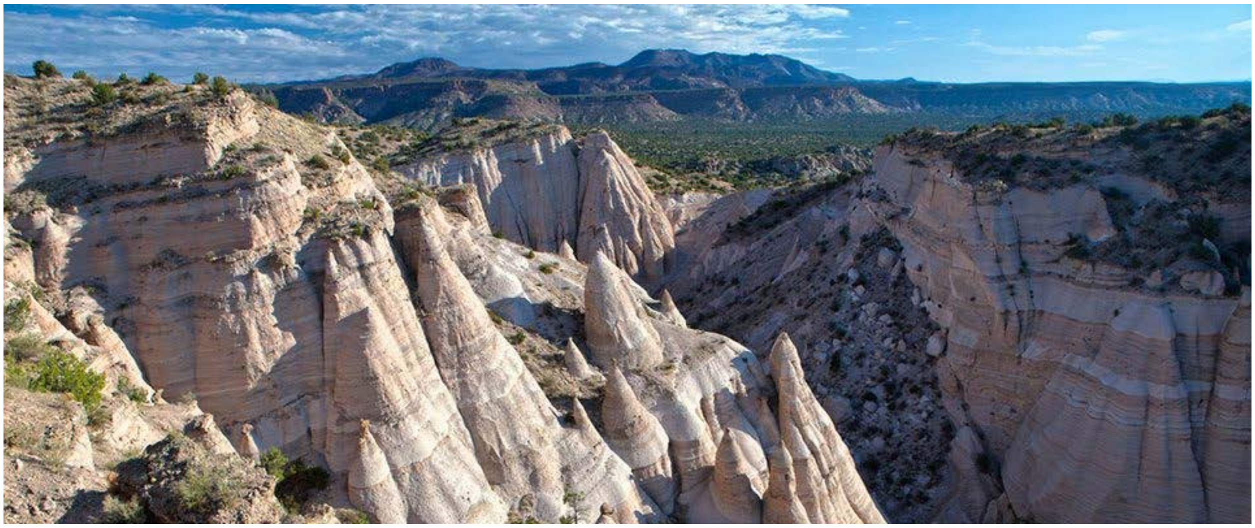

Field Trip, GeoPrisms RIE-TEI 2017

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Introduction

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Basins of the Rio Grande rift have long been studied both for their record of rift development and for their potential as host of natural resources. Early workers described the basin geomorphology and the character of infilling sediments (e.g., Siebenthal, 1910; Bryan, 1938; Speigel and Baldwin, 1963), and subsequent research compilations provided general stratigraphic and tectonic overviews of rift basins and described their geophysical characteristics within the crust (Hawley, 1978; Riecker, 1979; Baldridge et al., 1984; Keller, 1986). Subsurface knowledge gained from hydrocarbon exploration activities coupled with detailed surface studies of basins and their flanking uplifts were presented in Geological Society of America (GSA) Special Paper 291, edited by Keller and Cather (1994a). These studies addressed the structure, stratigraphy, and tectonic setting of individual basins spanning almost the entire length of the rift. Structural models of rifting presented in GSA Special Paper 291 have guided exploration for and management of natural resources and have been held as standards for comparison to other continental rifts (e.g., Faulds and Varga, 1998). Since publication of GSA Special Paper 291, a new generation of researchers has joined efforts to further investigate the basins of the Rio Grande rift, driven in large part by the need to better understand the important groundwater resources held by rift basins (e.g., Bartolino and Cole, 2002). The research has led to abundant new geologic, geophysical, and hydrogeological data that were highlighted in a special topical session at the GSA Annual Meeting in 2007. This volume is an outcome of that session, and includes papers that demonstrate the new perspectives on the rift and its basins that have developed from the new data, discoveries, and interpretations since 1994. We note, however, that rift research marches on and new data and insights continue to emerge, as highlighted at the GSA Rocky Mountain Section meeting in 2012.

