Steamboat Butte near Clayton, New Mexico is a textbook worthy example of an angular unconformity (see pg.6). As part of the New Mexico Geological Society Fall Field Conference, attendees were able to enjoy many of the fascinating rocks of the Clayton–Raton area. *Photo by Cynthia Connolly.*

Lite Geology

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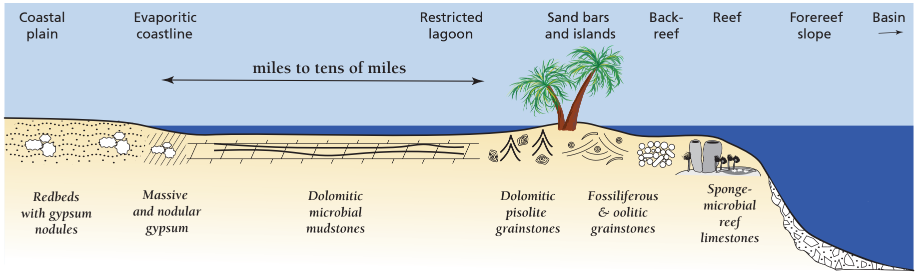
In this issue...

The Fascinating Rocks of NM

New Mexico is known as the "Land of Enchantment" for good reason. Stunning formations dot the state, presenting travelers with excellent places to visit. In this edition of Lite Geology, we investigate fascinating geology from around New Mexico. We start our journey in the southeast at the Permian Basin Capitan Reef, then head over to Carlsbad, to discover how Carlsbad Caverns formed. We then travel north to the Cretaceous /Tertiary (K/T) boundary, near Raton—stopping for lunch at Steamboat Butte. We'll also discuss "Rockiology," a Citizen Science project in which you and your students can participate. Next, we'll visit the Jemez Mountains, Valles Caldera complex and for our final destination, we'll examine the remnants of a volcanic neck at Ship Rock. Our "Through the Handlens" interview features Dr. Kate Zeigler, who discusses her work as a state-wide consulting geologist. Buckle up and get ready for a geologic tour of New Mexico's fabulous landscapes!

The Capitan Reef Complex of New Mexico and West Texas



Schematic reef system diagram showing the depositional environments and associated carbonate rock types. The forereef area undergoes wave erosion, forming coarser grained deposits. The reef crest is built up by organisms that form a calcareous framework. The backreef is a lower energy area in which carbonate mud is deposited. *Figure from* The Geology *of Southern New Mexico's Parks, Monuments, and Public Lands.*

First of all, what is a reef?

A reef is defined as an accumulation of sediment or bedrock, of abiotic or biotic origin, formed beneath the water surface. Natural abiotic processes include sediment deposition or bedrock erosion by tides, currents, and waves. Biotic reef types result from the buildup of calcareous material from numerous organisms, like coral, algae, bivalves, sponges, etc. Dominant reef-building organisms have changed through geologic time, from stromatolites during the Precambrian to algae during the Permian time and coral today. Coral reefs are the most well-known biotic reef, composed of predominately coral and coralline algae.

The formation & architecture of biotic reef systems

Biotic reef formation depends on the interplay of temperature, chemistry, water depth, sediment input, and salinity. Longer-term controls on reef formation are tectonic subsidence, climate, and sea-level changes. A generalized depositional environment cross section consists of the reef (highest topography), the forereef (a high energy environment on the reef's ocean side), and the backreef (a lower energy lagoonal area). The Capitan Reef Complex highlighted in this article is an example of a barrier reef (separated from land by a lagoon), which formed around the margin of the Delaware Basin of southeast New Mexico and west Texas.

Permian paleogeography of the southwest US

The Capitan Reef Complex is an example of a barrier reef, which formed a rim around the Delaware Basin of southeast New Mexico and west Texas. Like the Delaware Basin, the Midland basin to the east is another sub-basin of the larger feature commonly referred to as the "Permian Basin." During Permian time, the continents were joined as the supercontinent Pangea and the Earth was still in an ice age, both of which profoundly affected climate and sea level.

Capitan reef complex outcrops

The horseshoe-shaped carbonates of the Capitan Reef Complex measure over 1,800 ft thick, 2 to 3 miles wide, and over 400 miles long, cropping out in the Apache and Glass Mountains of west Texas and the Guadalupe Mountains of Texas and New Mexico. The fossil reef and associated shelf-to-basin deposits are exposed in both the Guadalupe Mountains and Carlsbad Caverns National Parks.

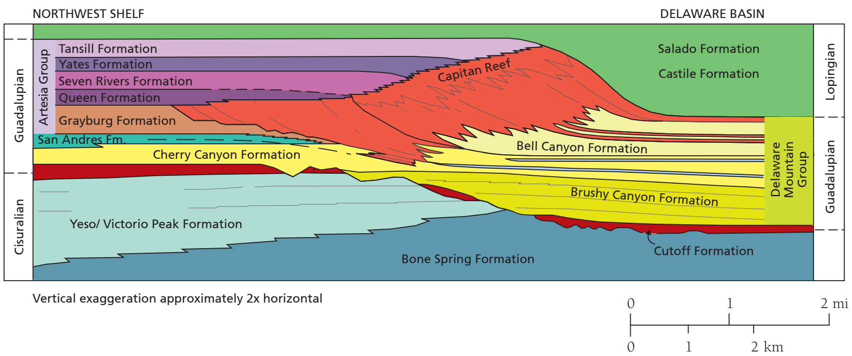
Many geology field trips visit the Guadalupe Mountains due to the spectacular cross-sectional views of the forereef, reef, and backreef deposits. Deeper water deposits (submarine canyon, slope channels, and basin floor) also crop out over extensive areas, and can be correlated to the deposits of the reef complex.

Why is the Capitan Reef Complex so important?

