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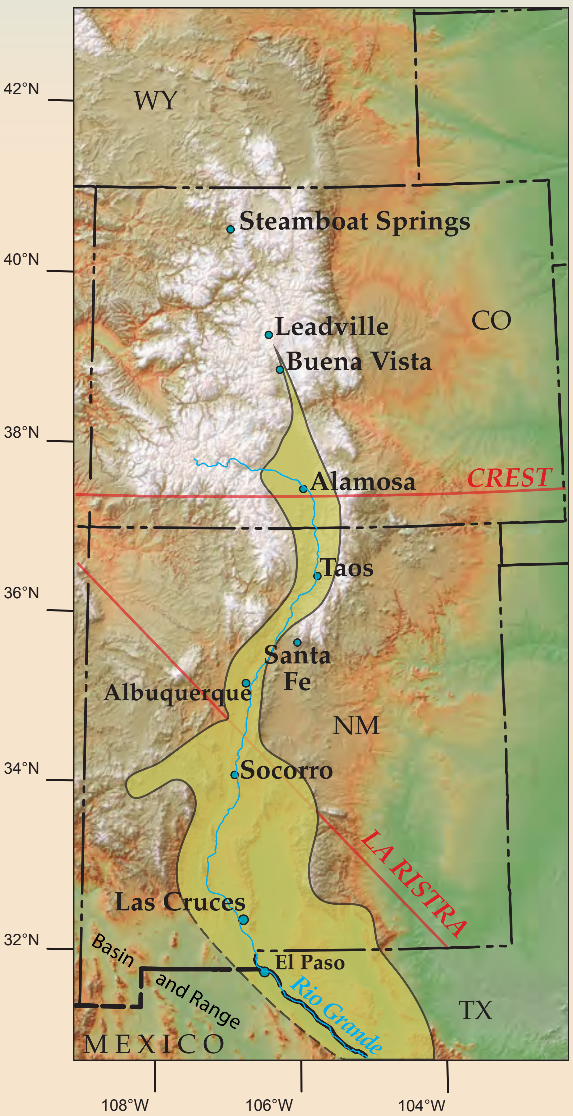
Our Growing Understanding of the Rio Grande Rift

The Rio Grande rift is a narrow, north-striking belt of *en echelon* (slightly overlapping, east or west stepping), elongated basins that bisects southern Colorado and New Mexico. The rift formed when the earth's crust stretched and thinned during westerly directed extension, starting about 36–37 million years ago. This has allowed hot mantle to move upward, creating volcanoes, hot springs, and mineral deposits, forming the topographically low area along which the Rio Grande flows. Geoscientists have long recognized the importance of the Rio Grande rift in localizing water and economic resources used by Native, Hispanic, and American inhabitants of this region.

Kirk Bryan from Harvard University, in his classic 1938 work relating water resources to the geology of New Mexico, was the first to describe the basins and flanking mountains of the Rio Grande rift. Bryan made the important observation 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 Cenozoic age. These sedimentary deposits were named the Santa Fe Formation (now 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 commonly fault bounded, and he noticed an asymmetry in some basins, particularly the San Luis Basin and the basins near Socorro. Bryan presented his observations before the development of the concept of plate tectonics, and no formation mechanism for the depression was proposed.



Physiographic expression of the Rio Grande rift, initially called the Rio Grande depression.

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, causing 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 sedimentary deposits in the neighboring Basin and Range province in Arizona and southwestern New Mexico. 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." The latter part of Kelley's career coincided with the acceptance of the concept of plate tectonics by most geologists. Plate tectonic theory provided a framework for Kelley's later publications about the Rio Grande rift.

