Lite Geology

The Rio Grande Rift

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View from the Knife Edge in the Sandia Mountains looking northwest across the Santo Domingo basin, which is a part of the Rio Grande rift. The Sandia Mountains are a classic example of a rift-flank uplift. The Sandias expose Proterozoic granite capped by Pennsylvanian limestone. The Jemez Mountains volcanic field is on the skyline. *Photo courtesy of Adam Read.*

In This Issue…

New Mexico Bureau Of Geology & Mineral Resources a division of New Mexico Tech

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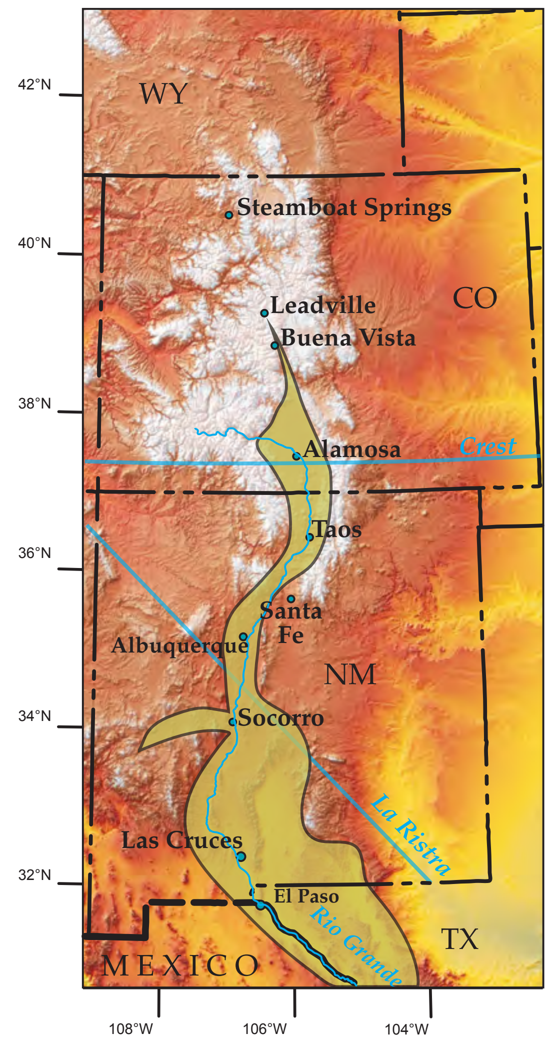
Conceptual Models of the Rio Grande Rift

Shari Kelley

The Rio Grande begins as an east-flowing stream in the San Juan Mountains in Colorado. The river turns near Alamosa, Colorado, and flows southward through a series of en echelon (slightly overlapping, east or west stepping), elongated basins that bisect southern Colorado and the state of New Mexico. The river turns southeastward again near El Paso, Texas, and ends in the Gulf of Mexico. The river's course through southern Colorado and New Mexico is controlled by a geologic feature known as the Rio Grande rift, which formed when Earth's crust stretched and thinned in an east-west direction starting about 36 million years ago (36 Ma). The stretching and thinning of the crust allowed hot mantle to well upward, creating youthful volcanoes, hot springs, and mineral deposits, as well as forming a topographically low area along which the river flows. Geologists working in New Mexico have long recognized the importance of the Rio Grande rift in localizing water and economic resources used by the region's native, Hispanic, and American inhabitants.

Our understanding of the geologic processes responsible for creating the basins and flanking mountains of the Rio Grande rift changed through the 20th century and continues to evolve today. Kirk Bryan from Harvard University, in his classic 1938 work relating water resources to the geology of New Mexico, was the first to recognize that the basins along the Rio Grande between central Colorado and El Paso, Texas, were filled with sandstone, siltstone, and conglomerate of the same general age. These sedimentary deposits were named the Santa Fe Formation (now called the Santa Fe Group) for exceptional exposures of these deposits north of Santa Fe. Bryan referred to the aligned elongated valleys along the river as the Rio Grande depression. He realized that the basins are often fault bounded, and he noticed an asymmetry in some basins, particularly the San Luis Basin and the basins near Socorro.

Vincent Kelley, a legendary geologist who worked at the University of New Mexico between 1940 and 1970, later documented that the valleys of the Rio Grande depression are bounded by northerly striking normal faults, which form when an area is under tension. This caused the valleys to drop down and the flanking mountains to rise relative to one another. The down-dropped blocks along the Rio Grande depression, called grabens, contain accumulations of sediments washed from the surrounding highlands that are much thicker than comparable structures observed in a province known as the Basin and Range in neighboring Arizona. Kelley suggested that the depression along the Rio Grande "structural belt" was due to "many miles" of horizontal, east-west directed, tensional displacement. In 1952, he was the first to propose that "deep-seated rifting in late Tertiary time probably is the underlying cause of the en echelon basins and uplifts which constitute the Rio Grande depression."

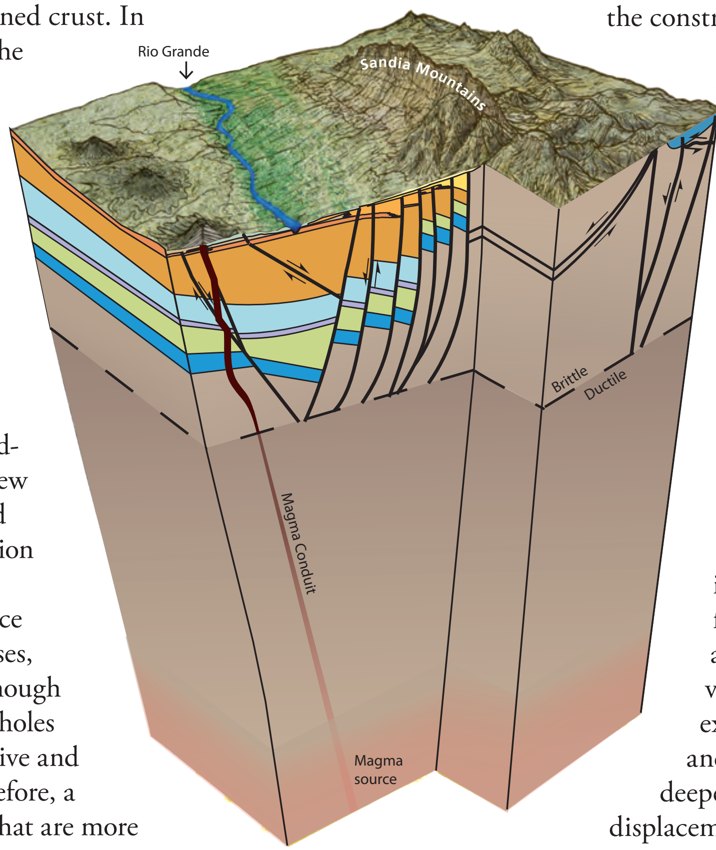


Map of the Rio Grande rift (gold shaded area along the Rio Grande). The CREST and LA RISTRA seismic lines are shown in blue.

Charles Chapin, who later became the director of the New Mexico Bureau of Geology and Mineral Resources, was one of the organizers of the annual New Mexico Geological Society fall field conference in 1971 in the San Luis Basin of Colorado. Chapin asked Vincent Kelley to contribute a paper about the Rio Grande rift to the field conference guidebook, but Kelley was too busy. Consequently, Chapin decided he would write a paper on the topic. In his typical fashion, Chapin dug deeply into the literature about rifts worldwide, and he drew upon his extensive experience as a field geologist in New Mexico and Colorado to write a definitive paper that outlined the boundaries of the Rio Grande rift. Chapin's research inspired increased interest in understanding the mechanisms driving rift formation worldwide, in part motivated by the fact that water and geothermal resources and mineral deposits (fluorite-barite) are commonly associated with modern rifts. The East African rift, the Baikal rift in Russia, and the Rhine graben in Germany are among the extensional features subjected to much scrutiny during the latter part of the 20th century. A great debate ensued concerning the origin of rifts.