OVERVIEW OF THE RIO GRANDE RIFT

The Rio Grande rift extends from Colorado, USA, on the north to the state of Chihuahua, Mexico, on the south, dividing the Colorado Plateau on the west from the interior of the North American craton on the east (Fig. 1). It is named for the Rio Grande, the major river that flows through most of its extent. Beginning with the paper by Chapin (1971), it has been widely recognized as a major late Cenozoic continental rift zone that is distinct from, but related to, the wider zone of extension in the Basin and Range region of the southwestern USA (Keller and Cather, 1994b; Baldridge et al., 1995).

Within the upper crust, the rift is characterized by a series of interconnected structural basins filled with thick accumulations of clastic sediments and local interbedded basalt flows. Several late Cenozoic volcanic fields are associated with the rift (Fig. 1), but the volume of magmatism is generally low in comparison to other continental rifts (Keller and Baldridge, 1999). An obvious east-northeast alignment of late Cenozoic volcanic fields, known as the Jemez lineament, crosses the rift between the Española and San Luis Basins and coincides with the orientations of rift-age structures such as the Embudo fault zone (Fig. 1). Workers have long speculated that the lineament is a long-lived basement weakness that influenced rift development and was a conduit for magma (e.g., Lipman, 1980; Aldrich and Laughlin, 1984), a speculation that is supported by recent deep seismic experiments (Magnani et al., 2004).

Topographically, the rift is associated with a series of elongated valleys flanked by northerly or northwesterly trending mountain ranges (Fig. 2). Individual valleys of the Rio Grande rift are easy to recognize in Colorado and northern New Mexico, but difficult to distinguish from the physiography of the broader

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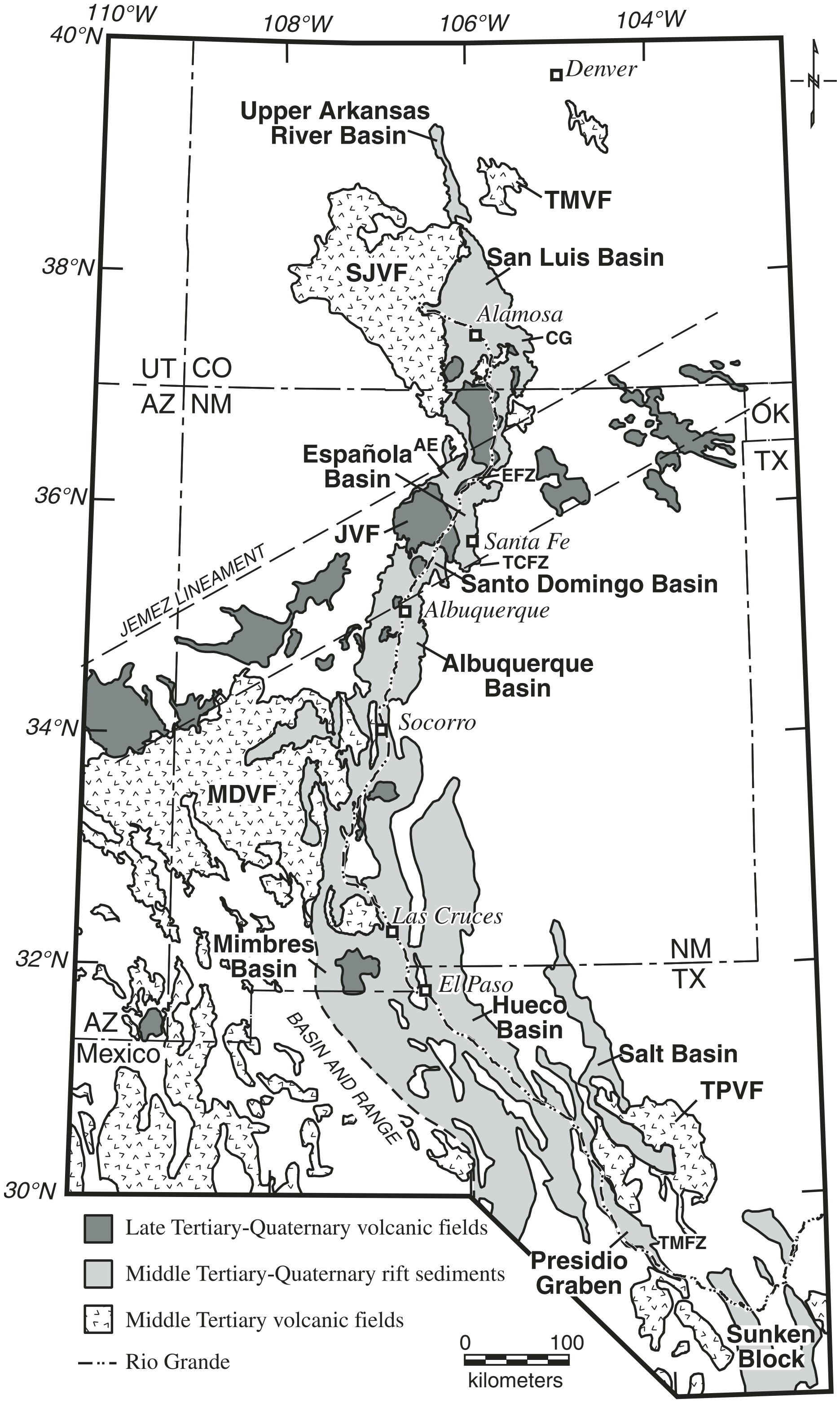

