New Mexico EARTH MATTERS

WINTER 2020

Dangers of Steep Slopes: Landslides, Rockfalls, and Debris Flows in New Mexico

Slope is an important feature of Earth's surface. It is fundamental to the hilly to mountainous terrain of much of New Mexico, and is a defining feature of many of our notable landmarks, such as Shiprock, the Sandia Mountains, and Sierra Blanca. Slope is an essential consideration in most engineering projects, including construction of roads and buildings.

People have an inherent sense that steeper slopes are more dangerous. This intuition is well founded, as many geologic hazards are associated with steep slopes—including landslides, rockfalls, and debris flows. There are enormous benefits to society from identifying areas susceptible to slope-related hazards, so that houses and roads are not built in these areas, or so that appropriate protective measures are taken.

Nature of Slope Hazards

It is helpful to consider "driving forces" and "resisting forces" when discussing slope hazards. Driving forces initiate or cause an action. Resisting forces counteract an action. Earth's gravity is the main driving force acting on any moving mass of soil or rock, causing the mass to accelerate to destructive velocities. Because the gravity force is constant, slope hazards commonly have a triggering event. Common triggers are events that "loosen up" or initiate erosion on a hillslope, such as an earthquake or a heavy rainstorm, although, many landslides and rockfalls have occurred in the absence of any obvious trigger.

A **landslide** can be defined as the movement of cohesive rock and/or sediment down a hillslope due to the influence of gravity over a "basal shear plane" (a surface along which the mass slides). In a "deep-seated landslide" the shear plane is more than 10 feet deep, and the landslide may mobilize bedrock as well as overlying sediment. In a "shallow landslide" the shear plane is less than 10 feet deep, and typically involves only soil or sediment. Landslides can move slowly to rapidly.

A **rockfall** consists of free-falling rocks, sourced from a cliff or steep slope, which can be as small as a pebble or as large as a house. The downward movement may be straight down initially, but the end stage typically involves bouncing along a lower slope. Factors that promote rockfalls can be divided into: 1) processes that cause bedrock to fracture, such as ice freeze-thaw, uneven solar heating of rock, swelling of clays, or prying by tree roots; 2) ground shaking from an earthquake; and 3) heavy rains. Rockfalls typically stop when encountering some combination of shallow slopes and rough surfaces, such as trees and boulders.

Debris flows are gravity-driven mixtures of mud, water, and other debris (such as sand, rocks, and wood) in drainages that have steep upper slopes. The water and sediment are commonly about equal volumes and are thoroughly mixed. Debris flows are most often triggered by high-intensity or prolonged rainstorms. The sudden addition of large amounts of sediment into running water creates the debris flow. The momentum of debris flows can cause them to flow far out onto alluvial fans or valley floors. In New Mexico, destructive debris flows commonly occur after wildfires have burned off hillslope vegetation. Healthy vegetation acts as a protective cover by intercepting rainfall, slowing down the velocity of sheet flow, and increasing water infiltration. Where vegetation is thin or absent, more water hits the ground and flows more quickly downslope, resulting in greater erosion.

Risks to Society

What parts of the state are threatened by landslides, rockfalls, and debris flows—and which of the three are the most hazardous? Debris flows pose the greater risk to many New Mexico residences because of their

View of a debris flow lobe extending into the Rio Grande in the Rio Grande Gorge near Pilar. Erosion of the toe of the debris flow by the river left large boulders in the river at Sleeping Beauty Rapid, much to the delight of the whitewater boaters. The debris flow occurred on July 25, 1991, after an intense rainfall event. The debris flow temporarily dammed the Rio Grande, and had an estimated volume of 4,700 cubic yards.

association with burned landscapes and the relatively common and widespread nature of wildfire in the state.

Santa Clara Canyon, in the northeastern Jemez Mountains, offers an example of the damage caused by post-wildfire debris flows in the years after it was scorched by the 2011 Las Conchas fire. Major thunderstorms in the summers of 2011, 2012, and 2013 eroded deep gullies on steep hillslopes in the upland tributaries of Santa Clara Canyon. In some cases, the mobilized sediment transformed to debris flows, with the resulting slurry of mud and gravel (including cobbles and boulders) covering a road and filling in four flood-control dams that had been protecting the village of Santa Clara Pueblo. Post-wildfire flooding in Santa Clara Canyon resulted in multiple Major Disaster Declarations, with public assistance grants totaling nearly $8 million for Santa Clara Pueblo alone. For comparison, the average annual cost of debris flow cleanup in New Mexico is estimated at several million dollars.