Geoscientists study these rocks to understand the architecture of shallow to deep marine deposits, facies distributions (the characteristics of rock types based on composition and mode of formation), and the vertical/lateral changes in porosity and permeability in a barrier reef setting. The spectacular outcrop exposure has allowed geologists to reconstruct how these sediments filled the basin as sea level rose and fell through time. This method, called sequence stratigraphy, involves dividing the basin fill into sequences of deposition that can be traced to changes in sediment supply and the space available for deposition. All of the information gathered in outcrop studies can be used to interpret the same subsurface, which act as aquifers and petroleum reservoirs. Scientists and engineers use this information to construct realistic 3D models for better extraction of water and/or hydrocarbons.

Paleontologists study the many diverse invertebrate species—including sponges, algae, bryozoans, and brachiopods (to name a

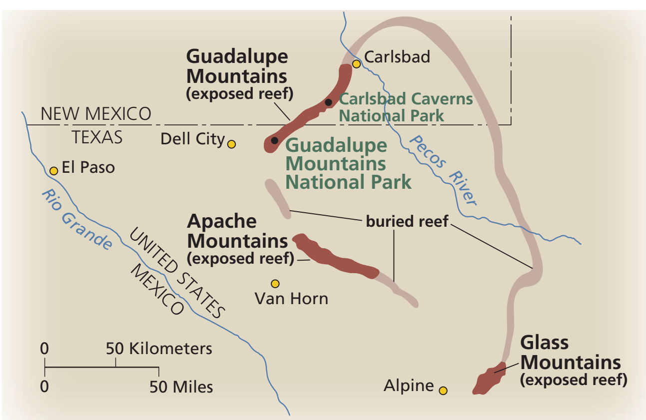
Photomosaic of the north wall of McKittrick Canyon in the Guadalupe Mountains of Texas. The viewer can trace the bedded shelf deposits of the Seven Rivers (SR), Yates (Y), and Tansill (T) formations, which grade into the massive Capitan Limestone. These units show a progradational (basinward-stepping) trend over time. *Image courtesy of the Texas Bureau of Economic Geology Online Guide to the Permian Reef Geology Trail, McKittrick Canyon, Guadalupe Mountains.* www.nps.gov/parkhistory/online_books/gumo/1993_26/intro.htm



Large-scale stratigraphic cross section showing major units of the Capitan Reef Complex from northwest to southeast across the Delaware Basin. *Figure from Permian Basin chapter of The Geology of Southern New Mexico's Parks, Monuments, and Public Lands.*

few) that are preserved in the reef complex units. These studies are important for understanding ancient reef ecology and biology, in which organisms acted as the main framework builders of the reef, and their relationship to changes in water depth through time.

Over 300 caves exist in the Guadalupe Mountains (~119 of which are in Carlsbad Caverns National Park), making this region a natural laboratory for cave and karst research. Speleologists study the structure, features, biology, and processes by which caves form.



Map showing exposed and buried sections of the Capitan Reef, as well as locations of National Parks. The Capitan Reef formed during Permian time at the periphery of the Delaware basin and consists of fossiliferous limestones. *Image courtesy of NPS & Encyclopedia Brittanica.*

Field geologist Matt Zimmerer photographs the progradational limestone units of the Capitan Reef Complex in Guadalupe Mountains National Park. *Photo by Kelsey McNamara.*

More Interesting Permian Basin Geology Facts:

- The Big Room at Carlsbad Caverns National Park is located in the massive limestone reef deposits of the Capitan Formation. This unit dips into the subsurface and acts as a freshwater karstic aquifer for the city of Carlsbad.
- Most caves of the world are formed by dissolution from carbonic acid. The caves found in the Guadalupe Mountains (including those of Carlsbad Caverns National Park) were actually formed from sulfuric acid! Hydrogen sulfide (H_2S) from oil-rich rocks at depth combined with oxygen at the water table to produce sulfuric acid, which aggressively dissolved limestone units to create the caves we see today.
- During the Late Permian, marine waters were becoming increasingly concentrated in dissolved solids due to extensive evaporation. This led to the deposition of potassium salt-bearing evaporite units like the Castile, Salado, and Rustler formations in the west portion of the basin, now known as the Carlsbad Potash Mining District. Potassium-bearing salts, such as sylvite and langbeinite, are mined mainly for use in fertilizers.

El Capitan, the most iconic peak of the Guadalupe Mountains, stands at 8,085 ft tall and is composed of reef limestone. The prominent sandstone unit (called Salt Flat Bench) in the foreground represents offshore channel sands of the Brushy Canyon Formation. *Photo by Kelsey McNamara.*

A limestone packed with fusilinid fossils (calcareous single-celled, filter-feeding organisms) that lived from the Pennsylvanian to the end of the Permian. *Photo by Kelsey McNamara.*

1 cm

For more information on the geology at Guadalupe Mountains and Carlsbad Caverns National Parks, please visit these links:

www.nps.gov/gumo/learn/nature/geologicformations.htm

www.nps.gov/cave/learn/nature/geologicformations.htm

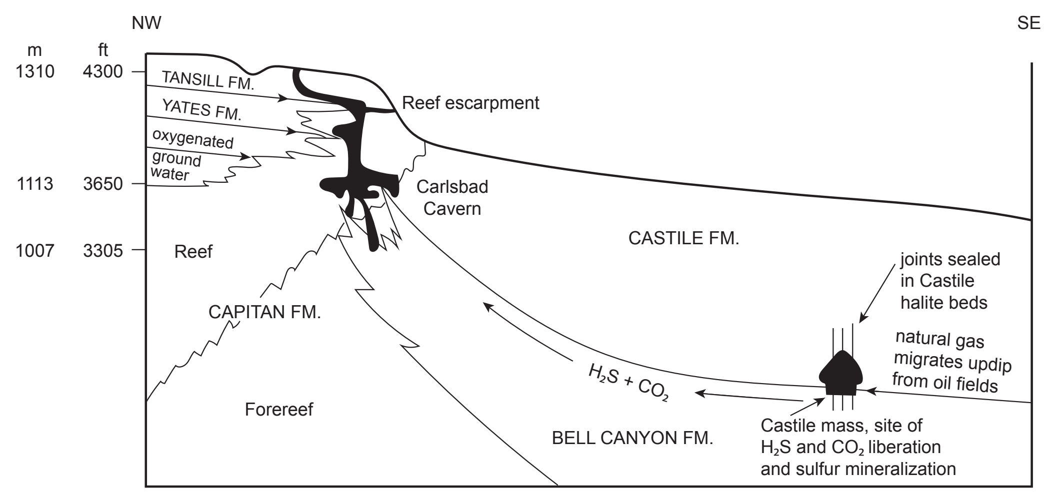
Kelsey McNamara

DEEP Thoughts about Carlsbad Caverns, New Mexico!!

