This month’s issue of Lite Geology is devoted to describing the geology of New Mexico’s ski areas. Consequently, we decided to dedicate this Earth Brief to a discussion of an important process that drives the economy of ski areas—snowmaking.

The practice of snowmaking at ski resorts across the United States started in the early 1950s with the invention of the snow cannon, and became common by the 1960s. Currently, eighty eight percent of North American ski areas create artificial snow. In New Mexico, Ski Santa Fe covers fifty percent of their ski runs with man-made, or artificial snow, and Red River has deployed snowmaking equipment throughout the ski area so that eighty five percent of the trails can be covered with man-made snow. The ski industry employs around 76,000 people in the United States. Snowmaking at ski areas is important in creating an early snow base, allowing natural snow to stick earlier in the fall and linger in the spring. Man-made snow is usually denser than natural snow and thus is more resistant to melting. Artificial snow remains on the ski runs seven to nineteen days longer, compared to natural snow.

Man-made snow is created by pressurized guns or fans that break a stream of water into small water drops that fly over 50 feet up into the air. The mist of water droplets then freezes and falls back to the ground as artificial snow. Artificial snow is dense because the droplets do not have time to form intricate ice crystals like those found in natural snow. Instead, machine-made snow is more like ice pellets. Making snow is quite an art because “good” snow is dependent on the local microclimate and lay of the land. Cold and dry conditions are the best. The temperature required for making snow is generally less than 28°F and 10°F is ideal. The ice crystallization process is enhanced if the mist of water contains impurities, which allows snowmaking at temperatures up to 31°F. In some cases, a protein derived from cultured bacteria has been introduced into the water droplets to improve the efficiency of snowmaking.
Cold Geology

Matthew Zimmerer

Water use for snowmaking can be a contentious issue. Snowmaking uses a lot of water. A six-inch layer of artificial snow that covers a 200-foot by 200-foot area requires approximately 75,000 gallons of water. A snow gun can produce an acre of snow every 2 hours. Ski area managers work hard to efficiently use water during the ski season by catching runoff from melting artificial snow, storing the water, then making new man-made snow from the recycled water. At the end of the ski season, most of the snowmelt returns to the local streams. About ten percent of the water used in snowmaking is lost to evaporation during the snowmaking process or to sublimation and evaporation of the machine-made snowpack.

Some ski areas acquire water from streams located at the base of the mountain and pump the water to storage facilities up on the hill. Sipapu, located 20 miles southeast of Taos, currently diverts 5.9 million gallons of water from the Rio Pueblo, a tributary to the Rio Grande, so that the ski area can open in November using artificial snow. In 2012, Sipapu wanted to expand its snowmaking capabilities, so the ski area negotiated a short-term lease to transfer water rights for 100 acre-ft (32.6 million gallons) from the Jicarilla Apache tribe for one year. Also in 2012, the ski area applied for a permit from the Office of the State Engineer for an additional 114 million gallons of water from the Rio Pueblo. Farmers downstream in Dixon and Embudo blocked the move because they use the river to irrigate winter crops and orchards in November. Sipapu countered with claims that eighty percent of the water used to make snow returns to the river, compared to the fifty percent return rate used in agriculture. Plans for obtaining additional water for Sipapu now appear to be on hold.

Other ski areas have chosen to take advantage of natural storage. Pajarito Mountain near Los Alamos dug out a 10-million-gallon, plastic-lined, holding pond near the top of the mountain designed to catch and store summer monsoon rainfall and spring snow melt. For many years the pond was nearly dry, but with the installation of a new weir system, the pond filled to capacity in 2015. For the first time, Pajarito Mountain was able to make snow and opened earlier than in recent years.

Some attempts to creatively use recycled water to make snow have ended up with unintended consequences. For example, the Snowbowl on the San Francisco Peaks in Arizona experimented with making one hundred percent of its artificial snow using treated sewage effluent from Flagstaff. However, the treated water still contained pharmaceuticals and other chemicals, which prompted protests and lawsuits by environmental groups and Native American tribes who consider San Francisco Peaks a sacred place.

Snowmaking is an essential component in ski resort operation that allows ski areas to open in drought years and to have extended ski seasons during wet years. Tourist dollars brought in by the ski industry are an important part of New Mexico’s economy. However, as competition for our scarce water resources increases, additional natural storage and water conservation measures will be needed at ski resorts to reduce concerns about water rights and impacts to the environment.

Additional reading
www.uvm.edu/~bwemple/pubs/shanley_wemple_law.pdf
www.ose.state.nm.us/Pub/TechnicalReports/TechReport-045.PDF

If you google the words “New Mexico” you’ll likely find images that depict our state as a high-desert wonderland. Views of red and yellow sandstones bathed in the summer sun, canyons cut by wild flowing rivers, and rugged mountains are all too common. Although these popular images accurately depict aspects of our geologic landscape, they often leave the impression of a state without a winter. However, in recent years New Mexico has become a destination for winter enthusiasts, a place where in a single day you can ski powder in the morning and play a round of golf in the afternoon. This issue of Lite Geology is dedicated to the role that geology plays in our winters, or something we like to call “cold geology.”

What causes the seasons?