Some researchers thought that rifts form by **active** upwelling of the mantle into the crust, which causes the overlying crust to bulge upward and crack under tension. Other scientists thought that rifts form more **passively** due to far-field extensional stresses cracking the crust (forces acting at plate boundaries hundreds of miles away), causing the mantle to later well up to replace the thinned crust. In either case, thinned crust and the presence of hot mantle at shallow depths cause basalt-rhyolite volcanism in the vicinity of rifts. Much of the early work, both in the Rio Grande rift and worldwide, was based on geologic observations made at the surface.

Our view of the rift basins along the Rio Grande changed starting in the 1970s with the addition of new technology and new data. Shell Oil Company drilled several deep petroleum exploration wells in the Albuquerque Basin, providing the first direct evidence of the rock types, unit thicknesses, and structure in this basin. Although we learned a lot from these dry holes (no oil!), drilling wells is expensive and provides limited coverage. Therefore, a number of physics-based tools that are more cost effective have been used to indirectly image the basins and the crustal structure of the Rio Grande rift. Seismic methods are based on the time it takes for energy from an earthquake, an explosion, or a vibrating truck to reach a receiving instrument. Seismic refraction experiments measure crustal thickness, and seismic reflection data can be used to detect buried rock layers, igneous intrusions, and faults. Measurements of minute changes in Earth's gravitational field can be interpreted to estimate basin depth and locate buried faults. Subtle variations in Earth's magnetic field associated with the presence of certain iron-bearing rocks are used to identify buried faults and volcanoes. Precise measurements of temperature as a function of depth combined with measurements of the relative ability of rocks to conduct heat are used to determine how much heat is emitted near the surface. These heat flow measurements are used to identify geothermal areas and buried, young igneous intrusions.



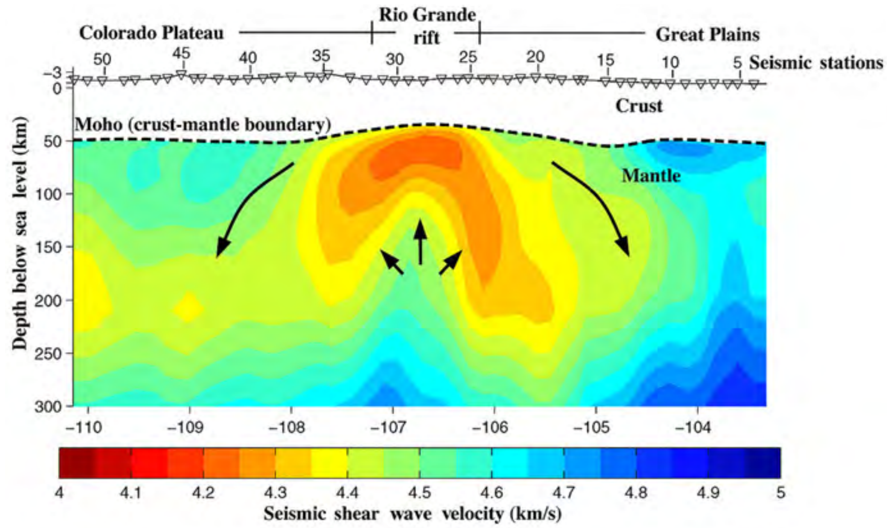
Simplified block diagram of the Albuquerque Basin half-graben modified from cross sections made by Sean Connell. The brown is Proterozoic basement; the blue and green layers are Paleozoic and Mesozoic sedimentary rocks, respectively; the purple and blue layers are older Tertiary sedimentary rocks; and the units colored in various shades of orange and yellow are rift-fill sedimentary rocks. The horizontal dashed line depicts the brittle-ductile transition in the middle of the crust. Rocks above the boundary are relatively cool and break brittlely along faults during extension. In contrast, rocks below the boundary are just a little bit hotter and the rocks flow more plastically during extension. Geologists think that faults end in this transitional zone, which typically occurs at depths of 6 to 9 miles (10 to 15 kilometers) in the crust.

Finally, advances in the technology used to determine when a rock formed have been key in figuring out when rifting began and the rate of its development. Kirk Bryan relied on fossils in sedimentary rocks to assign rock ages, whereas Vincent Kelley had access to early radiometric dating techniques. Charles Chapin facilitated the construction of a modern $^{40}Ar/^{39}Ar$ geochronology laboratory at New Mexico Tech. As a result, hundreds of high precision dates for volcanic rocks in Colorado and New Mexico are now available, which have helped us understand the timing of rifting processes.

What have we learned about the Rio Grande rift? First, seismic and gravity data and deep drilling have revealed that the basins of the Rio Grande rift are deep, in places as much as 20,000 feet (6.1 kilometers) deep, and asymmetric. The asymmetry varies from basin to basin. For example, the San Luis Basin and the Albuquerque Basin are deepest and have the largest fault displacements on the east side of the basin, whereas the Española Basin is deepest and has the largest fault displacements on the west side. As a result, rock layers are generally tilted to the east in the San Luis and Albuquerque Basins and to the west in the Española Basin. The alternating tilt of the Española Basin and the basins to the north and south is accommodated by northeast-striking faults. These transfer faults are referred to as accommodation zones. Furthermore, broad basins like the San Luis Basin and the Albuquerque Basin appear at the surface to be single basins, but gravity, magnetic, and seismic data indicate that each of these basins actually consists of at least three sub-basins. These revelations about the deep architecture of the rift basins have vastly improved our ability to locate, characterize, and manage water resources in New Mexico and Colorado.

Second, the Rio Grande rift has experienced quite modest extension (7%), although locally in the Socorro area, the extension is as high as 200%. Dates on volcanic rocks indicate that rifting began at about 36 Ma near Las Cruces and at about 22 Ma near Albuquerque. In other words, the initiation of rifting seems to get younger toward the north. Furthermore, the early rift basins were broad and shallow. The rift narrowed and the basins deepened dramatically between 14 and 16 Ma. The amount of rifting has decreased in the last 5 Ma.

Third, seismic data indicate that the crust beneath the Rio Grande rift near the latitude of Socorro, New Mexico, is 22 miles (35 kilometers) thick, much thinner than the crust beneath the Great Plains to the east and the Colorado Plateau to the west (31 miles, or 50 kilometers). Seismic methods have detected a thin magma body beneath the rift at a depth of 11 miles (18 kilometers) just north of Socorro. Although the heat flow is high along the Rio Grande rift, anomalously high heat flow in Colorado and northern New Mexico is not restricted to the rift. The latter two sets of observations have bearing on our evolving models of rift development.