Although not as costly or widespread as debris flows, rockfalls have caused deaths over the past 30 years, and are a persistent concern for the NM Department of Transportation along some highways. On July 11, 2008, three homeless people died in Gallup when a rock fell on them while they slept. One of the most problematic rockfall areas in the state is the Rio Grande Gorge along NM 68 between Taos and Española, where rockfall events occurred on September 12, 1988 and July 25, 1991. In 1988, a boulder struck a bus, killing five and injuring 14. In 1991, numerous rockfalls and debris flows trapped 20 cars and closed the highway for 19 hours. A 300-ton boulder ricocheted off the highway, creating a crater 45 feet long and 15 feet deep before coming to rest on the far side of the river. Cleanup costs for this one event were about $75,000. The average, annual cost of rockfall response in the state is estimated at tens of thousands of dollars.

Although deep-seated landslides are a common feature in the New Mexican landscape, they happen less frequently than debris flows or rockfalls. When they have occurred in the recent past, it is often due to human activity that destabilized a steep slope or a preexisting landslide. One of the more destructive modern landslides occurred on April 10, 2007, when a landslide covered 300 yards of the Farmers Mutual Ditch in San Juan County. The cost to remove the material and fix the ditch was $263,408. Landslides have damaged roads near Luna in southwestern New Mexico and on US 64 east of Tierra Amarilla. In 1993, a landslide damaged NM 570 near Taos. The expense of stabilizing the hillslope was so high that the Department of Transportation closed the highway.

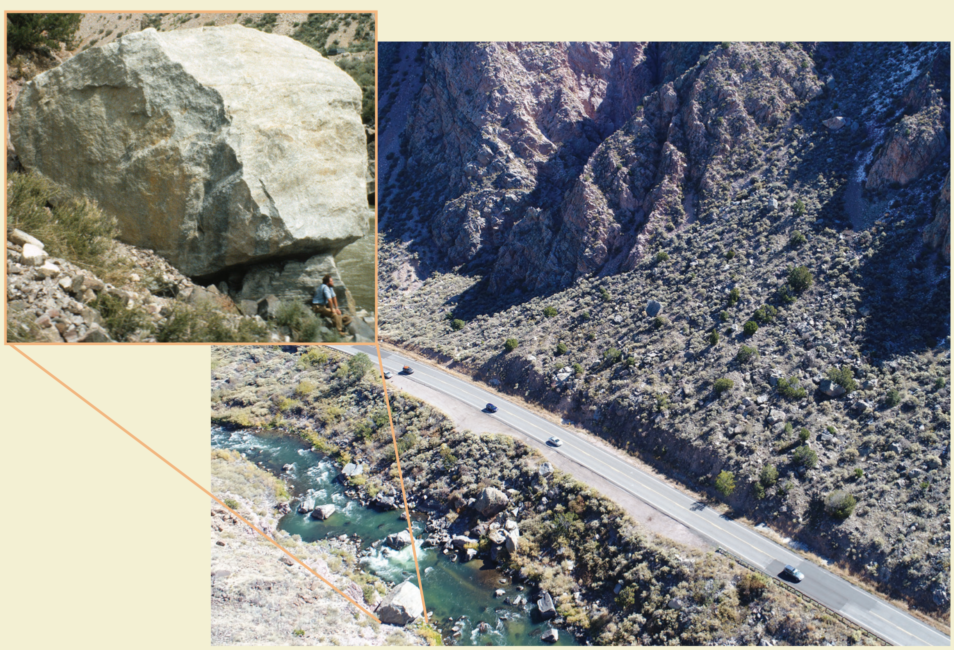
Because of their large size, landslides in populated areas tend to cause more damage than rockfalls. For example, the 2014 Oso landslide in Washington killed 43 people and destroyed 49 structures, and the 2018 landslide in coastal California destroyed a 0.3-mile stretch of SR 1 near Big Sur. Comparable landslides have not hit New Mexico in recent history, although smaller slides occur periodically.

