Lite Geology

New Mexico Bureau of Geology and Mineral Resources

San Juan Basin Tour, Research, and an *Alamosaurus*!

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San Juan Basin Tour, Research, and an *Alamosaurus*!

Welcome to our 51st edition of Lite Geology! Lite Geology 51 explores the San Juan Basin in the Four Corners area of northwestern New Mexico. Kevin Hobbs, New Mexico Bureau of Geology and Mineral Resources (NMBGMR) Field Geologist, lets you ride shotgun on a geologic road tour of the San Juan Basin. Geologist Kate Zeigler, owner of Zeigler Geologic Consulting, LLC, describes her work with Navajo Technical University (NTU), Navajo Transitional Energy Company, and Navajo Nation schoolchildren to excavate "Little Foot," a Late Cretaceous Period *Alamosaurus*. Our NMBGMR Mineral Museum Curator Kelsey McNamara provides an overview of San Juan Basin concretions for our Earth Briefs segment. Virginia McLemore, Senior Economic Geologist, shares her research on utilizing San Juan Basin coal and coal fly ash as a source of rare earth elements. Geochemist Bonnie Frey discusses the role of the NMBGMR/New Mexico Tech (NMT) partnership with NTU to use water filtration technology as a teaching tool for NTU students and as a way to improve water quality for the Navajo Nation. And lastly, our Through the Hand Lens series focuses on Talon Newton as he discusses his work as an NMBGMR hydrogeologist and his research on the effects of the 2015 Gold King Mine spill on the Animas River.

Cover Photo

Angel Peak is a 6,988-foot spire composed of San Jose Formation and Nacimiento Formation sandstone that overlooks more than 10,000 acres of scenic badlands. *Photo by Cynthia Connolly*

The Cretaceous and Paleogene Rock Units of the San Juan Basin

Kevin Hobbs

The geology of the San Juan Basin is visible to the many people who visit, live, or work in and near the basin. Tourists might get their first introduction to the rocks and landscapes of the region by visiting Chaco Culture National Historical Park or Navajo Lake State Park. Travelers on U.S. Routes 550 and 64 wonder at the geology through their windshields. Those who work in oil and natural gas extraction know the geology deeper in the subsurface, as they drill, operate, and abandon thousands of wells that reach hundreds of meters deep in the basin. And New Mexicans who get to live in the basin—including in the cities of Farmington and Aztec, smaller villages like Cuba and Lindrith, and portions of the Navajo Nation and Jicarilla Apache Nation—have their own connections to the region's geologic splendor. No matter what one's connections to the San Juan Basin might be, the geologic history preserved and visible in its rock units tells a fascinating story spanning millions of years. This article explains a portion of that history and offers suggestions on where best to view the rocks that tell it.

Like all geologic basins, the San Juan Basin contains sedimentary rocks that have been deformed by tectonic forces. In the center of the basin, subsidence of Earth's crust caused sedimentary rock layers that were deposited at the surface to be buried by up to 4.3 kilometers of additional sediment. (We know that because an oil well north of Aztec, New Mexico, drilled through that much sediment before hitting any non-sedimentary rock!) Around the margins of the basin, rocks were moved upward; the same rock units that are 4.3 kilometers deep in the basin's center can be viewed in surface outcrops around its margins. Small portions of the basin extend into Colorado, Utah, and Arizona, but the vast majority lies in New Mexico, and the rocks that are easily visible at the surface on public lands in our state are the focus of this article. For the most part, the rocks detailed below tell a story of continuous sediment deposition during the final major stage of tectonic development in the San Juan Basin, beginning at about 100 million years ago and lasting for 45 million years. Unfortunately, there is not one single site in the basin where all of the rocks telling this story can be seen in one place. Instead, we travel through the basin, viewing the rocks in the order in which they were deposited. A schematic section of these rocks is shown in Figure 1.

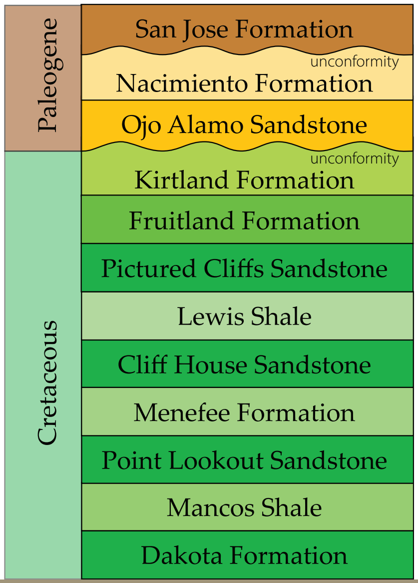


Figure 1. Simplified stratigraphy of Cretaceous and Paleogene sedimentary rock units in the San Juan Basin, New Mexico.

Figure 2. Sandstone of the Dakota Formation dipping to the left (east) at the Tierra Amarilla anticline near the White Ridge Bike Trails, San Ysidro, New Mexico. Note the symmetrical ripple marks atop the sandstone bed. *Photo by Kevin Hobbs*

Dakota Formation

Rock types: mostly sandstone, minor amounts of shale and coal
Age: ca. 95 Ma (million years ago)
Environment of deposition: sandy beaches, estuaries, and lagoons
Best San Juan Basin outcrops: Ponderosa Campground at Heron Lake State Park and White Ridge Bike Trails near San Ysidro (Fig. 2)

The Dakota Formation marks the beginning of a 25-million-year-long episode of San Juan Basin sediment deposition related to the Cretaceous Interior Seaway. At its highest, this vast inland sea stretched from the Gulf of Mexico to the Arctic Ocean and from Arizona to Minnesota; most of New Mexico was underwater at least once during this time. As the seas rose for the first time in the Cretaceous Period, sand was deposited on beaches across not only our state, but also across much of central North America. (The name "Dakota Sandstone" gives another clue to the wide geographic extent of this unit). Here in New Mexico, the Dakota Formation is often marked by cliff-forming sandstones; finer-grained shales and dark coals make up minor fractions of the unit as well.

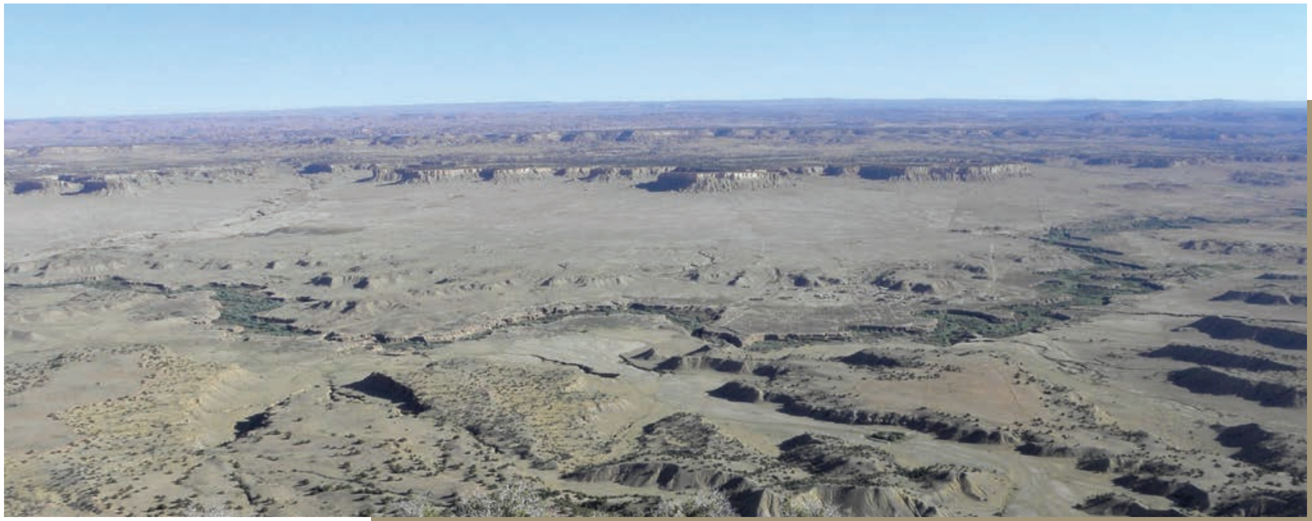


Figure 3. View of the Rio Puerco valley, village of Cabezon, and La Leña Wilderness Study Area as seen from Cabezon Peak in Sandoval County, New Mexico. The broad, flat valley of the Rio Puerco here is due to the easily erodible nature of the Mancos Shale that it flows over. Stronger but thinner Point Lookout Sandstone forms the light-colored cliff in the middle distance; that cliff is approximately 80 meters high. *Photo by Kevin Hobbs*

Mancos Shale

Rock types: mostly gray shale, minor amounts of limestone and sandstone
Age: ca. 95–85 Ma
Environment of deposition: offshore shallow marine
Best San Juan Basin outcrops: Rio Puerco valley near Cabezon Peak, including Cerro Chato and Cerro Cochino (Fig. 3), and plains north of the town of Shiprock

Sea level continued to rise after the Dakota Formation was deposited. The beach sands of the Dakota Formation were then submerged, and fine-grained mud was deposited atop them. During this time, the oceans covering New Mexico were warm, shallow, and relatively muddy. Fossils of sharks and ammonites are relatively common within these muds, with mollusks and gastropods found in the unit's limestones and marls. Mancos Shale is a weak and easily eroded rock; therefore, it does not form impressive cliffs. Look for good exposures in road cuts, arroyo banks, and immediately beneath sandstone cliffs.