In 1971 Charles Chapin, who later became 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 the San Luis Basin of Colorado. Chapin was encouraged to write a paper about the rift by Kelly Summers, a hydrologist interested in placing the geothermal resources of the state into a regional tectonic context. In typical fashion, Chapin dug deeply into the literature about rifts worldwide and drew upon his extensive experience as a field geologist in New

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Mexico and Colorado to write a definitive paper that outlined the boundaries of the Rio Grande rift. One of his illustrations was an idealized cross section that highlights many characteristic features of the Rio Grande rift. This cross section is a classic example of a conceptual model, which is a simple diagram that portrays complex relationships among geologic processes to explain multifaceted and often disparate data sets. Such a model provides a broad framework for data analysis and can be used as a roadmap to guide future research. This sketch sparked considerable new research.

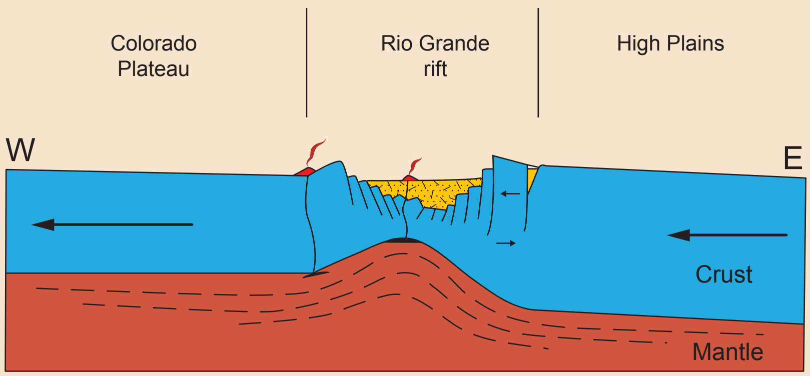
Chapin noted that the eastern margin of the rift is generally higher in elevation than the west side, and volcanic centers and hot springs are more abundant on the west side. In synthesizing these observations, Chapin suggested that the continental plate west of the rift is drifting west faster than the continental interior. Consequently, the east side of the rift developed greater structural relief by riding up on the mantle bulge, whereas the west side of the rift was relatively subdued because of crustal stretching as the crust pulled away from the mantle bulge. Later, Chapin and co-author William Seager pointed out that the Rio Grande rift is generally superimposed on older north-striking structural zones associated with earlier Pennsylvanian–Permian Ancestral Rocky Mountain and Late Cretaceous–early Cenozoic Laramide deformation.

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, as well as 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 twentieth 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 breaking the crust, 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 mapping and construction of cross sections using surface observations.

Our view of the rift basins along the Rio Grande changed in the 1970s with the addition of new technology and new data. First, 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. Thus, a number of physics-based tools that are more cost effective have since been used to indirectly image the basins and the crustal structure of the Rio Grande rift. Seismic refraction experiments were designed to measure crustal thickness. Seismic reflection data were collected to detect buried rock layers, igneous intrusions, and faults. Estimates of basin depth and the location of buried faults were determined with gravity data. Subtle variations in the earth's magnetic field associated with the presence of certain iron-bearing rocks were used to identify buried faults and volcanoes. The amount of heat emitted in the vicinity of the rift has been calculated from precise measurements of temperature as a function of depth combined with measurements of the relative ability of rocks to conduct heat. These heat flow measurements are used to identify geothermal areas and young igneous intrusions. Finally, advances in the technology used to determine when a lava flow erupted or when sediment was deposited 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 $^{40}Ar/^{39}Ar$ 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 constrain the timing of rifting processes.

What have we since learned about the Rio Grande rift? Drill hole, seismic, and gravity data have revealed that the basins of the Rio Grande rift are deep, in places as much as 20,000 feet (6.1 km) 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, although 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 a single basin, but gravity, magnetic, and seismic data indicate that each of these basins actually consists of at least three subbasins. 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.