Figure 1. Main features of the Rio Grande rift, showing basins and precursory and associated volcanic fields. Basins and volcanic fields discussed in this volume are labeled. Volcanic fields are denoted by large capital letters: JVF—Jemez volcanic field; MDVF—Mogollon-Datil volcanic field; SJVF—San Juan volcanic field; TMVF—Thirtynine Mile volcanic field; TPVF—Trans-Pecos volcanic field. Additional geographic and geologic features are denoted by small capital letters: AE—Abiquiu embayment; CG—Culebra graben; EFZ—Embudo fault zone; TCFZ—Tijeras-Cañoncito fault zone; TMFZ—Tascotal Mesa fault zone. AZ—Arizona; CO—Colorado; NM—New Mexico; OK—Oklahoma; TX—Texas; UT—Utah.

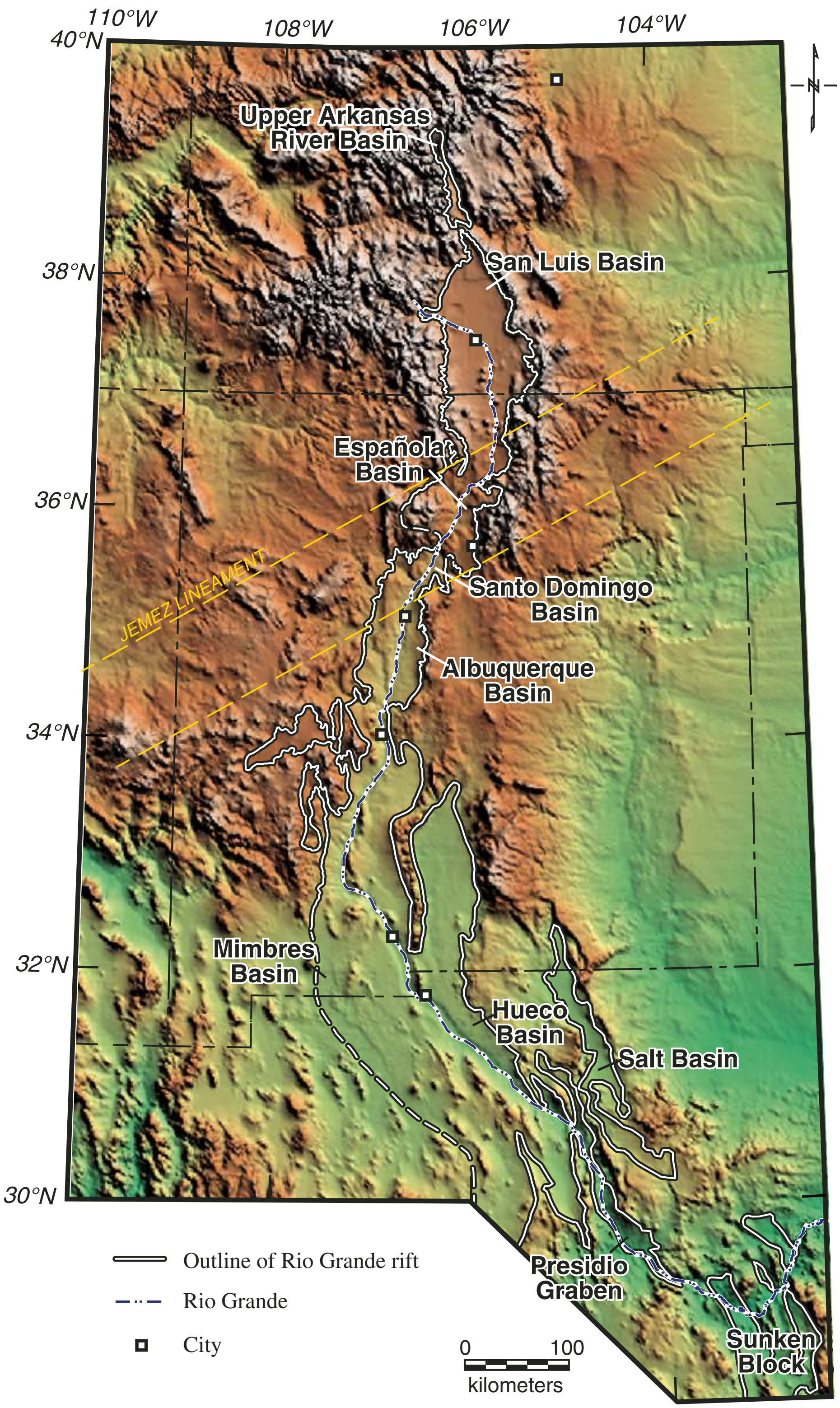

Figure 2. Color shaded-relief topographic map for the region of the Rio Grande rift. Outlines of basins and the Jemez lineament from Figure 1. Digital elevation model is from the National Aeronautics and Space Administration (NASA) shuttle radar topography mission.

Basin and Range in southern New Mexico, west Texas, and northern Mexico. Moreover, rift-related sedimentary and volcanic deposits are found outside of the valleys, and basin boundaries do not always conform to valley margins. Thus, the names and extents of basins and subbasins of the rift are inconsistently depicted in the literature. Some workers use only physiography to define the basins; other workers use major structural boundaries combined with physiography; yet others use the lateral extents of rift-related deposits, either inclusive or exclusive of the volcanic fields. Readers should be aware that we have not attempted to reconcile these differences among the papers in this volume. The rift basins of Figure 1 are outlined using a combination of physiography, limits of Neogene sedimentary deposits, and structure, using the following previous rift definitions and geologic maps as guides: Tweto et al. (1979), Keller et al. (1990), Keller and Cather (1994b), Dickerson and Muehlberger (1994), Baldridge et al. (1995), Richard et al. (2000), New Mexico Bureau of Geology and Mineral Resources (2003), and Garrity and Soller (2009).

Gravity maps can be used to enhance the view of the structural setting of the rift. Gravity lows are produced by thick sections of sediments within the structural basins, and steep gradients are associated with large vertical displacements at basin borders (Cordell, 1978). Although lows are produced by a wide variety of other geologic features as well, the lows within the outlined basins of the rift provide general clues to the locations of their deepest parts. Isostatic residual gravity data (Fig. 3) reflect density variations in the upper crust. The addition of preliminary data from Mexico (courtesy of G. Randy Keller, University of Oklahoma, 2012, personal commun.) provides a more comprehensive view of the gravity expression of the southern rift than has previously been presented.