Point Lookout Sandstone

Rock types: mostly sandstone with minor shale
Age: ca. 85 Ma
Environment of deposition: beaches
Best San Juan Basin outcrops: cliffs north of the village of Cabezon, La Leña Wilderness Study Area, and Elk Springs Area of Critical Environmental Concern near Cuba

After several million years of high sea levels, the oceans retreated again. Areas that were open ocean were once again beaches; Point Lookout Sandstone marks the deposits of this retreating shoreline. Farther north in Colorado's Mesa Verde National Park, Point Lookout Sandstone is up to 100 meters thick and forms some of the most prominent topographic features in the park. Here in New Mexico, Point Lookout Sandstone is not as thick, but it still forms cliffs because of its greater relative strength compared to the muddy and weaker rocks above and below it (Fig. 3).

Menefee Formation

Rock types: mix of sandstone and mudstone
Age: ca. 84–79 Ma
Environment of deposition: low-elevation rivers and deltas
Best San Juan Basin outcrops: south side of Chaco Canyon

After the shore of the Cretaceous Interior Seaway had retreated to lower elevations to the northeast of the San Juan Basin, rivers that were sourced in Arizona flowed northeast through the basin and toward the sea. These rivers were low-gradient, muddy streams; sands accumulated in their channels while muds and coal built up on their extensive floodplains. This mixture of sand, silt, mud, and coal became the Menefee Formation. Fossils of turtles, dinosaurs, and large trees clue in the geologist to its nonmarine origin.

Figure 4. Cliff House Sandstone in Chaco Canyon, New Mexico. Many of the human structures in “downtown” Chaco Canyon, including Chetro Ketl, Pueblo Bonito, and Hungo Pavi (seen here), were constructed from pieces of Cliff House Sandstone. *Photo by Kevin Hobbs*

Cliff House Sandstone

Rock types: mostly sandstone with minor shale
Age: ca. 78 Ma
Environment of deposition: beaches and barrier islands
Best San Juan Basin outcrops: cliffs in Chaco Canyon, especially on the north side above Pueblo Bonito and Chetro Ketl

The Cretaceous Interior Seaway did not stay down for long. After the Menefee Formation was deposited for a million years or so, sea levels rose again and another beach sand was deposited. This beach sand and the barrier island and shallow marine muds associated with it make up the Cliff House Sandstone, best observed in the cliffs of Chaco Canyon (Fig. 4). In fact, many of the larger human structures in Chaco Canyon, including Pueblo Bonito, are made of blocks of Cliff House Sandstone. Abundant shrimp, mollusk, shark, and ammonite fossils in Cliff House Sandstone indicate its origin in marine environments.

Lewis Shale

Rock type: siltstone and shale
Age: ca. 77 Ma
Environment of deposition: offshore shallow marine
Best San Juan Basin outcrops: Outcrops are rare but are visible in uppermost Chaco Wash and near Pueblo Pintado.

Like the Mancos Shale, the Lewis Shale represents a sea-level “highstand,” or episode when sea level was at its highest. In outcrops, this unit is poorly exposed and relatively thin. In the subsurface, however, it reaches a thickness of over 600 meters in the northern San Juan Basin. Lewis Shale represents the last time seawater covered the San Juan Basin; since it was deposited, terrestrial environments have been the only environments of deposition.

Pictured Cliffs Sandstone

Rock type: sandstone with minor siltstone
Age: ca. 76 Ma
Environment of deposition: beaches, deltas, and barrier islands
Best San Juan Basin outcrops: Pictured Cliffs of the San Juan River near Fruitland

As the sea retreated for the final time, the familiar environments of beaches, deltas, and barrier islands once again led to sand deposition in the San Juan Basin, this time as the Pictured Cliffs Sandstone. This unit is similar in composition and fossil assemblage to Cliff House Sandstone. As with the Cliff House Sandstone, past denizens of the San Juan Basin sought out the Pictured Cliffs Sandstone for making petroglyphs, hence the formation’s name.

Fruitland Formation and Kirtland Formation

Rock type: sandstone with minor siltstone
Age: ca. 76–73 Ma
Environment of deposition: beaches, deltas, and barrier islands
Best San Juan Basin outcrops: Bisti/De-Na-Zin Wilderness Area and Ah-Shi-Sle-Pah Wilderness Study Area

Sea levels continued to fall after deposition of the Pictured Cliffs Sandstone in the San Juan Basin, and rivers flowing from the southwest—perhaps sourced in mountains in southern Arizona—once again drained down to the retreating sea. A mountain-building event called the Laramide Orogeny began to cause subsidence in the growing basin, allowing over 700 meters of silt, mud, and sand to accumulate in the basin’s center north of Farmington. Elsewhere in the basin, subsidence was much weaker, and less than 100 meters of Fruitland and Kirtland formations sediments were deposited near Cuba. These formations are replete with fossils, including trees, dinosaurs, pterosaurs, crocodilians, turtles, and fish.

Many of the renowned hoodoos of the Bisti/De-Na-Zin Wilderness Area south of Farmington (Fig. 5) are formed in the Kirtland Formation.

After the Fruitland and Kirtland formations were deposited in the latest Cretaceous Period, there was a basin-wide episode of erosion that removed an unknown thickness of the upper Kirtland Formation.

Ojo Alamo Sandstone

Rock type: pebbly sandstone
Age: ca. 65 Ma
Environment of deposition: sandy rivers
Best San Juan Basin outcrops: Bisti/De-Na-Zin Wilderness Area, Glade Run Recreation Area, and Mesa Portales

After the erosion that marked the end of the Cretaceous Period, major tectonic shifts in the Four Corners region caused stream reorganization and major sedimentation in the San Juan Basin. Large mountains had risen to the north of the basin, and rivers draining them flowed southward (instead of the northeast-flowing rivers that dominated in the Cretaceous), depositing the relatively coarse-grained sands of the Ojo Alamo Sandstone. While few animal fossils are known in the Ojo Alamo Sandstone, large petrified trees—some with trunks as long as 35 meters—indicate its deposition in a nonmarine setting (Fig. 6).

Figure 5. Hiker (left) and dog inspecting the varied rock types of the Kirtland Formation in Bisti Wash, San Juan County, New Mexico. The lighter-colored layers are predominantly sands, whereas the darker layers are mudstones. *Photo by Kevin Hobbs*

Figure 6. A petrified log within the Ojo Alamo Sandstone at De-Na-Zin Wash, San Juan County, New Mexico. Note the thick, nearly pure sand layer overlying the log; this type of deposit typifies the Ojo Alamo Sandstone in this area. Elsewhere in the basin, the same formation contains conglomerates and mudstones. *Photo by Kevin Hobbs*

Nacimiento Formation

Rock types: a mix of mudstone, siltstone, and sandstone
Age: ca. 65–61 Ma
Environment of deposition: rivers and floodplains
Best San Juan Basin outcrops: Kutz Canyon, Angel Peak Scenic Area, and Aztec Ruins National Monument

The Nacimiento Formation has an enormous outcrop area in the San Juan Basin, and U.S. Route 550 follows this outcrop belt from Nageezi north to the Colorado border. The Nacimiento Formation is highly variable, often colorful, and forms stunning landscapes in much of the western basin (Fig. 7). The rocks in this unit include sandstone, indicating deposition in river channels, and mudstones, indicating floodplain deposition. Ancient soils preserved within the Nacimiento Formation show that during the 4 million years that it took to deposit the unit, there often were long episodes of non-deposition during which soils developed. Paleontologists have studied the mammal fossils from the Nacimiento Formation for nearly 150 years and for good reason: the formation preserves one of the longest and richest records of mammalian evolution after the end-Cretaceous extinction event at 66 Ma. Other common fossils include crocodilians, turtles, fish, and plants.

Figure 7. The Nacimiento Formation at Kutz Canyon, San Juan County, New Mexico. The variegated gray, white, and red colors of the Nacimiento Formation seen here are sometimes supplemented by blacks and greens. The cliff-forming yellow beds here are sandstones deposited in river channels. Most of the other beds are floodplain deposits of the same river systems. *Photo by Kevin Hobbs*

Figure 8. Yellowish brown sandstones and gray, purple, and red mudstones of the San Jose Formation in Gallo Canyon, Rio Arriba County, New Mexico. *Photo by Kevin Hobbs*

After the Nacimiento Formation was deposited in the early Paleogene Period, there was a basin-wide episode of erosion that removed an unknown thickness of the upper Nacimiento Formation.

San Jose Formation

Rock types: thick sandstones and colorful mudstones
Age: ca. 56–52 Ma
Environment of deposition: rivers and floodplains
Best San Juan Basin outcrops: Navajo Lake State Park, Mesa de Cuba, and Cañon Largo

The colorful and widely distributed San Jose Formation, found in most of the central San Juan Basin, represents the last record of sediment deposition related to the Laramide Orogeny in the San Juan Basin. It is also the youngest bedrock unit preserved in outcrops in the basin (though there are abundant younger surficial deposits that have not been lithified). Deposited by rivers flowing out of the then-growing mountains north and east of the San Juan Basin, the San Jose Formation is marked by thick, cliff-forming sandstones and multicolored orange, purple, and red mudstones (Fig. 8). Most of the highest cliffs and deepest canyons in the basin owe their existence to this unit's sandstones, and the Continental Divide cuts across the San Jose Formation for 50 kilometers, from just west of Cuba to the Jicarilla Apache Nation near Stone Lake.

