New Mexico
EARTH
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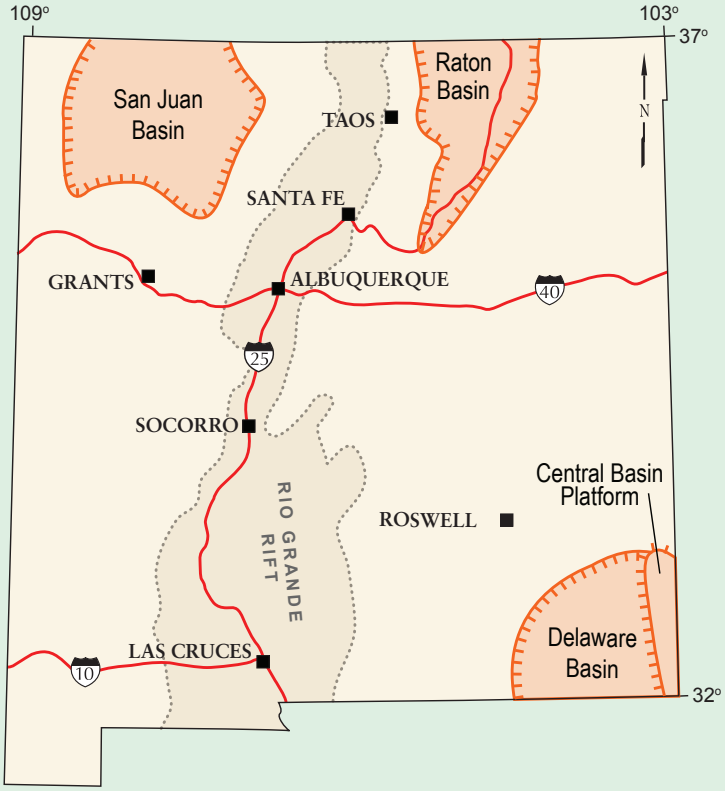
Induced Seismicity in New Mexico

New Mexico experiences moderate levels of earthquake activity, primarily because of extension along the Rio Grande rift, a large, fault-bounded geologic valley that runs north-south through the center of the state. Geologic studies of ancient earthquakes (known as paleoseismology) show that earthquakes as large as magnitude 6.5 (M6.5) or larger have occurred along the Rio Grande rift within the past several thousand years, and smaller earthquakes of M2.5–3.5 take place in various parts of the state every year. The highest concentration of naturally occurring earthquakes is near the Socorro Magma Body, where a M6.2 earthquake occurred on November 15, 1906. This was the largest historic earthquake in New Mexico and it damaged several buildings in Socorro.

Although there is a long history of naturally occurring seismicity in New Mexico, increasing numbers of earthquakes have been observed over the past several years in some parts of the state that did not experience much seismic activity in the past. These earthquakes are believed to be associated with human activities rather than tectonic or magmatic forces, and are referred to by the term "induced seismicity." Even though most induced earthquakes are too small to be felt by humans, or to cause any damage, in some places around the world induced earthquakes have damaged buildings and infrastructure. This has led to the installation of new monitoring stations in many areas to better understand the causes of induced seismicity and to minimize its risk.

What is Induced Seismicity?

Induced seismicity refers to an earthquake that is generated by human activity. Induced seismicity can be triggered by underground injection and/or withdrawal of fluids, by loading of water onto Earth's surface (for example, filling a reservoir), or by explosions from mining. Induced seismicity has been of increasing concern as humans develop new ways to use Earth's resources, including new methods of petroleum production, coalbed methane extraction, geothermal energy development, and carbon sequestration.



Map of the major oil/gas-producing basins and Rio Grande rift in NM.

Earthquakes result from the energy released when two sides of a geologic fault slide past one another. The reason that faults slip is because the shear stress along the fault plane becomes large enough to overcome the friction holding the fault in place.

Two common human activities that can affect the subsurface stress state and have been linked to induced seismicity are hydraulic fracturing (or "fracking," a technique for fracturing petroleum reservoirs to increase oil and gas production) and wastewater disposal. Fracking involves injecting fluids at high pressure for short periods of time, whereas wastewater disposal involves injecting fluids at lower pressure for longer periods of time. Both processes can cause induced seismicity, but fracking-induced earthquakes typically occur soon after the activity, whereas injection induced earthquakes can occur over longer timescales.