Variations in the general structural styles of the northern, south-central, and far southern portions of the rift are apparent from the new gravity map combined with topography (Figs. 2 and 3). In the northern rift, gravity lows within the easily recognized individual valleys in Colorado and northern New Mexico suggest they are underlain by structural basins that are commonly narrower than the valleys. The eastern borders of the individual valleys are en echelon and right stepping from ~20 km north of Socorro, New Mexico, to the Colorado–New Mexico state line. North of the Jemez lineament, the northern third of the San Luis Basin and the Upper Arkansas River Basin in Colorado have more northwesterly orientations. Between the vicinities of Socorro and Las Cruces in southern New Mexico, the multiple basins of the south-central portion of the rift have a structural style more akin to that of the Basin and Range (Chapin, 1971; Chapin and Cather, 1994). These generally northerly trending basins occupy a wide area, extending farther in both east and west directions compared to the borders of the Albuquerque Basin to the north. In the far southern portion of the rift, the northerly trends of structures and physiography are replaced by dominantly northwesterly trends within a 100 km zone that straddles the Texas-Mexico border. The western boundary of the southern rift is indistinct and subject to disagreement. The dashed boundary shown on Figure 1 follows Keller et al. (1990), where they observed a general transition from higher heat flow, somewhat thinner crust, and greater Quaternary fault activity on the east compared to the west. The gravity map (Fig. 3) suggests that the zone of prominent northwesterly trends crosses the rift, extending from the vicinity of El Paso, Texas, as far northwest as southeastern Arizona. Within these areas, tectonic features ranging in age from Paleozoic to Cenozoic all have dominantly northwesterly trends (e.g., Seager, 2004), suggesting possible genetic relationships.

Although not the focus of this volume, much recent research has centered on exploring the lithosphere and mantle below the Rio Grande rift, motivated in large part by two deep-looking seismic experiments that cross the rift obliquely: the Continental Dynamics–Rocky MOuntain project (CD-ROM) and Colorado Plateau/Rio Grande Rift Seismic Transect (LA RISTRA) experiments. These experiments show shallow, seismically slow mantle below the Rio Grande rift (Karlstrom et al., 2005; Gao et al., 2004; Wilson et al., 2005), consistent with upper-mantle convection and high heat flow in the rift and neighboring Jemez lineament (Reiter, 2009).

Previous workers have noted an increase in extension across the rift from north to south, prompting them to theorize that the rift is opening as a result of rotation of the Colorado Plateau (e.g., Cordell, 1982; Chapin and Cather, 1994). However, present-day relative motions of the Colorado Plateau and Rio Grande rift observed from GPS stations are inconsistent with this type of motion (Kreemer et al., 2010). The results suggest that extensional deformation is currently distributed broadly across the region rather than focused at the rift (Berglund et al., 2012).

SUMMARY OF CHAPTERS

Chapters in this volume focus on upper crustal basins of the Rio Grande rift and include a variety of topics, albeit with overlap: sedimentation history, rift basin geometries and the influence of older structure on rift basin evolution, faulting and strain transfer within and among basins, relations of magmatism to rift tectonism, and basin hydrogeology. Because many chapters bear on more than one topic, the volume is organized geographically with study areas progressing from north to south.