Carlsbad Caverns National Park (www.nps.gov/cave/index.htm) features one of the most impressive show caves in the world, Carlsbad Cavern. Anybody can traverse through the large natural entrance or take the elevator that descends 754 ft below ground to see the Big Room, which is the largest single cave chamber by volume in North America. Large stalagmites and stalactites, among other secondary cave formations or speleothems, beautifully decorate this surreal world that exists in the darkness, deep below the rugged landscape of the northern Chihuahuan Desert, about 20 miles southwest of Carlsbad, New Mexico.

If you have not been to this natural wonder, we highly recommend that you go. While you are walking down the winding path in this world-class cave, think about how this giant maze of passages came to be. Most caves exist in limestone and gypsum, which are relatively easily dissolved by water. Carlsbad Cavern was formed in the Capitan Limestone, deposited along the margin of the Delaware Sea approximately 270 million years ago. Subsequent tectonic events resulted in the formation of the Guadalupe Mountains, where Carlsbad Cavern and hundreds of other caves are located. Many of these caves are very large. Carlsbad Cavern has 34 miles of known passage and the nearby Lechuguilla Cave has over 150 miles of mapped passage. While to most people, Carlsbad Cavern looks like just another cave, until recently, geologists considered the origin of this cave and others in the area to be one of the great unsolved mysteries. These caves are characteristically different from most other known caves. They have very large rooms, and passages are arranged in complex maze patterns that seem unrelated to surface topography or groundwater flow paths. Another interesting feature is the presence of large deposits of gypsum and other minerals within the caves.

Most caves that occur in limestone are formed by rain and snowmelt that seeps downward through soil and along fractures in the underlying rock. Carbon dioxide dissolved in this water forms carbonic acid (a weak acid), which slowly dissolves the rock and enlarges fractures to eventually become cave passages. This type of cave is called an epigenic cave and is generally formed from the top down. The spatial arrangement of passages in these caves commonly looks like typical stream networks or follows the regional fracture pattern in the area, which is not observed for many of the caves in the Guadalupe Mountains. For nearly 60 years (1930–1990), scientists came up with many different theories to explain how Carlsbad Cavern and other caves in the area were formed. Today, it is accepted that Carlsbad Cavern is a hypogenic cave, meaning that the water that dissolves the limestone comes from below, essentially forming the cave from the bottom up. It is thought that fluids rich in hydrogen sulfide gas, from the Delaware Basin oil fields to the southeast, migrated upwards towards the Guadalupe Mountains into the Capitan Limestone. Mixing of these fluids with oxygenated groundwater formed sulfuric acid. Sulfuric acid is a very strong acid that aggressively dissolved large amounts of limestone to form these large, mazy caves. A byproduct of the dissolution of limestone by sulfuric acid is gypsum, which is seen in large quantities in these caves. Originally, it was thought that hypogenic caves were rare and made up only 10% of known cave systems. Researchers are now beginning to recognize the importance of hypogenic processes in the formation of large cave systems all over the world.



This is a conceptual model of the formation of Carlsbad Cavern. Fluids rich in carbon dioxide and hydrogen sulfide gas migrated upwards towards the Guadalupe Mountains into the Capitan Limestone. Mixing of these fluids with oxygenated groundwater formed sulfuric acid, which aggressively dissolved large amounts of limestone to form this world famous cave system. *Figure from Hill, Carol 1987, Bulletin 117: Geology of Carlsbad Cavern and other caves in the Guadalupe Mountains, New Mexico and Texas.*

Talon Newton

K/T Boundary Report

Species on Earth are constantly evolving and going extinct over time; including plants, mammals, reptiles, and even microorganisms. Mass extinction occurs when an event happens that causes a widespread and rapid decrease in biodiversity on Earth. There have been a total of five mass extinction events in the course of geologic time, the most recent taking place at the end of the Cretaceous period, approximately 66 million years ago. This extinction event is most noted for the decimation of the dinosaurs, however, approximately 80% of all species were also eliminated.

Just west of the town of Raton, a rough, dirt road leads to one outcrop location of the iridium layer marking the K/T mass extinction. Photo courtesy of Google Earth. *Location headings by Marissa Fichera.*

The K/T (Cretaceous-Tertiary) boundary refers to the layers of rock that mark this extinction event. Across the globe, a thin (mm-to cm-scale) layer of iridium-bearing clay is present in the rock record, overlying Cretaceous-aged strata and underlying Tertiary-aged strata. Outcrops of the boundary exist in hundreds of places worldwide including in the Raton Basin of New Mexico. What is so significant about the iridium? Iridium is a rare-earth element common only deep within the Earth's mantle and in extraterrestrial rocks. The amount of iridium in this layer is hundreds of times greater than normal. What could cause this anomalously high amount of iridium to be present at this exact time in geologic history?

Signage displaying outcrop location of the iridium K/T boundary layer in New Mexico's Raton Basin. *Photo by Marissa Fichera.*

Iridium layer marking the mass extinction event at the end of the Cretaceous, including decimation of the dinosaurs.
Photo by Marissa Fichera.