Induced seismicity is not a new phenomenon. One of the earliest observations of induced seismicity occurred in the 1920s at the Goose Creek oil field, where the earthquakes were attributed to pumping fluids out of the ground. In the 1960s, subsurface disposal of fluid at the Rocky Mountain Arsenal in Colorado triggered hundreds of earthquakes large enough to be recorded, with the largest being a M4.8. In other locations, seismicity was suspected to be induced, but it was not proven due to lack of sufficient monitoring. With improved monitoring, a clear correlation between

earthquake-causing human activities and rises in earthquake activity can be established.

The number of induced earthquakes has increased significantly in recent years. Beginning around 2008, increases were noticed in Texas, Oklahoma, Ohio, Canada, and Italy near areas where hydraulic fracturing or wastewater disposal was occurring. The most notable increase was in Oklahoma, where over 800 earthquakes larger than M3.0 were recorded in 2015, an increase from only one event in 2005. The largest earthquake recorded in Oklahoma was a M5.8 in 2016 in Pawnee that caused damage to some structures. Since 2015, the rate of induced seismicity in Oklahoma has significantly declined, with only 36 events greater than M3.0 recorded in 2020.

This decline is likely due to the combined efforts of regulators and industry to significantly decrease the amount of fluid injected into the deep formations believed to be the most responsible for induced seismicity. While early concern about induced seismicity focused on earthquakes caused by fracking, it is now understood that the majority of induced earthquakes are associated with subsurface fluid disposal. Not all wastewater wells trigger earthquakes. Factors such as the properties of the rocks at depth, fluid injection rate, preexisting stress state, and proximity to faults can all affect whether earthquakes will occur in a particular area. Better understanding these factors allows well placement in areas that are less likely to cause seismicity.

Induced Seismicity in New Mexico

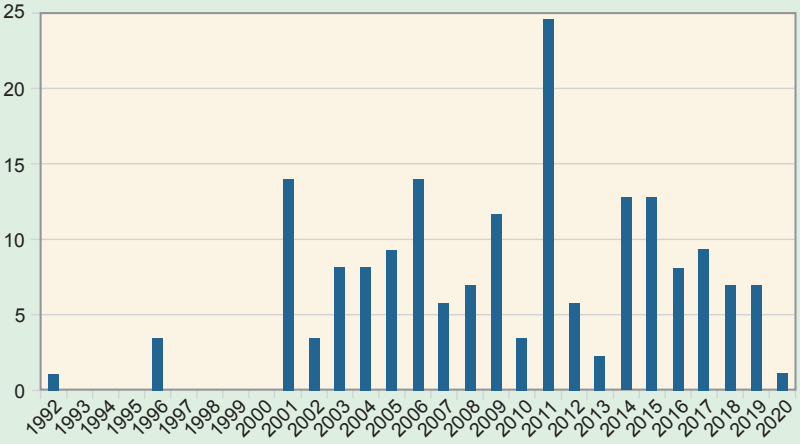
Most recorded induced seismicity in New Mexico has occurred within two large geologic basins: the Raton Basin in northeastern New Mexico/southeastern Colorado and the Delaware Basin, which is part of the Permian Basin, in southeastern New Mexico/western Texas. Both of these areas have experienced a rise in seismicity associated with increased amounts of wastewater injection in recent years.

