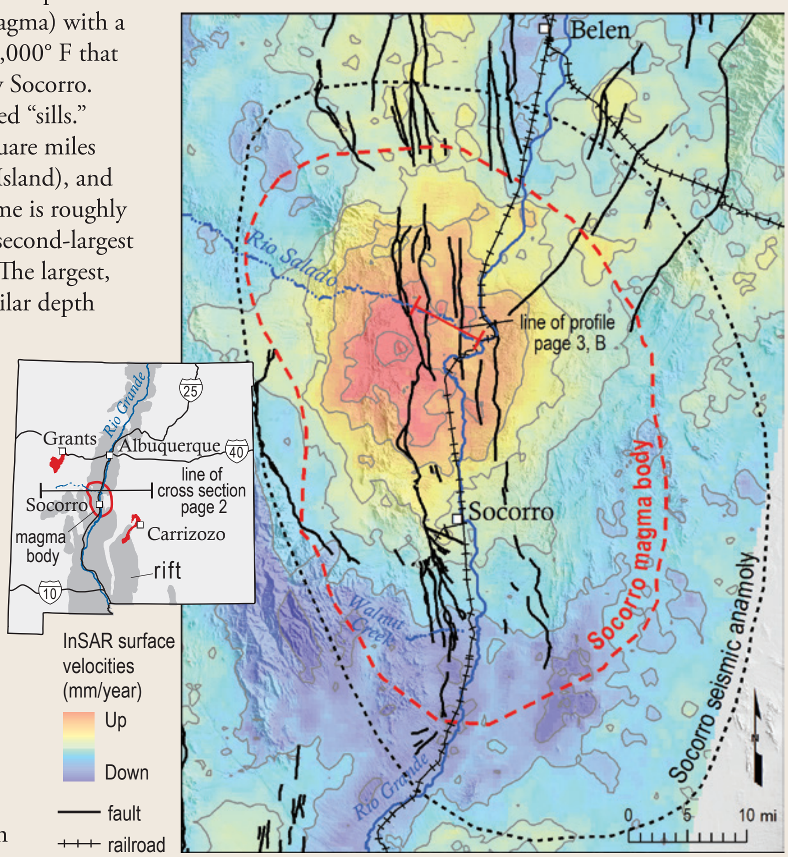
New Mexico
EARTH
MATTERS

WINTER 2019

The Socorro Magma Body

New Mexico is famous for its magnificent and diverse landscapes and geological features. However, one of the most unusual geological features in the state is not directly observable at the surface—the Socorro magma body. The magma body is a pancake-shaped mass of molten rock (magma) with a temperature of approximately 2,000° F that is situated about 12 miles below Socorro. Such flat magma bodies are called "sills." With an area of about 1,300 square miles (larger than the state of Rhode Island), and a thickness of 400 feet, its volume is roughly 130 cubic miles, making it the second-largest magma body known on Earth. The largest, in South America, rests at a similar depth and has a volume of about 1,200 cubic miles. Most magma bodies are shallower and smaller, typically only a few miles deep, with volumes of less than a few cubic miles. For comparison, the recent volcanic eruptions of Mount St. Helens and Pinatubo discharged magma volumes of less than one cubic mile. Because of its size and geologic setting, the Socorro magma body may be both a volcanic hazard and an earthquake hazard.

The magma body lies within the central Rio Grande rift, a massive geologic feature that splits New Mexico from south to north. The rift formed by east-west, tectonic extension and thinning of Earth's crust and relatively rigid upper mantle during the last 25 million years. The crustal thinning has allowed hot mantle to rise, decompress, and melt below the rift, thus generating the molten rock of the magma body (and many of the state's young volcanoes).