After the San Jose Formation was deposited, there likely were more sediments deposited atop it. However, millions of years of uplift and erosion have removed any overlying rocks, and the San Jose Formation therefore marks the final chapter in the bedrock sedimentary history of the basin. Each of the rock units described above tells a complex story of the erosion, deposition, climate, plants, animals, and tectonic development of the San Juan Basin, and geologists are far from finished in our attempts to understand it. Along with colleagues from many New Mexican universities, museums, and industries, scientists at the NMBGMR continue research into San Juan Basin geology, including groundwater hydrology, paleontology, petroleum geology, and carbon sequestration.

Using a "Little" Dinosaur to Encourage STEM Pathways for Middle School Students on the Navajo Nation

Kate Zeigler and Matt Owens

In the fall of 2021, a group of professional paleontologists partnered with the Navajo Transitional Energy Company (NTEC) to excavate a "little" dinosaur within the Navajo Coal Mine's lease area. Usually, dinosaur material within the mine lease is excavated as part of mitigation and salvage efforts in the path of mine expansion. However, Little Foot, as our "little" dinosaur is dubbed, does not fall within any potential area that would be disturbed. This fossil locality presented a wonderful opportunity to share geoscience, paleontology, and mining science with middle school students from several schools around the Navajo Nation, as well as with students in the environmental science program at Navajo Technical University (NTU; Figs. 9 and 10). Most kids go through a dinosaur-obsessed phase, but the majority transition to other interests in elementary school. NTEC felt that Little Foot could be used to reignite the excitement of the dinosaur phase in older students to encourage them to consider a career in a STEM discipline. Indigenous people are underrepresented in STEM disciplines, and NTEC seeks to expose local students and teachers to STEM activities at the mine whenever possible.

Little Foot is tentatively identified as a juvenile *Alamosaurus* (Fig. 11), a member of the long-necked dinosaur group referred to as sauropods. His bones are scattered across an area of low badlands, and he lived during a time when the landscape looked incredibly different from the current sagebrush-dominated high desert. As the middle school students arrived at the quarry, the paleontologists led them in a discussion of the striking contrast between the paleoenvironment of Little Foot's day, a swampy coastal region, and today's landscape. They then examined the quarry and discussed how to properly excavate a dinosaur, including developing a grid system, taking careful notes, and crafting plaster jackets for the safe removal of fossil material.

Figure 9. Students from Navajo Technical University prepare to tour the site with Kate Zeigler and her team to learn more about Little Foot and his landscape. *Photo courtesy of Abhishek RoyChowdhury*

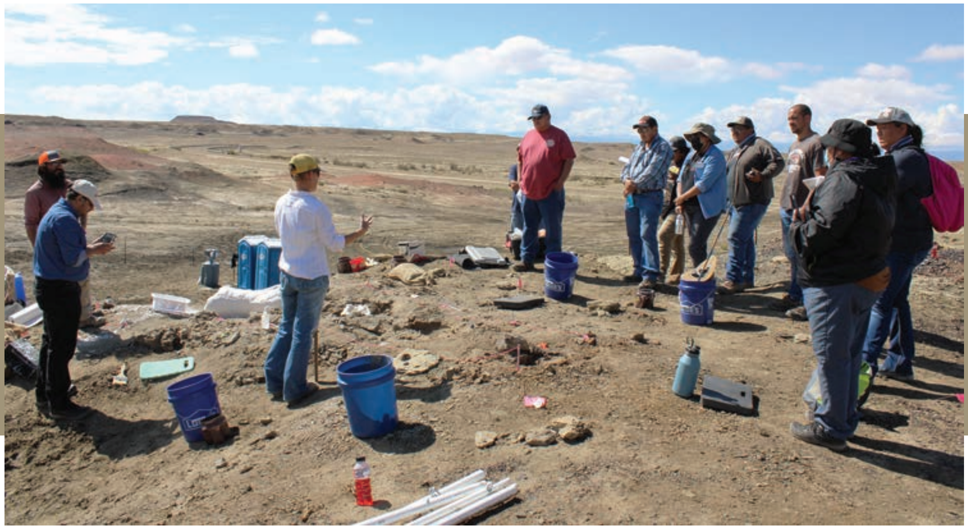


Figure 10. Students from Navajo Technical University meet Little Foot and learn how grid systems are laid out and used to understand more about the orientation and association of the bones. *Photo courtesy of Abhishek RoyChowdhury*

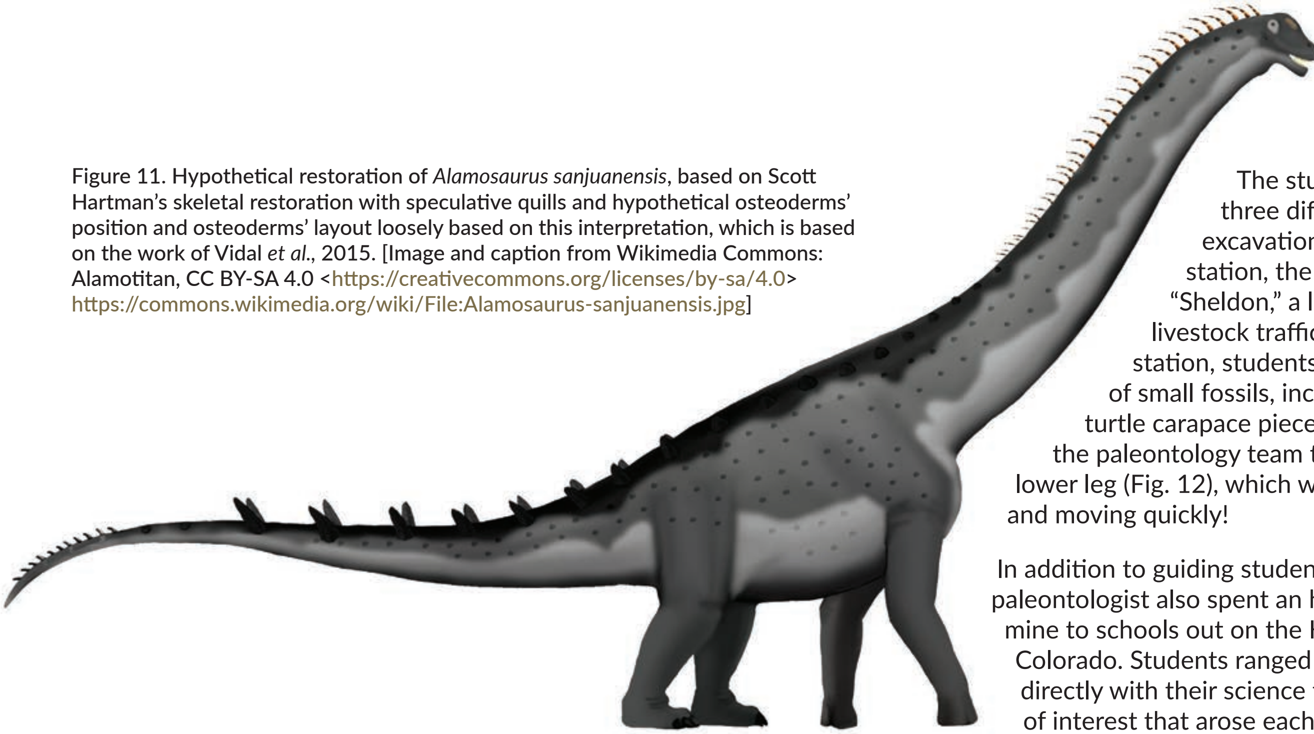


Figure 11. Hypothetical restoration of *Alamosaurus sanjuanensis*, based on Scott Hartman's skeletal restoration with speculative quills and hypothetical osteoderms' position and osteoderms' layout loosely based on this interpretation, which is based on the work of Vidal *et al.*, 2015. [Image and caption from Wikimedia Commons: Alamotitan, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0> https://commons.wikimedia.org/wiki/File:Alamosaurus-sanjuanensis.jpg]

The students were then split into groups that rotated through three different stations. One station focused on learning proper excavation techniques on bones still in the ground. At a second station, the students used a consolidant to attempt to put back together "Sheldon," a large fossil turtle carapace that had been broken by local livestock traffic through the quarry before excavations started. At the third station, students used sieves to sift away sediment and recover a variety of small fossils, including ray and shark teeth, crocodile bone fragments, and turtle carapace pieces. The NTU students had the opportunity to work with the paleontology team to craft a large plaster jacket around part of Little Foot's lower leg (Fig. 12), which was an exciting half-hour of applying plaster and burlap and moving quickly!

In addition to guiding students who were able to visit the quarry in person, the senior paleontologist also spent an hour each week live-streaming presentations from the mine to schools out on the High Plains of northeastern New Mexico and southeastern Colorado. Students ranged from second grade through eighth grade, and we worked directly with their science teachers to structure each streaming session around topics of interest that arose each week. This provided an amazing opportunity for kids from rural agricultural communities to witness videos of the excavation and participate in Q&A sessions with the paleontologist and mine personnel.