The Raton Basin

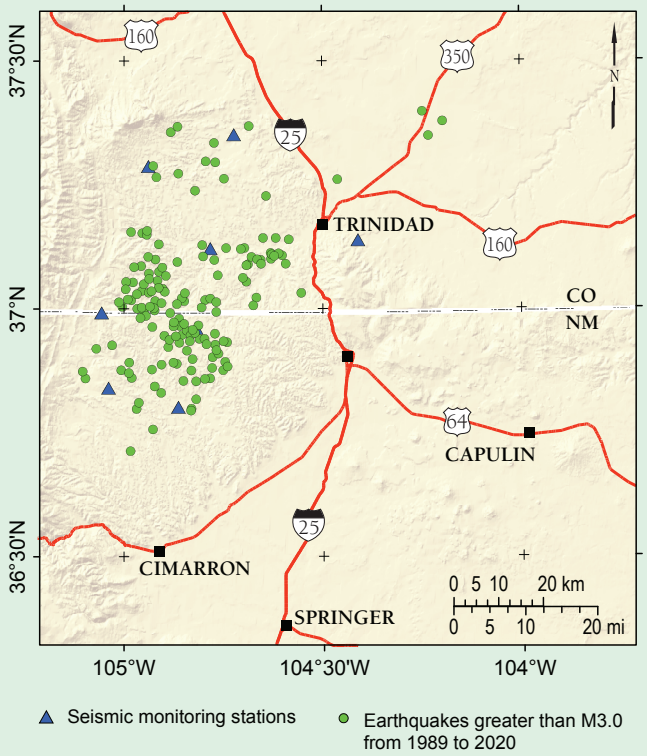
The Raton Basin spans the New Mexico-Colorado border west of Raton, New Mexico and Trinidad, Colorado. It has a long history of coal mining, but more recently methane gas has been extracted from the coal deposits. Methane production began in 1994 in the Colorado portion of the basin, and in 1999 in New Mexico. Significant amounts of water are produced as a byproduct of methane extraction, which is then reinjected deep beneath the coal layers.

Earthquakes have been felt by residents of the Raton Basin from the late 1800s to the present day. The largest, and most damaging earthquake recorded in the basin was a M5.3 event in 2011, located approximately 15 miles southwest of Trinidad. Although the area has a long history of seismic activity, in the last two decades, a large increase in the number of earthquakes has been observed in the Raton Basin. Improvements to seismic networks allow us to detect more small earthquakes now than in the past, so to compare old and modern earthquakes, we only consider earthquakes large enough to be detected equally in the past as they are today. The minimum magnitude of detection since 1990 is M3.0. From 1990–2000 four earthquakes larger than M3.0 were recorded, whereas from 2001–2020 we have recorded 151 earthquakes larger than M3.0.

The volume of wastewater injected below ground in the Raton Basin increased rapidly in 2001, and the earthquake rate greatly increased in the following years. In the Raton Basin, wastewater is injected about one mile below the surface. Most earthquakes occur about 1–4 miles deeper than the injected wastewater. Researchers at the University of New Mexico used data from a new network of seismic stations installed in 2016, along with a machine-learning approach, to find approximately 40,000 earthquakes that occurred in the Raton Basin between 2016 and 2020. Most of these earthquakes are extremely small and are not detectable by humans. The new techniques allow for a minimum magnitude of detection as low as M0.5. Even though such earthquakes don't pose a risk themselves, they help us understand the faulting mechanisms that can also produce larger earthquakes. By looking at many earthquake locations, we are able to identify the faults on which they occur, allowing us to identify the areas with the greatest seismic risk. In the Raton Basin, we have used this technique to identify 40 distinct faults, each extending about a mile in length. Approximately 70% of the earthquakes occur in the New Mexico portion of the basin, with the remaining 30% in Colorado. We were surprised to find very few earthquakes since 2016 in the area that hosted the largest earthquake, the 2011 M5.3 in Colorado, because this area was previously the most active. The new earthquake detection and location results show that earthquake activity can turn on and off in different portions of the basin over time.



Number of Raton Basin earthquakes larger than M3.0 from 1992 to 2020.



Map of events in Raton Basin larger than M3 from 1989 to 2020.

The Delaware Basin

The Permian Basin is a large, oil and gas-producing basin that spans western Texas and southeastern New Mexico. Oil production in the basin dates to the 1920s. The western portion of the basin is referred to as the Delaware Basin, and is the location of the majority of the oil and gas production in New Mexico. Production originally peaked in the 1960s–1970s, with a resurgence in the 2000s due to the widespread use of enhanced oil recovery techniques.

Reports of earthquakes in this area date to the 1920s when people migrated into the region to work in the oil fields. These early earthquakes were not necessarily induced, as this area also has some naturally occurring seismicity. In the mid-1960s, an earthquake cluster was identified on the Central Basin Platform, just east of the Delaware Basin, that may have been connected to oil production activities in the area. However, as seismic instrumentation was first installed in the region only in the early 1960s, it's difficult to know the true extent of seismic activity before that time period.