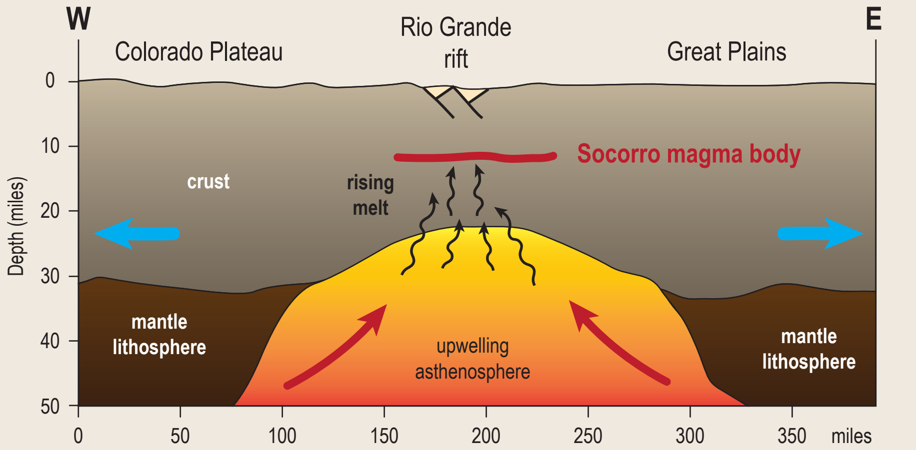


Shaded relief map of Socorro region showing outlines of Socorro magma body and Socorro seismic anomaly. The map also shows the locations of railroad tracks, the Rio Grande and Rio Salado, major faults of the Rio Grande rift, and the location of terrace profiles on page 3. The colors show changes in distance between "interferometric synthetic aperture radar" (InSAR) satellites and land surface over about 20 years. The orange-colored bullseye over the magma body represents the uplift of the land due to inflation of the magma body below. The small inset map shows the Rio Grande rift (gray color), the Socorro magma body (red outline), the young Grants and Carrizozo lava flows (red shapes), and the location of cross section on page 2.

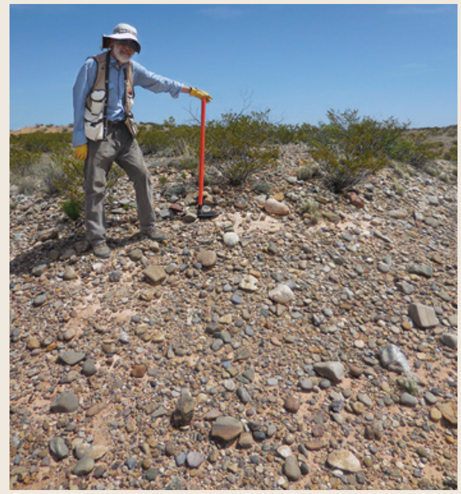
The Discovery

The discovery of the Socorro magma body is a marvelous tale of geophysical sleuthing that began in the 1960s by Dr. Al Sanford, a former New Mexico Tech professor of seismology, and his graduate students. The Socorro area experiences many small earthquakes, most of which are too small to feel, but they can be detected by seismometers. Professor Sanford wondered about this zone of microearthquakes, which he named the "Socorro seismic anomaly."

To better understand the earthquake swarm, Sanford's team placed seismometers around the Socorro region. They found that the earthquakes occur between 1 and 10 miles depth. However, some seismometers recorded unusual seismic waves that arrived after the direct seismic waves from the earthquake, which piqued Sanford's curiosity. Studying these seismic waves led his team to two key conclusions: 1) the late-arriving seismic waves were reflections from a mysterious layer below the earthquakes; and 2) the reflective layer was liquid—an unexpected result. By determining many locations for the points of seismic wave reflection, they were able to map the lateral extent of the



Schematic, west-east, geologic cross section, showing the position of the Socorro magma body in the middle of Earth's crust. The magma body is only 400 feet thick, but is 12 miles below the surface, so its thickness is exaggerated in the figure. The body lies below the Rio Grande rift, which is extending in a west-east direction, as shown by the horizontal arrows. Hot, upwelling asthenosphere (curved red arrows) erodes the mantle lithosphere, a small fraction (1–2 percent) of which melts and percolates upward (wiggly black arrows), periodically inflating the magma body, and causing earthquakes and surface uplift. For the location of this section, see figure on page 1.



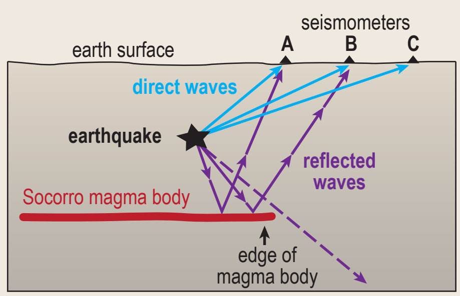
Geologist Dave Love standing on the eroded edge of an ancient river terrace along the Rio Salado. This terrace is older than those discussed in this paper, but a nearby terrace yielded a cosmogenic isotopic age of about 26,000 years.

liquid body. And, because the only possible liquid layer to exist at such depths is molten rock, presto, the Socorro magma body was discovered!