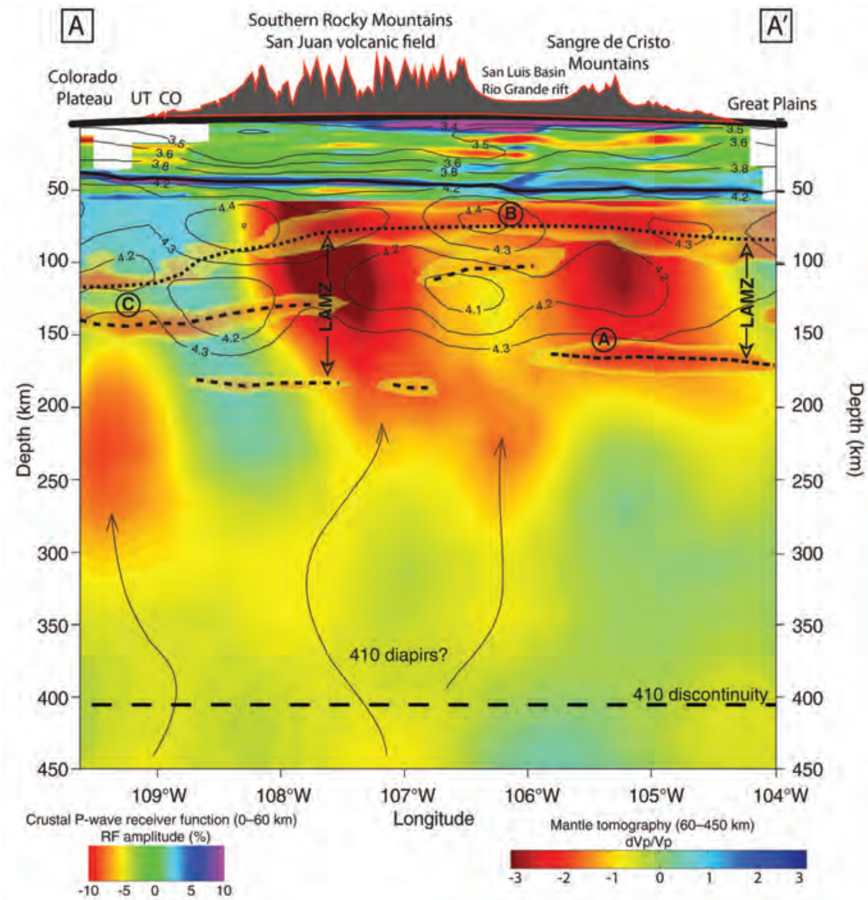
Tomographic cross section along the LA RISTRA seismic line beneath the Rio Grande rift. The orange and yellow areas depict parts of the mantle that are seismically slow. These areas are interpreted to represent hot, upwelling mantle material. *Image from Wilson et al. (2005).*

Our perceptions of rifting are shifting again as a consequence of the acquisition of new data using seismic tomography, which uses seismic energy from natural earthquakes to map the velocity structure of the interior of Earth, particularly the upper mantle, to depths of 254 miles (410 kilometers). Seismic waves travel quickly through parts of the mantle that are dense, and more slowly through parts of the mantle that are less dense. The density of the mantle is affected by chemical composition and temperature. When geophysicists identify a part of the mantle where the seismic waves slow down, that area is usually colored red on maps or cross sections, whereas areas of higher velocity are colored blue. Now the trick is interpreting the physical characteristics of the seismically slow mantle because we cannot go down there to collect samples. Is the area seismically slow because it is hot, or does the area contain partially molten rock or other fluids? Is the seismically slow area made up of a low-density rock type? In geologically active areas like the Rio Grande rift, we tend to interpret the red, low-velocity areas on maps and cross sections as hot or partially molten rocks. A large seismic tomography experiment called LA RISTRA was run from central Utah to southeastern New Mexico across the Colorado Plateau, the Rio Grande rift, and the Great Plains. The resulting cross section of S-wave velocity clearly shows that the crust is thinned in the rift and appears to show that hot mantle is moving upward under the Rio Grande rift, especially along the eastern margin adjacent to the Great Plains. The upwelling is restricted to the shallow mantle.

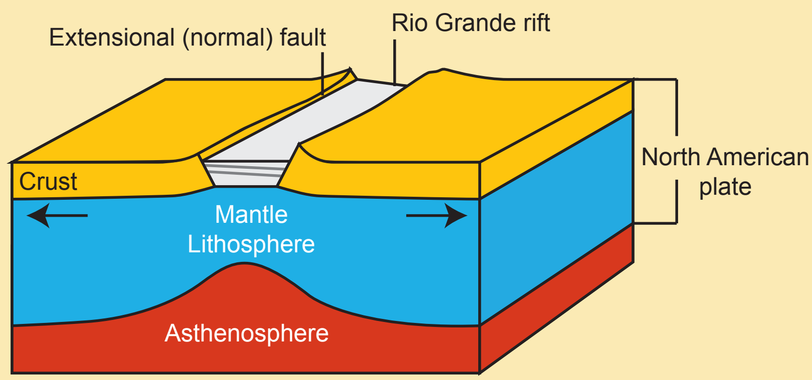
Recent GPS surveys, which detect small changes in horizontal and vertical distances between geographic points, indicate that the North American continent is generally moving west due to broad-scale plate tectonic forces, but the area on the west side of the rift is moving west faster than the Great Plains to the east. This differential velocity between the east and west sides of the rift is causing the rift in New Mexico and southern Colorado to widen at a measured rate of 1 inch (2.5 centimeters) every 40 years. The widening is not restricted strictly to the rift, but it also affects the western Great Plains and the eastern Colorado Plateau. The combination of the seismic tomography and GPS data suggest that the rift is forming because the region to the west of the rift travels west more quickly than the region to the east, and the mantle is passively upwelling into the thinned, stretched rift.

Just when we think we have it all figured out, we collect another batch of data that causes us to rethink our interpretations. New seismic tomography data from another experiment called CREST in southwestern Colorado reveal a complex image of the mantle and indicate that the crust is thinned across a broad region outside the surface expression of the Rio Grande rift. The seismically slow parts of the mantle are NOT beneath the Rio Grande rift as expected, but they are located to the east and west of the accepted boundaries of the rift. Researchers are puzzling over the new data. The most likely explanation is that pieces of lithosphere below southwestern Colorado detached starting about 25 Ma and slowly descended into the deep layers of mantle. These lithospheric pieces hit a boundary in the mantle at about 254 miles (410 kilometers), causing deep mantle material to move up during the last 10 Ma, overprinting the shallow mantle signature of the rift. Stay tuned as our thoughts about rifting advance as new data sets are gathered.

Tomographic cross section from CREST data showing low relative P-wave velocity beneath the San Juan Mountains and the Sangre de Cristo Mountains in southern Colorado. Note that the Rio Grande rift is not clearly defined in the mantle on this cross section. The arrows depict a possible <10 Ma disturbance of the boundary in the mantle at a depth of 254 miles (410 kilometers) that has caused hot material to rise and overprint the mantle signature of the Rio Grande rift. The lithosphere-asthenosphere mixing zone (LAMZ) is shown as dashed lines. Mantle xenoliths are pieces of mantle brought to the surface during volcanic eruptions and thus are valuable for constraining the chemical composition of the mantle. Point A shows the interpreted depth of origin of Devonian diamond-bearing xenoliths from Stateline, Colorado; B= mantle xenoliths in the eastern Colorado Plateau region; C= xenoliths from Navajo volcanic field. *Image from Karlstrom et al. (2012).*



Earth's Crust-mantle Structure Shari Kelley



Generalized block diagram showing the components of Earth's crust and upper mantle.

The plates of plate tectonics include both the crust and the uppermost mantle. This combined section is called the lithosphere. The continental crust that underlies New Mexico is typically 19–31 miles (30–50 kilometers) thick and is made of granitic to mafic rock with a density of 2.7 grams/cubic centimeter. The uppermost mantle is made of dense rock 3.3 grams/cubic centimeter of mafic composition; this portion of the mantle is relatively rigid or stiff. The crust and the lithospheric mantle are separated by a boundary called the Moho. On average the lithosphere is about 62 miles (100 kilometers) thick. The lithospheric plates move around on a more plastic part of the mantle called the asthenosphere. In tectonically quiet areas, the structure of the mantle is well ordered and the lithosphere-asthenosphere boundary is sharp and easy to identify on tomographic cross sections. However, in tectonically active areas like the Rio Grande rift, the lithosphere-asthenosphere boundary is not sharp, but is a broad zone, as depicted in the last two cross sections of the previous article.