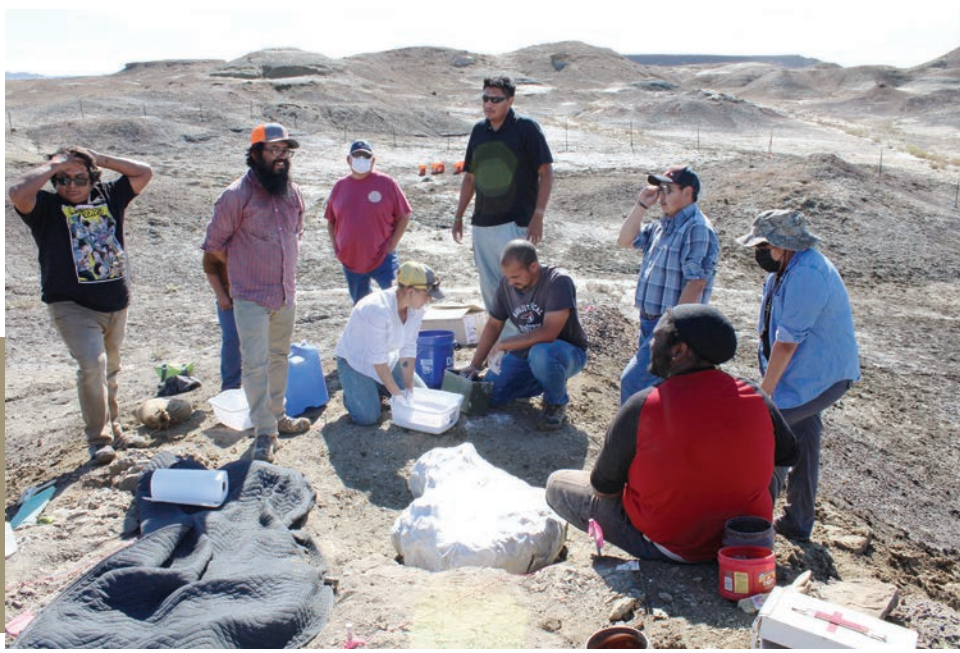


Figure 12. Students from Navajo Technical University complete a plaster jacket containing the lower leg bones of Little Foot under guidance from Kate Zeigler and her team. *Photo courtesy of Abhishek RoyChowdhury*

As the day's visits wrapped up, personnel from Navajo Coal Mine and the paleontology team spent time discussing the coal mine, how mining works, and potential job opportunities in mining, geoscience, and paleontology. Our impression at the end of each day was that the majority of the students thoroughly enjoyed the experience, and many had their own stories to tell of finding fossils with their families around the Navajo Nation. Working hands-on in the field was a unique way for students to truly see how paleontologists and mining personnel go about their daily jobs. It was worth the long, hard days of getting Little Foot out of the ground to see eyes light up and jaws fall open as students got to know our "little" dinosaur, and we hope to provide similar opportunities into the future.

Acknowledgments: Fieldwork on the Navajo Nation was conducted under a permit from the Navajo Nation Minerals Department. Any persons wishing to conduct geologic investigations on the Navajo Nation must first apply for and receive a permit from the Minerals Department: P.O. Box 1910, Window Rock, AZ 86515, phone (928) 871-6587.

Earth Briefs: Oddities & Curiosities—Concretions of the San Juan Basin

Kelsey McNamara

What is a Concretion?

The word *concretion* is a great example of geology jargon, so let's start with an explanation! Concretions are hardened mineral masses that form in sediment and sedimentary rocks by the precipitation of minerals around a nucleus (or core). The nucleus is often organic (like a bone, shell, leaf, or fossil) and less frequently inorganic (such as a pebble or mineral).

Concretions are generally harder than the surrounding rock, allowing them to weather out of a softer or poorly cemented host rock. Concretions vary in shape (spherical to ovular, lumpy, and pipe-shaped) and size (microscopic to larger than a car). Concretions are composed of a variety of minerals, such as iron oxide, pyrite, barite, calcite, and silica.

Concretions are found worldwide and on other planets. Famous examples include but are not limited to iron oxide spheres of the western United States (aka moqui marbles) and Mars (aka blueberries); pyrite concretions of Kansas (aka pop rocks); siderite concretions of Mazon Creek, Illinois (which often include nuclei of fossil plants); and septarian concretions of Utah (limestone concretions filled with a network of calcite-lined veins).

New Mexico also has a wide range of concretions representing all the types mentioned above. These oddly shaped geological curiosities are usually misidentified as fossils (typically dinosaur brains, hearts, or eggs), meteorites, or artifacts because of their unusual shapes compared with "normal-looking" rocks.

Figure 13. Different types of concretions. A) I'm holding a large, UFO-shaped septarian concretion from the Pennsylvanian Madera Group, Socorro County, New Mexico. B) A pyrite concretion, locality unknown. C) A calcium-carbonate-rich sandstone concretion cored by a yellow calcite crystal, locality unknown. D) Iron oxide concretions with interior fern fossils from Mazon Creek, Illinois. *Photos by Matt Zimmerer (A) and Kelsey McNamara (B, C, D)*

When a concretion looks like something we recognize but actually is not, we call it a petrifact or, in the case of fossil look-alikes, a pseudofossil.

Quick Recap: San Juan Basin Geology

The San Juan Basin of the Four Corners region is one of the best places in our state to observe concretions. The San Juan Basin is a classic example of a sedimentary basin, or a portion of the Earth's crust where prolonged subsidence causes sediment accumulation. This basin formed during the Laramide Orogeny, a mountain-building event that started about 75 million years ago. Throughout this vast swath of time, depositional systems changed from those on land to those at sea and back again, leaving behind sediments that eventually turned into the limestones, shales, mudstones, siltstones, and sandstones we see today.

Northwestern New Mexico is the perfect place to observe this record of sedimentation, with rocks ranging in age from Triassic to Paleogene. In addition, the area has abundant secondary features formed from diagenesis, or the physical and chemical changes in sediments after they are deposited and buried. Some examples of diagenetic features are fossils (organisms replaced by minerals), bitumen (formed by the transformation of organics into hydrocarbons), and last but not least—concretions!

Concretions from the San Juan Basin: Photo Gallery

We have some interesting San Juan Basin concretions in the Mineral Museum collection, pictured on the next page with a color-coded map.

The San Juan Basin is a big place, and our small photo gallery is by no means comprehensive. However, if you find yourself walking around and you stumble upon a strangely shaped rock, it might very well be a concretion! Figure 14 shows a nice display of New Mexico concretions, revealing variations in size, morphology, and composition.

Figure 14. A display of several concretions from New Mexico with a focus on the San Juan Basin area, presented at the Albuquerque Fall Gem, Mineral, and Jewelry Show. Case provided by Bob Regner. *Photo courtesy of Bob Regner*

Figure 15. A Four Corners area map with the San Juan Basin outlined in red. The colored diamonds indicate localities where the concretions in the photos were collected. (Map originally published in USGS Fact Sheet FS-147-02, 2002, https://pubs.usgs.gov/fs/fs-147-02/FS-147-02.pdf).

Figure 16. Cannonball- to egg-shaped sandstone concretions in mudstone of the Cretaceous Fruitland Formation and Kirtland Formation in the badlands of the Bisti/De-Na-Zin Wilderness Area south of Farmington, New Mexico. *Photo by Kelsey McNamara*

Figure 17. Interior of a sandstone concretion showing white, stubby quartz crystals surrounded by dogtooth spar calcite crystals. Found in the Lybrook, New Mexico, area in the Paleocene Nacimiento Formation. Gift of Dennis Umshler. *Photo by Kelsey McNamara*

Figure 18. A barite concretion with a lumpy external morphology! This piece was found on Ceja Pelon Mesa near Cuba, New Mexico, in the Paleocene Nacimiento Formation. Gift of Roy Greiner. *Photo by Kelsey McNamara*

Figure 19. Abundant yellow calcite crystals occupy the interior of this large limestone concretion, which formed around an ammonite fossil! Limestone and septarian concretions are known to be found in the Cretaceous Mancos Shale of the Rio Puerco valley near Cabezon Peak, New Mexico. Gift of Al and Betty Tlush. *Photo by Kelsey McNamara*

