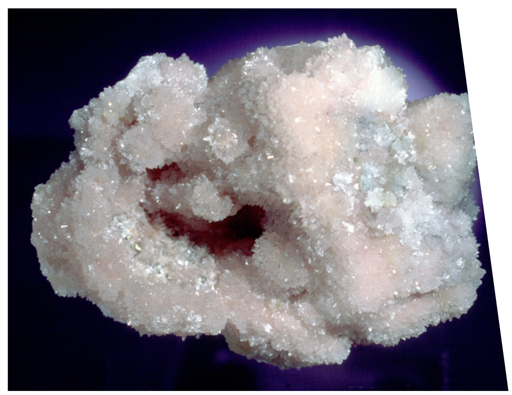
Note the cleavage traces within the specimen. This twinned, rhombohedral calcite crystal is from the San Pedro Mine, Santa Fe County, New Mexico. This specimen is 3.9 inches across. Located at the NMBGMR Mineral Museum (No. 12684). *Photo by Virgil Lueth.*



Modified scalenohedral crystals of calcite from the Continental Mine, Grant County, New Mexico. These forms are also known as "dog tooth spar." This specimen is 5.5 inches tall. Located at the NMBGMR Mineral Museum (No. 13006). *Photo by Virgil Lueth.*

Ball-like calcite from the Kelly Mine, Socorro County, New Mexico is actually comprised of many fairly large, blade-like crystals. This specimen is 7.87 inches across. Located at the NMBGMR Mineral Museum (No. 6122). *Photo by Virgil Lueth.*

Calcite colored from trace amounts of vanadium (?) from Horse Canyon, Utah. This specimen is an unusual color for calcite, although specimens of any color have been documented. This specimen is 5.11 inches across. Located at the NMBGMR Mineral Museum (No. 11445). *Photo courtesy of Debra Wilson.*



Pink calcite growing as a cave-like form from the Continental Mine, Grant County New Mexico. Notice the crude rhomb form on the right side of the mass which is being covered by a myriad of smaller crystals. Most of the visible crystals are of a small, needle-like habit. The change in crystal form within the specimen suggests changes in chemical composition of the fluid from which the crystals precipitated over time. This specimen is 7.87 across. Located at the NMBGMR Mineral Museum (No. 15493). *Photo by Virgil Lueth.*

Scalenohedral calcite modified on the end by prisms resulting in a flattened tooth-like crystal from the Kelly Mine, Socorro County, New Mexico. This specimen is 5.5 inches across. Located at the NMBGMR Mineral Museum (No. 6194), C.T. Brown Collection. *Photo by Virgil Lueth.*

Calcite “Nail-head” habit from the Continental Mine, Grant County, New Mexico. Compare this with the other pieces from the Continental Mine to gain an appreciation for how variable crystal habit can be from a single locality! This specimen is 3.5 inches across. Located at the NMBGMR Mineral Museum (No. 15224). *Photo courtesy of Jeff Scovil.*

Calcite in the Rock Record

Calcite in the Sedimentary Record

The mineral calcite is very common in the sedimentary record, either forming much of the rock itself or found as the cement that holds grains together. Sedimentary rocks are divided into three major categories: 1) biochemical, 2) chemical, and 3) clastic. Calcite occurs in each type of sedimentary rock in variable amounts depending on the process of formation.

Biochemical Rocks

The most common way that biochemical rocks, like limestone, are produced is from organisms that take calcium and carbonate ions from marine or fresh water to create their living structures (shells or skeletons). Depending on the water chemistry at the time, creatures will build skeletons of calcite or its polymorph, aragonite (a polymorph is a mineral with the same chemical formula, but with a different crystal structure). Because aragonite is metastable at the Earth’s surface, it is commonly replaced by calcite. Once organisms die, the skeletons accumulate as layers of calcareous sediment, which are then buried, compacted, and lithified into carbonate rock.