Sedimentation History

As basins within the Rio Grande rift underwent tectonic subsidence they were filled with sediments and interbedded volcanic rocks. Sedimentation history, constrained by dates on volcanic rocks, has been used as evidence to evaluate both the onset and rates of rift extension (e.g., Chapin and Cather, 1994). In this volume, Kelley et al. (Chapter 5) document an early Oligocene onset of rifting from accumulation of two redefined conglomerate units and stratigraphic relations across major fault zones within the now-inactive westernmost Española Basin area. Koning et al. (Chapter 8) also interpret localized Oligocene subbasins in the eastern Española Basin but they document peak extension

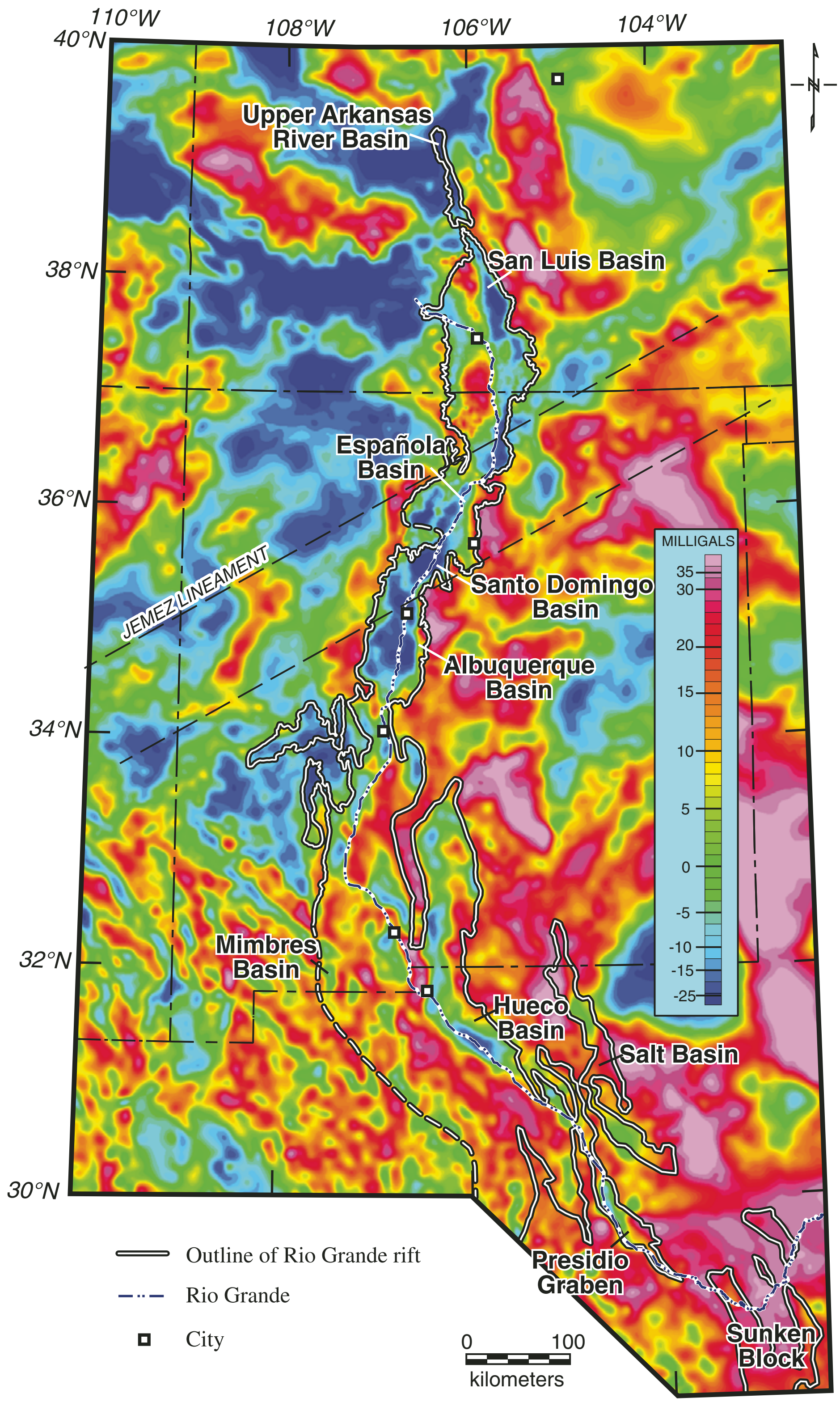

Figure 3. Isostatic residual gravity map for the region of the Rio Grande rift. Outlines of basins and Jemez lineament from Figure 1. Data are from the Pan American Center for Earth & Environmental Studies (PACES) gravity database of the United States hosted by University of Texas at El Paso (http://research.utep.edu/Default.aspx?tabid=37229), Gillespie et al. (2000), and B. Drenth (2011, personal commun.). Mexico data are courtesy of G.R. Keller (2012, University of Oklahoma, personal commun.). A regional field was removed, which was computed from an Airy isostatic model of regional topography. This approach is a reasonable way to focus on features of the upper crust, even if the model is not suitable for the area (Simpson et al., 1986).

during the middle to late Miocene from maximum rates of both sediment accumulation and fault throw. Slate et al. (Chapter 12) summarize important tephrochronology correlations that provide chronological control for such estimates of sediment accumulation and fault slip. WoldeGabriel et al. (Chapter 9) use new $^{40}Ar/^{39}Ar$ dates from volcanic flows sampled in wells from the eastern Jemez volcanic field, stratigraphic correlations, and geochemistry to suggest that the currently active western margin of the Española Basin was sporadically reactivated several times from at least middle Miocene to Plio-Pleistocene time. Fault slip rates for other rift margins are estimated by Maldonado et al. (Chapter 6) from offsets of several dated lava flows in the Abiquiu embayment of the Española Basin and by Ruleman et al. (Chapter 3) for the eastern margin of the central San Luis Basin.