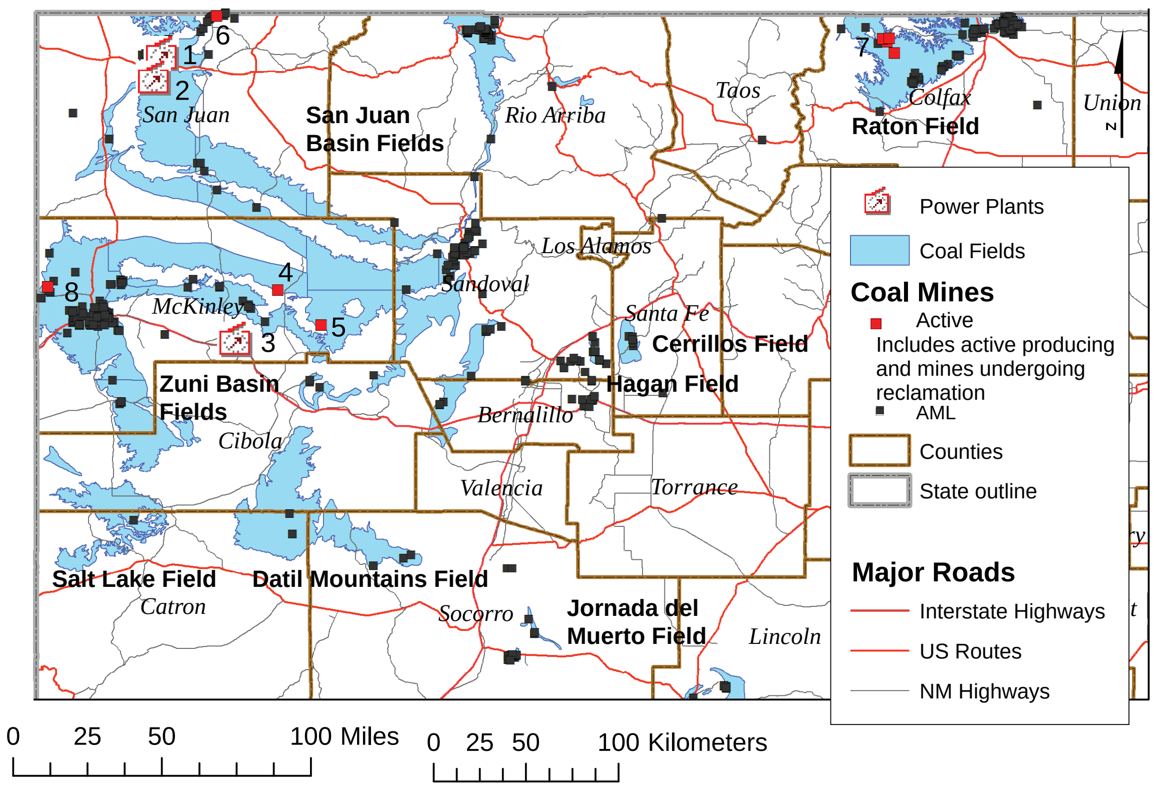
Figure 20. Azurite (a blue copper-bearing mineral) concretions in sandstone from the Nacimiento Mine, Sandoval County, New Mexico, on the eastern edge of the San Juan Basin. Malachite (a green copper-bearing mineral) is also found at this locality. These concretions formed by copper mineralization in the Triassic Agua Zarca Sandstone of the Chinle Formation. Gift of Jerry Simmons. *Photo by Kelsey McNamara*

Rare Earth Elements and Critical Minerals in Late Cretaceous Coal and Related Strata in the San Juan and Raton Basins, New Mexico

Virginia McLemore

Coal is a sedimentary rock composed of more than 50% by weight organic material and is formed by the compaction of decaying plant material deposited in ancient peat swamps or mires. Coal is readily combustible and is burned for fuel. It is primarily used in generating electricity in power plants, but it is also essential in manufacturing steel; in the production of cement, carbon fibers and foams, medicines, tars, and synthetic petroleum-based fuels; and in home and commercial heating. Several factors in addition to the thickness and quality of the coal determine whether a coal deposit is economic: 1) the technology available for extraction, 2) distance from the deposit to a market, and 3) the transportation network available. Throughout the history of coal mining in New Mexico, these factors have changed. In the future, the concentration of critical minerals, including rare earth elements (REE), could be a factor in producing coal deposits.

Spanish settlers used small amounts of coal several centuries ago in New Mexico for home heating by mining outcrops on a sporadic basis. Coal mining on a significant scale began in New Mexico in 1862, when U.S. Army troops from Fort Craig opened the Government Mine in the Carthage coal field (Socorro County) to supply coal for smithing at Forts Seldon, Bayard, and Stanton. Coal mining continued to expand in the 1880s throughout New Mexico, supplying the railroads with fuel. Coal production increased dramatically in the 1960s with the construction of electric generating plants and the introduction of large-scale surface mining in northwestern New Mexico to supply those plants. The combination of inexpensive surface-mineable coal and the increased demand for electric power in Arizona, New Mexico, and California led to the opening of many mines in the San Juan Basin. Today, however, most of these mines are closing because coal produces carbon dioxide and other greenhouse gases, and the United States is shifting to green technologies such as solar and wind power.



1 San Juan-Public Service Co. of NM plant and San Juan underground mine (Westmoreland)
2 Four Corners-Arizona Public Service Co. plant and Navajo mine (Bisti Fuels Co., LLC)
3 Escalante-TriState plant
4 El Segundo mine (Lee Ranch Coal)
5 Lee Ranch mine (Lee Ranch Coal)
6 La Plata (reclamation)
7 York Canyon and Ancho mines (reclamation)
8 McKinley mine (reclamation)

Figure 21. Map showing coal fields, electrical generating plants, and coal mines in the San Juan Basin.

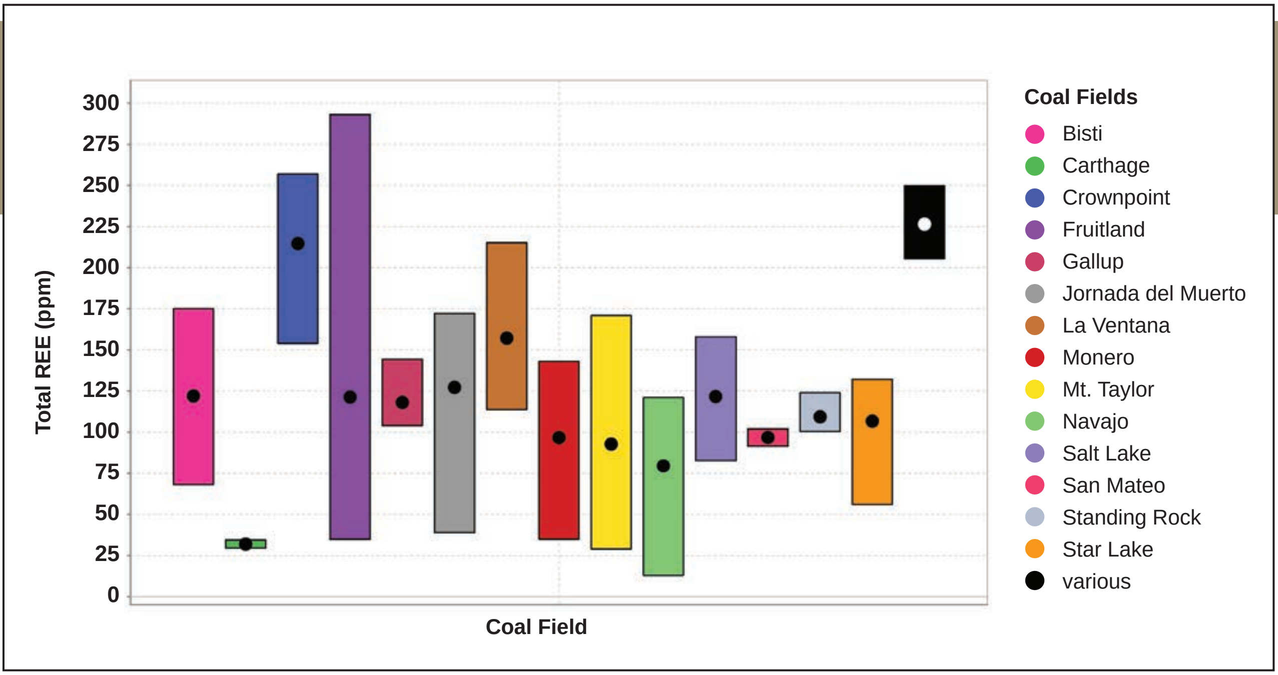


Figure 22. Bar graph showing range in concentrations of total rare earth elements (REE; lowest to highest concentration in parts per million) in coal samples from various coal fields and areas in New Mexico and Arizona. Each color bar is a separate coal field. The black circles within bars are the average value for each coal field.

Coal also contains minerals that are noncombustible and do not burn. These minerals could contain REE and other critical minerals that can be recovered from coal mining or from coal ash that remains after coal is burned. The U.S. Department of Energy (DOE) has awarded New Mexico Tech a contract to examine REE and other critical minerals in coal and associated strata in the San Juan and Raton basins in northern New Mexico (entitled Carbon Ore, Rare Earth, and Critical Minerals [CORE-CM] Assessment of San Juan River-Raton Coal Basin, New Mexico). Critical minerals are mineral resources that are essential to our economy but might have supply disruptions. Most critical minerals are imported into the United States. Many critical minerals are found in the San Juan and Raton basins of New Mexico in rocks other than coal. The purpose of the DOE project is to 1) identify, quantify, and characterize the distribution of critical minerals, including REE, in coal beds and related stratigraphic units in the San Juan and Raton basins of New Mexico; 2) identify possible sources of critical minerals and REE in the basins; 3) identify the coal mine and nonfuel carbon-based waste products that could contain critical minerals and REE; and 4) test and develop new technologies for identifying and quantifying critical minerals and REE in high-fidelity geologic models.

Some of the associated deposits that could also contain REE and other critical minerals include coal refuse and mine waste, coal ash, interstitial clays, shales, volcanic ash beds, acid mine drainage, associated sludge samples, mine dumps, other nonfuel carbon-based products, and process waters. Beach-placer sandstone deposits are another type of associated strata containing critical minerals; these are accumulations of heavy, resistant minerals (i.e., high specific gravity) that form on upper regions of beaches or in longshore bars in a marginal-marine environment (Fig. 23). They form by mechanical concentration (i.e., settling) of heavy minerals by the action of waves, currents, and winds. Coal deposits form in swamps farther inland from the beach. We are also characterizing humate deposits for their possible critical mineral content. Humates are weathered coal and are used in agricultural, environmental, industrial, livestock, and cosmetics industries.

Brick red clinker deposits (also known as natural scoria and red dog deposits) are associated with some coal beds in the San Juan Basin coal fields. These clinker deposits are believed to originally have been coal beds that caught fire and burned in place. Such fires were caused by forest or grass fires, lightning strikes, or even natural combustion!