Brachiopod limestone, the valves of these invertebrates are composed of calcite, which the organisms extracted from shallow marine waters. *Photo by Kelsey McNamara.*

Limestones exhibit a wide range of grain sizes (clay to gravel-size) and textures (sedimentary structures, in-situ preservation of fossil material, etc.), which geologists use to interpret depositional environments.

Because calcite is dissolved in weakly acidic rain or groundwater, limestone in outcrops may exhibit an ‘elephant skin’ texture. This is a good way to tell that you’ve found a limestone, because not all limestones contain recognizable fossils!

Chemical

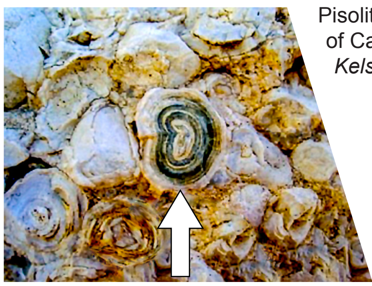
Chemical sedimentary rocks are formed from direct precipitation of minerals out of a saturated fluid. A common example of a calcite-rich chemical sedimentary rock is called *travertine*. Travertine, a form of limestone, occurs from calcite deposited in warm or hot springs. Travertine is often light–to rust-colored, shows banding, and is used for building and ornamental décor. Another porous variety of limestone, called *tufa*, is precipitated in ambient waters, or waters more close in temperature to the surrounding air.

Characteristic elephant skin texture on the surface of a limestone hand sample. *Photo by Kelsey McNamara.*

Speleothems, or cave formations, are also chemical in origin. Caves and other karst landforms are created from dissolution of limestone bedrock. During this process, rainwater moving through the soil zone interacts with CO_2 and becomes weakly acidic. As the water percolates downward, it dissolves the bedrock. Speleothems, like stalagmites and stalactites, are inorganically precipitated in these void spaces.

Another example of a calcite-rich chemical sedimentary rock is an *oolite*, or *oolitic* limestone. Ooids are small (0.25–2 mm in diameter), spheroidal coated grains that form in warm, supersaturated shallow marine or lake environments. The layers are usually calcium carbonate and the nucleus is a small rock or shell fragment. Coated grains that are larger than 2 mm in diameter are referred to as pisoids, and the resulting rock is termed a *pisolite*, or *pisolitic limestone*.

Calcium carbonate minerals are strongly chemically reactive and are susceptible to dissolution and precipitation during diagenesis (any physical or chemical changes that occur from deposition, during or after lithification). Because of this, the biochemical vs. chemical origin of a carbonate rock is not always obvious.



Pisolitic limestone near the entrance of Carlsbad Caverns. *Photo by Kelsey McNamara*.

Clastic Rocks

Clastic sedimentary rocks are produced from the weathering and erosion of pre-existing rocks. Broken fragments, or clasts, are transported, deposited, and lithified (turned into rock). Shale, sandstone, and conglomerate are common types of clastic sedimentary rocks. For some clastic sedimentary rocks, the grains are held together or cemented by calcite. Calcite-rich rocks such as limestone, or shells composed of calcite, may occur as fragments in a clastic rock. For instance, coquina is a rock composed of gravel-size shells or shell fragments, usually cemented in a sandy matrix.

This small spring is precipitating travertine before your very eyes! The different colors are due to various species of heat-loving bacteria. Soda Dam, Jemez District, Santa Fe National Forest. *Photo by Matt Zimmerer.*

Modern beach deposits in Abu Dhabi, composed of predominately cerithid gastropod shells. If buried and turned to rock, the sediment will be preserved as coquina. *Photo by Peter Scholle*.