The Rio Grande rift has experienced quite modest extension (7 to 22 percent), although locally in the Socorro area, the extension is as high as 170 percent. The amount of regional extension based on geologic evidence is about 50 percent, or 14 miles (22km), over the last 32 million years near the latitude of Socorro. Dates on volcanic rocks indicate that rifting began about 36 million years ago near Las Cruces and around 37 million years ago in central Colorado. The timing of initiation of rifting roughly coincided with the late Eocene–Oligocene peak of Cenozoic

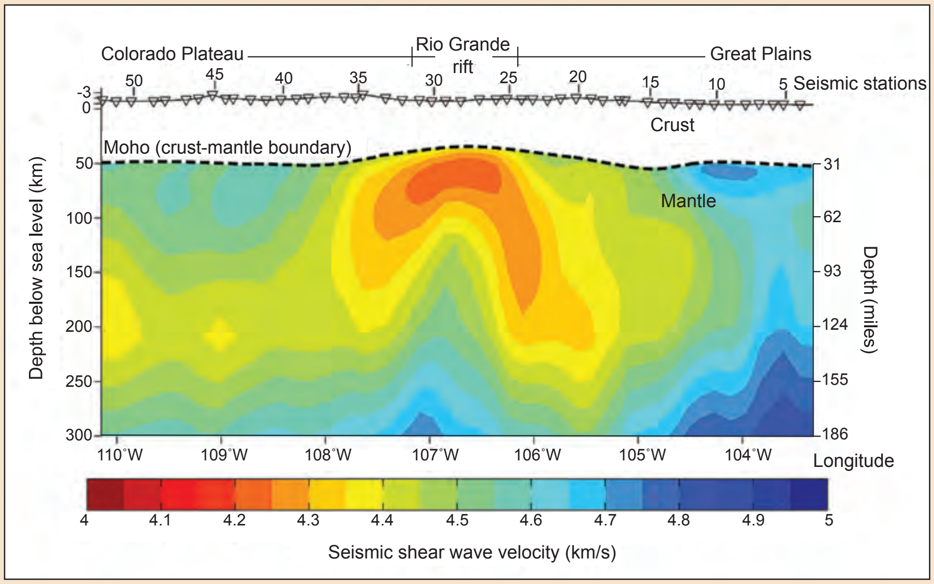


Idealized cross section of the Rio Grande rift from Charles Chapin's 1971 paper.

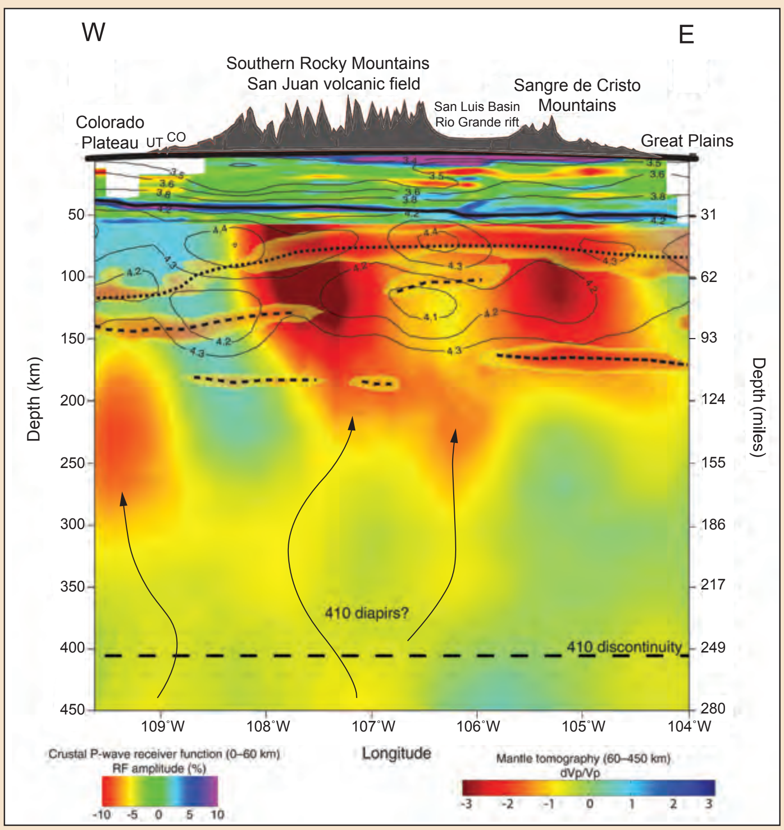
volcanism, particularly in southern New Mexico, where caldera clusters become progressively younger to the southwest. In northern New Mexico, the early rift basins were broad and shallow. The rift narrowed and the basins deepened dramatically between 14 and 16 million years ago. The amount of rifting has decreased in the last 5 million years.