Figure 23. Sanostee beach placer sandstone deposit, San Juan County, New Mexico. The dark layer at the top of the cliff is the beach placer sandstone that contains zircon, rutile, monazite, and other minerals. *Photo by Virginia McLemore*

Figure 24. Brick red clinker deposits beneath sandstone in the San Juan Basin. Clinker was once coal that caught on fire in place. *Photo by Virginia McLemore*

In some areas of the western United States, evidence suggests that prehistoric humans may have ignited some of the coal beds in place. Natural clinker deposits are quarried and used to make roads, bricks, and other industrial products. In New Mexico, natural clinker deposits along with the adjacent coal beds are being sampled as part of the project to determine whether these deposits could have elevated concentrations of REE or other critical minerals.

In the Figure 24 photo of a clinker and coal deposit near Star Lake in the San Juan Basin west of Cuba, one can see the clinker deposits in place above unburned coal deposits. This deposit ranges in thickness from 10 to 20 feet. A thin clay bed separates the clinker deposit from the underlying unburned coal seam. The clinker was quarried for use in local roads, and the coal was mined to heat local houses. The brick red color of clinker deposits is in sharp contrast to the normal gray, tan, and black colors in the Cretaceous beds of the San Juan Basin and is an excellent exploration indicator for nearby coal seams.

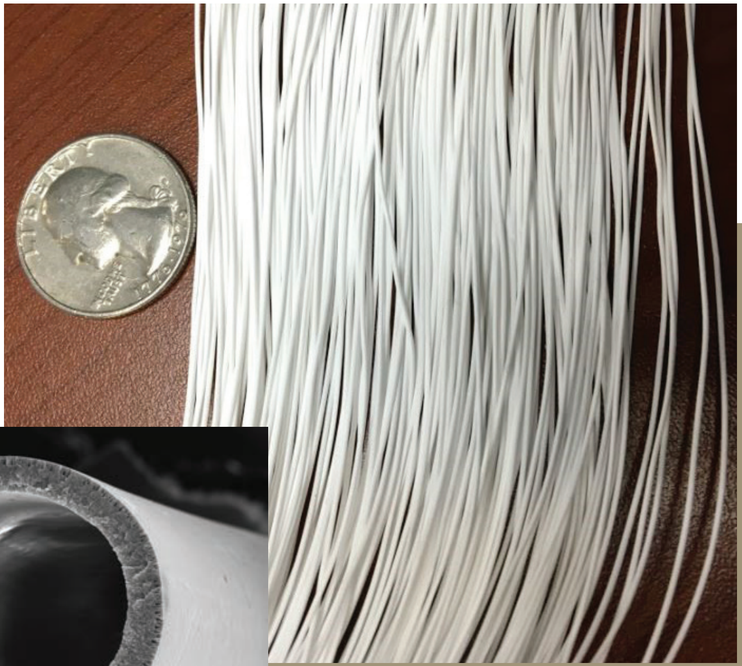
We are in the first year of this project and plan to finish next year. Results so far indicate a few coal beds have elevated REE. Additional studies will identify their mineralogy and examine potential methods of recovering the REE and other critical minerals. The principal investigators on the project are Dr. Navid Mojtabai (NMT Mineral Engineering Department), Dr. Virginia McLemore (NMBGMR), and Dr. William Ampomah (NMT Petroleum Recovery Research Center). NMT graduate and undergraduate students are working on the project (Figs. 25 and 26). San Juan College, Los Alamos National Laboratory, and Sandia National Laboratories are partners in this project.

Figure 25. NMT students sampling coal seams at the El Segundo Mine, McKinley County, New Mexico. *Photo by Virginia McLemore*

Figure 26. NMT students Devlon Shaver and Peter Lyons examining a coal outcrop at the El Segundo Mine, McKinley County, New Mexico. *Photo by Virginia McLemore*

Filtration System Becomes Teaching Tool and Improves Water Quality

Bonnie Frey



Access to clean water is a challenge for many in the Navajo Nation, and new challenges introduced during the COVID-19 pandemic have brought the issue into the national spotlight with even more urgency. More than 30% of people on the Navajo Nation live without indoor plumbing and instead haul water; sometimes they must drive hours to access good-quality water. These conditions can lead to reduced sanitation—a situation that exacerbated the COVID-19 outbreak on the Navajo Nation.

A joint endeavor between Navajo Technical University (NTU) and New Mexico Tech (NMT) will help address the availability of clean water on the Navajo Nation. The NTU-NMT Navajo Nation Water Purification Project (N[4]WPP) seeks to install filtration technology developed by NMT's Petroleum Recovery Research Center at wells on the Navajo Nation that are currently not suitable for agricultural or livestock use. Besides the immediate benefit of providing purified water at these locations, the team seeks to train NTU and NMT students in all aspects of this project, such as working with local agencies and communities on site selection, conducting hydrologic research on water quantity and quality at the test site, and installing and maintaining state-of-the-art equipment. The long-term goal of this partnership is creating a next-generation workforce capable of addressing water resource issues, running these and similar water systems, and taking leadership roles in water management across the Navajo Nation. Staff at NMBGMR are working with the project team to collect data about wells that could benefit from filtration and to provide water analyses.

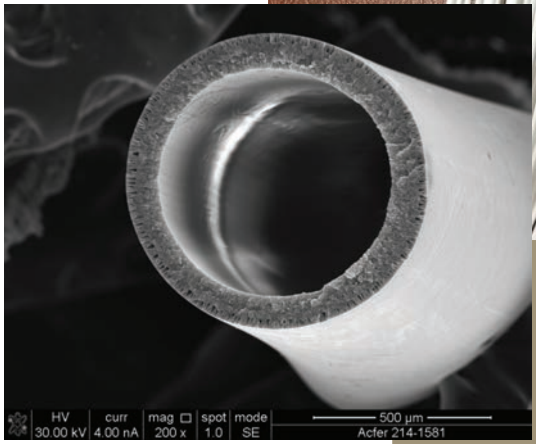


Figure 27. The membrane filters created by the Petroleum Recovery Research Center at NMT are part of a new filtration system that can remove high levels of salts and metals from contaminated water. The inset shows the membrane at a scale of 500 micrometers (image by field-emission SEM). *Photos courtesy of Jianjia Yu, Petroleum Recovery Research Center*

The filtration system the team intends to install is a desalination system that uses polyvinylidene fluoride hollow-fiber membranes (Fig. 27) to filter produced water during oil and gas recovery. Produced water is groundwater that is pumped to the surface during oil and gas extraction. Its composition can vary, but it can be several times more saline than seawater and can contain oil residue, sand or mud, heavy metals, fracking fluids, and bacteria. This new desalination technology has been shown to reject more than 99% of the salt in produced water samples.

To test the system, a 3.5 wt% sodium chloride solution, which is about the weight percent of total dissolved solids (TDS) in seawater, was fed through the system for 200 hours. The TDS concentration of the resulting purified water was less than 2.5 mg/L (Fig. 28; the TDS concentration of seawater is about 35,000 mg/L) while maintaining a steady water flux of more than 480 liters per hour. There was no significant scaling during the filtration period—an important difference from reverse osmosis (RO) systems, which can suffer from scaling of the system.

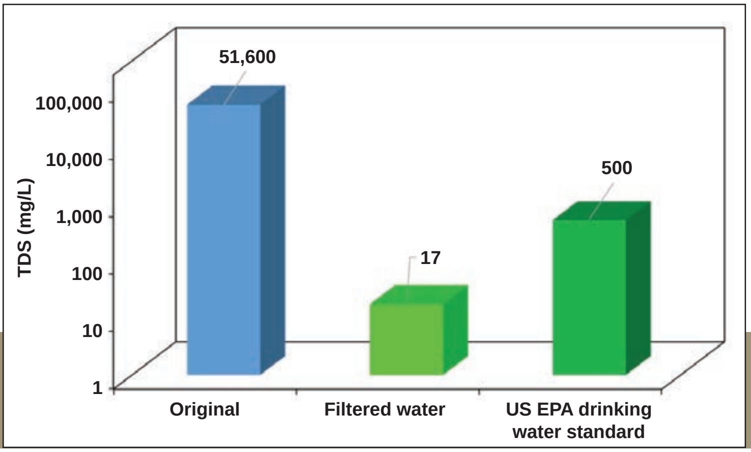


Figure 28. Tests on the filtration system successfully removed salts. Well water with a total dissolved solids (TDS) concentration of 51,600 mg/L was run through the system and resulted in filtered water with 17 mg/L TDS, about 30 times lower TDS than the U.S. EPA limit for drinking water.