Many theories have been proposed regarding the K/T extinction but few have received serious consideration. The most widely known of these hypotheses is the "asteroid theory," formulated by Walter and Luis Alvarez in the 1980s. This theory postulates that a meteorite impacted Earth and the massive amount of rock debris ejected into the air covered the Earth in darkness for at least several months. Lack of sunlight caused photosynthesis to cease, the global food chain to be disrupted, and left various species unable to survive.

There is abundant evidence in the rock record to support this theory. The Chicxulub impact crater, located near the Yucatan Peninsula in Mexico, was discovered in 1978, by geophysicist Glen Penfield. The crater, measuring 180 km in diameter, is one of the largest identified impact structures on Earth. An impact blast of this magnitude would scatter iridium-rich meteorite and other small debris worldwide. Additional evidence found in North American K/T boundary clays includes shocked quartz fragments and glass spherules, both caused by an abrupt increase in pressure associated with the impact. The shocked quartz zone extends west into Pacific Ocean sediments but is minimal elsewhere, suggesting the impact occurred near North America.

Another working hypothesis attributes the K/T extinction to the Deccan mega-eruptions; short-lived but massive volcanic eruptions occurring close to the India–Africa plate boundary. The Deccan volcanism began suddenly just before the K/T extinction, with a rate of eruption that was at least 30 times the rate of Hawaiian volcanism today. Enormous amounts of basalt were deposited over what is now the Deccan Plateau of western India, forming lava beds called the Deccan Traps. Estimates of volcanism of similar intensity suggest that aerosols and ash would have risen into the stratosphere, causing worldwide darkness, global cooling, and severe weather events—all of which would have negatively impacted species survival.

The general consensus is that the K/T mass extinction was likely caused by a combination of these two catastrophic events. Research is ongoing at the New Mexico Bureau of Geology and Mineral Resources, with scientists currently attempting to obtain a more accurate age constraint on the North American K/T boundary clays.

Marissa Fichera

Steamboat Butte Lunch Break Lesson Plan: Creating an Edible Angular Unconformity

New Mexico landscapes are composed of an array of amazing geology. While attending the New Mexico Geologic Society Fall Field Conference, we visited an impressive angular unconformity named Steamboat Butte near Clayton, New Mexico. This lesson plan is designed to teach students about unconformities (especially angular unconformities) and provide a nice snack at the same time! Bon appétit!

Background

Unconformities represent breaks in the rock record, or missing geologic time. There are three types—disconformities, nonconformities, and angular unconformities. Disconformities are the most common and are characterized by lithified sedimentary layers, an interval of erosion or non-deposition, and then the formation of additional sedimentary rock. Disconformities may be difficult to visualize without the assistance of radiometric dating or index fossils. A nonconformity is the erosional surface on uplifted, underlying, igneous or metamorphic rock that is later buried by younger sedimentary rock. The nonconformity in the Sandia Mountains that is visible from the La Luz trail, features Sandia Granite, overlain by sedimentary rocks and is known as, "The Great Unconformity." It represents a break in time of approximately 1.1 billion years! An angular unconformity occurs when layers of deposited sedimentary rock are uplifted, tilted, and then weathered along the upper portion. Younger layers of sedimentary rock and sediments are then deposited horizontally on top. In all of these unconformities, the eroded strata indicate missing geologic time. Steamboat Butte is an example of an angular unconformity that we will model in sandwich form.

For more information visit:
https://geoinfo.nmt.edu/publications/periodicals/earthmatters/17/n1/em_v17_n1.pdf

Materials

Food service gloves

Picture of Steamboat Butte as a model

Parchment paper as a cutting/sandwich surface/wrap for eating the sandwich

Twelve-inch submarine sandwich roll per group of four

Various meats, cheeses, and vegetables

Condiments of choice (make sure that modest amounts are portioned out to each group and applied after the model is complete)

One knife per group

Napkins (This can get a bit messy!)

Procedure:

- Discuss the types of unconformities. There are also online videos that may be used.
- Give each student group of four a copy of a picture of Steamboat Butte.
- Make an angular unconformity:
  1. Place a 12" submarine roll on parchment paper
  2. Cut sub roll length-wise with the knife (if needed) to create sandwich surface
  3. Construct sandwich using ¾ of available food ingredients (leave ¼ for top)
  4. Push ends of sub sandwich towards the middle
  5. Horizontally cut about 1 inch off of the peak of the sandwich and set aside
  6. Cut sandwich in half at fold (each half sandwich is now split between two people in each group)
  7. Place remaining layers of cheese and meat on the top of sandwich
  8. Answer questions, describe your construction and enjoy!

Madilyn "Maddie" Bennett, Mistress of the Edible Angular Unconfomity, constructs model sedimentary layers.

Lithified horizontal layers represented by a nice looking sandwich!

Maddie gives the layers some uplift and tilt before cutting the peak and placing layers of meat and cheese the top. Photos by Cynthia Connolly.

Which one is which? Edible Angular Unconformity with some missing geologic time in the background. The original Steamboat Butte for comparison. Sandwich photo courtesy of Madilyn Bennett. *Photos by Cynthia Connolly*.

Lesson Questions:

What do the sandwich layers represent?

Inland sea levels rose and then fell multiple times and left behind sediments during each cycle. These sediments lithified and became layers of rock seen at Steamboat Butte.

What did bending the sandwich represent?

Bending the sandwich represented upward lift and tilting of the strata.

The piece of sandwich that was cut off and set aside represents what?

The sandwich piece represents erosion of rock layers. These pieces of sediment get carried away and are no longer part of the historical rock record, so they are considered to be missing time.

Why did you place more food layers on the top of the model?

After part of the butte was weathered away, more sediments were deposited on top and lithified.

What did you learn from this angular unconformity modeling experience?

Answers will vary.

Going Further: How would this model differ if you were modeling: a disconformity? A nonconformity?