Third, seismic data indicate that the crust beneath the Rio Grande rift near the latitude of Socorro, New Mexico, is 22 miles (35 km) thick, much thinner than the crust beneath the Great Plains to the east and the Colorado Plateau to the west, where the crust is 28–31 miles (45–50 km) thick. Seismic methods have detected a thin, 330-foot (100-m) thick magma body beneath the rift at a depth of 12 miles (19 km) that is 25 miles (40 km) wide at the latitude 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 a bearing on our evolving models of rift development.

Our perceptions of rifting are shifting again as we acquire new data using an imaging technique called seismic tomography, which uses seismic energy from natural earthquakes to map the velocity structure of the interior of the earth, particularly the upper mantle to depths of 250 miles (400 km). 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; areas of higher velocity are colored blue. Interpreting the physical characteristics of the seismically slow mantle is tricky because we cannot go to the earth's interior to collect a sample. Is the mantle volume seismically slow because it is hot, or does the mantle volume contain partially molten rock or other fluids? Is the seismically slow mantle 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 deep-imaging seismic program known as LA RISTRA (Colorado Plateau/Rio Grande Rift Seismic Traverse Experiment) has used seismic instruments located across the Colorado Plateau, the Rio Grande rift, and the Great Plains to produce a tomographic image. The results, which are illustrated as a cross section of differential shear-wave velocity, clearly show that the crust is thinned in the rift and appears to show that hot mantle is moving upward under the Rio Grande rift. According to another interpretation of these data, the main zone of upwelling is focused along the eastern margin of the rift adjacent to the Great Plains near longitude 106°W. The upwelling is restricted to the upper mantle at depths of 30–186 miles (50–300 km).

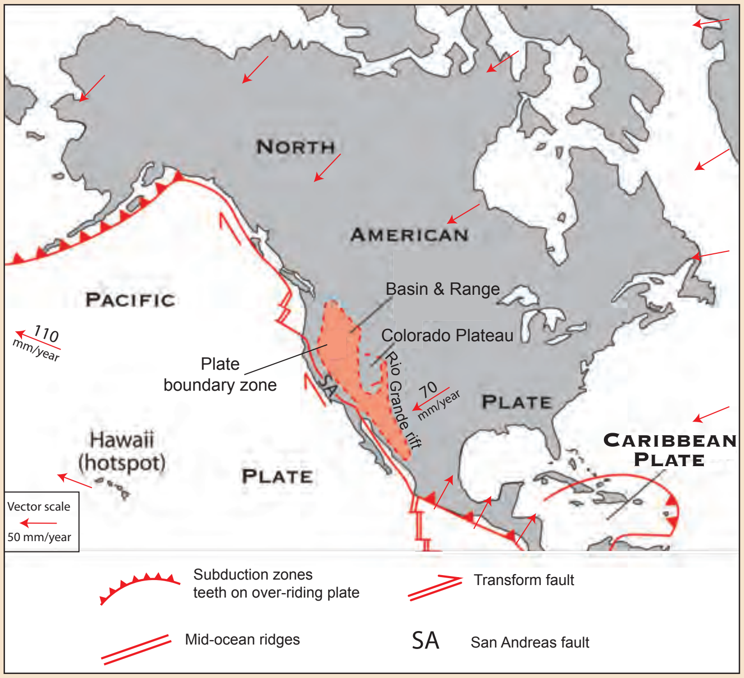


Tomographic cross section of the Rio Grande rift along the LA RISTRA seismic line. The orange and yellow areas depict parts of the mantle that are seismically slow. These areas are interpreted to represent hot, upwelling mantle material. Image from Wilson et al. (2005). The interpretation that upwelling is focused along the eastern margin of the rift is discussed in Reiter and Chamberlin (2011).