Most deep-seated landslides in New Mexico are inactive features from geologic periods when Earth's climate was cooler and wetter. However, inactive landslides can be reactivated if destabilized by natural erosion or human excavation. Accordingly, it is important to map both the likelihood of slopes producing landslides and actual landslide deposits, and to be aware of the potential consequences of human activities in any type of landslide terrain.

Mapping the Threats in New Mexico

The NM Bureau of Geology recently produced statewide maps depicting the "susceptibility" of the landscape to generate deep-seated landslides and rockfalls. Susceptibility is the tendency of features in the landscape to produce a given hazard. It conveys where a natural hazard is more likely to occur. However, susceptibility does not explicitly reveal the frequency or magnitude of the hazard, such as a large versus small rockfall. The word's usage in geology is akin to how a person might use the word in everyday life. A person might say "my fair skin makes me susceptible to sunburns," but that does not tell the listener how often the person gets a sunburn nor the intensity of the burn.

Aerial photograph of the 1993 landslide that closed NM 570 in the Rio Pueblo de Taos gorge 8 miles southwest of Taos. The expense of stabilizing the hillslope was so high that the road was permanently closed. Note the prominent head scarp (crescent-shaped breakaway zone) at the top of the slide.



Photos of rockfalls within the Rio Grande Gorge. Triggered by three days of rain in July of 1991, a 300-ton boulder rolled down the cliff, hit the highway (creating a crater 45 feet long and 15 feet deep), and imbedded itself on the far side of the river. The inset shows the boulder, which was promptly named "Baby Huey" by rafters. For scale, note the geologist sitting beneath Baby Huey.

Our maps used geographic information system (GIS) methods to grid a map area into cell blocks and evaluate susceptibility based on the landscape characteristics of each cell. The cell blocks measured 1640 by 1640 feet. For the locations of prior landslide and rockfall events, we used a statewide map published in 1990 by the U.S. Geological Survey (USGS Open-file Report 90-293).

Rockfalls

We used two methods to discern rockfall hazards. First, we identified previous rockfalls, and assumed that future events will likely occur in the same general locations. This is analogous to plotting accidents along a highway, noting where the frequency is abnormally high, and assuming those areas are likely to have future accidents. This approach is somewhat flawed for rockfalls, as big rockfalls are more noticeable than small rockfalls on aerial photographs. To address this particular bias, we employed a second method that only considers slope.

We used slope because accurate, digital, topographic data are available statewide. The slope-based method involves using a GIS to determine the maximum slope-angle within 1000 feet of rockfalls mapped in the USGS report, and assuming that the rockfall originated at this or higher slope angles. A 1000-foot radius was chosen because that is roughly the average of the spatial uncertainty of the USGS maps. A plot of the maximum slope values approximates a bell-shaped curve whose peak corresponds to the mean (average) of the data. Statistics were then used to define three hazard-susceptibility classes. Areas with slopes of 17° and higher are classified as "high susceptibility." Areas with slopes of 8° to 17° are classified as "moderate susceptibility," as are 5° to 17° slopes within a 1540-foot buffer around the moderately susceptible areas. All gentler slopes are classified as "low susceptibility." Our susceptibility maps are color-coded, with red colors indicating higher hazard potential.