The path our planet takes around the Sun is not a perfect circle. Our orbit is slightly flattened into an elliptical or oval-shape. Thus, there are times in our orbit when the Earth is closer to the Sun and other times when we are further away. The variation in the proximity of Earth to the Sun is not what causes our seasons, a common misconception. Instead, we owe the seasons to the fact that Earth’s axis (the imaginary line connecting the north and south poles that we rotate about once per day) is currently tilted at about 23.5 degrees relative to the plane of our orbit. In the winter months when the northern hemisphere is tilted away from the Sun, we receive less solar radiation, and the days grow shorter and colder.
In the summer months the northern hemisphere is tilted toward the sun, and we receive more solar radiation as the days grow longer and the weather gets warmer. This also explains why the northern hemisphere’s winter coincides with the southern hemisphere’s summer; when the north is tilted away from the Sun the south is tilted toward the Sun.

Operating on much longer timescales than seasonal fluctuations, and with more dramatic impacts, are glacial and interglacial periods when the average global air temperature either decreases or increases. These climate cycles are related to three variations in Earth’s orbit. The first is called eccentricity, or the degree to which earth’s orbit resembles a perfect circle. The second is called obliquity, which is variation in the tilt of earth’s axis between about 22.1 and 24.5 degrees relative to our orbital plane. The last variable is called precession or the wobble (like that of spinning top) of the earth’s axis relative to the fixed stars. The periodicity of eccentricity, obliquity, and precession are about 100,000 years, 41,000 years, and 26,000 years, respectively, and are collectively known as Milankovitch cycles (named after the Serbian geophysicist and astronomer Milutin Milankovitch). These cycles cause variation in the amount of solar radiation reaching our planet. Prolonged periods of decreased solar radiation cause glaciers to advance because of longer and more intense winters and limited melting during cooler summers. The last glacial period ended about 15,000 years ago. The evidence for this last glaciation is best seen in the erosive power of moving ice, which carves U-shaped valleys into mountain slopes. Evidence for some of the southernmost alpine glaciers in the United States can be found throughout northern New Mexico, such as in the Sangre de Cristo Mountains outside of Santa Fe. Although we are in an interglacial period now, the average global temperature is increasing significantly faster than expected from natural causes alone. Coupled with the observation that average CO₂ levels in the atmosphere are increasing rapidly, this has led an overwhelmingly large percentage of scientists to conclude that the burning of fossil fuels and release of greenhouse gases are currently accelerating global climate change.

How does geology influence winter weather?

New Mexico, like much of the western United States, is characterized by mountainous terrain. Mountains have a unique effect on local climate and an especially important role in New Mexico’s winter weather. As a weather system moves across the landscape, air masses are forced upward and over topographic barriers, a process called orographic lift. The air begins to cool (at a rate of about 3-degrees Fahrenheit per 1,000 feet of elevation), water vapor condenses into liquid water, and the droplets will form a cloud. If the rising air mass cools to below freezing temperatures, water droplets nucleate as ice onto dust particles. The falling ice crystals combine into larger particles and a snowflake is born. As long as the air mass below the snowflake is below or near freezing, the snowflake will make its way to the ground.

A multitude of geologic processes have been operating for millions (billions really) of years to create the high desert and mountains of New Mexico, which ultimately influence our winter weather. In particular, geologic
processes that encourage mountain formation have helped to shape all of our popular ski areas. Although too numerous for the scope of this article, a few of the more recent geologic events are worthy of discussion with respect to their impact on winter weather.

Perhaps most relevant to the link between New Mexico’s geology and winter weather is the ongoing formation of the Rio Grande rift. Rifting is an extensional process that causes two tectonic plates to move away from each other, or in the case of the Rio Grande rift, a single plate breaks into two segments that pull apart. Inevitably, two geologic events occur during rifting: extensional faulting and volcanism. Both of these processes form mountains.

During extension, the earth’s crust breaks and moves along normal faults. The crust on one side of the fault moves upward to form a mountain, while the crust on the opposing side of the fault moves downward to form a basin, commonly called a graben. The Rio Grande rift extends from central Colorado to northern Mexico, containing numerous rift basins and adjacent mountain ranges. The Sacramento Mountains, the Sandias, and the Sangre de Cristo Mountains are all examples of mountains uplifted along the flanks of the Rio Grande rift. Although somewhat debated, rifting might have begun as early as 36 million years ago and is still active today.

Volcanic activity related to rifting is another process of mountain building. During extension, the lithosphere (the layer beneath the crust) begins to thin like taffy getting pulled apart. The upper part of the asthenosphere (the layer of mantle beneath the lithosphere) rises to fill the void of the thinning lithosphere. The asthenosphere moves upward into regions of lower pressure, which causes the mantle to melt. These melts move through the crust and some eventually erupt as lavas and tuffs. Over time, erupted material can build large volcanic edifices. Similar to rift-flanking mountains, these large volcanoes affect weather patterns. Volcanism related to early extension began by about 36 million years ago and the youngest eruption is the 3,000-year-old McCarty’s flow south of Grants. Many of the popular winter destinations of New Mexico are related to volcanic activity. Mt. Taylor, a favorite location of cross-country skiers, is an extinct stratovolcano that was active between 1.3 and 3.8 million years ago. Much of the prized downhill skiing near Taos and Red River are on rocks related to the 25-million-year-old Questa caldera, a volcano that was subsequently uplifted by the Rio Grande rift.