Tomographic cross section 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; instead the red, low-velocity mantle is present west and east of the rift below the high mountain peaks of Colorado. The arrows depict a possible < 10 million year disturbance of the 250 mile (410 km) boundary in the mantle that has caused hot material to rise and overprint the mantle signature of the Rio Grande rift. The diffuse lithosphere-asthenosphere boundary zone is shown as dashed lines.

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, as predicted by Chapin in 1971. 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 one inch (2.5 cm) every 40 years. The widening is not limited to the rift, but also affects the western Great Plains and the eastern Colorado Plateau. This observation emphasizes another shift in the conceptual model of the Rio Grande rift. During the 1970s and ‘80s the Rio Grande rift was viewed as an intraplate rift. Now the western United States between California and New Mexico is viewed as a broad zone of related deformation. Examination of global seismic tomographic data by many geoscientists reveals one fundamental characteristic that is present in the North American plate in all interpretations of the data: the western U.S. is underlain by seismically slow and presumably hot mantle, and the interior of the continent is seismically fast and presumably cold mantle. The Rio Grande rift is at the boundary. The combination of both local and global seismic tomography and recent GPS data suggests that the Rio Grande 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 lithosphere.



Map showing the relative velocities of the North American plate and the Pacific plate, shown as red arrows. The orange area highlights parts of the North American plate that accommodate the difference in direction and velocity of motion between the North American and Pacific plates. The San Andreas fault accounts for 80 percent of the divergence. GPS measurements show that the western United States moves 1 to 4 mm/yr faster (total velocity 71–74 mm/yr) compared to the central United States (total velocity 70 mm/yr). Data from Moores and Twiss, 1995.

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 (Colorado Rockies Experiment and Seismic Transects) 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 but are located to the east and west of the accepted boundaries of the rift. Researchers are puzzling over the new data. A possible explanation is that pieces of lithosphere below southwestern Colorado detached starting 25 million years ago and slowly descended into the deep layers of mantle. These lithospheric pieces hit a boundary in the mantle at about 250 miles (410 km), causing deep mantle material to move up during the last 10 million years, overprinting the shallow mantle signature of the rift. Low velocity zones within the crust are associated with the rift in Colorado. These new observations are causing us to formulate new strategies for geothermal exploration and seismic and volcanic hazards evaluation. Stay tuned as our thoughts about rifting advance as new data sets are gathered.

—Shari Kelley and Richard Chamberlin

We thank Charles Chapin for sharing his story with us and for his helpful comments on the article.

Shari Kelley is a senior geophysicist and field geologist with the New Mexico Bureau of Geology and Mineral Resources. Her research interests include applying thermochronology to tectonic problems, mapping volcanic fields, and evaluating the geothermal potential of the Rio Grande rift in New Mexico.

Richard Chamberlin is an emeritus senior field geologist at the New Mexico Bureau of Geology and Mineral Resources. He has extensive experience in and knowledge of the geology of the Socorro area.

Suggested Reading

Tectonics of the Rio Grande depression of central New Mexico by V. C. Kelley, 1952. In: Rio Grande Country, New Mexico Geological Society, Guidebook 3, pp. 93–105.

The Rio Grande rift, part I: modifications and additions by C. E. Chapin, 1971. In: *San Luis Basin (Colorado)*, New Mexico Geological Society, Guidebook 22, pp. 191–201.