How Do We Know What's Beneath Earth's Surface? Douglas Bland

We can't drill down to the center of Earth, or even beyond the thin crust to investigate the mantle below. So, we must use indirect methods to figure out the structure, composition, and variations in the crust and upper mantle. These five investigative tools help scientists figure out what lies beneath the surface of Earth.

Seismic Reflection and Seismic Refraction are two seismic techniques that measure the travel time of waves of seismic energy generated from shots (such as explosions, vibrations, or weight drop) on Earth's surface. The waves travel through the subsurface, and then back to arrays of highly sensitive ground motion detectors (geophones) on the surface. In the subsurface, the seismic waves encounter interfaces between materials with different seismic velocities, often created by geologic materials or rock layers of different densities. A portion of each seismic ray that strikes a density interface is **refracted** (bent) into the underlying layer or along the interface, and the remainder is **reflected** (bounces) directly back to the surface. The geophones measure differences in the travel times of the seismic rays caused by the interfaces, which are then developed into two-dimensional or three-dimensional images showing underground structures and layers. Seismic refraction surveys are much less costly, but reflection surveys generally have better resolution and are more effective for deeper targets. Both are limited to the upper crust of Earth.

Seismic Tomography is an imaging technique that uses seismic waves generated by earthquakes to create computer-generated, three-dimensional images of Earth's interior, including deep into the mantle. Man-made explosions in boreholes can be used for more localized investigations. Scientists compile digital earthquake records from hundreds of seismometers all over the world to calculate the average speed of different types of seismic waves. Then, they map out regions where the waves traveled slower or faster than average. Waves travel faster through cold, stiff materials, like a tectonic plate subducting into the mantle, and slower through warmer materials, like hot molten rock rising toward the surface.

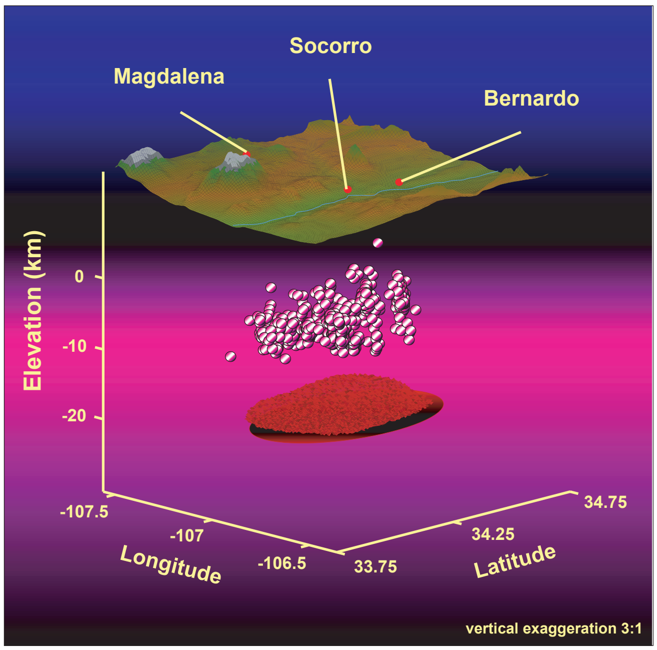
Gravity Surveys use instruments that contain a tiny mass attached to a sensitive spring to measure slight differences in the strength of Earth's gravitational field. This field is affected by the density of subsurface rocks, among other factors. Different rock types have different densities. For example, igneous rocks in general are more dense than sedimentary rocks, so the tiny mass in the instrument will be pulled downward more strongly above a buried igneous rock compared to a buried sedimentary rock. Measurements are taken in grid patterns, which are transformed into maps showing density variations. These are used to model images of the subsurface geometry of different rock bodies, including location, size, and rock type.

Aeromagnetic Surveys use a magnetometer aboard or towed behind an aircraft to measure minute differences of Earth's magnetic field. These differences are caused in part by differing concentrations of magnetic minerals in Earth's crust, most commonly the iron mineral magnetite. Because rock types differ in their content of magnetic minerals, magnetic maps can be created that allow visualization of the geologic structure of the upper crust in the subsurface, particularly the geometry of igneous intrusions or orebodies, and the presence of faults and folds.

Earth Briefs—The Socorro Magma Body and the 2009 Earthquake Swarm Douglas Bland

The Rio Grande rift that divides New Mexico from Colorado to Texas has many fascinating geologic elements. The Rio Grande valley and its flanking mountains, volcanoes, and earthquakes are some of them. One intriguing feature is the Socorro Magma Body.

Anecdotal information and records show that many of the earthquakes felt in New Mexico have been concentrated in a relatively small area near Socorro, in the Rio Grande rift. In fact, the two strongest New Mexico earthquakes in the past 150 years occurred here in 1906. At magnitude 6.0, they caused significant damage to buildings in Socorro and were felt as far away as El Paso and Las Vegas, New Mexico. This area of concentrated seismic activity is called the Socorro Seismic Anomaly (SSA). It covers less than two percent of the state's land area, but accounts for about 45 percent of New Mexico earthquakes above magnitude 2.5. What is causing these quakes?



Three-dimensional cross section showing the Socorro Magma Body (red pancake), location of earthquakes from 1975 to 1995, and the land surface. *Image courtesy of New Mexico Tech, Earth and Environmental Science Department.*

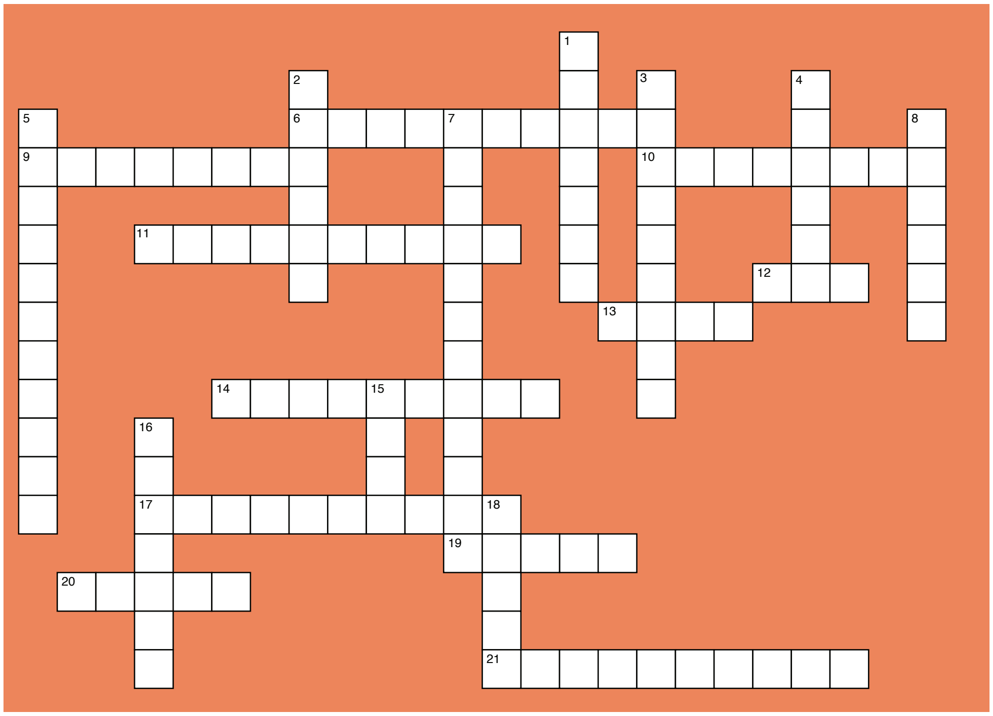
The land surface above the SSA is rising at a rate of an inch and a half every 10 years. Information from multiple sources, including observations of seismic waves from distant earthquakes, indicates a body of magma exists under the SSA. It is about 1,300 square miles in aerial extent but only about 500 feet thick, and is located about 11 miles deep. This uplift and other data indicate that fresh magma is being injected into the Socorro Magma Body through a conduit from the mantle below. This creates stress on the overlying brittle rocks, which break and cause earthquakes. Material within and just above the body is molten or lubricated by hot fluids, so magma and rock in this region can move without causing earthquakes. Scientists believe that magma upwelling from the mantle on a much larger scale is partly responsible for the evolution of the Rio Grande rift, where many volcanoes and volcanic rocks are found.