Geologically, most magma is short lived, rising buoyantly from where it melted to areas of lower temperature, where it cools and quickly solidifies into rock. Therefore, the Sanford team had captured, in time, a rare geologic feature that was well worth studying.

Other magma bodies are known to cause deformation of Earth's crust, usually observed as uplift of the land's surface, due to injection of new magma into the magma body, similar to inflating a balloon. In the 1970s, geologists from Cornell University wondered if the Socorro magma body had caused uplift of the land. At that time, the best way to study this was to precisely resurvey railroad grades that were accurately surveyed in the early 1900s when benchmarks were established. This so-called "releveling" showed that the land above the Socorro magma body had risen as much as about 6 inches since the early 1900s, yielding an average rate of uplift about 1/8 inch per year. This seems slow on a human time scale, but is racing compared to most geological movements.

More recently, scientists from Scripps and Caltech studied the surface uplift with satellite-based "interferometric synthetic aperture radar" (InSAR). InSAR precisely measures the distance between Earth's surface and the satellite, using travel times of radar pulses (which travel at the speed of light) transmitted from satellites and reflected back from Earth. By comparing results from several satellite passes over about 20 years, they confirmed that much of the Socorro area is rising at a rate of about 1/8 inch per year.



Idealized, vertical cross section showing seismic wave paths and reflection points that allowed early researchers to discover the depth and edge of the Socorro magma body.

New Mexico Tech Research

The discovery raised more fascinating questions than it answered.

1) What is the age of the Socorro magma body?
2) How did it evolve? Is it a "one-shot deal" or is magma injection long-lived and geologically persistent? Was magma injected continuously or episodically?
3) What exactly causes the surface uplift above the magma body?
4) What causes the earthquakes above the magma body?

The answers to such questions are important for understanding hazards related to volcanic eruptions and earthquakes. Answers are emerging from recent work by New Mexico Tech geologists who have been analyzing the uplift of the land surface and developing computer models of the magma body.

How old is the magma body?

The team at New Mexico Tech has mapped and obtained ages of river terraces along two rivers that cross above the Socorro magma body, the Rio Grande and the Rio Salado. River terraces are preserved remnants of flood plains abandoned during river down-cutting episodes, which can happen when sea-level drops or when Earth's surface uplifts (such as above magma bodies). These ancient river terraces are normally flat. So when high-precision, elevation measurements showed that some of the terraces are arched, the research team suspected that the Socorro magma body was responsible. So, if they could determine the ages of the terraces, they could begin to bracket the age of the magma body.

River flood plain ages can be calculated from "cosmogenic isotopes" present in minerals in the sediment. Such isotopes form near the land surface where soil and sediments are bombarded by cosmic rays. The cosmic rays interact with the minerals to create trace amounts of radioactive isotopes such as chlorine-36, which build up over time. Old river terraces have accumulated more of these cosmogenic isotopes than young river terraces, because the "cosmogenic clock" is "set" when the river floodplain is formed. Therefore, by carefully measuring cosmogenic isotopes in specific locations, the age of the river terrace can be calculated.

The team's findings were striking. The lowest (youngest) Rio Salado terrace is about 3,000 years old and not arched. In contrast, the next higher terrace (about 26,000 years old) is arched about 26 to 40 feet over a 15 mile length above the Socorro magma body. Higher, the older (up to about 600,000 years) Rio Salado terrace remnants appear to have been tilted along with the 26,000 year-old terrace, but apparently were not arched separately. From this, the New Mexico Tech team concluded that the Socorro magma body has inflated at least twice, somewhere between 26,000 and 3,000 years ago, and again in a modern uplift event of up to 6 inches in the last century, that was documented by the railroad releveling project done in the 1970s and more recent satellite measurements.

What causes the earthquakes?