New Mexico has a rich and colorful geologic history, fitting for a state that hosts a diverse suite of climates and activities for all to enjoy during the winter. Whether you are someone who prefers the warmth and sunshine of the valley floor or the winter storms of the mountains, you have geologic processes to thank for that landscape and the related weather.

It turns out that the cinder used by the New Mexico Department of Transportation (NM DOT) is a dark-colored scoria (a volcanic rock with a frothy or bubbly texture formed during explosive eruptions) or crushed up lava rock. Both are typically associated with basalts (the same kind of lavas you see at the Albuquerque Volcanoes, Valley of Fires near Carrizozo, or the Malpais near Grants). The cinder is typically applied with salt or immediately after salt. Cinder is ideal for traction because of its abundance and cheapness; New Mexico has lots of extinct basaltic volcanoes. As vehicles travel over the cinder, the tires grind up the ice, which is why the NM DOT specifications call for angular particles. Also, its dark color allows cinder to readily absorb sunlight and quickly melt snow and ice. In sunny New Mexico, the ability of cinders to warm up quickly allows less usage of highway salt than in the eastern and central U.S., which is nice for roadside plants.

Quarries at two extinct volcanoes supply much of the cinder for New Mexico’s roads. One is found 12 miles west of Santa Fe and is part of the Cerros del Rio volcanic field, which was primarily active between 2.2–2.7 million years ago. Not too far away lies well-preserved camel tracks on cinder-bearing volcanic sand. The second volcano, called Twin Mountain, is much younger (~40,000 years old) and lies 5 miles northwest of the little town of Des Moines (31 miles east of Raton). While driving in a wintery world of ice and snow, it’s ironic to think that this cinder came from hot and fiery volcanic eruptions in the geologic past.
Fun Facts about Ski Areas in New Mexico

Red River
Base: 8,750 feet
Summit: 10,350 feet
Vertical drop: 1,600 feet
Trails: 57
Average snowfall: 214 inches

Taos Ski Valley
Base: 9,200 feet
Summit: 12,481 feet
Vertical drop: 3,281 feet
Trails: 110
Average snowfall: 305 inches

Angel Fire
Base: 8,600 feet
Summit: 10,677 feet
Vertical drop: 2,077 feet
Trails: 80
Average snowfall: 210 inches

Pajarito Mountain
Base: 9,031 feet
Summit: 10,441 feet
Vertical drop: 1,410 feet
Trails: 40
Average snowfall: 160 inches

Santa Fe
Base: 10,350 feet
Summit: 12,075 feet
Vertical drop: 1,725 feet
Trails: 79
Average snowfall: 225 inches

Sandia Peak
Base: 8,678 feet
Summit: 10,378 feet
Vertical drop: 1,700 feet
Trails: 39
Average snowfall: 125 inches

Sipapu
Base: 8,600 feet
Summit: 9,255 feet
Vertical drop: 1,055 feet
Trails: 41
Average snowfall: 190 inches

Ski Apache
Base: 9,600 feet
Summit: 11,500 feet
Vertical drop: 1,900 feet
Trails: 55
Average snowfall: 180 inches

Ski Cloudcroft
Base: 8,400 feet
Summit: 9,100 feet
Vertical drop: 700 feet
Trails: 25
Average snowfall: 120 inches
Imagine skiing down a crater wall into the top of a magma chamber. Essentially, that is what you are doing when you spend the day at Red River. The geology of the Red River ski area is dominated by the presence of a geological structure that is coincident with the course of the Red River. It is a deep fault valley that represents the southern margin of the Questa caldera. This fault structure disrupts rock units that span the entire geologic time scale, except the youngest river and landslide deposits, and creates the steep terrane of the ski area. The wall of the caldera is to the south (of the north facing ski area) which consists of Precambrian metamorphic rocks and granites overlain by Tertiary age volcanic rocks. On the north side of the valley are the volcanic rocks that filled the moat of the great caldera. Granite intrusions invaded the volcanic rocks inside the moat and were the center of hydrothermal mineralization (notably molybdenum at the Questa Mine) around 25 million years ago. The circulation of hot mineralized fluids produced the profound “alteration scars” that line the valley, mostly on the northern side. Rapid weathering of these “scars” produces abundant regolith that periodically flushes down the canyons during heavy precipitation events, creating the dangerous debris flows that often close the highway during the summer monsoon season.
Taos Ski Valley is a place like no other. Located within the Taos Range of the Sangre de Cristo Mountains and reached via a twisting road up rugged Rio Hondo Canyon, New Mexico’s most famous ski area is a world class alpine ski resort that hosts some of the steepest terrain in North America. The rocks underpinning its slopes expose the roots of ancient precursors of today’s mountains. Among the oldest and highest grade metamorphic rocks in New Mexico, they are composed of 1.7-1.8 billion-year-old metamorphosed sedimentary and volcanic rocks that were subsequently intruded by granites 1.4 billion years ago. Over their history, these rocks have been buried, folded, faulted and experienced multiple episodes of uplift and erosion. Today, as a result of rift related extension that began about 25 million years ago, these high jagged peaks, including New Mexico’s highest (Wheeler Peak), tower 5,600 feet above the Taos plateau and are still rising. This renewed tectonism uplifted the mountains relative to the surrounding basins. The fault zone along the western flank of the Taos range has experienced over 7,000 feet of vertical displacement.