Caliche

Calcite can also be found in sediments that have yet to be turned into rock. If you live in an arid or semiarid region such as New Mexico, you might notice a white coating on rocks, white cement bounding gravel-sized clasts, and/or layers of white fine-grained cement near the surface. These calcite-rich mineral deposits are known as caliche. Caliche occurs as a light-colored cement found at or near the surface, formed from the precipitation of calcium carbonate. Calcite is readily dissolved and precipitated in groundwater, depending on pH, temperature, and dissolved ion concentrations. Calcite migrates and accumulates through a variety of processes, including the leaching of carbonates from upper layers of the soil, groundwater rising through capillary action, and calcite in dust carried and deposited by wind.

Well developed calcic soil (caliche) in the Camp Rice Formation near Hatch, New Mexico. Arrows in lower right point to laminated carbonate, which indicates that this soil formed during a long interval of landscape stability. Black monopod for scale is 4.9 feet long. *Photo by Andy Jochems*.

Concretions

Kelsey McNamara

Concretions are compact, secondary mineral deposits formed in all rock types, but most common in sedimentary rocks. These masses are characterized by a variety of shapes (from tube-like to spheroidal) and are usually composed of calcite, silica, or iron oxide cements. In certain landscapes, concretions litter the surface because they are more resistant to erosion than the surrounding (relatively weakly-cemented) bedrock.

These odd features have sparked the curiosity of many, and are frequently misinterpreted as dinosaur eggs, bones, or turtle shells (just to name a few!). However, precipitation of mineral material does commonly occur around some type of nucleus, like a fossil.

The most famous calcite concretions are called septarian nodules, which exhibit angular cracks filled with calcite. This specimen has been cracked open, revealing a void space filled with yellow calcite crystals. *Photo by Kelsey MacNamara.*

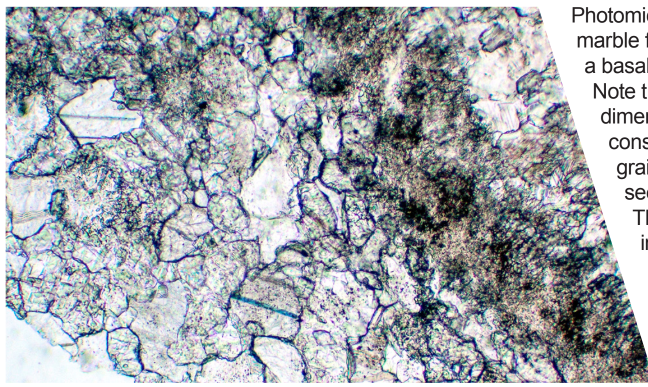
Calcite concretion that grew around an ammonite fossil! The interior of this concretion shows intergrown yellow calcite crystals. Specimen was found in Cretaceous Mancos Shale in Sandoval Co., New Mexico. Gift of Al & Betty Tlush to the NMBGMR Mineral Museum. *Photo by Kelsey McNamara.*

Calcite in the Metamorphic and Hydrothermal Record

Calcite Holds up to Heat and Pressure—Metamorphism

Virgil W. Lueth

When a pure limestone is heated and squeezed, unlike many rocks, no changes occur to the mineralogy. Calcite remains calcite. The process of recrystallization is all that occurs in the absence of other elements. Any fossils in the rock get erased and calcite crystals become more uniformly sized



Photomicrograph of a calcite marble formed at the contact with a basaltic dike and limestone. Note the uniform grain size, dimension, and the relatively consistent angle between grains. Dike contact can be seen at upper right corner. The field of view is .079 inches. *Photomicrograph by Virgil Lueth.*

and eventually grow larger as temperature and pressure increase. The rock becomes a mosaic of randomly oriented calcite crystals with mutual grain boundaries at about 120 degrees, producing a "sugary" looking rock geologists call marble.

Marbles form adjacent to igneous intrusions or, more commonly, in areas of convergent plate boundaries, where regional metamorphism is active. Pure marbles are not exceptionally common because most limestones are not pure. If they contain some clay, quartz, or other mineral impurities, the calcite reacts with them to form calc-silicate (calcium-bearing) minerals (e.g. diopside and grossular). Most marbles are very white, but if they contain some iron or other elements, they can be colored pink or blue.