Tectonics, by E. Moores and R. J.Twiss, 1995; W.H. Freeman and Co., ISBN 0-7167-2437-5.

Alternative Perspectives of Crustal and Upper Mantle Phenomena Along the Rio Grande rift, by M. Reiter and R. M. Chamberlin, 2011. In: *GSA Today*, v. 21, no. 2, pp. 4–9, doi: 10.1130/GSATG79AR.

Geology and groundwater conditions of the Rio Grande depression in Colorado and New Mexico, by Bryan Kirk, 1938. In: *Regional Planning, Part 6, Upper Rio Grande: Washington National Resources Committee (Planning Board)*, pp. 197–225. http://cgsdocs.state.co.us/Docs/ERC/GEOLOGY AND GROUND-WATER CONDITONS OF THE RIO GRANDE DEPRESSION-BRYAN 1938.pdf

Mantle-driven dynamic uplift of the Rocky Mountains and Colorado Plateau and its surface response: Toward a unified hypothesis, by K.E. Karlstrom, and the CREST working group, 2012. In: *Lithosphere*; v. 4; no. 1; pp. 3–22, doi: 10.1130/L150.1

Imaging the Seismic Structure of the Crust and Upper Mantle Beneath the Great Plains, Rio Grande Rift, and Colorado Plateau Using Receiver Functions, by D. Wilson, R. Aster, et al., 2005. Geophys. Res., 110, B05306, doi:10.1029/2004JB003492.

Bureau News

Geology Hall of Fame

Shari Kelley, the bureau's senior geophysicist and field geologist, was honored by the Department of Geological Sciences at her alma mater, New Mexico State University, with the 2011 Alumni Hall of Fame Award in recognition of outstanding professional achievement. After completing her bachelor's degree at NMSU, Shari earned a Ph.D. in geophysics from Southern Methodist University. Her research has included geologic mapping, applications of apatite fission-track thermochronology, and geothermal exploration.

GSA Fellow

Steve Cather, Senior Field Geologist, was made a Fellow of the Geological Society of America, an honor accorded to fewer than fifty geoscientists each year. Steve has worked in New Mexico for over thirty years. His research interests include large-scale structural evolution and sedimentation processes in the Southwest. His research is based on detailed field mapping. Steve has published extensively on his work.

Rockin' Around New Mexico

This year's teachers' workshop, "Rockin' Around New Mexico," returned to the Valles Caldera National Preserve Science Education Center in Jemez Springs and visited places inaccessible last summer due to the Las Conchas fire. From July 9 to 12, teachers representing grades K through 12 participated in field exercises and classroom activities that focused on water quality, fire ecology, the volcanic history of Valles caldera, current and future seismic risks on local faults, and earthquake safety in schools. Rockin' Around New Mexico relies on the New Mexico Bureau of Geology/New Mexico Institute of Mining and Technology, New Mexico Department of Homeland Security and Emergency Management, New Mexico Geological Society, and other agencies and private companies for funding and instructor support. For information on the 2013 workshop, contact Susie Welch at **susie@nmt.edu.**

Earth Science Week 2012

The American Geological Institute has sponsored Earth Science Week each year since 1998. This national and international event is designed to help the public, teachers, and students gain a better understanding and appreciation for the earth sciences, and to encourage proper stewardship of our planet. Celebrated October 14–20, 2012, the theme for this year is "Discovering Careers in the Earth Sciences."

The New Mexico Bureau of Geology and New Mexico Tech participate in this event each year. Our governor, Susana Martinez, has issued a proclamation declaring October 14–20 as Earth Science Week in New Mexico. Free toolkits containing posters, DVDs, brochures, bookmarks, fact sheets, postcards, an activity calendar, and much more are available to teachers. Two-minute radio broadcasts recorded by NMT professionals will air at noon each weekday during Earth Science Week on KUNM. These broadcasts, and those recorded in previous years are posted on our web site at: **http://geoinfo.nmt.edu/events/esweek/home.html**. For more information, please contact Susie Welch at the Bureau of Geology at: **susie@nmt.edu**, or visit AGI's web site at: **http://www.earthsciweek.org/index.html**.