Figure 29. NMBGMR hydrologist Ethan Mamer trains NTU student Malynndra Tome to conduct water sampling at a well in the Navajo Nation. *Photo by Laila Sturgis*

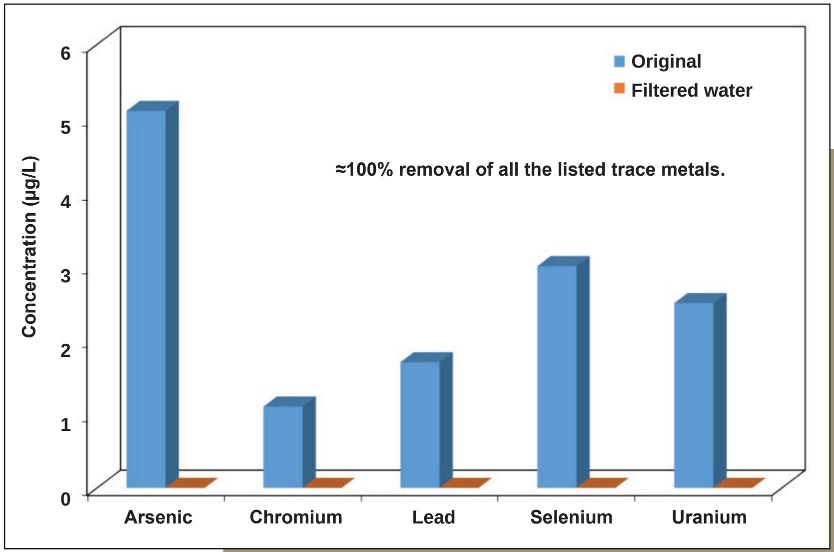


Figure 30. Well water with TDS of about 350 mg/L was run through the system. The result showed that the system can significantly lower trace metals, such as arsenic, chromium, lead, selenium and uranium, in relatively clean well water.

The team conducted an additional test in November 2021 to see how well the system removes metals, even at low levels, from samples and to begin training students in water sampling (Fig. 29). Although the water from the well already met U.S. EPA regulations for municipal waters, the test showed that the system could remove almost 100% of trace elements (Fig. 30).

During operation, the membranes are loaded in PVC piping, and hot source water is circulated around the membranes (Fig. 31). Cool filtered water is run through the membranes. The vapor pressure of the hot source water pushes water through the membrane walls to the cool solution within the membrane pores, leaving salts and metals in the hot waste stream. The clean water is collected in a tank where its conductivity is measured to verify system quality. Because of the high output, low scaling tendency, and minimal power required for water heating, cooling, and monitoring control, the system is low-cost to operate and maintain and can be skid-mounted for ease of installation. These features are valuable for installation in remote locations. A pilot-plant installation is underway near Farmington this year.

To read more about water issues on the Navajo Nation and throughout the country, please see the 2011 report from the Navajo Nation Department of Water Resources (Strategy Document) and the 2019 report from the non-profit organizations Dig Deep and U.S. Water Alliance (Close the Water Gap).

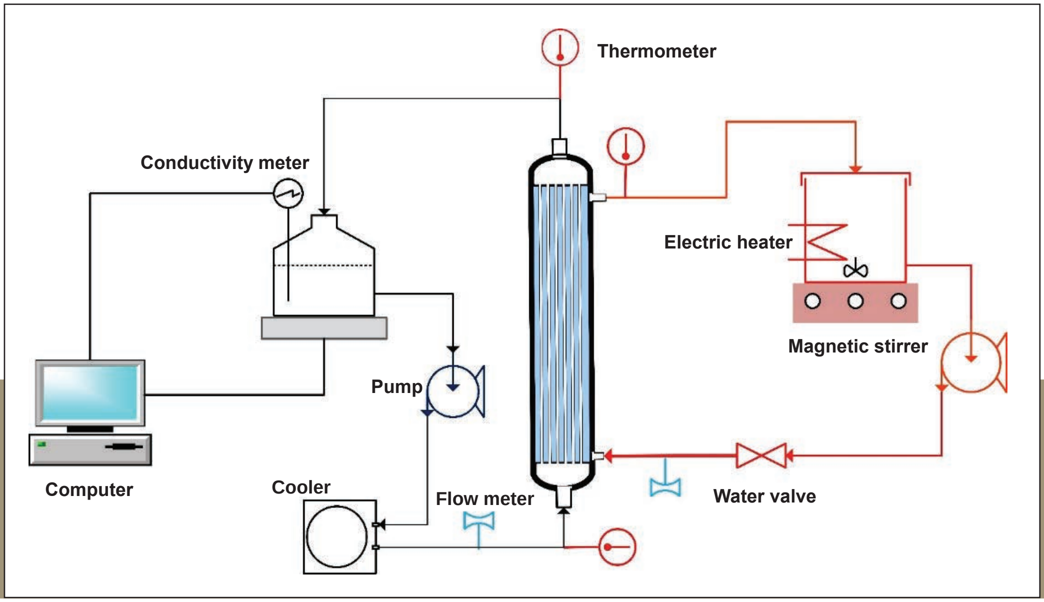


Figure 31. Schematic of the filtration system. Also called desalination, this system runs the hot source well water through the central tube on the outside of the membranes. Cold purified water is run through the membranes. The vapor pressure of the hot source water forces water through the membranes to the inside of the membranes, increasing the volume of the total purified water and leaving the salts and other contaminants in the hot water flow. The clean water is collected in a tank where its conductivity is measured until the water is used.

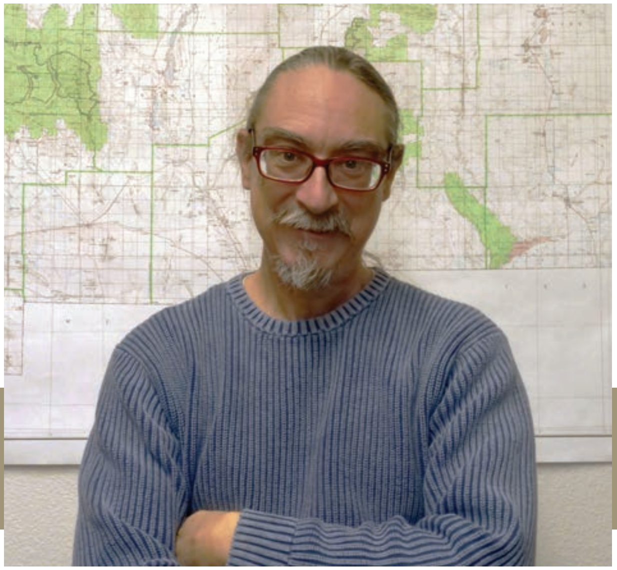
Through the Hand Lens with Talon Newton

What is your educational and professional background?

I obtained a BS in geology and an MS in hydrology from New Mexico Tech (NMT) in 2001 and 2004, respectively. In 2004, I moved to Belfast, Northern Ireland, to work on my PhD at Queen's University, Belfast. I stayed there for 2 years and completed my fieldwork and lab work. In 2006, I moved back to Socorro, New Mexico, where I worked at Hydrosphere, an environmental consulting firm, for a year. The NMBGMR offered me a full-time job in the fall of 2007, and I have been with the Bureau ever since. In 2013, I finally finished my PhD dissertation and got my PhD in civil engineering (YAY!). At NMBGMR, I enjoy my job as a hydrogeologist doing water research in New Mexico.

What inspired you to become a geoscientist?

From a very young age, I wanted to be a scientist when I grew up. I thought scientists were really cool and smart. After graduating high school, I went to NMT and started as an astrophysics student. Well, I quickly realized that astrophysics is HARD and that I liked rock climbing better than going to class. So, after a couple of semesters, I dropped out and moved to Albuquerque, New Mexico, where I worked several random customer service jobs mainly to fund my recreational activities, which included hiking, rock climbing, and cave exploration. My hobbies introduced me to geoscientists, who studied the rocks that I climbed and the caves that I explored. In 1998, I decided to go back to school and ended up pursuing a degree in geology. Studying geology really gave me a new perspective on the world. I was fascinated by the processes that slowly (over billions of years) formed the world as we know it and how the resulting landscapes and environments ultimately affect where and how we live our lives. Everything we do in life (where we live, our technology, architecture, culture, and more), believe it or not, is related to geology! After I got my BS in geology, I decided to continue my education, focusing on groundwater hydrology and chemistry because water resources are extremely important, especially as the global population grows and we experience the pressures of climate change. As with everything else, when evaluating a hydrologic system (including groundwater occurrence, flow directions, flow velocities, and water chemistry), it always comes down to the geology!