Red marble tombstone, Kegyeleti (Funerary) Park in Hungary. Grave memorial of László Kossuth. [CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=62818357] *Photo courtesy of Globetrotter19.*

Why is Marble Used in Statuary?

Virgil W. Lueth

Humans have chosen to fashion marble into statues for a very long time. Many of the reasons for this are due to the properties of the mineral calcite. It is used for its striking white color, ease of workability, and its translucency. The white color comes from its purity. The workability is favored because of the uniform grain size, random orientation of the grains, and low hardness. These features allow for the delicate carving with standard tools. The slight translucency provides "depth" to the sculpture which is enhanced when polished. Interestingly, marble statues, if protected from acid rain, get harder with time.

The only problem with marble statuary is it can be fragile. The material also stains easily, even from being touched due to hand oils. Marble is also susceptible to dissolution by acids. Statues are melted away in areas where acid rain is prevalent, so old statues placed outdoors are being lost with time and pollution.

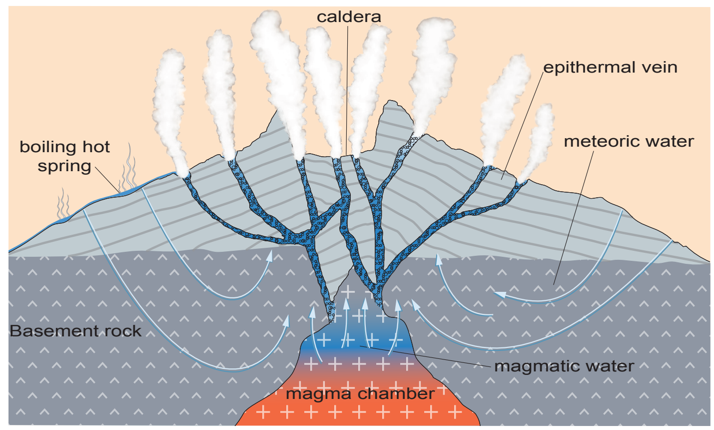
Sibylle, Schönbrunn by Joseph Baptist Hagenauer, 1773. Located in Austria. [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)]. *Photo courtesy of Herzi Pinki.*

Hydrothermal Deposits—Calcite in Hot Water

Virgil W. Lueth

The formation of calcite in hydrothermal environments depends on carbon dioxide and a source of calcium. Hydrothermal water can come from the magma (magmatic water) or circulating groundwater originated as rain (meteoric water) although the largest component is usually meteoric. Most carbon dioxide in hydrothermal systems comes from the mantle or dissolution of carbonate-bearing rocks. The acidic hydrothermal waters dissolve calcium-bearing minerals along the flow pathway and calcite precipitates when carbon dioxide is lost (effervescence), water is lost (boiling), the temperature drops, or it encounters another fluid of differing chemistry.

Calcite precipitates from hot waters (hydrothermal fluids) during variable processes of boiling, dilution, and condensation. At higher temperatures, calcite tends to replace other minerals and not form crystals. At lower temperature, calcite forms crystals in open spaces along a vein or in a *vug*. Often the shape of the crystal indicates what processes were active during precipitation. Calcite from boiling waters tends to form platy crystals, rather than the more common equant crystal types. In addition, different ions in solution can also influence the shape of crystals, producing particular forms that reflect a concentration of certain ions.



Types of hydrothermal waters and how they move around near a magmatic intrusion.