The thickness and facies of basin sediments are controlled by the interplay of tectonic and climate processes (e.g., Leeder and Gawthorpe, 1987; Leeder and Mack, 2007) that influence parameters such as accommodation space, transport energy, and sediment supply from diverse source terrains. Connell et al. (Chapter 15) present a comprehensive assessment of Pliocene through mid-Pleistocene rift sedimentation within the Albuquerque Basin using stratigraphic and geomorphic analyses coupled with magnetic-polarity and $^{40}Ar/^{39}Ar$ age constraints to demonstrate shifting patterns of sedimentation due to a combination of tectonic and climatic controls. Several studies also illustrate tectonic and climate effects on sedimentation within the San Luis Basin. Ruleman et al. (Chapter 3) use surficial mapping, neotectonic investigations, geochronology, and geophysics to establish the evolution of a newly recognized subbasin in the southern San Luis Basin and demonstrate the influence of intermingling of climatic cycles and spatially and temporally varying fault activity. Machette et al. (Chapter 1) summarize evidence for Lake Alamosa, a closed basin in the northern San Luis Basin that formed when Pliocene eruptions of Servilleta Basalt dammed external drainage until a bedrock sill was overtopped during a mid-Pleistocene lake highstand at ca. 430 ka. Within the Culebra graben of the eastern San Luis Basin, Armstrong et al. (Chapter 2) use sophisticated mineralogical and geochemical assessments and geochronology of volcanic clasts ranging from trachybasalt to rhyolite to favor potential source areas from the Thirtynine Mile volcanic field for lower Santa Fe Group sediments.

Rift Basin Geometries and the Influence of Older Structure

Geophysical and drill-hole assessments of the basin depocenters indicate that they are typically asymmetric in cross section and contain thickest deposits adjacent to one or more major normal faults, giving them overall half-graben forms. Grauch and Connell (Chapter 16) and Drenth et al. (Chapter 4) discuss rift-sediment thickness variation for the Albuquerque and central San Luis Basins, respectively, based on gravity inversions calibrated to a variety of geologic and geophysical constraints; their models demonstrate complex basin shapes due to displacements on multiple faults within subbasins. Rodriguez and Sawyer (Chapter 13) develop two- and three-dimensional electrical resistivity models from magnetotelluric data aided by analysis of regional borehole resistivity data for areas of the Albuquerque and Española Basins; these provide constraints on the thicknesses of volcanic cover and depths to pre-rift rocks.