Rising from a base elevation of 9,321 feet to a high point of 12,481 feet at Kachina Peak, Taos Ski Valley’s precipitous north-northeast facing slopes offer an abundance of advanced expert only terrain. Until recently, reaching Kachina Peak required a long and arduous trudge up its notoriously steep ridgeline. With the opening of the Kachina Peak quad chair in 2015-2016, skiers and snowboarders can now zip to within a stone’s throw of the summit. This improvement realized a longtime dream of original owner Ernie Blake who founded the ski area in 1955, and is part of an ambitious new era of development that commenced with the sale of the ski area by the Blake family in 2013. The actual high point of Kachina Peak is marked by a windswept rock cairn composed of shattered metamorphic remnants of the mountain itself. From its dizzying rim, you see below you a huge arculate snow-capped bowl and steep chutes in the distance to your left. These topographic features are Pleistocene 15,000-year-old glacial cirques, scoured remnants of the last major ice age.

Standing in the crisp high desert mountain air, with light fresh powder gleaming like diamonds in the sun and gazing at breathtaking views of the alpine scenery and peaks stretching northward into Colorado, you realize there are few better places to be.

Angel Fire Ski area lies at the southern end of the picturesque high alpine Moreno Valley between two subranges of the Sangre de Cristo Mountains; the Taos Range to the west and the Cimarron Range to the east. The Sangre de Cristo Mountains were initially uplifted, folded and thrust faulted around 45-70 million years ago. Since that time the landscape has undergone additional faulting, volcanic activity, and erosion. The present day high alpine valley developed around 5 million years ago when extension caused high angle normal faults to form along the base of the surrounding mountains, resulting in an asymmetrical down dropped block, or half-graben, that tilts towards the east.

Driving into the valley from the north your eye is drawn to the rounded dome that dominates the skyline just southeast of the ski area. Rising to an elevation of 11,086 feet, Agua Fria Peak is the remnant of a shield volcano that erupted around the same time the valley formed. This type of volcano results when very fluid, basaltic lavas erupt and flow like honey from a vent, forming a low profile, gently sloping volcano similar to those of the Hawaiian Islands. It is the largest of several volcanic vents in the area that erupted around the time as the valley formed during latest Miocene to early Pliocene time (5 million years ago).

Prior to opening in the winter of 1967, herds of cattle roamed the terrain now occupying the ski area. Since that time it has evolved into one of New Mexico’s most popular ski destinations, offering...
Spectacular views and fresh air. Photos courtesy of Angel Fire Resort

Pajarito Mountain Ski Area

Matthew Zimmerer

Pajarito Mountain Ski Area is a special New Mexico ski destination. Of all our ski areas, Pajarito is the only one that can claim you are skiing down the flanks of a dormant supervolcano, better known as the Valles caldera. Pajarito Mountain and Valles caldera are located at the intersection of the Rio Grande rift and Jemez lineament, a southwest to northeast trending zone of crustal weakness that has been the focus of volcanic activity since the Miocene. The caldera is within the Jemez volcanic field, where there has been more-or-less continuous volcanic activity between 14 million years ago and the last eruption at about 68,000 years ago. The climax of volcanic activity happened at 1.2 and 1.6 million years ago when two supervolcano eruptions shook northern New Mexico. Valles caldera was formed during the younger super-eruption and the ski area is located on the topographic rim and flank of this supervolcano. The majority of the rocks in the ski area are a volcanic unit called the Pajarito Mountain dacite. This lava flow erupted about 3 million years ago, and thus is older than the formation of the caldera. The road up to the ski area passes by large boulders and outcrops of the Bandelier Tuff, which is the ash-flow tuff that erupted during the formation and collapse of the caldera. All the volcanic activity since the caldera eruption has been located within the caldera. The top of the ski area provides an excellent view into southeastern section of the caldera. Most of the small mountains within the caldera are piles of lava flows erupted from the

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Pajarito Ski and Summer Resort

The small ski resort of Sipapu is nestled deep within the heart of the massive Sangre de Cristo Mountains, a subrange of the Southern Rocky Mountains. A short 30-minute drive to the east from the ski area takes you out of the mountains and onto the Great Plains, whereas a similar drive to the west leads you into the Rio Grande rift. The resort itself is located along the Rio Pueblo, which is largely fed by the huge amounts of snow that the high peaks surrounding the ski area receive each winter. Some of the highest mountains of northern New Mexico, such as Jicarita and Truchas Peaks, are found just south of the resort. Exposed within the resort and along the Rio Pueblo are various types of sedimentary rocks deposited during the Pennsylvania and Permian Periods (about 300 to 250 million years ago). During this time, much of the southwestern United States was covered by extensive rivers and shallow seas. The sediments deposited by these systems were buried, lithified into rocks, and uplifted from near sea level to over 8,000 feet. When these rocks were vertically displaced is still somewhat of a debate. Early mountain building most certainly began about 70 million years ago during the Laramide Orogeny. However, uplift may have continued throughout the last several million years too. In addition to the beautiful geologic scenery of the area, the ski resort also holds the impressive title for the “longest ski season in New Mexico.” The resort typically opens before most ski areas and likewise, stays open for an additional week or so after the lifts have stopped running at other resorts.