Calcite in the Igneous Record

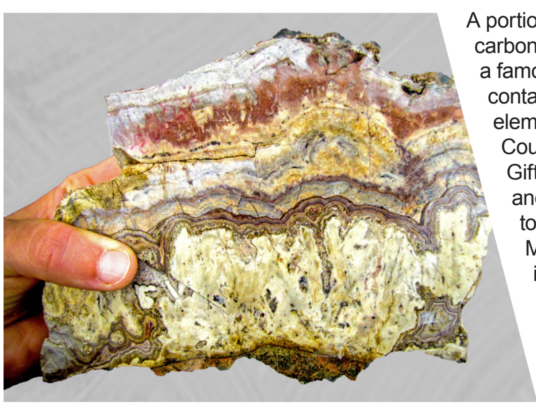
Matt Zimmerer

Calcite formed from igneous processes (crystallized from lava or magma), is relatively rare in the geologic record. However, there is one special type of magma, called carbonatite, which sometimes contains calcite. Whereas most magmas are rich in silica, carbonatite magmas are rich in carbonate minerals, a class of minerals that includes calcite. Some, but not all, carbonatite deposits contain calcite that actually crystallized from magma. Like all magmas, carbonatite magmas can crystallize within the earth to form intrusions or can erupt to form lava flows. Although carbonatites are exceptionally rare, there are a few ancient carbonatite deposits in central New Mexico. Carbonatite deposits are of interest to geologists because they commonly contain rare earth elements, which are important for manufacturing high-end technological equipment.

Calcite can also be found in igneous rocks, not as a primary mineral that crystallized from magma, but as a secondary mineral that formed after the magma or lava had crystallized into solid rock. For example, many of the lava rocks in New Mexico contain open spaces, called *vesicles*, which are fossil gas bubbles. After emplacement of the lava, water flowing through the rock will sometimes precipitate calcite and other minerals into the vesicles. Mineral-filled vesicles, known as amygdaloidal, can be quite spectacular and popular with rockhounds!

Example of calcite within vesicles in a basaltic lava flow. Many of the vesicles are free of secondary minerals. However, a few vesicles, like those to the right of the penny, contain calcite. *Photo by Matt Zimmerer.*

Calcite and amethyst from an amygdoidal cavity in the Parana basalt of Rio Grande do Sul, Brazil. Gift of Wayne and Deanna Sorenson to the NMBGMR Mineral Museum. *Photo by Kelsey McNamara.*



A portion of the “Goldie” carbonatite vein, a famous deposit containing rare earth elements, from Custer County, Colorado. Gift of Garry Adams and Virginia Kistler to the NMBGMR Mineral Museum, in memory of Jack W. Adams. *Photo by Kelsey McNamara.*

New Mexico’s Enchanted Geology

Maureen Wilks

Approximately 250 million years ago, southeastern New Mexico was covered by an inland sea rimmed by coral reefs, in what is now known as the Delaware Basin. These reefs made up of calcium carbonate (both calcite and aragonite) and skeletons of marine animals, formed thick limestone deposits, including the Capitan Reef Limestone. Today the remnants of this tropical paradise can be seen in the rocks that form the Guadalupe Mountains and hidden beneath them lie over 300 caves, including the spectacular Carlsbad Caverns; New Mexico’s only National Park, which was established in 1930.

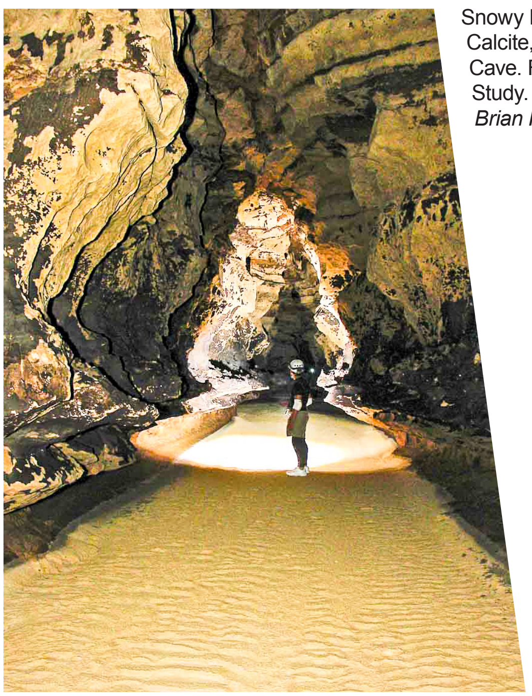
The caves were formed 4–6 million years ago, well after the limestones formed and the oceans receded. The caves formed when hypogenic (upward moving) groundwater, charged with hydrogen sulfide (H_2S) derived from deeper formations in the Delaware Basin, migrated upward through fractures and faults into the Capitan Reef limestone. At the same time, rainwater moving downward carried oxygen (O_2) mixed with the H_2S to form sulfuric acid (H_2SO_4). Calcite is dissolved when it comes in contact with sulfuric acid. The newly formed sulfuric acid began to dissolve the limestone bedrock and form cave passages. This process, referred to as sulfuric acid *speleogenesis*, formed the cave system, including the famous Big Room in Carlsbad Caverns. The Big Room is the sixth largest cave chamber in North America and one of the largest in the world.