If a disconformity were being modeled, sandwich layers would have been eroded away (cut off) or not deposited at all for some time (an amount of time that can represent millions of years!), before more layers were deposited on top. It would be difficult to tell if the model was a disconformity without radiometric dating or index fossils. To build a sandwich nonconformity model, a certain type of food would need to represent igneous or metamorphic rock. It would need to be uplifted, eroded (part could be cut off) and then buried by a sandwich item that represents younger sedimentary rock.

Cynthia Connolly

Rockiology: Citizen Science for You and Me!

Biologist Kaarin Goncz readies Quebradas calcite samples for transport to Johns Hopkins University to find out if they contain microbes. *Photos by Cynthia Connolly.*

How would you like to help out scientists studying microbes in extreme environments? Dr. Jocelyne DiRuggiero is a professor in the Department of Biology at Johns Hopkins University in Maryland. Her lab investigates how microbes that live in extreme environments, called extremophiles, adapt to stresses in their environment. Extremophiles are microorganisms, which include single-celled organisms such as bacteria and archaea, as well as multi-celled, microscopic organisms such as tardigrades. Extreme environments can include a whole range of places! Examples include hydrothermal vents located at the bottom of the ocean that that spew water up to 800°F or, the bottom of frozen lakes in Antarctica. Extreme environments can also include places that are very dry or have very high salt concentrations. Dr. DiRuggiero also studies the genetic and functional diversity of microbes in these environments. Because there are so many of these environments, Dr. RiRuggiero has started a citizen scientist project to help her gather information. She is asking people who live near some of these extreme environments, or who are traveling, to help her collect specimens. Her project is called "Rockiology."

Microorganisms have inhabited the Earth for 3.4 billion years of its history. They are essential for the evolution of its minerals, its major geochemical cycles, and its atmosphere, yet the extent of their diversity remains vastly unexplored. Understanding the link between the geochemistry we observe and the impact of microbial activity is critical if we want to learn more about our own biosphere and how to better conserve and protect the environment from climate change and increasing desertification. Planets and moons we have explored so far, such as Mars, harbor extreme environmental conditions with similarities to some of the most remote and punishing places on Earth. It therefore makes sense to study microorganisms that live in extreme environments if we want to learn more about the type of life we might find elsewhere in the universe.

You can assist Dr. DiRuggiero by collecting specific types of rocks found in the desert to help her understand topics that range from climate change, to our chances for finding life elsewhere in the Universe. There are many types of rocks, all over the world, that have been colonized by microbes. DiRuggiero is currently analyzing rocks that were obtained on expeditions to the world's deserts. These expeditions have produced many excellent samples, but they need more data in order to answer their big questions. If you sign up to participate in the study on the Johns Hopkins website and send in pictures of your finds, DiRuggiero will let you know if you should send in your sample(s). Once the specimens get to her lab, DiRuggiero will study the geochemistry of the rocks and will identify the microbes inhabiting them. You will be able to see whether data obtained from your samples are used in journal publications or shared at conferences. If you want to know more, visit their website

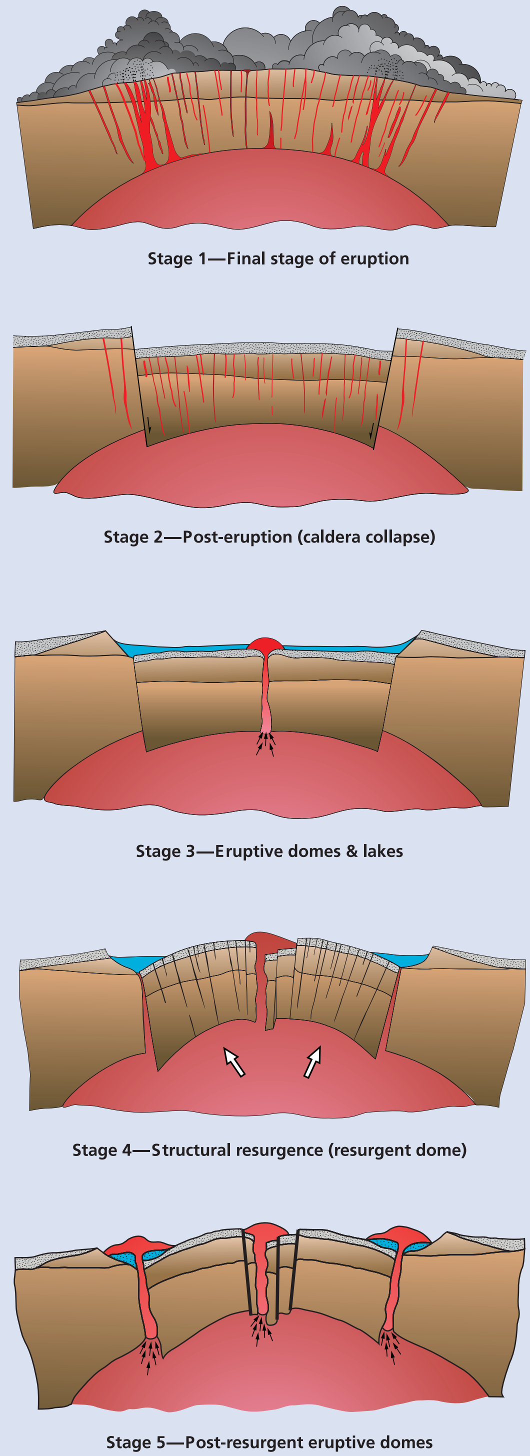
https://krieger2.jhu.edu/biology/labs/diruggiero/rockiology/

Kaarin Goncz

The World-Renowned Rocks of the Valles Caldera, Jemez Mountains, New Mexico

The iconic Valles Caldera in the Jemez Mountains of north-central New Mexico is the remnant of a 1.25 million-year-old volcano that initially erupted large amounts of gas-and silica-rich magma in the form of pumice, causing circular cracks to form around the top of the volcano. Cataclysmic collapse of the top of the volcano into the underlying magma chamber along the ring-shaped fractures then triggered the eruption of enormous clouds of hot ash, dust, gas, and rock that rolled across the landscape. The clouds eventually lost their momentum, settling and cooling to form a rock known as ash-flow tuff. The picturesque orange and white cliffs that skirt the Jemez Mountains are composed of ash-flow tuff; geologists call this rock unit the Bandelier Tuff.