Until recently, the largest cluster of induced seismicity recorded in New Mexico occurred near the Dagger Draw oil field, northwest of Carlsbad. Oil production began in 1969, but was low until the field was redeveloped in the early 1990s. The field produced large volumes of wastewater that were reinjected deep beneath the surface. Although peak production was in 1996, the largest increase in seismic activity in the area occurred in 2001, and the activity was concentrated in an area approximately 10 miles west of the field. The largest event associated with this cluster was a M4.1 earthquake on March 28, 2010. The time lag was unusual, as induced seismicity is typically more closely associated in time and space with injection activities in nearby wells. Researchers surmised that the wastewater slowly migrated from the injection site to an area with existing faults during that time period. The Dagger Draw story demonstrates that the association between fluid injection and seismicity can be complex, and highlights the importance of understanding the geologic structure of areas where induced seismicity occurs. Hydrocarbon production in the Dagger Draw field declined significantly throughout the 2000s, and seismic activity in the area dropped to baseline rates after 2012.

In 2015, seismographs recorded an increase in seismic activity near Pecos, Texas. Seismicity in the area continued to rise into 2020, and studies have associated the seismicity with nearby wastewater injection and fracking activities. The area near the New Mexico-Texas border has seen an increasing number of earthquakes during this time period, with the largest earthquake in the region occurring on March 26, 2020, a M5.0 event that was located 25 miles west of Mentone, Texas, and was felt by people in Carlsbad and El Paso. The majority of the recent seismicity in the Delaware Basin has occurred in Texas, although earthquake activity has also risen in New Mexico. The largest earthquake in southeastern New Mexico in 2020 was a M3.0 event near Lovington on June 28 that was followed by a cluster of over 70 quakes. The Lovington event occurred in an area that was not previously observed to be seismically active, highlighting the importance of monitoring all areas that could experience induced seismicity.

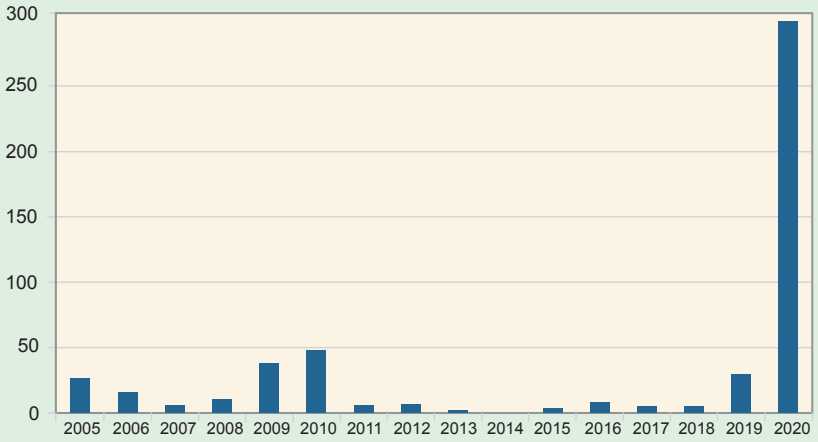
The rise in seismicity in the Delaware Basin has prompted several projects conducted by researchers at the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) and in Texas to improve monitoring and better understand the causes of induced seismicity. One project uses a technique called "template matching," where known earthquakes are used as templates to detect additional events that may have been missed. Using such an expanded catalog, along with techniques to more accurately locate events, will allow for a more complete understanding of induced seismicity in the region. We are also working on techniques involving machine learning to more quickly locate earthquakes so that information can be rapidly disseminated to operators, regulators, and the public.