Even though cave formation at Carlsbad ceased around 4 million years ago, calcite is now crystallizing back in the cave. Groundwater moving through fractures in the overlying bedrock enters the cave environment as ceiling drips. At this point, CO_2 is released (degassed) from the drip water, making it less acidic and less able

Calcite precipitates out of solution forming a column. *Photo courtesy of Peter Jones.*

to keep calcite in solution, so calcite crystallizes out on the ceiling and floor of the cave, forming stalactites and stalagmites. Because stalactites and stalagmites are often formed by the same drip source, they may occur in pairs, sometimes merging to form columns. Carlsbad Cavern is regarded as one of the most spectacularly decorated caves in the world.

Impressive deposits of white calcite, caused by intermittent flowing waters, occur in the Snowy River Passage of the Fort Stanton Cave. Snowy River is a significant passage within Fort Stanton Cave, and is the longest cave formation in the world. (Mammoth Cave in Kentucky lays claim to the world's longest cave system with more than 400 miles of mapped cave passages). Discovered in 2001, approximately 15 miles of previously unknown passage have been mapped, without reaching the end. In the Red Velvet Passage, amazing fine-grained red calcite, thought to be due to iron in the calcite, has been deposited on the walls, floor, ceiling and as stalactites and stalagmites. Unfortunately, due to the threat of White Nose Syndrome (WNS), which has killed eight-million bats in the eastern and southern states, and has been identified in nearby western Oklahoma, the cave has been placed in a recreational caving moratorium pending research and monitoring of the unwanted arrival of WNS.



Snowy River Passage Calcite, Fort Stanton Cave. Fort Stanton Cave Study. *Photo courtesy of Brian Kendrick.*

Red Velvet Passage, Fort Stanton Cave. Fort Stanton Cave Study *Photo courtesy of Garrett Jorgensen.*

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Earth Science Technology Review: Unmanned Aircraft Systems (UAS)

Andy Jochems

Already popular among recreationalists and in certain industries, unmanned aircraft systems (UAS), more commonly known as "drones," are seeing increased use in the earth sciences. These light-weight, easy-to-fly aircraft are operated remotely and allow geologists to map or monitor areas that are difficult or hazardous to access. Even off-the-shelf drones can be equipped with lightweight cameras and sensors to collect a variety of high-resolution data.

Searching for "drones," "UAS," or "UAV" (unmanned aerial vehicles) on Amazon will turn up hundreds of aircraft and accessory products with a wide range in price. The New Mexico Bureau of Geology & Mineral Resources owns two UAS—a DJI Phantom 4 and a custom-built hexacopter. The Phantom 4 costs between $1,300–2,000, depending on accessories, storage capacity, and enhanced features, such as an integrated touch-screen display on the remote control. Custom models can be built for as little as several hundred dollars, but require some effort to find proper templates and instructions on the web.