In August and September 2009, 431 small earthquakes ranging in magnitude from 1.0 to 2.5 shook the Socorro region over 26 days. Such swarms are not uncommon here; swarms occurred in 1849–51, 1904, 1906–7, 1959, 1983, 1989–90, and 2005, and other years. Conventional wisdom held that these swarms were likely related to magma movement associated with the Socorro Magma Body. However, swarms are also common in highly fractured rocks of continental rift zones that are not the direct result of magmatic movement. Data analysis of the 2005 and 2009 Socorro swarms points to a series of microquakes caused by fluid movement through brittle rock overlying the Socorro Magma Body that has been extensively fractured due to extension across the Rio Grande rift and uplift of the region. Previous magma bodies in the same general area as the current one probably caused the high heat flow and uplift seen today.

Future earthquake swarms near Socorro are a virtual certainty, possibly including some damaging quakes. But the eruption of a new volcano here in our lifetime is unlikely. In geologic time, however, anything is possible.

Crossword Puzzle

Douglas Bland and Shari Kelley



Across

6. measures crustal thickness
9. tomography experiment from Utah to NM
10. basin with rocks tilting west
11. detects igneous intrusions
12. tomography color for low-velocity rocks
13. tomography color for high-velocity rocks
14. New Mexico river
17. not symmetric
19. upper layer of Earth
20. graben in Germany
21. maps velocity structure of Earth

Down

1. physics-based imaging tools
2. down-dropped block
3. offset parallel structures
4. hot material beneath the crust
5. basin with rocks tilting east
7. survey to identify buried faults
8. Russian rift
15. region of stretched, thinned crust
16. variations of this measure basin depth
18. tomography experiment in Colorado

The answers to the clues are located in the Rio Grande rift article in this issue of *Lite Geology.*

The solution to the puzzle is found on the last page of this issue.

New Mexico's Most WANTED MINERALS

Virgil W. Lueth

OLIVINE

Mantle xenolith with large crystals of forsterite olivine, black grains of enstatite, and small, bright blue-green grains of chrome diopside. This specimen and one carat, faceted crystal of forsterite (peridot) are from Kilbourne Hole, Doña Ana County. *Photograph courtesy of Virgil Lueth,* New Mexico Bureau of Geology museum specimen #13114—gift of Donald Moore.

DESCRIPTION: Olivine is the name given to a group of silicate minerals comprising a doubly charged cation and silica tetrahedron with the general formula of X_2SiO_4, where X is Mg, Fe, or Ca. The most common is magnesium-rich olivine, forsterite, which is a beautiful green. Less common iron-rich olivine is called fayalite, which varies from yellow-brown to black. A very rare related mineral is called monticellite [$Ca(Mg,Fe)SiO_4$], which is typically colorless to gray. Olivine exhibiting crystal faces and terminations is rare and is typically metamorphic. It has a Moh's Hardness of 7.0. It has a white streak when tested on unglazed porcelain. It has a very weak cleavage and usually a conchoidal (curved) fracture, like glass.

WANTED FOR: Olivine is very refractory (hard to melt). A rock composed entirely of olivine, called dunite, is mined and crushed for metal castings. Faceted, clear, and gemmy crystals of forsterite, called peridot, are used in jewelry. The rare varieties, fayalite and monticellite, are collected as curiosities.

HIDEOUT: Forsterite is most commonly found in mafic to ultramafic rocks as phenocrysts (large crystals). Masses or clots of forsterite olivine are sometimes found in basalt as xenoliths (foreign pieces of the mantle brought up by magma). Rocks composed almost entirely of forsterite, called dunites, are associated with ophiolites, slices of the ocean crust that sometimes include pieces of the mantle. At the opposite end of the magmatic spectrum, fayalite is found only in felsic intrusive rocks, like obsidian. Granitic intrusions into dolomite may cause contact metamorphic formation of forsterite or monticellite crystals.

LAST SEEN AT LARGE: Forsterite, the most common variety of olivine in New Mexico, can be found in many of the basalt flows around the state as glassy dark phenocryst grains. In northwest New Mexico forsterite crystals are associated with the diatremes of the Navajo volcanic field where ants pile green olivine grains around their holes along with red pyrope garnets. Olivine xenocrysts are notable from maar volcanoes in the Kilbourne Hole area of Doña Ana County and the basalts north of T or C, east of Elephant Butte Lake. Fayalite is reported from the Cornudas Mountains, Otero County, and the Jemez Mountains in Sandoval County. Monticellite has been identified in the Tres Hermanas Mountains, Luna County.

ALIASES: Forsterite, Fayalite, Peridot.

New Mexico's Enchanting Geology

Douglas Bland

WHERE IS THIS?

Photo courtesy of Adam Read.

This photo shows several features of the Rio Grande rift in the Albuquerque area. It was taken along the crest of Sandia Peak, east of Albuquerque, looking northwest. The Sandia Mountains are an uplifted crustal block on the eastern boundary of the Rio Grande rift. The rock in the core of the range is granite that's 1.4 billion years old, here visible as massive tan cliffs. Above the granite are linear limestone beds of Mississippian and Pennsylvanian age, about 300 million years old. These two rock types meet at the "Great Unconformity," where rock layers representing more than a billion years (almost a quarter of all Earth's history) were eroded away before the limestone was deposited.

The valley below is the Rio Grande valley just north of Bernalillo, stretching toward Santa Fe on the right side of the photo. The valley represents the center of the Rio Grande rift. It is filled with as much as 20,000 feet of sediments washed off the surrounding mountains and carried down the Rio Grande. On the left side of the photo, the Jemez reservoir is visible. This reservoir is not designed to permanently impound water but contain flood flows of the Jemez River; therefore, it is often dry.

The Jemez Mountains form the western border of the rift, seen here on the horizon in the center of the photo. Surface volcanism is a common feature of continental rift development, as magma wells up from the mantle deep inside Earth. Two gigantic volcanic eruptions around 1.6 and 1.2 million years ago produced most of the surface rocks in the Jemez Mountains. Geologically speaking, many of the volcanoes along the Rio Grande rift are young, and future eruptions are likely.

 Richard Chamberlin

Using Block Models to Illustrate Crustal Extension in the Rio Grande Rift

Grade Level: Grades 9–12

NM Science Standards: Listed at end of this article.

Objectives:

Students will:

1. Become familiar with the mechanical behavior (deformation characteristics) of cold crustal rocks near Earth's surface compared to hotter rocks at depth.

2. Use block models to illustrate how the cold upper crust within the Rio Grande rift accommodates ductile stretching in the underlying hot lower crust.