20th Anniversary for *Lite Geology*

This year we celebrate the twentieth anniversary of *Lite* Geology. First published in 1992, the periodical originated when then-director Chuck Chapin assembled a team of staff members to create an informative yet entertaining publication focused on earth science topics and current issues in New Mexico, one that would appeal to a broad audience and serve as an outreach tool for educators and the public. Early issues of *Lite* Geology contained whimsical cartoons, creative short features, and articles on topics ranging from mineral resources to geologic hazards to New Mexico's enchanting geology. Over the years the original quarterly print publication evolved into a semi-annual online publication. Today *Lite* Geology is available as a free download from the New Mexico Bureau of Geology and Mineral Resources website, along with the entire collection of back issues. Each issue now includes short articles, classroom activities, puzzles, and links to online resources. Some of the early editors are still on the job and have been joined in recent years by other bureau staff. We welcome your input for future issues. Check out the latest issue at **http://geoinfo.nmt.edu/publications/periodicals/litegeology/home.html**

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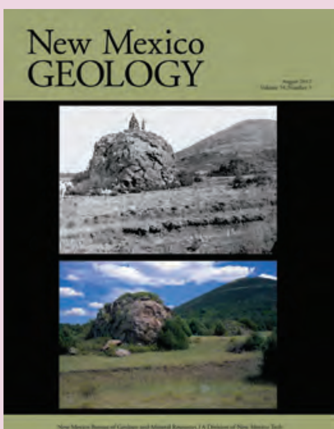
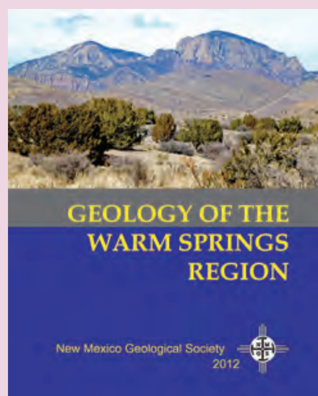


New Mexico Geology. *New Mexico Geology*, the bureau's technical quarterly journal, has been publishing peer-reviewed research papers for 34 years. A 1-year subscription is $15; a 2-year subscription is $25. Single issues are $4 plus shipping and handling.

The current August 2012 issue includes the third part of a year-long special series of articles honoring the 100th anniversary of New Mexico's statehood, "The geology of New Mexico as understood in 1912." Also included is a paper on middle Turonian stratigraphy, "Evolution of the Late Cretaceous oyster genus *Cameleolopha* Vyalov 1936 in central New Mexico." Visit the *New Mexico Geology* web pages at **geoinfo.nmt.edu/publications/periodicals/nmg** to subscribe online, to view past issues, and to download published papers and guidelines for manuscript submissions.



Geology of the Warm Springs Region. This is the 63rd in a series of annual guidebooks of the New Mexico Geological Society, published for the 2012 fall field conference. ISBN: 978-1-58546-098-4. $65.00 book, spiral-bound road logs only $25.

Majestic mountain sky islands, deep dark canyons, and hidden springs interrupt the vast desert landscape of the Warm Springs region in south-central New Mexico. This guidebook examines the spectacular geology that led to the formation of these landforms in what may well be the most geologically complex part of New Mexico. Rock exposures in this region represent almost the entire record of geologic time, from granites over a billion years old to modern river deposits of the Rio Grande. Six road logs explore different portions of the Warm Springs region, 26 minipapers discuss specific geologic features along the way, and 30 scientific papers provide details on geologic features and processes. These articles discuss a wide range of geological topics including regional geology, impact structures, igneous and sedimentary petrology, stratigraphy, paleontology, and earth resources. Available in October.

For more information about these and other bureau publications:

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