Deep-seated Landslides

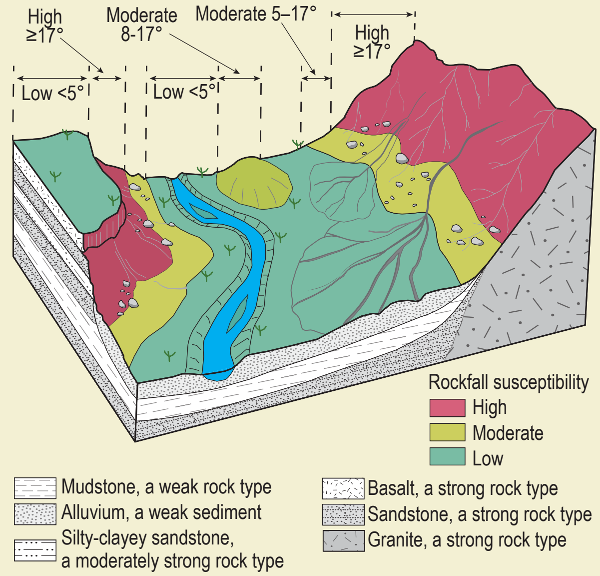
We used a logistic regression method to map susceptibility to deep-seated landslides. This method builds statistical models that relate landscape features to the likelihood of landslide occurrence in well-studied "training" areas and then applies the resulting models to the entire state. The appeal of this method is that it can take a variety of inputs (such as slope angle and "strong rock type" versus "weak rock type"), objectively determine the influence of each input on landslide occurrence, and combine the inputs so as to calculate a "landslide occurrence prediction rating" between 0 (no landslide) and 1 (definitely a landslide).

The important landscape features are slope angle, slope curvature, slope aspect (north-facing versus south-facing), and the characteristics of the rocks and sediments. The influence of each of these factors varies with the geologic setting. For example, where rock layers are tilted, such as in the Rio Grande rift, susceptibility is strongly influenced by the presence of weak rock layers interbedded with stronger rocks along which the landslide can slide. In contrast, where rock layers are flat, such as in the Colorado Plateau, slope angle is the strongest predictor of susceptibility.

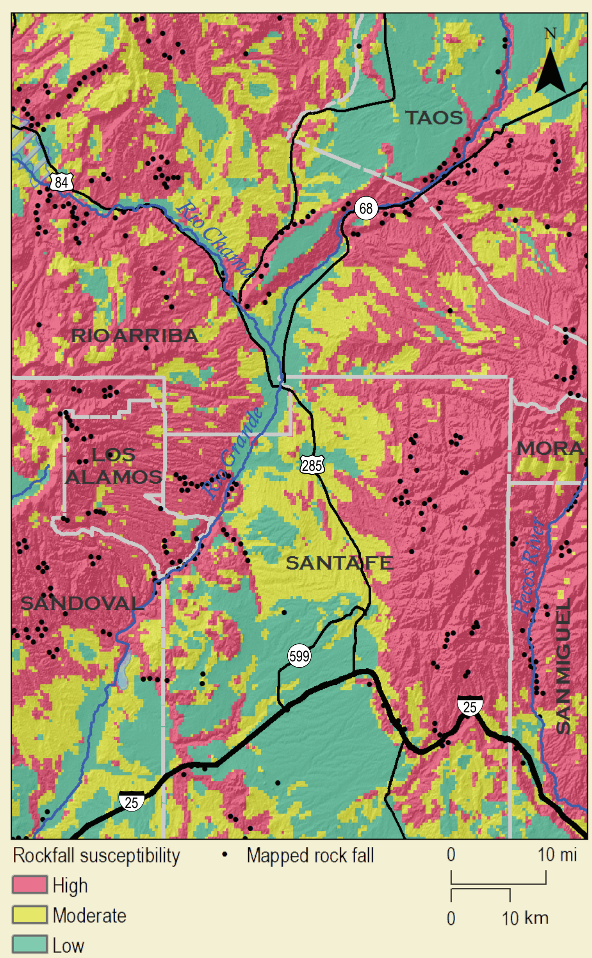
Overall, at a statewide scale, steep slopes, weak rocks, and interbedded weak and strong rocks are most highly correlated to landslide occurrence. We applied the equations developed on our training areas to the remainder of the state to determine ratings of landslide susceptibility. We then divided these ratings into four susceptibility categories (high, moderate, moderately low, and low) based on comparing the relative ratings to known landslide occurrences mapped by the USGS. For example, in the Española-Los Alamos-Taos area, shown on the accompanying maps, we concluded that steep slopes underlain by relatively weak rocks are most susceptible to deep-seated landslides.

Using the Maps

Our rockfall and landslide maps provide valuable information for scientists, engineers, and decision makers who work in regional planning, regional land use, and hazard mitigation planning. The maps will be useful for designing transportation or utility corridors and for large public works projects. The maps have already been used to update the NM Natural Hazard Mitigation Plan, produced by the NM Department of Homeland Security and Emergency Management in 2018.