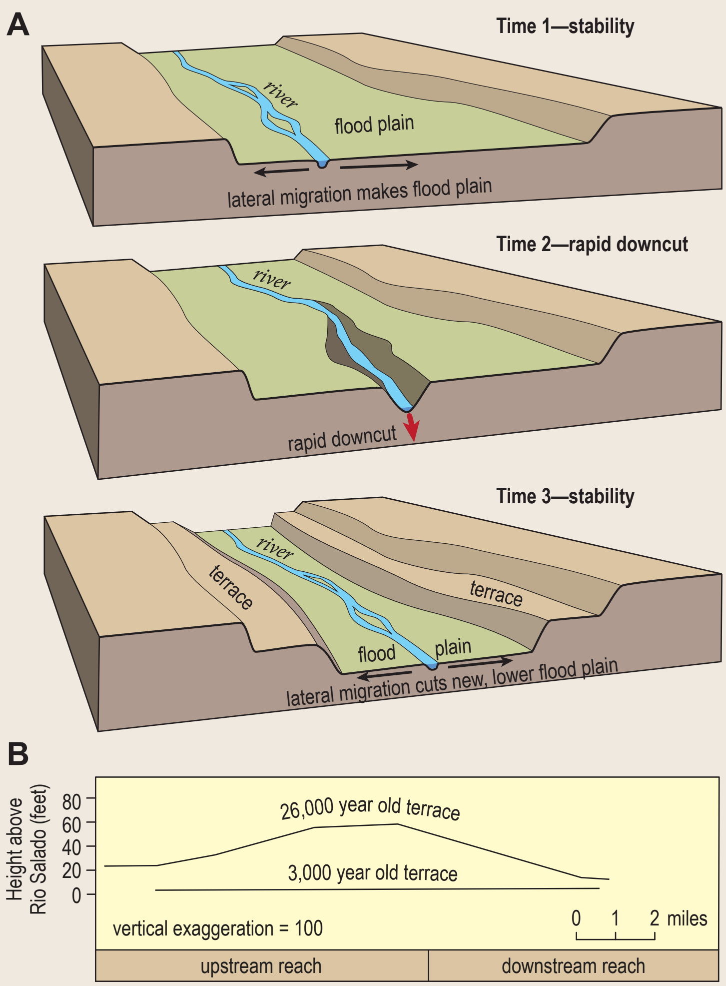
The New Mexico Tech team also developed computer models to study the earthquake activity above the Socorro magma body. The models used elastic (spring-like) rock properties and conductive heat flow to calculate how the crust deforms as a result of magma being injected into the body.

Earthquakes associated with the Socorro magma body occur mainly on buried faults along the Rio Grande rift. They are clustered in both space and time. Most researchers have assumed that these earthquakes were triggered by an increase of the fluid pressure in rock pores due to heat-driven, fluid circulation above the magma body, but this is not proven. As a result of the high fluid pressures in the rock pores, the faults in the crust above the Socorro magma body would "slip" easily, causing an earthquake. This pore-fluid pressure effect is explained in more detail in the text box on page 4.

The computer models provide insights into why earthquakes occur some distance above the magma body. In this "seismogenic zone" (where earthquakes occur), the crust is brittle, and relatively cool (less than 575° F). Generally, the maximum depth of earthquakes is controlled by downward-increasing temperature and pressure in the crust. Increases in temperature and/or pressure inhibit fault slip, and therefore inhibit earthquakes. Pressure increases downward, and so when pressures are high, faults do not slip. This is a similar effect to sliding an empty versus full chest over carpet, in which the empty chest slides more easily. Simultaneously, downward-increasing temperature causes rocks to become weak and "mushy," favoring rock deformation in a ductile manner (flowing, rather than breaking), rather like smearing a warm chocolate bar instead of breaking a cold one.

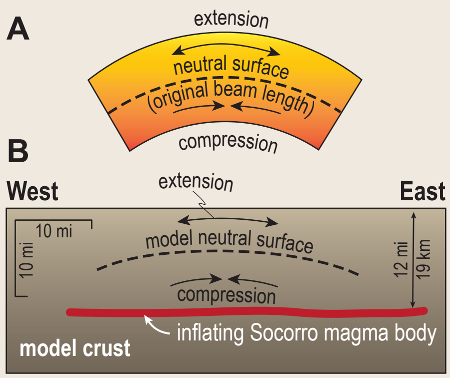
The computer models show that arching of the crust above the inflating Socorro magma body stresses the crust, triggering earthquakes, and that the earthquakes should occur above the magma body, just as Professor Sanford deduced in the 1960s. Injection of magma into the Socorro magma body arches the crust, like flexing a beam. When a beam bends, the convex side of the beam lengthens, generating tensile (pull-apart) forces. The concave side shortens, generating compressive forces. Both types of forces decrease toward the center of the beam, reaching zero along a "neutral surface" there.