Monitoring Earthquakes in New Mexico

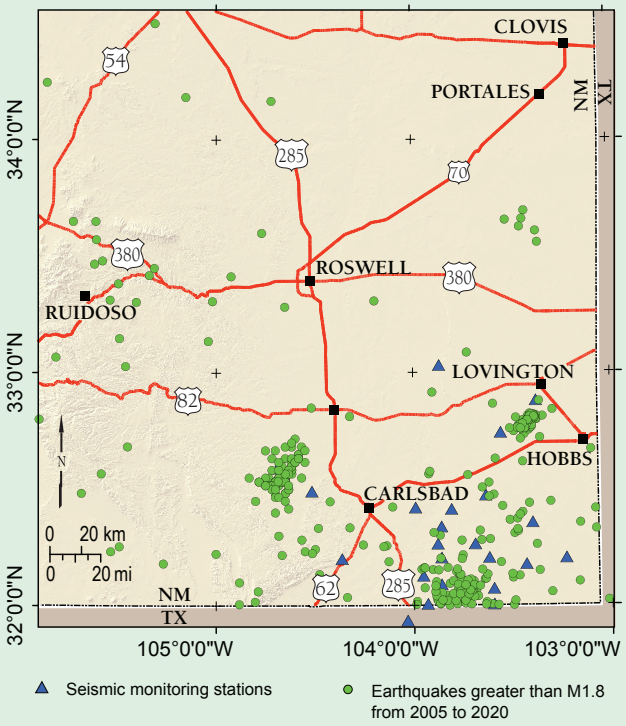
Seismic monitoring in New Mexico began in 1962 when Professor Al Sanford set up a monitoring station above the Socorro Magma Body near the New Mexico Tech campus. In recent years, researchers have installed additional monitoring stations in other parts of the state, including those that experience induced seismicity.

Between 2008 and 2016, only one station operated continuously in the Raton Basin. In 2016, researchers at the University of New Mexico established a seven-station seismic array in the basin. The new array provides more sensitive detection and better resolution of the subsurface locations of earthquakes.

Monitoring of the Delaware Basin began in the 1970s when the area was being investigated as a potential site for the Waste Isolation Pilot Plant (WIPP), a storage facility for nuclear waste. The current, permanent



Number of southeastern New Mexico earthquakes larger than M1.8 from 2005 to 2020.



Locations of southeastern New Mexico earthquakes larger than M1.8 from 2005 to 2020.

network in southeastern New Mexico was established in the 1990s by the New Mexico Tech Seismological Observatory (NMTSO). Since 2018, the network has increased from nine single-component stations to a total of 15 monitoring stations, including 3-component broadband stations that are able to more completely record the seismic signal. Additionally, the NMTSO has collaborated with the U.S. Geological Survey to establish 14 stations for a total of 25 monitoring stations in southeastern New Mexico. The Texas state legislature also established a new seismic monitoring program in 2015 called TexNet that officially began operation on January 1, 2017. TexNet monitors the Texas portion of the Delaware Basin, along with other areas of Texas that could potentially experience induced seismicity.

These improved monitoring networks and associated research have greatly improved our understanding of the processes behind induced seismicity. Earthquake locations are computed by using the arrival time of the seismic waves at multiple stations to calculate the point of origin, known as the hypocenter. Data collected from a larger array of stations yields a more accurate determination of the location. In particular, it can be difficult to precisely calculate the depths of earthquakes without a seismic station nearby. Precise depth estimates are essential for determining the cause of induced seismicity. Along with improved station coverage, we have also used new information about the geology of the region to more accurately locate seismic events.

As we increase our awareness about the potential for certain human activities to cause potentially damaging earthquakes, upgrading our state monitoring networks and improving the techniques for data processing will be necessary to ensure that such activities can be conducted safely. Most recently, earth scientists in New Mexico have mapped earthquake faults in the Raton Basin and developed a daily public notification system of earthquakes in the Delaware Basin. We are also working with hydrogeologists and engineers to better understand the connection between wastewater injection and seismicity in several areas of the state. These and future investigations will enable us to further improve our capabilities for monitoring induced seismicity, understand the causes of induced seismicity, and mitigate the risks of destructive earthquakes.

—Mairi Litherland and Margaret Glasgow

Mairi Litherland is the manager of the New Mexico Tech Seismological Observatory at the New Mexico Bureau of Geology and Mineral Resources. Her work focuses on understanding earthquakes and seismic hazards in New Mexico. Margaret Glasgow is a Ph.D. candidate at the University of New Mexico studying induced seismicity in the Raton Basin and the seismic structure of the mantle transition zone.

The authors thank Dr. Dave Love (NMBGMR), Dr. Michael Young (Bureau of Economic Geology, Univ. of Texas at Austin), and Dr. Susan Bilek (Earth & Environmental Science Dept, NM Tech) for technical reviews.