3-D drawing of rockfalls in a hypothetical landscape, illustrating the slope-based susceptibility categories (low, moderate, and high) that were used to map rockfall hazards in New Mexico.



Rockfall susceptibility map for the area between Taos and Santa Fe, showing our three slope-based susceptibility categories and rockfalls mapped by the U.S. Geological Survey.

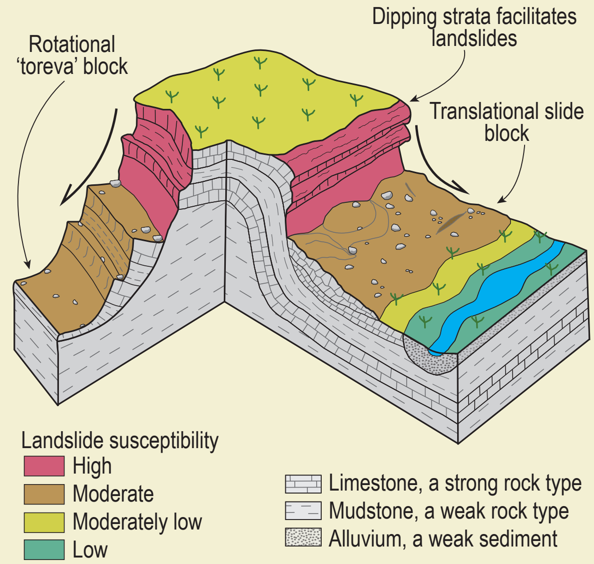
Where are the Landslide and Rockfall Hazards?

By comparing the hazard susceptibility maps with known instances of rockfalls and landslides, we can evaluate the hazard threat anywhere in the state. Not surprisingly, our maps show a high correspondence of predicted susceptibilities with those areas where past rockfalls or deep-seated landslides have occurred, such as along the Rio Grande Gorge.

The threats are relatively low in the flat, southeastern part of the state, east of the Sacramento Mountains and Carlsbad. The threats increase north of I-40, where highly susceptible areas coincide with escarpments, steep-sided volcanoes, and deep canyons. Nearly all mountains and badlands that flank the Rio Grande north of Socorro have a high to moderate susceptibility, with landslide susceptibility varying with rock type. The cities of Taos, Española, and Albuquerque were built on low-sloping land, and generally exhibit low susceptibilities. Santa Fe has low to high susceptibilities, with moderate and high susceptibilities on the steeper slopes.

Northwestern New Mexico is characterized by flat terrain interspersed with mesas, hills, and mountains. Steep-sided mesas are highly susceptible to landslides, as are the Chuska Mountains. Rockfall hazards are a concern near Mount Taylor and along mesas and steep-sided canyons.

The southern part of the state, extending southwestward from Alamogordo, is characterized by wide expanses of flat land punctuated by isolated, steep-sided mountain ranges, such as the west slope of the Sacramento Mountains. As expected, highly to moderately susceptible areas coincide with the steep mountain slopes, with rock type being an important consideration for deep-seated landslides. The hilly to mountainous terrain in west-central New Mexico, from Silver City northward to near US 60, is moderately to highly susceptible, except on wide valley floors and the Plains of San Agustin.



3-D drawing of deep-seated landslides in a hypothetical landscape, showing how slope and geologic factors can influence landslide susceptibility.