In the computer model, this neutral surface is subhorizontal and at about 10 miles depth, exactly where the deepest earthquakes occur above the Socorro magma body. It appears that the east-west, tensile stresses in the crustal beam cause the faults to slip, resulting in earthquake swarms. Below the neutral center of the crustal beam, east-west, compressive stresses will "clamp" faults and inhibit them to slip. This explains why no earthquakes occur in the 2-mile-zone between 10 miles



(A) *Sequential, schematic block diagrams that illustrate the process of river terrace formation from flood plains developed during times of river stability. Each time the river downcuts, a river terrace may be preserved. If these terraces are age dated, such as by using cosmogenic isotopes, geologists may be able to reconstruct the history of downcutting.* ***(B)*** *Transect parallel to the Rio Salado showing heights of the lowest two terraces above the modern floodplain. The lowest terrace (approximately 3,000 years old) is not recognizably arched, suggesting that there has not been much surface uplift in the last 3,000 years. However, the next older terrace (approximately 26,000 years old) is arched by about 26 to 40 feet, suggesting that there has been major surface uplift between about 26,000 and 3,000 years ago.*

of depth and the top of the magma body at 12 miles depth. The computer models also show that arching of the crust above the Socorro magma body is the result of magma injection. This means that as long as the land surface around Socorro continues to rise, the magma body is being actively injected with magma, and earthquakes will continue to occur.



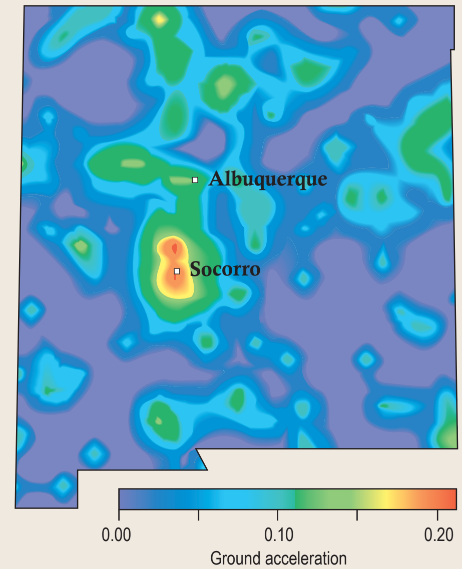
Flexure of the crust above the Socorro magma body. ***(A)*** *Schematic diagram of a theoretical "flexed beam" showing the neutral surface, with zones of extension above and compression below. The curvature of the beam is greatly exaggerated in the drawing.* ***(B)*** *A mathematical model of the forces in the crust indicates that above the Socorro magma body there should be similar "flexed beam" conditions of extension in the upper crust and compression in the lower crust. Therefore, as the magma body inflates by the injection of more magma, the crust above bends—like the "flexed beam"—generating earthquakes in the uppermost crust and uplift of the land surface.*

Implications for Earth Science Research

The Socorro magma body is fun to work on because it is unique—the only known magma body of its kind in the U.S. Good earth-science research, however, has relevance beyond the local study. How geologically unique is the Socorro magma body? Well, globally, mid-crustal rocks that are now exposed at the surface show that igneous bodies like the Socorro magma body are fairly common, but most are simply old and have solidified. It is difficult or impossible to address the types of questions posed above using such ancient, fossilized, magma bodies, so study of an active magma body can greatly advance our understandings of earthquake risks, surface uplift, and magma intrusion processes.

Is the Magma Body a Geologic Hazard?