The Valles caldera is famous for three geologic features that formed during and shortly after the eruption: the Bandelier Tuff, the Redondo Peak resurgent dome, and the post-caldera rhyolite domes that encircle the caldera, which were intruded along the ring fractures. Mid-20th-century scientific investigations of these features profoundly shaped geologists' perception of the evolution of explosive supervolcanoes and served to solidify the concept of plate tectonics. This revolutionary research was led by three U.S. Geological Survey geologists, Clarence Ross, Robert Smith, and Roy Bailey, who constructed a geological map of the Jemez Mountains between the 1940s and 1970. Through careful examination of the physical and chemical characteristics of the Bandelier Tuff during decades of mapping and integrating that information with published observations of similar rocks worldwide, Smith and Ross published an important paper in 1961. This paper describes the emplacement mechanism of ash-flow tuffs and the subsequent physical and chemical processes that affect these rocks as they settle and cool. Prior to this work, many geologists had a hard time recognizing and understanding the importance of ash-flow tuffs. This richly illustrated publication includes numerous descriptions and photographs of outcrops of the Bandelier Tuff that aid in the identification of key attributes common in tuffs worldwide. Bailey and Smith were also the first to develop the concept of a resurgent dome when they mapped Redondo Peak, a prominent topographic feature near the center of the Valles caldera that now stands about 3,300 feet above the surrounding caldera floor. Bailey and Smith recognized that lake beds deposited in the caldera shortly after it formed 1.25 million years ago were broken, tilted, and intruded by post-caldera magmas pushing up from below. Thus, Redondo Peak is a manifestation of the uplift of the caldera floor driven by rapidly emplaced post-caldera magma.

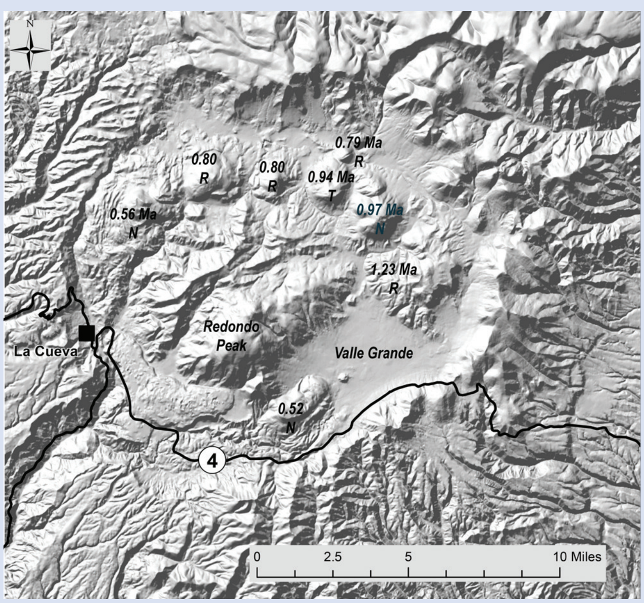


Evolution of the Valles caldera. *Figure from The Geology of Northern Parks and Monuments, and Public Lands book.*

Photograph of the Bandelier Tuff showing dark-colored rock fragments and light-colored pieces of pumice in an ashy matrix. Note the poorly sorted nature of the tuff.

Photograph of the bottom of the Bandelier Tuff showing pumice resting on older tan sediments overlain by fine-grained ash that grades up into poorly sorted ash-flow tuff. This outcrop is along State Road 4 about 1 mile west of White Rock, NM. *Photos by Shari Kelley.*

Later Smith, Bailey, and Ross were joined in the Jemez Mountains by other U.S. Geological Survey colleagues in the early 1960s; these geologists were attempting to determine if "magnetic stripes" that had been observed on the sea floor of the Atlantic Ocean supported the idea of sea-floor spreading and continental drift. During the 1950s and 1960s, scientists had learned that volcanic rocks record times when the Earth's magnetic field points north like it does today (normal) and other times when the field points in the opposite direction (reversed). This record of polarity-reversal versus time was well documented in basalts on the ocean floor, but to confirm that magnetic field reversals are truly a global phenomenon, scientists needed to establish that volcanic



Hillshade of the Valles caldera showing the ages and magnetic polarity of the ring fracture domes. N=normal, R=reverse, and T=transitional.

rocks on land preserve the exact same polarity record. Richard Doell and Brent Dalrymple came to the Jemez Mountains to measure the polarity of the magnetic field preserved in volcanic rock units within the caldera. They also had to determine the radiometric age of each of the sampled rock units. They learned that the Bandelier Tuff and the oldest ring fracture rhyolite, Cerro del Medio, have reversed polarity (1.25–1.23 Ma), Cerro Abrigo is normal (1.0 Ma), the earliest eruption on Cerro Santa Rosa is transitional between normal and reverse (0.94 Ma), Cerro San Luis, Cerro Seco, and the second eruption of Santa Rosa (0.8–0.79 Ma) are reversed, and the remainder of the domes that erupted after 0.79 Ma are normal. The normal polarity measurement found on Cerro Abrigo is called the Jaramillo event, named after nearby Jaramillo Creek in the Valles caldera. This result filled in a missing piece of the puzzle in the land-based polarity record and helped win the acceptance of plate tectonic theory.