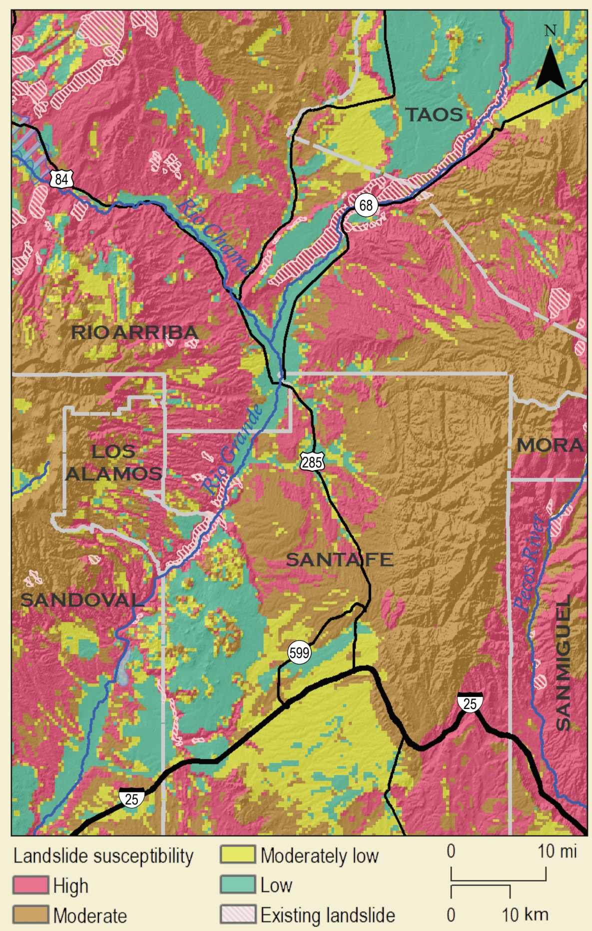
Effects of Climate Change

Climate influences the susceptibility of the landscape to slope-related hazards. Colder conditions during Ice Ages likely promoted rockfalls in high-altitude terrains due to enhanced freeze-thaw and other ice-related processes. Most deep-seated landslides are inactive, and formed in cooler and wetter climates. The degree of water infiltration and subsurface geologic conditions appear to be important. For example, a landslide study in White Rock Canyon showed a link between landslide activity and wetter paleoclimate conditions between 20,000 and 10,000 years ago, presumably due to higher water content in shallow sediments, higher water tables, and/or higher flood discharges along the Rio Grande.

In New Mexico, climate change is expected to lower infiltration of rain and snow melt. Wildfire intensity and frequency is expected to increase. Modeling predicts that whereas the summer monsoon may weaken with global warming, the intensity of localized precipitation may actually increase. This combination could promote debris flows (especially post-fire debris flows) and rockfalls. Intense rainfall events may trigger local landslides, but statewide rates may not notably change, or may possibly decrease, due to overall lower infiltration of water due to drier conditions.

—Daniel J. Koning and Colin T. Cikoski
(New Mexico Bureau of Geology and Mineral Resources)

Thanks to Anne Tillery of the U.S. Geological Survey for information on the Santa Clara Canyon debris flow. We also thank Ann Youberg, Dave Love, and David McCraw for technical reviews.



Deep-seated landslide susceptibility map for the area between Taos and Santa Fe, showing our susceptibility categories (low, moderately low, moderate, and high), and landslides mapped by the U.S. Geological Survey.

For Further Information

New Mexico Bureau of Geology rockfall susceptibility map:
https://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=595
New Mexico Bureau of Geology deep-seated landslide susceptibility map:
https://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=594

Bureau News

Bureau Scientists Named Geological Society of America Fellows

Dr. Matt Heizler and Dr. Virginia McLemore were acknowledged as among "the best of our profession," during the Geological Society of America 2019 Annual Meeting. Dr. Heizler was recognized for his sustained record of distinguished contributions of geoscience research, particularly for argon geochronology research, as well as for his scientific originality and perseverance. Dr. McLemore was recognized for her sustained record of distinguished contributions of geoscience research. She has also been notably productive in applied geoscience and the training of geologists.

Peter Scholle Receives Distinguished Service Award

Dr. Peter Scholle, Emeritus Director and State Geologist, received the West Texas Geological Society Distinguished Service Award for exceptional contributions to geological sciences, industry or geological professions, particularly in the West Texas region. Dr. Scholle is a renowned expert in carbonate rock sedimentology, diagenesis, and hydrocarbon exploration, and has published several books on carbonate and clastic depositional models and internal rock fabrics. He has also promoted geoscience education as a professor, and has developed computer-based classroom materials to help students visualize the processes of rock formation.

Bob Eveleth Inducted into the New Mexico Mining Association Hall of Fame

Bob Eveleth, Emeritus Senior Mining Engineer, was inducted into the New Mexico Mining Association Hall of Fame. He was recognized for major contributions to New Mexico's mining history, recognition of the importance of mineralogy to the mining industry, and for his role in development and curation of our Mining Archives.