Important considerations for selecting UAS include payload capacity and battery life, as well as the specific field use of the aircraft. Added weight decreases speed and flying time, which in turn affects what sensors the drone can be equipped with, especially if the site of interest is far. The Phantom 4 can carry as much as 17.64 ounces; with a payload of 3.5–7.05 ounces (the weight of a GoPro camera, for instance), it will have an expected flight time of around 30 minutes. It can fly up to 45 miles per hour with lighter loads.

Image taken from camera aboard UAS above Arroyo de la Parida near Socorro, New Mexico. Mountains in background include Socorro Peak (left), Strawberry Peak (center), and Magdalena Mountain (skyline). *Photo by Matt Zimmerer.*

Although no license is required to fly drones as a hobby, pilots must be certified if their UAS will be used commercially. All users must follow an ever-expanding set of rules and regulations. For example, drones cannot be flown higher than 400 feet above the ground and, not surprisingly, are restricted near airports and military bases. Some models are equipped with GPS locks that prevent their operation in forbidden airspace. Both hobbyists and commercial pilots must register their aircraft with the Federal Aviation Administration.

UAS are reaching nearly every corner of the geosciences, but more established uses include topographic and hazard mapping, made possible by aerial photos and elevation data (including Light Detection and Ranging, LiDAR) collected during fight. On-board GPS systems allow repeat flight-paths that are especially useful in hazard analysis. Three dimensional models may be generated from data collected by UAS, as in structure-from-motion photogrammetry. A study conducted in France used this technique to generate photomosaics from a quadrotor drone that showed clear meter-scale fissure development and rockfall on a landslide surface.

Matt Zimmerer flying a UAV. *Photo by Kelsey McNamara.*

Neva and Hoodoo watching the drone on a flight. *Photo by Kelsey McNamara.*

Other emerging geologic applications of UAS technology include measuring and monitoring temperature and atmospheric or volcanic gases, as well as mineral exploration using magnetometers suspended from drones. They are also excellent educational tools, allowing students to better visualize surficial geology and increasing their skills in collecting and analyzing data.

Data can either be collected in real-time or downloaded onto an external computer. The latter requires post-processing before the data can be analyzed. Although many sensors designed for UAS come with proprietary software, there is an array of free open-source software available online.

With a shallow learning curve and increasing affordability, expect to see more UAS in the field, and in earth science classrooms. UAS may be limited to 400 feet, but the sky is at least the figurative limit for drones in geologic research and education. Drones have already begun to revolutionize mapping and monitoring, particularly for repeat measurements in time-sensitive studies like those of rapid geologic hazards.

Many thanks to Jake Ross and Matt Zimmerer, the bureau's UAS experts, for their input on this article.

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Through the Hand Lens: Education Outreach Program Changes

Susie Welch managed the Education Outreach Program at New Mexico Bureau of Geology for twenty five years. In August of 2017, Ms. Welch officially retired, although like many Bureau employees, she still plans to be around intermittently to provide expertise and support. Susie developed, edited, and contributed to Lite Geology. She initiated and managed the Seismic Sleuths Tremor Troop, now called Rockin' Around New Mexico, as a summer teacher training class. Susie visited schools for geoscience education outreach and led groups through the Mineral Museum. She procured grant funding, created activities for the Mineral Museum, and made it possible to build

Susie Welch, Bruce Harrison, and Matt Zimmerer check out rotational slump at Rockin' Around New Mexico, Las Vegas 2016. *Photo by Kelsey McNamara.*