Matthew Zimmerer

From the base of the ski area at an elevation of 8,600 feet you can ride the Chili Express to the summit at an elevation of 10,674 feet. As you ride the Chili Express you will ascend through snow covered slopes that overlie east dipping sandstones, siltstones and mudstones of the Permo-Pennsylvanian Sangre de Cristo formation. This 5,000-feet-thick sequence of sediments was deposited on ancient plains 300 million years ago, during a time when the climate was becoming drier and cooler. At the top of the ski lift the snow commonly hides a deposit of slightly welded ash flow capping the summit. The tuff was derived from an explosive volcanic eruption in which the particles were hot enough at the time of deposition to stick together or “weld.” The age of the tuff is not known. There is speculation that it may be related to formation of the Questa caldera at 26 million years ago, that it was erupted around the same time as the overlying 5-million-year old basalts, or that it may have originated from older vents now hidden beneath the basaltic flows. In any case, your vantage point at the top of the mountain offers spectacular views of the Moreno Valley and surrounding high peaks, including Latir, Stateline and Wheeler Peaks, as well as distant peaks in Colorado.
View from near the top of Pajarito Ski Area looking along a run and into the Valles caldera. The mountains in the center and right of the photo are part of the topographic rim of the caldera. The peak in the left of the photo is one of volcanic domes within the caldera. Photo courtesy of Michelle Bourret.

volcanic domes along the caldera margin. Redondo Peak, the highest peak in the caldera, is a resurgent dome that was uplifted by magma soon after the caldera erupted. While skiing down the slopes take in the distant views of the Sangre de Cristo Mountains and the Española Valley, an uplifted mountain and down dropped basin of the Rio Grande rift, respectively.

Ski Santa Fe

At 10,350 feet, Ski Santa Fe has the highest base elevation of all the New Mexico ski areas. Because of its elevation, the ski area is often one of the first to receive early season snow and likewise, can maintain a snowpack into the late spring. Ski Santa Fe owes its high elevation to thousands of small- to moderate-sized earthquakes that have slowly uplifted the eastern flank of the Rio Grande rift more than 5,000 feet above the valley floor. These peaks, collectively known as the Sangre de Cristo Mountains, are near the southern terminus of the Rocky Mountains, a mountain belt that extends another 3,000 miles to the north and into Canada. Erosion of the uplifted mountains has stripped away all of the sedimentary rock layers, exposing metamorphic rocks and granitic intrusions that underlie most of the state. These rocks were formed between 1.4 and 1.8 billion years ago, when the continent was just beginning to take shape. At this time, volcanic arc islands were colliding with what we now call North America. New Mexico may have looked somewhat similar to the islands and landscape of present day Indonesia. The igneous and metamorphic rocks in the ski area represent the deep roots of the volcanic arc, where magmas (i.e., the granitic rocks) were intruded into the country rock (i.e., the metamorphic rocks). The ski area has some of the best views of north-central New Mexico including the Sandia Mountains to the south and the 1.2 million-year-old Valles caldera in the Jemez Mountains on the west side of the Rio Grande rift. The high peak seen to the north from near the top of the ski area is called Lake Peak, which sits above Nambe Lake. This area is popular with backcountry skiers because of the steep, north facing slopes, which were formed by erosion from alpine glaciers during the last glaciation approximately 15,000 years ago.

An outcrop of metamorphic rock exposed near the ski area base at Ski Santa Fe. Similar rock types are exposed in the large cliffs throughout the ski area. Ski pole handle for scale. Photo by Matt Zimmerer.

View from the top of Lift 1 at Ski Santa Fe, looking southwest into the valley of the Rio Grande rift. The sign points to the prominent peaks in the distance, many of which are related to the formation of the rift. High peaks to the west (right-side of the photo) are part of the Jemez Mountains. Photo by Matt Zimmerer.
The geology of Sandia Peak Ski Area is a testament to the relentless power of geologic processes. The ski area is located on the eastern slope of the Sandia Mountains, and because of its proximity to Albuquerque, the area is quite popular for winter enthusiasts. The locale is also popular with geologists, particularly those interested in collecting marine fossils from the limestone outcrops along the Sandia Crest and on the eastern slopes. But how did marine fossils get to an elevation of over 10,000 feet in the middle of the desert? These sedimentary rocks were deposited in a warm shallow sea about 300 million years when New Mexico was much closer to the equator. Sea creatures were buried in lime muds after they died and those sediments eventually compacted and turned into limestone. Since the time of deposition, the North American tectonic plate has slowly made its way north to its current position. The Sandia Mountains and the marine fossils were uplifted relative to the adjacent valley approximately 10 to 20 million years ago as a result of crustal extension from the Rio Grande Rift.

The uplifted Sandia Mountains also expose 1.4 billion-year-old granites beneath the limestone layers. The contact between the granite and the limestone represents 1.1 billion years of missing time from the geologic record, something geologists call an unconformity. However, because this unconformity represents so much time, it is often referred to as “The Great Unconformity.”