Spectacular Amethyst Donated to Mineral Museum

The Mineral Museum recently received a generous donation of a large amethyst geode, known as "the igloo," from New Mexico Tech grads Anne Brenner and Cortney Stewart. The Brazilian geode was part of a large donation that included three, smaller, sectioned, amethyst geodes. These sizable crystal cavities were mined from lava flows in the ~130 million-year-old Paraná flood basalts. The mineralization of quartz and celadonite, with lesser calcite and gypsum, took place about 70 million years ago in large voids within the lava flows. The igloo is on display in the Bureau of Geology atrium, and the three smaller geodes will be crafted into end tables. Be sure to admire these gorgeous specimens the next time you visit the Mineral Museum.

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Cover photo of Kasha-Katuwe Tent Rocks National Monument, New Mexico

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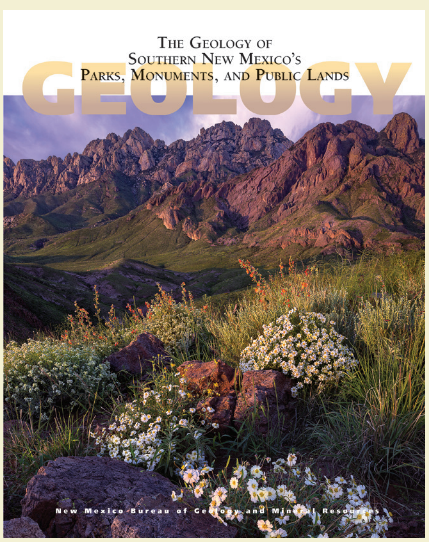
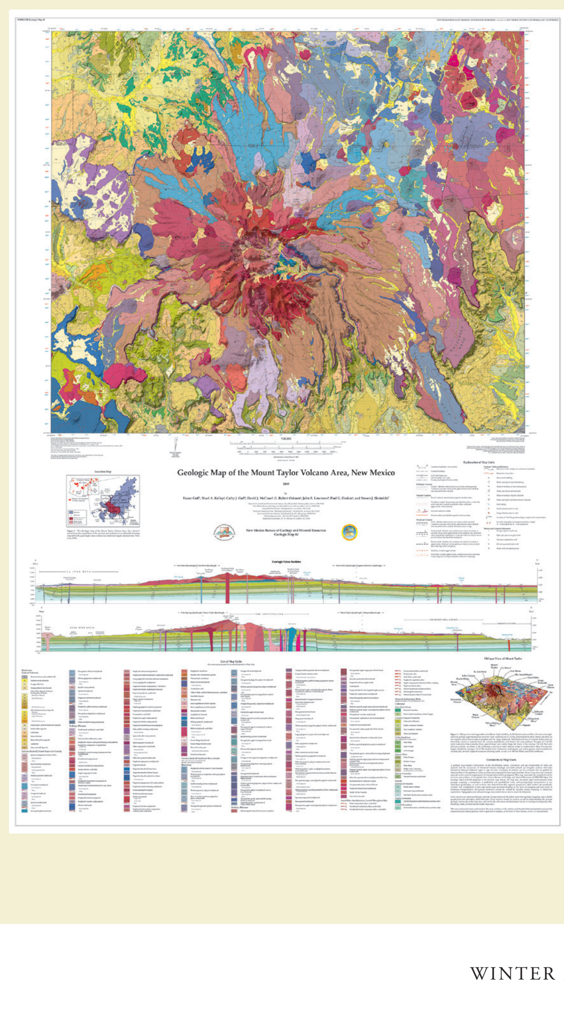
Publications

The Geology of Southern New Mexico's Parks, Monuments, and Public Lands will be published in Spring 2020!



The new Mount Taylor geologic map will be available in 2020!

The Geologic Map of the Mount Taylor Volcano Area, New Mexico is a 1:36,000 compilation of six recently mapped NMBGMR 1:24,000 geologic quadrangles that encompass this extinct composite stratovolcano. Mount Taylor is New Mexico's second young volcanic complex, after the Jemez Mountian Volcanic Field, which includes the Valles caldera. This timely map and accompanying report, resulting from over a decade of thorough work, synthesizes the current geologic understanding of this important landscape feature of the state.



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