For Further Information

The NMTSO posts real-time feeds of the seismic data we collect along with the locations of detected earthquakes on our website at geoinfo.nmt.edu/nmtso/.

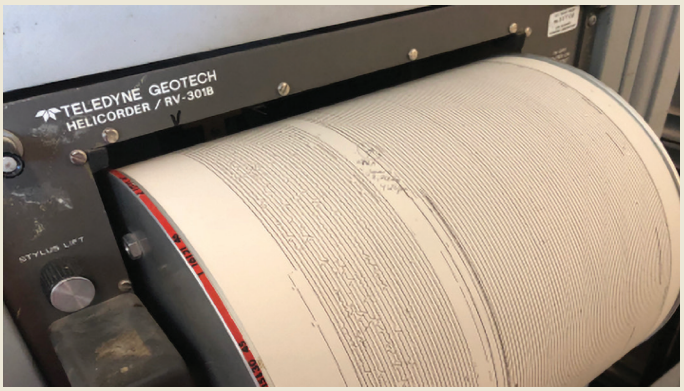
You can find out more about earthquakes around the world at the USGS earthquake hazards page: usgs.gov/natural-hazards/earthquake-hazards/earthquakes.

Photograph of NMTSO seismic station in the Delaware Basin in southeastern NM.

How Do We Measure the Size of Earthquakes?

Before the invention of seismometers, scientists were only able to estimate the magnitude of earthquakes based on reports of the amount of shaking felt and damage done in various locations around the earthquake. In the 1930s, Charles Richter developed a scale for measuring local magnitudes in southern California by looking at the amplitude of the seismic event as recorded on a seismometer. Over time, scientists have developed new methods of measuring the magnitude of earthquakes based on seismic data. Most large earthquakes today are measured using moment magnitude, which calculates the magnitude of an earthquake based on the size of the rupture and the amount of slip. Larger areas of slip release more energy, which produces a larger magnitude earthquake.

Modern seismometers are able to detect extremely small earthquakes, even into the negative magnitudes, which are too small even to be felt by humans. For example, a crack propagating across a windshield could be considered a "glass quake" and has a magnitude of approximately -2 (negative 2). The largest earthquake ever recorded was a M9.5 earthquake in 1960 in Chile. The earthquake magnitude scale is a logarithmic scale, where each increase of 1 on the magnitude scale for an event releases approximately 32 times the amount of energy! Very large magnitude events are very rare, whereas smaller events are much more common.



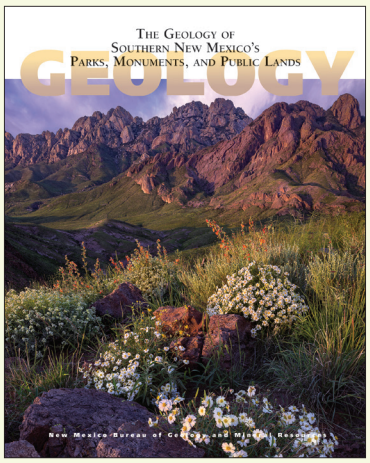
This paper seismic recorder from the New Mexico Tech Seismological Observatory was used to record earthquakes until the advent of digital recording methods. Seismic data are now stored on computers, and data from our network can be viewed in real time at geoinfo.nmt.edu/nmtso/.

Bureau News

Top Research Award Bestowed to Nelia Dunbar

The New Mexico Tech 2021 Distinguished Research Award winner is Dr. Nelia Dunbar, State Geologist and Director of the New Mexico Bureau of Geology and Mineral Resources. The winner was chosen by a committee of faculty and researchers from a list of candidates nominated by their colleagues. One of her nominators wrote "I regard Nelia as one of the best volcanic petrologists in the country." Nelia earned her M.S. (1985) and Ph.D. (1989) at New Mexico Tech, has worked at the Bureau of Geology since 1992, and has led the agency since 2016. She has established an international reputation for dating and studying volcanic ash in Antarctica, where she has spent 23 field seasons, as well as in New Mexico and other parts of the world, using the electron microprobe lab that she established here at NM Tech. Nelia has been awarded dozens of NSF grants, and as an Adjunct Faculty member, Nelia taught the electron microprobe class for 36 semesters, and has advised nearly 50 graduate students.