Teacher Background:

This lesson examines differences in the behavior of hard and brittle rocks near Earth's surface and deeper rocks at elevated temperatures and pressures, which make them ductile (deformable and stretchable), more like taffy. Taffy is a familiar example of how a substance deforms differently depending on temperature and how fast it is deformed. Hit cold taffy with a hammer, and it will shatter (similar to the block model). Pull warm taffy slowly, and it will stretch like a rubber band. Heat taffy to its melting temperature, and it will flow like syrup.

How can geologic processes (plate tectonics) *stretch* "hard" crystalline rocks, such as granite? The lower two-thirds of the 18-mile- (30-kilometer-) thick crust *under* the Rio Grande rift is hot enough to stretch like taffy. The uppermost 6 miles (10 kilometers) of the crust in the rift is relatively cold and brittle, so it accommodates extension by breaking into large blocks about 6 miles thick (vertical dimension) and of variable width (horizontal dimension) and of variable geometry. The continental crust to the east (Great Plains) and west (Colorado Plateau) of the rift axis is colder, thicker, and stronger, so the rift margins resist breaking into small blocks and generally move like wide coherent "rafts" (small tectonic plates).

To mimic the geologic process of rifting reasonably, our block models must be scaled proportionally to dimensions and angular relationships similar to that of the real world. Modes of extension in the cold and brittle upper crust of the Rio Grande rift are fundamentally controlled by the geometry of fault blocks that accommodate stretching. Tall and narrow blocks that are bound by steeply inclined parallel faults commonly accommodate extension by sliding and tilting like dominoes. Geologic maps and seismic profiles show that tilted blocks in the rift are mostly about 1.25–3 miles (2–5 kilometers) wide (east-west dimension). Small earthquakes in the Socorro region of the rift occur at depths that do not exceed 6 miles (10 kilometers), which is interpreted to be the approximate maximum vertical dimension of actively extending fault blocks. Faults are planes of shear failure that form at about 30° to the maximum compressive force, which in this case is gravity. In other words, extensional faults prefer to initiate at 60° from the horizon. Symmetrical keystone-shaped blocks, bound by inward-dipping faults, are called grabens, which can accommodate moderate amounts of extension by subsiding into the ductile middle and lower crust. Blocks bound by outward-dipping faults (not modeled here) tend to rise and are called horsts. Margins of the Rio Grande rift, such as the Sandia Mountains, and wide horst blocks, such as the Caballo–Jornada del Muerto–San Andres block, are commonly up-warped (bent upward) by hot buoyant rocks in the ductile middle crust. Geometrically controlled fault-block response to gravity and thermally induced buoyancy of large ductile rock masses are two of the main forces that cause uplift and subsidence in rifts. The forces that drive horizontal plate motions are a continuing topic of research. Note that one relatively wide tilted fault block can form a sedimentary basin on the low side (often called a "half graben") and a tilted mountain block on the high side (almost never called a "half horst"). The main article in this issue provides a more detailed explanation of the rifting process. Examples of the above features with Google Earth coordinates are available at: **http://geoinfo/education/exercises/sanlorenzo/home.html**

Method Overview:

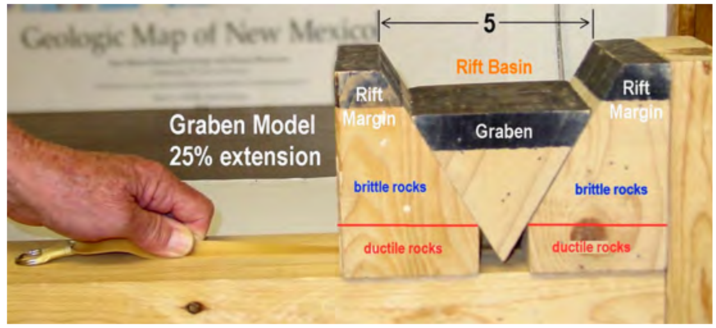
Here is a link to an animation by W.W. Norton that illustrates the entire rifting process, from unbroken continent to spreading sea floor.

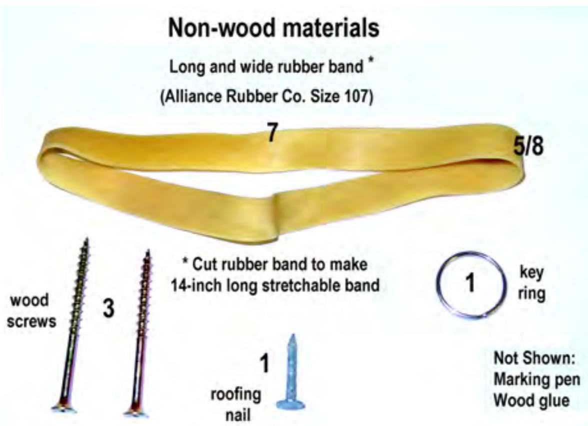
http://www.wwnorton.com/college/geo/egeo2/content/animations/2_7.htm

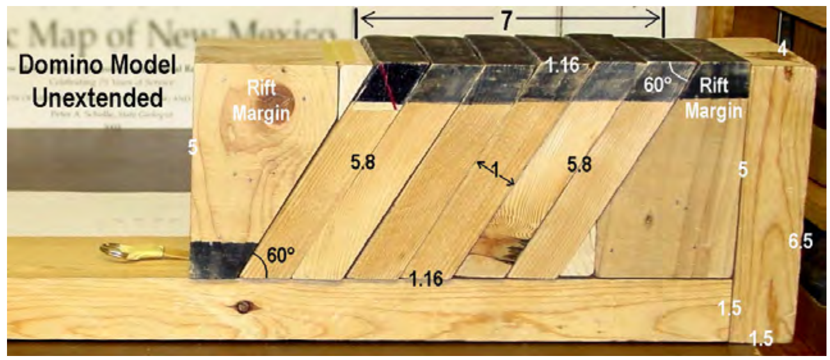
Our fault-block model illustrates only part of the process.

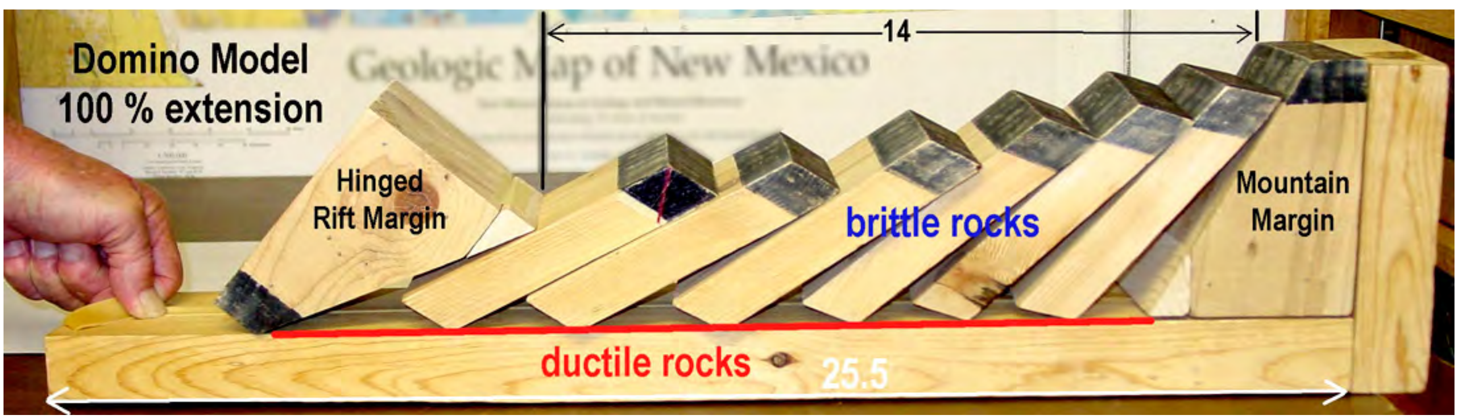
Classroom demonstration models of brittle upper crust and stretchable lower crust can be made with wooden blocks and a long rubber strip. Alternatively, foam-core poster board can be used to make block models, if similar angular relationships and block dimensions (proportions) are maintained. The block models simulate a brittle upper crustal layer overlying a ductile layer (rubber band) that can be stretched to demonstrate subsidence of a symmetric graben block or progressive tilting, subsidence, and sliding apart of asymmetric "domino-like" blocks. The rubber band mimics hot rocks in the lower crust that stretch like taffy, without forming faults.