Rain and melting snow have since carved small stream valleys into the bedrock. Some of the ski runs follow these erosional features. Looking west from the Sandia Crest you can see the rift valley, the extinct Mt. Taylor stratovolcano, and the dormant Valles caldera. The fantastic view to the east is of the San Pedro Mountains and the Interior (Great) Plains. This low-relief physiographic province, which has remained tectonically undisturbed (as compared to the continental margins), extends for hundreds of miles into the midcontinent. Keep in mind that as you look to the east you would have to travel eastward to the European Alps before crossing peaks as high as the one you are skiing down. The ski area can be reached by driving the Sandia Crest Scenic Byway (NM 536) on the east slope of the mountain or by riding the Sandia Peak Tramway up and over the Great Unconformity from the city. Whichever route you choose surely offers a geologically rewarding experience!
A block of metamorphosed and silicified Sierra Blanca volcanic rock exposed in one of the ski runs at Ski Apache (hammer for scale). This block of volcanic rock is “floating” in the main mass of intrusive granite that comprises most of the mountain. Photo by Fraser Goff.

Quarry on the north side of the highway at the entrance to Ski Cloudcroft. Rocks exposed belong to the Yeso Formation, a collection of interbedded sandstones, shales, and limestones. Many of the sandy units have the characteristic salmon color common in the Yeso. Yellow mudstones are also present along with blockier pieces of grey limestone (lower left). Most of these units also contain gypsum (yeso in Spanish) characteristic of the formation. Photo by Trevor Kludt.

Ski Apache

Sierra Blanca, the mountain on which the ski area is built, is the tallest peak in southern New Mexico at 11,981 feet above sea level. The geology of the Ski Apache area is dominated by the intrusion of the granitic Three Rivers stock into coeval volcanic rocks. Essentially, you are skiing in the “guts” of a magma chamber that intruded its own volcano. Most of the rocks at the ski area are the main mass of the intrusion although large xenoliths of volcanic host rocks are found in places. These xenoliths are typically silicified and altered by contact metamorphism. Although you are on an extinct magmatic system, the elevation of the mountain is not caused by the volcanic activity. The formation of the Rio Grande rift is responsible for the lofty heights as the range sits on the eastern shoulder of the rift.

Although not present in the ski area, some of the southern-most glacial features in the Rocky Mountains can be observed on the north face of Sierra Blanca viewed from the crest of the ski area. A shallow cirque is present and a number of glacial moraines can be discerned along the north fork of the Rio Ruidoso. While at the top, by looking west you peer into the Rio Grande rift from its eastern shoulder. Over 7,425 feet of relief can be experienced by gazing down into depths of the Tularosa Basin at the White Sands National Monument (4,000 feet) from the 11,425 foot perch at the top of the gondola run.

Ski Cloudcroft

The Cloudcroft ski resort is one of the southern-most ski resorts in the United States. The ski hill at Cloudcroft rests upon the Rio Bonito Member of the Permian age San Andres Formation and the Yeso Formation. San Andres contains gray carbonate rocks that are often fetid (smell like rotten eggs) when broken, while the Yeso consists of yellow mudstones with abundant gypsum, and salmon colored sandstones. These gypsiferous and organic-rich rocks were deposited as muds in a desert lagoon environment during the Permian. The entire mountain range was uplifted beginning 30 million years ago as part of the opening of the Rio Grande rift with the Sacramento Mountains forming the eastern shoulder. In the vicinity of the ski area, the San Andres rocks are gently folded into an anticline that roughly follows the crest of the range. Overall, the rocks in the Cloudcroft area all dip eastward (inclined toward Artesia) and represent the recharge zone of the great artesian aquifer source region of southeastern New Mexico. Groundwater has slowly dissolved the rocks along fractures and created pathways for snow and rain high on the mountains to slowly flow eastward, underground, and (at one time) erupt like geysers when well drilling intersected the artesian groundwater system in the Pecos Valley.
In bountiful snow-packed years the mountains across New Mexico provide endless trails of cross country skiing and snow shoeing. Only 6 resorts however provide groomed trails and a reliable snow pack throughout the winter months. One of these resorts, Enchanted Forest in northern New Mexico, lies 3 miles east of Red River. The trails for both skiing and snowshoeing meander through forests and mountain meadows and provide stunning mountain vistas. Animal tracks will reveal the wildlife around you, and you may be rewarded with sightings of squirrels, cottontails, deer, or other animals. Birds abound and can be heard chattering in the trees or seen flying among the trees and above the forest. Look for ravens, mountain chickadees, Stellar’s jays, nuthatches, woodpeckers, and many other birds. Buried beneath the pristine white snow is the story of the creation of the basement crust that underpins New Mexico; a story of upheaval, erosion, deposition, burial, heat and pressure that took place over 1.5 billion years ago. In the summer when the snow has melted the intrepid hiker can see the exposed metasediments, metavolcanics and intrusive granites from the Proterozoic era that tells the story of early crustal formation. Just down the road in the Red River valley, young Miocene (24 Ma) volcanic rocks rest on top of these Proterozoic rocks.

As you ski among the forests of Ponderosa Pine and Douglas Fir you might ponder on 1.5 billion years of time between the Proterozoic and Miocene. Where are the rocks between? There are three possible explanations for this enormous gap in the geologic record: 1) no rocks were deposited during this time, 2) rocks were deposited but are now covered by the Tertiary rocks, or 3) rocks were deposited but have subsequently been eroded away. Perhaps a combination of all three?