Does the Socorro magma body pose a volcanic eruption hazard? This is a difficult question to answer with certainty. The magma probably has a basalt composition, similar to basalt flows that erupted near Grants and Carrizozo about 3,000 to 5,000 years ago, so it could potentially feed a modern eruption. Such an eruption might be non-explosive, like most Hawaiian eruptions, locally damaging in the path of flows, but not catastrophically explosive. However, if the rising magma were to encounter groundwater (such as beneath the



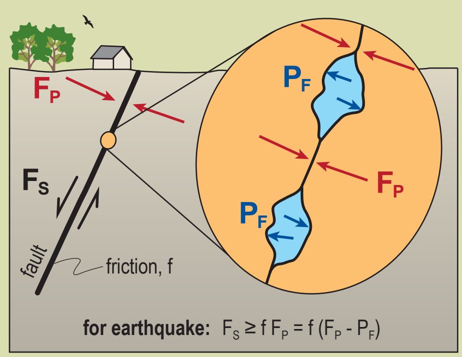
This probabilistic seismic hazard map of New Mexico shows the expected distribution of ground motion from earthquake activity. The Socorro seismic anomaly clearly has the highest level of seismic hazard in the state. The abnormally high number of historic earthquakes is attributed to inflation of the Socorro magma body.

Rio Grande), then an explosive, steam-driven eruption might occur. The relatively great depth of the Socorro magma body and the absence of directly overlying, geologically young, eruptive centers argue against a high eruption hazard. Eruption forecasting, like weather forecasting, is most accurate over weeks to days, because it is based mainly on being able to detect increased seismicity with

Earthquakes and Fluid Pressure

Between earthquakes (during the "interseismic period"), most crustal faults do not slip, because they are frictionally locked (although some faults "creep" slowly and steadily without earthquakes). During the interseismic period, tectonic shear force parallel to the fault builds steadily due to slow tectonic motion. Very rapid fault slip during an earthquake rapidly releases the shear force, shaking the surrounding region. "Interseismic shear force" is stored elastically in rocks surrounding faults, like a compressed spring, but is three-dimensional.

An earthquake starts when "shear force" (F_S) parallel to the fault exceeds the product of friction times the force perpendicular to the fault (F_P). However, F_P is counteracted by "pore-fluid pressure" (P_F). In essence, the perpendicular "clamping" force is opposed



Schematic cross section of a rift-related fault, illustrating the mechanical effect of pore-fluid pressure (P_F) in triggering earthquakes. The enlarged detail shows that pore-fluid pressure (P_F) counteracts the clamping effect of fault-perpendicular force (F_P), which works with friction against slip. Therefore, earthquakes can be triggered by increases in pore-fluid pressure alone, although our model results suggest that inflation-related flexure of the crust above the magma body may also be a cause.

and reduced by the pressure of fluids within the rock. Thus, a P_F increase can trigger earthquakes if sufficient shear force has accumulated.

Most experts assume that P_F increases locally and temporarily above the Socorro magma body when heated pore-fluids flow or expand, triggering earthquakes. Similarly, P_F increase is the main cause of "induced seismicity" that occurs when unwanted water—such as is pumped out of the ground along with petroleum—is disposed of by pumping it too rapidly into deep wells, increasing the pore-fluid pressure and triggering earthquakes. A common misconception is that hydraulic fracturing ("fracking") of oil-production wells causes earthquakes, but these are exceedingly rare.

characteristics indicating subsurface magma movement. As long as the Socorro seismometers operate, any rising magma will hopefully be detected before it reaches the surface!

Does the Socorro magma body pose an earthquake hazard? Yes, it does. However, estimating seismic hazard is difficult and imprecise, and regional deformation rates and the earthquake history must be considered. Frequent, small earthquakes above the magma body suggest that the Socorro region has increased risk of a damaging earthquake relative to many other parts of New Mexico. Large earthquakes release much, but not necessarily all, of this slow, tectonic force build up. Thus, in order to evaluate earthquake hazard, the geologic record of large earthquakes must be compared to the rate of force accumulation, which is a difficult task—similar to weather forecasting—but with much less information. The small earthquakes that are common above the Socorro magma body do not relieve much force.

The Rio Grande rift is actively extending east-west, but slowly, at less than about 1/25 inch per year (compared to the approximately 1 inch per year slip rate of California's San Andreas fault). Damaging earthquakes are rare in New Mexico, although, interestingly, the most recent was near Socorro in 1906, and was perhaps triggered by inflation of the Socorro magma body. However, geologists believe that the recurrence interval for such earthquakes may be thousands of years. Thus, it is possible (but not certain) that the 1906 earthquake relieved enough tectonic stress that Socorro may be safe from earthquakes for a while.