Block Models of Crustal Extension in the Rio Grande rift
(edge dimensions in inches)









Method:

Model Assembly (wood-working experience helps)

1. From 1″ thick finished lumber (e.g., 1.25″ x 6″—actual size 1″x 5.5″), cut wooden "fault" blocks according to the illustrations. Remember to allow for the thickness of "saw cuts." Slabs of 1″ thick wood can be glued together to make the 4″ x 5″ x 6.5″ graben block (before cutting). The 25.5″ long base frame and 6.5″ tall buttress block can be cut from 1″ or 1.5″ thick wood stock. Note that for the model to work, the angles should be as shown, but the dimensions can be slightly different—as long as each block is the same height after being cut.

2. After the blocks are cut, their tops can be colored with a marking pen to illustrate a continuous (undeformed) rock layer (or layers) about 1″ thick

3. Cut the 7″-long rubber band to form one 14″-long strip; then nail one end of rubber strip to one end of the base frame (a pre-drilled nail hole will avoid splitting the base); then screw the buttress block over the roofing nail to secure one end of rubber strip to the base frame.

Looking north-northwest at west-tilting blocks of the Lemitar Mountains. The original geometry of the blocks determined the direction they toppled. *Photo courtesy of Richard Chamberlin.*

4. Tie or tape the "pull ring" to the loose end of the rubber band (this is optional).

5. Place loose fault blocks on the base frame as seen in the illustrations. Note that one of the graben margin blocks has been turned upside down for the domino model in order to mimic a *continuous* upper crustal layer. You can also change the width of "domino blocks" by taping the sides of two blocks together using masking tape. Also try taping three "domino blocks" together. Graben blocks need not be triangular prisms, but can also have a wide base (like a flat-bottomed barge).

Model Demonstrations

1. Keep in mind that the "domino model" represents large mountain-sized blocks 6 miles (10 kilometers) high and about 1.4 miles (2.3 kilometers) wide (scaling factor 1″ = 2 kilometers). In the real world, how much topographic relief would form between the extended blocks? In the real world, what would "fill in" this topographic relief?

2. On each of the models, pull the rubber band slowly, allowing the blocks to move apart. Note that occasionally the blocks get "stuck" and then make abrupt slips. In the real world, what would you call the abrupt slip events?

3. Observe how the graben model subsides, without tilting. Do you think the 1″ high vertical cut at the bottom of the "graben model" has an equivalent structure in the real world? (Hint: how does magma get to Earth's surface to form a volcano?) As designed, the base of the graben model does not truly represent a 12-mile-thick ductile lower crust, so the vertical cut allows for subsidence into the air space (which is a "ductile" gaseous fluid).

4. Observe the blocks on the "domino model" as they progressively tilt and slide apart with increased extension. Do you think the gaps that form between the lower parts of the "domino blocks" would form in the real world? Remember the blocks are 6 miles high and 1.2 miles wide in the real world. Are real world fault blocks of the Rio Grande rift as rigid (strong) as small wooden blocks?

New Mexico Science Standards—Strands and Benchmarks

Strand II: Content of Science

Standard III: Understand the structure of Earth, the solar system, and the universe, the interconnections among them, and the processes and interactions of Earth's systems.

Grade 9–12 Benchmark II: Examine the scientific theories of the origin, structure, energy, and evolution of Earth and its atmosphere, and their interconnections. Performance Standards: Characteristics and Evolution of Earth

3. Describe the internal structure of Earth (e.g., core, mantle, crust) and the structure of Earth's plates.

5. Explain plate tectonic theory and understand the evidence that supports it.

7. Describe convection as the mechanism for moving heat energy from deep within Earth to the surface and discuss how this process results in plate tectonics, including:

A) geological manifestations (e.g., earthquakes, volcanoes, mountain building) that occur at plate boundaries.

profile of a new mexico earth science teacher

Bonnie is a science teacher at the Infinity High School, an alternative school in Belen. She began her teaching career in Connecticut and taught for nine years before becoming a partner in a family business. Bonnie later worked in the aerospace industry as a process engineer, quality manager, and production manager. When she moved to New Mexico eight years ago, she returned to teaching, first in Socorro and then in Belen.

Bonnie was awarded *Teacher of the Year* at Infinity High School in 2008 and 2011. She participated as a panelist on the "Experimental Education in the Schools Panel" at the 2010 *Getting Kids Outside* coalition meeting. She was recognized as the *Outstanding Science Teacher of 2010* by the New Mexico Academy of Science. For 2011 she received two awards: the *Excellence in Teaching Science* award for the high school level from the New Mexico Science Teachers Association, and *Outstanding Earth Science Teacher* from the National Geoscience Teachers Association in the Southwest Division.

Educational background:

Bachelor's of science in education from Eastern Connecticut State University

Master's of science for teachers (MST) program at New Mexico Tech including the green technologies certificate

Specialties in teaching: I am highly qualified in math and science and currently teach ninth through twelfth grades at Infinity High School. I teach earth science, physical science, life science, applied science, and math.

How do you address the need for students to learn about earth science? I am especially proud of our applied science program, which I initiated. This program promotes the resources of New Mexico—its geology, mining industry, water issues, native species of flora and fauna, culture, history, and related career opportunities. Students explore their state and investigate the treasures it holds for them and their future. The applied science program is a four-hour block on Fridays that combines classroom, lab, and field classes to address state standards and career opportunities. The first year's topic was geology. After some background instruction, students hiked the hills around Socorro with New Mexico Tech geologists. They learned to identify rocks and minerals while thinking about careers in the field of geology. The next year students studied life science at the Sevilleta Refuge by mapping plant and animal life, hiking, and other activities in other areas. They worked with professors from UNM and other professionals. They got hot, sweaty, and dirty, or cold and dirty, as they drew grids and mapped life in the grids. Students have studied environmental science and have been involved with the bosque education monitoring project (BEMP) through Bosque Academy in Albuquerque, and the Whitfield project in Belen. Last year students studied water as a resource, mapped the new Infinity High School campus, and xeriscaped it with appropriate plants and other materials. They also engineered and installed a drainage system to stop severe erosion along one side of the building.

Do you use any of the lessons and resources from Rockin' Around New Mexico in your classroom?

In 2006 as a graduate student in the master's of science for teachers program at New Mexico Tech, I took my first *Rockin' Around New Mexico* class and I was hooked. I use mineral identification kits in earth science and in life science (a dichotomous key exercise). The rocks I have collected get used in classes for fossil, rock, and mineral identification (*The Mystery of the Scarlet Streak*). I use the resources and materials from *Rockin'* in all of the science classes I teach wherever they fit. The *Rockin'* class, as well as the New Mexico Mining Association's *Dig It* program inspired my master's thesis; *Mining for Energy in New Mexico*. I developed a curriculum for teaching students about the mineral resources of New Mexico with emphasis on the coal and uranium industries, and mining. I continue to use my *Rockin'* background as a basis for the applied science classes I teach. Themes in past years have included *Mining for energy in New Mexico*, *Geology of New Mexico,* and *Water as a resource*. This year the theme is *Alternative energy*, and we are exploring and analyzing the cause and effects of fossil fuels (coal, uranium, oil, natural gas) vs. solar, nuclear, wind, bioenergy, and geothermal on our future and our environment.