For more information on Enchanted Forest Resort and other cross country ski resorts:

http://www.enchantedforestxc.com/
http://www.cross-countryski.com/newmexico.html

Kelsey McNamara skiing with her dogs, Hoodoo and Neva, in the Magdalena Mountains. Photos by Matt Zimmerer.
Monitoring Avalanches in the 21st Century

Thousands of skiers and snowboarders flocked to the slopes this winter, but only a fraction of them sought adventure outside of the confines of ski areas. These backcountry snow-enthusiasts experienced pristine winter landscapes that come with a daunting risk: destructive avalanches, capable of reaching speeds up to 130 miles per hour. Luckily, new technologies are emerging that can help scientists and winter recreationalists alike understand the mechanics and conditions behind these unpredictable natural hazards.

Avalanches are a type of gravitational mass movement that can occur when snow accumulates on slopes steeper than 20-30°. They typically begin when snow cover slides along a mechanically weak zone, either between the snow and ground surface or within the snowpack. However, avalanches can initiate through a variety of motions, including falls, topples, and slumps. Large avalanches are capable of burying anything in their path. Rapid changes in snowpack strength, such as during or following a large snowstorm, are the most common natural triggers of avalanches.

Many mountainous areas in the western United States are prone to avalanches. Despite improved forecasts from local and regional avalanche centers and outreach campaigns urging backcountry enthusiasts to carry safety kits, the number of avalanche fatalities has actually risen over time. Thirty people perished in avalanches in the United States during the winter of 2015-16. The last recorded avalanche fatality in New Mexico was in 1996. Avalanches also have an economic impact—real estate and infrastructure in winter recreation destinations can suffer millions of dollars of damage from their destruction. Unfortunately, the inner mechanics and destructive force of avalanches have not been well understood.

Enter GEODAR (GEOphysical flow dynamics using pulsed Doppler radAR), a new type of radar system capable of resolving physical processes within avalanches. A 2016 study by Anselm Köhler of the Swiss Federal Institute for Snow and Avalanche Research, describes the use of this innovative technology. Köhler and his colleagues used the specially developed GEODAR system to monitor the inner dynamics of artificially triggered avalanches in the Sionne Valley of Switzerland.

GEODAR works by emitting radar pulses toward an active avalanche. Köhler and his colleagues mounted GEODAR on the opposite side of the valley from an avalanche test zone and affixed sensors recording parameters such as flow height, impact pressure, velocity, and density in the avalanche path. Because the radar emits wavelengths larger than the tiny snow crystals that make up the low-density power cloud that accompanies most avalanches, it can effectively “see through” to the underlying, higher density flows and surges. The radar waves can then penetrate up to 10 m of dry snow.

In addition to GEODAR, the authors obtained high-resolution vertical profiles from frequency-modulated, continuous-wave (FMCW) radars mounted in caverns underlying flow paths. They also conducted laser scanning from helicopter flights to obtain snow depths.

Together with GEODAR, these data helped the researchers understand how avalanches erode and deposit snow along their paths. Perhaps more importantly, the data showed that avalanches don’t consist of a single, massive flow but rather numerous surges of varying size, the largest of which may contain more mass than the initial avalanche. As a result, avalanches distribute snow and debris in a more uneven manner than previously recognized.

One important implication of the GEODAR dataset is that most avalanche models don’t accurately portray the mass and forces within avalanches, and therefore underestimate their potential to cause damage. Hopefully, with GEODAR as a guiding tool, researchers can better inform decision makers and the public of just how destructive avalanches can be.

References:

For more information about avalanches and avalanche safety:
Colorado Avalanche Information Center
http://www.avalanche.state.co.us/
Know Before You Go Avalanche Safety
http://kbyg.org/
Taos Avalanche Center
http://taosavalanchecenter.org/
Through the Hand Lens: Profile of a New Mexico Earth Scientist—Dr. Nelia Dunbar

When Dr. Nelia Dunbar accepted the position of State Geologist and Director of the New Mexico Bureau of Geology and Mineral Resources in October, 2016, she became the first woman to hold those titles. Nelia joined the bureau in 1992, but her first experience with New Mexico geology was in 1982, when she participated in a summer geology field camp in Silver City. She is a geochemist who completed both her M.S. (1985) and Ph.D. (1989) degrees at New Mexico Tech. Nelia’s web page features many of her research interests and professional contributions, and can be found here: https://geoinfo.nmt.edu/staff/dunbar/home.html

While she was growing up, Nelia’s family lived in the Middle East and North Africa. She discovered New Mexico, and fell in love with the arid southwestern region and geology during the above-mentioned summer field camp, and headed back to the area for graduate school. She and her husband, Bill McIntosh, also a geologist, live on a 25-acre farm in Lemitar, just north of Socorro, where they have been since 1992. The rural areas around Socorro are not only great for geology, but are also a great place to own horses, and ride horseback, which is another of Nelia’s lifelong interests.

What are your responsibilities as Director of the NM Bureau of Geology and State Geologist?

As director of the New Mexico Bureau of Geology and Mineral Resources, I am responsible for overseeing the research and service activities of the state geological survey. I work closely with many of the staff to keep current on their activities, and to provide advice when needed. I report to the president of New Mexico Tech, who I keep informed about bureau activities and events. I represent the bureau at the state legislature, to other state agencies, and at national meetings. My scientific background is mainly in the study of volcanic rocks, and I received funding for, and previously directed the electron microprobe laboratory, where I now act as advisor. I am an adjunct faculty member in the Earth and Environmental Science department at New Mexico Tech, where I have taught classes and advised graduate students.