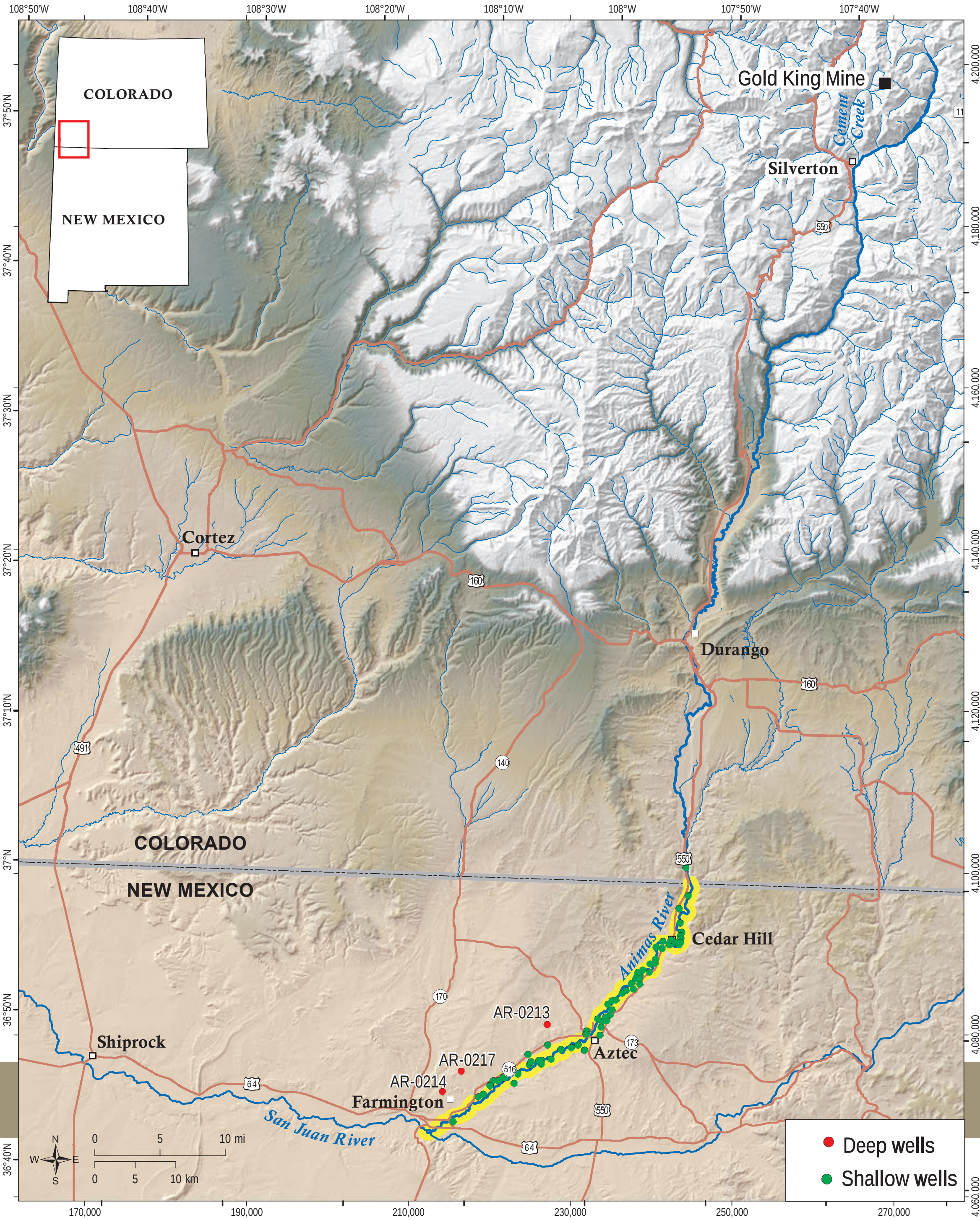
Talon Newton, hydrogeologist at the NMBGMR. *Photo by Cynthia Connolly*

What are you most proud of professionally?

My work mostly focuses on increasing our knowledge about water resources in New Mexico. While rivers such as the San Juan, the Rio Grande, and the Pecos do provide significant water supplies for many residents in New Mexico, groundwater is an important resource and is used for everything, including domestic, agricultural, municipal, commercial, and industrial uses. And with future projections of a significant decrease in surface water supplies due to climate change, the importance of groundwater as a resource will only increase. Therefore, it is important to understand how precipitation (rain and snow) ultimately makes its way from the high mountains to the basins at lower elevations, where we can pump it and use it. This is a very difficult job in a state like New Mexico due to the complex geology. The good news is that science builds on itself over time. For the many different hydrogeology studies that I have been involved with, we utilize existing information about the systems from previous researchers, and we collect new data to improve our conceptual models of the hydrologic systems in different areas of the state. This additional data and increased knowledge about these complex systems is being used by many different people, such as scientists, water planners, environmental consultants, farmers, and many others to create better hydrologic models, better manage our future water resources, provide clean water to New Mexico residents and wildlife habitats, and make informed decisions about how we use this precious resource. I feel that my job affects real people and their lives. I am very proud to be part of this scientific process.

Describe the work you have done in the San Juan Basin related to the Gold King Mine spill.

On August 5, 2015, the accidental breach of the Gold King Mine located in the Silverton Mining District, Colorado, resulted in the movement of millions of gallons of bright orange water through the Animas River in northwestern New Mexico, feeding into the San Juan River near Farmington (Fig. 32). The water was loaded with dissolved metals and contaminated sediments, which posed a possible risk to people and the environment downstream. As part of a collaborative effort by multiple federal and state agencies to assess potential downstream impacts of the spill, researchers from the NMBGMR conducted a study that focused on potential adverse impacts to the quality of shallow groundwater adjacent to the Animas River. Many residents in local communities, including Cedar Hill, Aztec, Farmington, and parts of the Navajo Nation, use this water for domestic and agricultural purposes. This was a difficult task because there were very few water chemistry data



to provide information about the chemical composition of the groundwater before the spill. We measured the depth to water from many existing domestic wells in the area to figure out the direction of groundwater flow and specifically whether the Animas River gained water from the shallow aquifer (conditions referred to as "gaining river") or water from the river recharged the shallow aquifer. The good news is that the Animas River is usually gaining water from the aquifer along this reach. This means that it is unlikely that contaminated water in the river actually flowed into the aquifer. However, there was evidence that in some specific areas, under specific flow conditions, water from the river could potentially flow into the aquifer. We also collected many water samples from domestic wells and analyzed them for different chemical constituents, including potential contaminants from the Gold King Mine spill (iron, aluminum, manganese, lead, copper, arsenic, zinc, cadmium, and mercury). With the exception of iron and aluminum, these contaminants of concern were all found to be well under U.S. EPA health standards.

Ultimately, we found no evidence of adverse impacts to groundwater from the Gold King Mine spill. Groundwater/surface water interactions (i.e., river gaining water from groundwater) do not favor groundwater contamination from river water, and most contaminants of concern were not observed at high levels in the groundwater. The elevated concentrations of iron and manganese were found to not be related to the spill, as they occurred in this system naturally. This study also allowed us to characterize the hydrogeologic system and gain a much better understanding of it. For example, we identified a natural increase in sulfate concentrations along the groundwater flow path due to deep groundwater being forced into the shallow system because of the local geologic structure and variations in the ability of water to move through the underlying rocks. Again, it always comes down to the geology!

Figure 32. Our study focused on the reach of the Animas River outlined in yellow, from the Colorado/New Mexico state line to Farmington.

About

New Mexico Bureau of Geology and Mineral Resources

Hours, excluding New Mexico Tech holidays, are:

Monday through Friday, 9 am to 5 pm
Saturday and Sunday, 10 am to 3 pm

Founded in 1927, the New Mexico Bureau of Geology and Mineral Resources in Socorro, New Mexico, is the New Mexico state geologic survey. We are a research and service division of the New Mexico Institute of Mining and Technology, serving New Mexico through a wide range of geologic and hydrologic mapping, research, and analytical services, as well as educational and outreach activities. *Photo by Frank Sholedice*

Mineral Museum

The Bureau's mineralogical collection contains more than 16,000 specimens 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. We like to show off our home state's minerals, as well as give students an idea of how minerals end up in products we use every day. For teachers, students, and other groups, we offer free tours of the museum. Museum staff can also identify minerals or rocks for visitors. Please call ahead to ensure someone will be available. For more information on the museum, please visit our website: geoinfo.nmt.edu/museum

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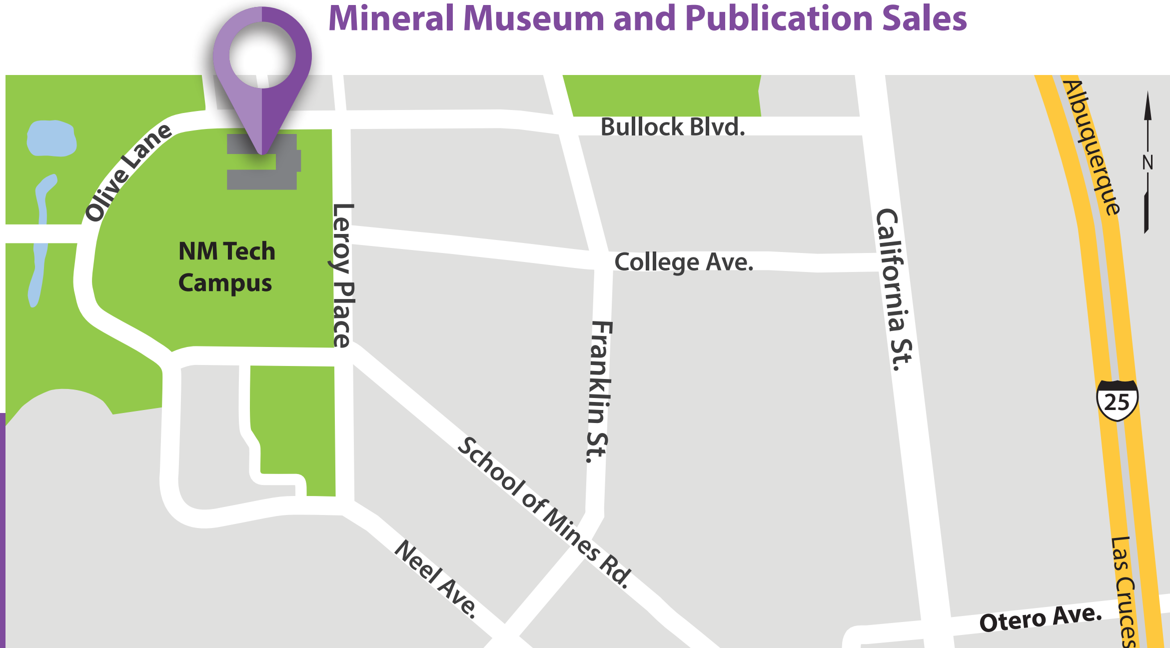
New Mexico Bureau of Geology and Mineral Resources Mineral Museum and Publication Sales



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