When did you fall in love with geology? I became interested in geology after coming to New Mexico, especially when I started the MST program at NM Tech. The requirements included geology classes.

Do you have any advice or suggestions for other earth science teachers? Students need to be problem-solvers (sometimes thinking outside the box), not memorizers. My goals as an educator are to have students learn how to use the tools and resources available to enhance their thinking, and then they can expand their horizons and be the innovators we need for the future. I believe students need to be involved in and responsible for their learning, their lives, and the society in which they live if they are to make a positive impact in this world.

What is your favorite lesson in earth science? One of my favorite lessons is hiking San Lorenzo Canyon. I was first introduced to Dr. Richard Chamberlin and Dr. Dave Love from the New Mexico Bureau of Geology at a Sevilleta Wildlife Refuge Open House. They led an adult group on a hike of the canyon explaining the geology of the area. I called upon these same geologists to lead a student hike to investigate the habitat of the area as part of a course I was teaching on the various habitats of New Mexico. This hike became an annual exploration. Each year the focus changed; first the habitat, second the geology, and last year the role water has played in forming the canyon. In February 2011 water and ice were present and their affects were definitely evident. We looked at erosion, studied brickification to determine water flow, examined mineralization caused by water deposition, and saw evidence of how water flows underground. Additional information on the geology of San Lorenzo Canyon can be found at: **http://geoinfo/education/exercises/sanlorenzo/home.html**

Bonnie Dodge and students study the angular unconformity at San Lorenzo Canyon. This angular unconformity is a contact between two rock formations where the younger horizontal sediments rest on top of the eroded surface of older tilted rocks. Please see **http://geoinfo/education/exercises/sanlorenzo/home.html** for a more detailed explanation of this feature. *Photo courtesy of Bonnie Dodge.*

What are your favorite Web links and resources? My favorite resources are people; New Mexico Bureau of Geology staff, local authorities, and officials. When I determine a subject for my applied science class I go to the Internet to look for local information. Here are some examples of Web sites I have used for the topic of geology in New Mexico:

The World-Wide Earthquake Locator is hosted by Edinburgh Earth Observatory. This site features animations and current information about world earthquakes

http://tsunami.geo.ed.ac.uk/local-bin/quakes/mapscript/home.pl

Constructing a shake table

http://www.sciencebuddies.org/science-fair-projects/project_ideas/CE_p013.shtml

Constructing earthquake proof buildings

http://www.discoveryeducation.com/teachers/free-lesson-plans/constructing-earthquake-proof-buildings.cfm

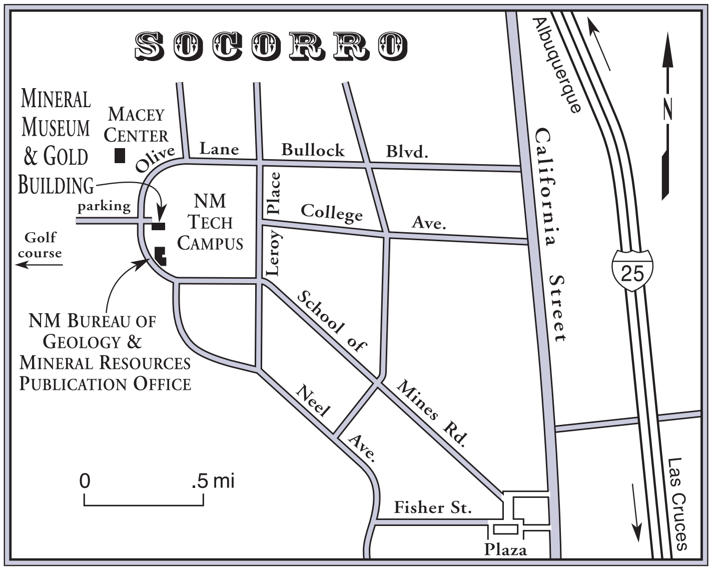
The Dynamic Earth [Macromedia Flash Player]

http://www.mnh.si.edu/earth/main_frames.html

A great book for classroom experiments on earthquakes is: *Earthquakes: Mind-boggling Experiments You Can Turn into Science Fair Projects*, by Janice Van Cleave, 1993, John Wiley & Sons.

What is your favorite geologic feature in New Mexico? I have no favorite feature because there are so many exciting things to see and do in New Mexico, and I still have so much more to explore in the state. Even the sites I have seen always have something new to reveal.

Short Items of Interest to Teachers and the Public



THE MINERAL MUSEUM ON THE CAMPUS OF NEW MEXICO TECH IN SOCORRO, NEW MEXICO

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8 a.m. to 5 p.m., Monday through Friday

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The Mineral Museum is located in the Gold Building on the campus of New Mexico Tech in Socorro. 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 2,500 minerals are on display at a time.

For teachers 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 Web site at: **http://geoinfo.nmt.edu/museum/**

Dr. Virgil W. Lueth
Senior Mineralogist and Curator
vwlueth@nmt.edu
575-835-5140

Bob Eveleth
Senior Mining Engineer and Associate Curator (emeritus)
beveleth@gis.nmt.edu
575-835-5325

To Schedule a Museum Tour, Contact:

Susie Welch
Manager, Geologic Extension Service
susie@nmt.edu
575-835-5112

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UPCOMING EVENTS FOR TEACHERS AND THE PUBLIC

The Geological Society of America, Rocky Mountain Section meeting –Rio GeoFiesta!

May 9–11, 2012, Albuquerque, New Mexico

The special theme of this session is "Multidisciplinary studies of the Rio Grande rift: basins, volcanism, geophysics, and hydrogeology," which covers a broad range of topics on the southeastern Basin and Range and Rio Grande rift.
For information on sessions, field trips, and registration, visit the Web site at:
http://www.geosociety.org/sections/rm/2012mtg/

Rockin' Around New Mexico

July 9–12, 2012,

Jemez Springs, New Mexico

This summer our annual teacher workshop, *Rockin' Around New Mexico* will return to the Jemez Mountains. Because of the fires burning in the Jemez in summer 2011, we did not have access to all of the planned sites, so we will continue studies on the geology of local seismic, volcanic, and geothermal features related to the Valles caldera, along with instruction on seismic hazards and school safety in New Mexico. The 3-day workshop is for active K–12 classroom teachers or pre-service teachers. A one-hour graduate credit is available through the master's of science for teachers at New Mexico Tech. Interested teachers should contact Susie Welch at 575-835-5112 or **susie@nmt.edu**

Teacher Resources:

Japan tsunami debris flotsam in the North Pacific Ocean

March 11, 2012 marked the one-year anniversary of the M 9.0 earthquake and tsunami that devastated the coastline of Japan. As the tsunami waters receded, millions of tons of debris including buildings, cars, appliances, and personal items were dragged out to sea. Ocean current experts Curtis Ebbesmeyer and James Ingraham are using computer models to project when the flotsam from Japan will arrive at the coastlines of the western United States and Hawaii. Some debris believed to be from the Japan tsunami has been found on beaches in the North Pacific Ocean less than one year after the event. Keep track of the debris reports by visiting their Website and blog at **http://beachcombersalert.org/**. You can subscribe to the Beachcombers' Alert newsletter and receive 2 issues per year.

Lite Geology readers may recall earlier issues that featured stories of these two scientists tracking floating bathtub toys that were washed overboard from a ship in 1992 while en route from Hong Kong to Tacoma, Washington. Data logged from following the paths of these tub toys and other floating objects helped the two scientists model the Japan tsunami flotsam trajectory.

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