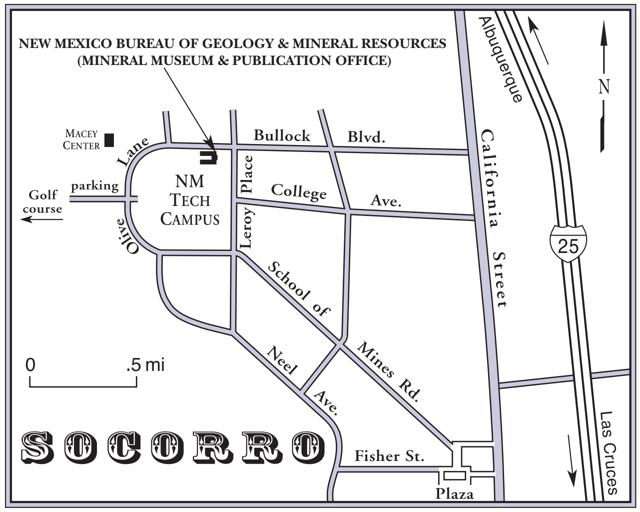
the 3-D Augmented Reality Sandbox (SARnd Box). The SARnd Box allows classroom visitors to digitally visualize and manipulate landscapes by creating them in gypsum sand. Susie coordinated Bureau participation in Earth Science Day at the Legislature, Celebrate Sevilleta, and many other events. Susie also served as a board member for the New Mexico Science Teachers Association (NMSTA).

In addition to her work duties, Susie is known for her kindness, altruism, and community involvement. For many years, Susie has led and been a member of the Socorro Storehouse board, (a local food pantry). She has contributed to organizing and helping with the Socorro Empty Bowls Gala to feed the hungry. She also has helped raise money for our local day shelter, Puerto Seguro, and can play a mean African/ Middle Eastern djembe or dumbek! Although not gone or forgotten, Susie has done much for the Bureau of Geology and her efforts are greatly appreciated. Thank you, Susie Welch; we wish you much happiness in your retirement.

Although there is no replacing Susie Welch; Cynthia Connolly was hired, November 2017, as the new Bureau of Geology Education Outreach Manager. Cynthia Connolly has a B.S in Biology from the University of New Mexico and a B.S. in basic science, a teaching certificate, and a Masters in Science Teaching from New Mexico Tech. Cynthia has taught for eight years at the middle school and high school level, and for four years operated a small afterschool program that taught K-8th grade students. Cynthia Connolly is a New Mexico Science Teacher Association board member and is a member of the American Association of University Women (AAUW).

Cynthia looks forward to continuing the programs and publications originated by Susie Welch, such as the Seismic Sleuths, Tremor Troops/Rockin' Around New Mexico class and *Lite Geology*. In addition to these projects, Cynthia hopes to create new programs and activities to engage teachers, students, and the general populace, including: geocache and "hike to the peak" facebook promotions, an educational Bureau of Geology calendar, lesson plan and curricula material and links, and grant writing assistance for the Bureau and New Mexico schools.

Cynthia Connolly at Kasha-Katuwe Tent Rocks National Monument, Slot Canyon Trail. *Photo courtesy of Madilyn Bennett.*



The Mineral Museum is on the campus of New Mexico Tech in Socorro, New Mexico

Monday through Friday 9 a.m. to 5 p.m.
Saturday and Sunday 10 a.m. to 3 p.m.
Closed on New Mexico Tech holidays

Bureau of Geology building is located at the corner of Leroy Place and Bullock Blvd. on the campus of New Mexico Tech in Socorro. Visitor parking on the east side of the building provides convenient access to the Mineral Museum and Publications Sales office.

Mineral Museum

The bureau's mineralogical collection contains more than 16,000 specimens of minerals from New Mexico, the United States, and around the world, along with mining artifacts and fossils. About 5,000 minerals are on display at a time.

For teachers, students, and other groups, we offer free tours of the museum. We like to show off our home state minerals, as well as give students an idea of how minerals end up in products we use every day. Museum staff can also identify rocks or minerals for visitors. Please call ahead to ensure someone will be available. For more information on the museum, please visit our website at: geoinfo.nmt.edu/museum/

Dr. Virgil W. Lueth: Senior Mineralogist and Museum Director

575-835-5140; virgil.lueth@nmt.edu

Kelsey McNamara: Museum Curator

To schedule a museum tour, contact:
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Cynthia Connolly: Education Outreach

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