Popular Book Wins Regional Prize



The Geology of Southern New Mexico's Parks, Monuments, and Public Lands was selected as the winner of the 2020 Southwest Book Design and Production Award in the "scholarly and technical" category. The award recognizes quality and creativity in book design, and distinction in production. Written by geoscientists for the interested public, the full-color book reveals the fascinating geology of the state's many national and state parks and monuments (including Carlsbad Caverns and White Sands), and other publicly accessible lands. The book is the second of two popular volumes on the geology of our public lands—the first, published in 2010 and updated in 2020, covered the northern half of the state.

Mapping Program is Awarded $583,603

The Geologic Mapping Program was awarded $583,603 through the federal STATEMAP program to continue detailed mapping of key areas in the state. The mapping team will focus on three regions, the Rio Grande watershed, the lower Pecos River watershed, and the I-40 corridor near Gallup. "The Geologic Mapping Program has long emphasized the importance of generating new geologic map data for our stakeholders, and will continue to do so with this funding," said Dr. Mike Timmons, Deputy Director and manager of the Mapping Program. STATEMAP is funded by the USGS National Cooperative Geologic Mapping Program, with matching funds provided by the State of New Mexico.

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801 Leroy Place
Socorro, New Mexico 87801-4750

1015 Tijeras Avenue NW, Suite 200
Albuquerque, New Mexico 87106
(505) 366-2530

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Cover photo of Kasha-Katuwe Tent Rocks National Monument, New Mexico
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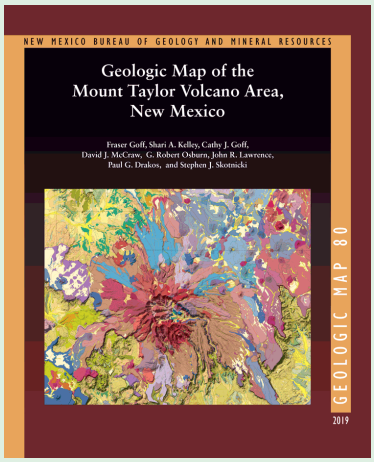
Plus, most of our geologic maps (GM and OF-GM series), resource maps, and hydrologic sheets are now also free. Visit https://geoinfo.nmt.edu/publications/maps/home.html

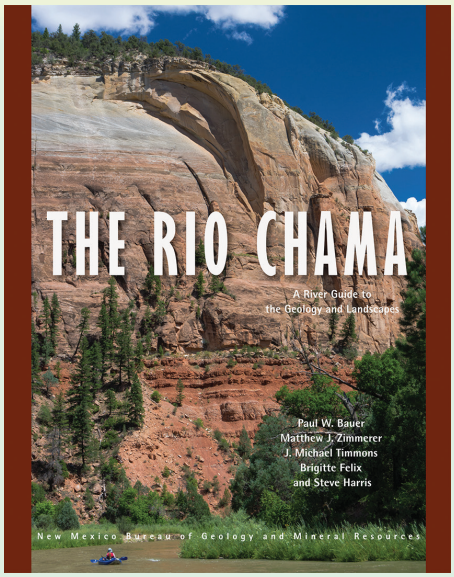
Available Now!
Mount Taylor map and guidebook



The Rio Chama, A River Guide to the Geology and Landscapes will be available soon!

The 135-mile Rio Chama of northern New Mexico is a major tributary of the Rio Grande. From its alpine headwaters at the Continental Divide of the glaciated San Juan Mountains in southern Colorado, this hidden gem flows across the Colorado Plateau in a spectacular canyon cut into Mesozoic sedimentary rocks, in places up to 1,500 feet deep. Towering, vibrant, sandstone cliffs, heavily wooded side canyons, superb camping, and a diversity of historical sites offer an outstanding wild river backdrop for the boater, angler, hiker, or camper.

This water-resistant guidebook contains detailed river maps of the seven sections of the Rio Chama, plus its three resplendent reservoirs, from the Colorado headwaters to its confluence with the Rio Grande near Española. The Chama Canyon section, below El Vado Dam and through the Chama Canyon Wilderness, is one of the finest, multi-day, whitewater trips in the Southwest.



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Allosaurus, the top Jurassic predator, inhabited the Rio Chama area about 150 million years ago.