—Gary Axen, Jolante van Wijk, Fred Phillips, Bruce Harrison, Brad Sion, Shuoyu Yao (Department of Earth and Environmental Science, New Mexico Tech), Dave Love (New Mexico Bureau of Geology and Mineral Resources)

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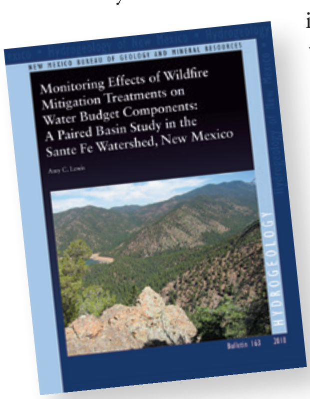
New Publications

Free Reports and Maps!

Almost all of our technical monographs (bulletins, circulars, and memoirs) are now available for free download, including our 2018 bulletin on aquifer lifetime projections for east-central New Mexico (Bulletin 162). Plus, most of our Geologic Maps (GM and OF-GM series), Resource Maps, and Hydrologic Sheets are now also free.

Bulletin 163—Monitoring effects of wildfire mitigation treatments on water budget components: a paired basin study in the Santa Fe watershed, New Mexico

A paired basin study in the Upper Santa Fe River watershed following forest restoration has successfully measured water budget components in a treated and an untreated (control) basin. The paired basin study was established to investigate questions that have arisen with regards to changes in water yield from forest treatments.



The chloride mass balance and water budget equations force agreement in the water budget components, and thus, the integration periods that consider the cycling of chloride through each basin will impact the estimated evapotranspiration and recharge rates. The results from nine years of data collection and analysis show that evapotranspiration, while greater in the treated basin than the control before and after treatments, appears to be declining in the treated basin. An increase in streamflow in the treated basin is only evident in years with a greater percentage of winter precipitation.

Mount Taylor Puzzle

The geologists who recently mapped Mount Taylor have solved the geologic puzzle! Can you? This vibrant 19 x 27 inch, 1,000-piece puzzle version of our-soon-to-be released geologic map of Mount Taylor (expected 2019) will keep you geologically entertained.

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Bureau News

Virginia McLemore (right) and Stacy Timmons receive the Mankin Award in Indiana.

Memoir 50 Wins National Award

The Association of American State Geologists awarded *Energy and Mineral Resources of New Mexico* (Memoir 50/Special Publication 13) the annual Charles J. Mankin Memorial Award at the Geological Society of America conference. The award is given to a map or report by a state geological survey. The award is named for Charlie Mankin (1932–2012), who served as Director of the Oklahoma Geological Survey for 40 years.

Published jointly by the New Mexico Bureau of Geology and Mineral Resources, and the New Mexico Geological Society, the series was edited by Virginia McLemore, Stacy Timmons, and Maureen Wilks. The boxed set of six volumes provides a modern summary of New Mexico's energy and mineral resources. Written by New Mexican experts, the chapters cover oil, natural gas, coal, uranium, metals, industrial minerals and rocks, and the Valles Caldera geothermal system. Each volume traces the geology, history of development, and economic importance of the resource.

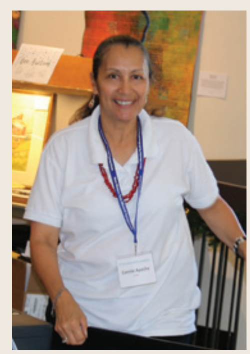
The Mineral Museum Wins at Denver Gem & Mineral Show

The Mineral Museum took the top prize in the museum display category at the 2018 Denver Gem & Mineral Show, the second largest show in the U.S. Each year, the show hosts nearly 100 exhibits that are constructed by curators, collectors, and prospectors. The show theme was "*Minerals of Mexico*."

The winning display of Mexican minerals.

The Mineral Museum in Socorro, on the campus of New Mexico Tech, contains a spectacular collection of over 18,000 specimens from all over the world, including gems, gold, silver, agates, geodes, meteorites, petrified logs, and much more. Museum hours are 9 to 5 Monday thru Friday, and 10 to 3 Saturday and Sunday.

Connie Apache Awarded New Mexico Geological Society Honorary Membership



Each year, the New Mexico Geological Society recognizes an individual who, over the years, has made extraordinary contributions to the society, and presents the person with a lifetime honorary membership. This year, Connie Apache, the administrative services coordinator at the New Mexico Bureau of Geology and Mineral Resources, was the awardee. Congratulations, Connie, on this well-deserved honor!

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