Shari Kelley

Ship Rock: The Monolith of Northwest New Mexico

View of Ship Rock with the San Juan Mountains in the background. The yellowish sediment in the foreground is Mancos Shale. On the right is a south-southeast trending dike that has intruded the shale. Ship Rock is the solidified remnants of a volcanic throat that once laid 2,500–3,300 ft below an ~25–26 million-year-old volcano. *Photo courtesy of Kirt Kempter.*

It can be seen from about 50 miles away as you cruise down either Highway 64 or 491. The dark protrusion on the horizon slowly rises in height as you drive steadily closer. Your eye cannot help but to be drawn to this towering feature. You might wonder, “What is that?” To me, it resembles a towering, spired castle or cathedral. But many early travelers thought it was more akin to a clipper ship, and hence named it Ship Rock. The Navajo people call it Tsé Bit’a’í or “rock with wings,” and it features prominently in many of their legends and myths. Rising 1,700 ft above the surrounding lowlands and at 1,500 ft in diameter, Ship Rock is one of the most distinctive geologic features in northwest New Mexico.

The monolith of Ship Rock constitutes the deep remnants of the magma plumbing system underneath a maar-diatreme volcano that erupted ~25–26 million years ago. A maar-diatreme volcano forms when magma moving upwards through the Earth’s upper crust encounters groundwater. The heat from the magma rapidly converts groundwater to steam under confining pressure, creating highly explosive eruptions that form a crater on the Earth’s surface flanked by a low ridge of ejected material (called a “maar” in geologic jargon). This material also backfills the “throat” (neck) beneath the crater, called a “diatreme.”

The maar crater that existed above Ship Rock has long since eroded away, as has the country rock that once lay immediately beneath the crater and surrounded the throat. The country rock that had eroded consisted of Tertiary Chuska Sandstone underlain by Upper Cretaceous sedimentary rocks (Mesa Verde Group and upper Mancos Formations). What remains is the dark-brown, resistant, central feeder pipe (volcanic neck) of the volcano rising above yellowish, low-lying hills of Mancos Shale. This neck consists of back-filled breccia (fractured and broken-up rock, commonly sand to pebble size), composed of erupted volcanic rock, plus country-rock debris. In hand specimen, the country rock is often difficult to distinguish from volcanic materials.

Near the top of Ship Rock and along some of its margins, layering in the brecciated material dips inwards towards the center of the neck. This indicates that the volcanic throat was once open to some degree, with ejected material and broken-up country rock falling and slumping back into it. This observation, combined with the estimated thickness of the original country rock (prior to erosion), indicate that the current level of exposure is about 2,500–3,300 ft below the original crater.

The loose material in the throat was intruded (crosscut) by many thin sheets of minette. Minette is an igneous rock crystallized from molten magma. At Ship Rock, it is dark-gray to greenish-gray and composed of a gold-tinted mica (phlogopite), green olivine, and needle-like, black pyroxene crystals set in a finer-grained matrix. Minette is crystallized from an unusual type of magma with high

Close-up view of the dike, with Ship Rock in the background. View to the north. *Photo courtesy of Kirt Kempter.*

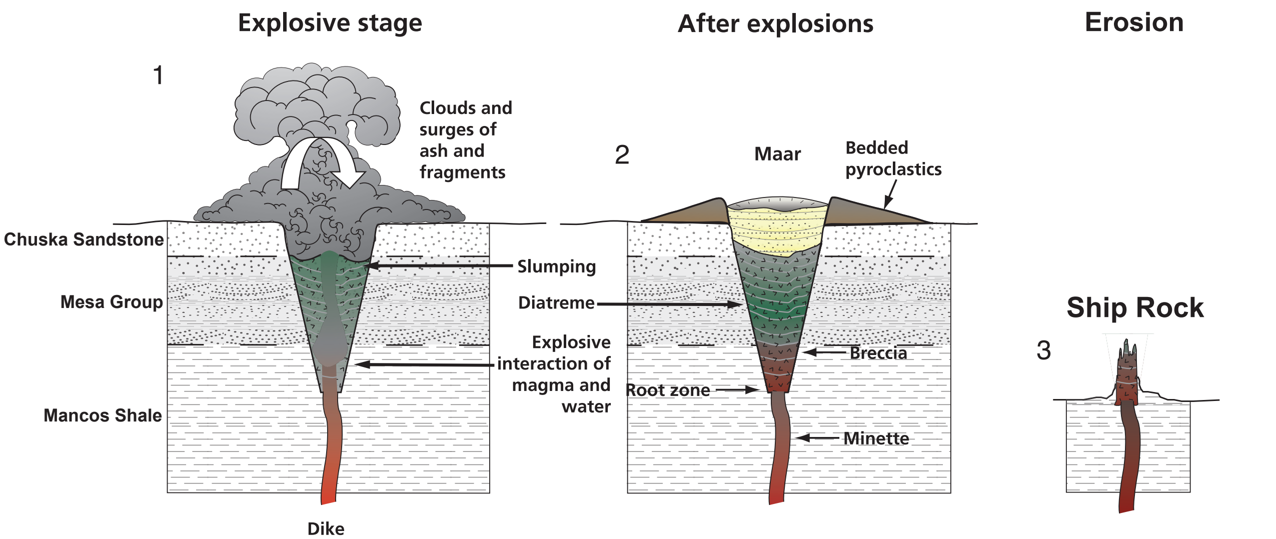


Illustration of how Ship Rock formed. In the explosive stage, ascending minette magma (molten rock) vaporized groundwater in a series of powerful eruptions, forming a crater that was backfilled by ash and breccia composed of broken-up country rock and volcanic fragments. After the explosions ended, a shallow crater remained at the surface surrounded by a low rim of ejected material (maar). At depth, ascending minette magma flowed upward into open-spaces and fractures in the breccia and then solidified. During the past 24 million years, erosion has stripped away the relatively softer Chuska sandstone and Upper Cretaceous sedimentary rocks, leaving the harder diatreme that we know as Ship Rock. *Figure from The Geology of Northern Parks and Monuments, and Public Lands book*

concentrations of potassium, typically thought to originate from low amounts of melting in the Earth's mantle. Calcite veins are also common in Ship Rock. These were likely formed after the eruption, via precipitation from groundwater moving through the breccia and minette of the volcanic throat.