It’s such an honor for me to hold the position of state geologist. I have a deep loyalty to our bureau and am doing my best to continue to advance the incredible work being performed there. We have a really wonderful staff of smart people, who are very creative and dedicated to understanding the geology of New Mexico. Many of our staff members are geologists, and we have many different fields of geology represented. The Bureau of Geology is a collaborative organization and people work well together.
Understanding earth science allows people to understand the world in which they live. When people understand the importance and complexity of their environment, they are more likely to appreciate and protect the landscape. Because New Mexico is such a geologically interesting state, I would say that geology is all around us, and defines many aspects of people's perception of our state. The path of the green-bordered Rio Grande, that runs the length of our state, is geologically controlled. Shiprock, Cabezon Peak, the Jemez Mountains, Capulin Peak, the Zuni-Bandera and Carrizo Malpais were all produced by volcanic activity. The iconic Sandia Mountains, Sangre de Cristo Range, and Hermit Peak are all composed, in part, of very old igneous rocks that have been uplifted and exposed by tectonic forces. White Sands, near Alamogordo, contains geologically formed gypsum sand dunes. The beautiful red, orange, yellow and white bluffs in the northwestern parts of our state were formed by deposition of sands, either as windblown dune fields, or in shallow marine environments, that later became rock.

Also, and equally important, understanding earth science allows our civilization to make appropriate and prudent use of geological resources. Much of our electricity is produced by burning oil, gas, or coal, all of which are geologically formed. Buildings in New Mexico, from traditional adobe structures, to modern concrete buildings, to roadways and bridges, depend on a wide variety of mineral resources, many of which can be found in our state. Also critically important for our water-limited state is that measuring, and appropriately using our groundwater resources requires a detailed understanding of the geology of the aquifers in which this water is stored. So, earth science, and earth scientists, impact people's lives on a daily basis, whether they know it or not.

The Bureau of Geology's community outreach efforts, particularly with New Mexico's public schools, are essential and critical to the Bureau's mission. We work with teachers, interact with the public, and host a mineral museum, bookstore, and several geological archives in order to serve the people of New Mexico. Visit the New Mexico Bureau of Geology website for more information about the programs and resources at the bureau. This short video provides an overview of the NM Bureau of Geology.

https://geoinfo.nmt.edu/index.html

Why is it important to inform the public about Earth Science?

Because I like solving puzzles! Here is a link to a video where I explain why I became a scientist: http://portal.knme.org/video/1498944874/

Why did you decide to become a scientist?

The Valles caldera in the Jemez Mountains of New Mexico provides an excellent laboratory to study the volcanic process that shaped the landscapes here. A group of K-12 teachers at a Rockin' Around New Mexico summer workshop in 2012 gather to hear about the eruption history of the caldera system before taking a tour inside the Valles Caldera National Preserve.
My first real earth science research project was done as an undergraduate, when I studied the geochemistry and mineralogy of volcanic ash from prehistoric eruptions of Mount St. Helens. My masters and doctorate work centered on explosive volcanism – understanding how volcanoes work. Throughout my career, my research has focused on volcanic ash, as well as understanding the driving forces behind the world’s most explosive volcanic eruptions. In addition to working on many volcanoes within New Mexico, including our own “supervolcano” in the Jemez Mountains, I have conducted fieldwork around the world, including extensive work in New Zealand, and 21 field seasons working on volcanoes in Antarctica, funded by the National Science Foundation. I’ve also studied volcanism in Ethiopia, Peru, Bolivia, and Ecuador.

What is your favorite geological feature in New Mexico?

Without a doubt, my favorite geological feature in New Mexico is the Jemez Mountain Volcanic Field, and particularly features associated with the very large eruptions that formed the Valles and associated Toledo calderas. This volcanic landscape not only has tremendous beauty, but holds clues that have allowed scientists to study and understand the world’s most powerful class of volcanic eruptions. During a very large eruption from the Jemez Mountains, the Rio Grande was completely dammed by pumice, in the area of White Rock Canyon. When the dam broke, a huge water and pumice flood coursed down the Rio Grande. There are pumice chunks the size of watermelons near Socorro from this event! Even though this was not witnessed by any humans, imagining what it must have looked like is one of my favorite New Mexico geological images.

Do you have any hobbies that relate to your love of geology?

As a child, I always wanted a rock polisher. A few years ago, my husband, Bill, got me one for my birthday. I loaded it up with all kinds of rocks, did the tumbling, and they turned out great! But, I somehow haven’t gotten back to it since then, so it’s currently a dormant hobby.

—Thanks to Thom Guengerich for contributions to this story.
The Mineral Museum is on the campus of New Mexico Tech in Socorro, New Mexico

9 a.m. to 5 p.m., Monday through Friday
10 a.m. to 3 p.m., Saturday and Sunday
Closed on New Mexico Tech holidays

Bureau of Geology building is located at the corner of Leroy Place and Bullock Blvd. on the campus of New Mexico Tech in Socorro. Visitor parking on the east side of the building provides convenient access to the Mineral Museum and Publications Sales office.

Mineral Museum

The bureau’s mineralogical collection contains more than 16,000 specimens of minerals 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.

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

Publication Sales Office

A wide selection of resources for teachers is available, including publications on New Mexico's geology. Many are written for the amateur geologist and general public.

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