Another distinctive feature of Ship Rock consists of the six dikes that radiate away from a point just west of the central part of the neck. Dikes are wall-like topographic features that form when magma intrudes into a fracture below the Earth's surface, and then crystallizes and cools to form a rock. The longest dikes at Ship Rock are 5.5, 2.5, and 2 mi in length and trend slightly east of due-south, east-west, and northeast (respectively). The south-trending dike is only a few feet thick and nearly 100 ft high in some places. It may have supplied the magma to the diatreme that is now Shiprock.

Shiprock is an intriguing feature to contemplate while driving in northwestern New Mexico. It is truly the "rock of legends" for the native people of the area. Plus, for those interested in geology (particularly volcanoes), Shiprock provides a unique illustration of what the throat of a volcano would look like if you were 2,500–3,300 ft below the surface.

A note of caution: Ship Rock is sacred to the Navajo people and under jurisdiction of their tribal authority. Walking or climbing on it (or its dikes) is strictly forbidden without written permission from the proper Navajo authority. You can still enjoy Ship Rock though by using Google Earth or viewing it from the public highway.

References and further information:

The Navajo Volcanic Field by Steven C. Semken (in Volcanology of New Mexico, New Mexico Museum of Natural History and Science Bulletin 18, p. 79-83).

Ship Rock, New Mexico: The vent of a violent volcanic eruption by P.T. Delaney (Geological Society of America Centennial Field Guide, Rocky Mountain Section, v. 2, p. 411-415).

Navajo (Dineh) Volcanic Field

www.nmnaturalhistory.org//volcanoes/navajo-volcanic-field

The Ship Rock Landform

www.geoinfo.nmt.edu/tour/landmarks/Ship Rock/home.html

Ship Rock and the Navajo Volcanic Field, Navajo Nation (*The Geology of Northern New Mexico's Parks, Monuments, and Public Lands*, edited by L. Greer Price).

Dan Koning

Through the Hand lens with Dr. Kate Zeigler

Geologist Dr. Kate Zeigler enjoys a visit to the New Mexico Bureau of Geology before her speech, "Tales of a Free-Range Geologist: Wrangling Windmills to Roping Mastodons." *Photo by Cynthia Connolly*

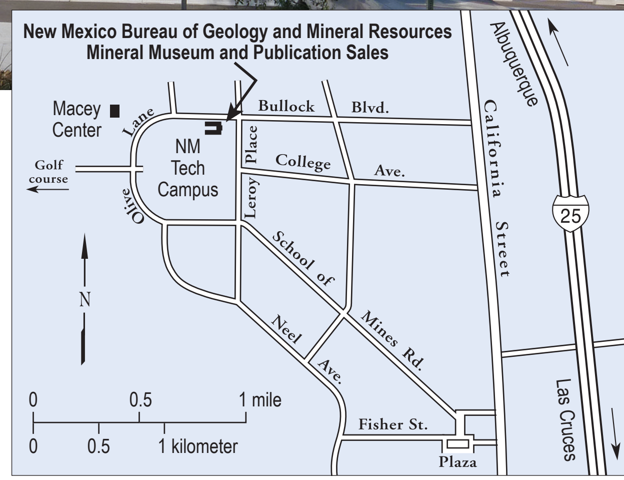
My name is Kate Zeigler, and I am a free-range consulting geologist who travels extensively throughout northeastern New Mexico, southeastern Colorado, western Oklahoma, and down to the chaos of the Permian Basin. I primarily work on groundwater resource management for agriculture on the High Plains, but I also work with the Bureau of Land Management and various companies to protect fossil resources on public lands, and migrate damage by ground-disturbing activities like road construction. I also work with a team of petroleum engineers and geologists to peer into the depths of the Permian Basin to figure out safe places deep below the surface to store the produced water associated with oil and gas extraction.

My educational background includes a B.A. from Rice University in Geology and Anthropology and I completed two senior theses, both centered on paleoclimate-related topics. My M.S. was from University of New Mexico and I studied how a Late Triassic bonebed found in northern New Mexico was formed (spoiler alert: it was a wildfire!). My Ph.D. was a mix of studying stratigraphy and paleomagnetism of Late Triassic rocks in the Chama Basin. So, I've spent a lot of time learning to "hear" the story of the rocks and tell it, which is really what stratigraphy is all about. It's the story of our planet as it's recorded by the rock record. My professional background has developed from my educational background and consists of using stratigraphy to figure out groundwater resources, protect and mitigate fossil resources and help explore the depths of the Permian Basin. I was inspired to become a geologist because it was the next best thing to being a Triceratops, which was really my primary goal in life as a three-year-old.

Professionally, I am most proud of learning how to reach across some formidable barriers to work in collaboration with ranchers and farmers to learn about their groundwater resources and how to conserve them. It's a unique and challenging task because we sure don't speak each other's languages! But I feel as though my team has learned to find the common ground and we're making progress. But there are always hurdles to any path. A big one for me has been having to learn things that are outside my comfort zone. Groundwater is a very different topic compared to paleomagnetism! But I think this has forced me to grow as a geoscientist and become adaptable, which in turn has kept my company going through rough times, like the oil crash of 2015. Additionally, it's been a challenge just to learn how to run a business! They don't teach you about gross receipts taxes or employee-related issues in a geoscience program.

Geoscience is a critical part of human life and activity on this planet and I'd like to see it become a greater part of K–12 curriculum. From how we understand the history of life on this planet, to where our water comes from and goes to, and on to where all the materials we use in everyday life come from: geology is an integral part of us. The coffee mug you're sipping from as you read this—where did that clay come from? How did humans even figure out how to make a coffee mug? How about the soil that gave rise to the coffee plant? And the water you used to brew that coffee—how did that get to your tap? There's still so much to learn about our world and it's important to instill that curiosity and love for our world in the next generation.

Kate Zeigler



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