The basins of the Rio Grande rift developed upon an already complex landscape that had been shaped by earlier tectonic events. These events include continental accretion during Precambrian time, the Pennsylvanian–Permian ancestral Rocky Mountain orogeny, the Cretaceous–Eocene Laramide orogeny, and Oligocene magmatism at local centers (Fig. 1). Structures developed during the earlier tectonic events probably had a large influence on subsequent extensional faulting and the geometry of rift basins (Baldridge et al., 1995; Karlstrom et al., 1999; Kellogg, 1999). For example, at the southeastern margin of the Española Basin, Lisenbee (Chapter 10) documents multiple phases of Laramide deformation associated with movements along the major northeast-striking Tijeras-Cañoncito fault zone that also displaced a rift-related north-plunging syncline. Averill and Miller (Chapter 17) interpret velocity variations from a 205-km-long seismic refraction/reflection survey that crosses the Basin and Range province and southern Rio Grande rift in southernmost New Mexico and west Texas. They show mid-Tertiary to Holocene rift basins to depths of 1–3 km that overlie older features interpreted to be the result of Paleozoic- to early Tertiary–age tectonic activity.

Faulting and Strain Transfer within and among Basins

Whereas basin depocenters mark the focus of extension along major normal faults within the Rio Grande rift, these centers commonly are not aligned along the strike of the rift. The specific structural mechanisms that allow strain transfer among such offset basins can be complex (e.g., Faulds and Varga, 1998). Several different types of accommodation and transfer zones are now recognized within the Rio Grande rift. Discrete transfer fault zones oriented at high angles to the rift strike include the Embudo fault zone linking the San Luis and Española Basins (Muehlberger, 1979; Kelson et al., 2004; Goteti et al., Chapter 7) and the Tascotal Mesa fault zone of western Texas (Henry, 1998; Dickerson, Chapter 18), both of which probably reactivated preexisting crustal weaknesses. In contrast, broad accommodation zones composed of overlapping normal faults are also well recognized within the rift, such as for the Santo Domingo Basin (Smith et al., 2001; Minor et al., Chapter 14). A previous model for a discrete transfer fault zone to separate east- and west-tilted half grabens within the Albuquerque Basin (e.g., Russell and Snelson, 1994) is no longer supported by the more complex subbasin geometries defined by Grauch and Connell (Chapter 16). Whereas rift formation proceeded under directions of least-principal paleostress whose azimuths have varied from southwest to northwest (Zoback et al., 1981; Aldrich et al., 1986; Wawrzyniec et al., 2002; Minor et al., Chapter 14), inversions from fault slip data (Minor et al., Chapter 14) and mechanical models (Goteti et al., Chapter 7) demonstrate the potentially complex paleostress histories of accommodation zones.

Relations of Magmatism to Rift Tectonism

Volcanism in the southern Rocky Mountains both preceded and accompanied development of the Rio Grande rift (Lipman and Mehnert, 1975; Chapin et al., 2004; Fig. 1). Large mid-Tertiary volcanic fields of the San Juan Mountains and Mogollon-Datil form western flanks and partly underlie the Rio Grande rift. During the Miocene–Quaternary filling of basins, volcanism was subordinate in volume to sedimentation throughout much of the rift (Keller and Baldridge, 1999), yet mafic volcanic rocks show increasing contributions from asthenospheric sources in response to thinning of the lithosphere during rifting (e.g., Perry et al., 1987). Maldonado et al. (Chapter 6) present major- and trace-element data on 20–2 Ma mafic lava flows and dikes within the Abiquiu embayment that suggest that they were generated from multiple lithospheric sources that shallowed through time, consistent with rift-related lithospheric thinning. Dickerson (Chapter 18) presents petrographic, geochemical, and geochronological data that document emplacement of lavas of rift geochemical character within the Tascotal Mesa fault zone from ca. 26 Ma to 17 Ma. WoldeGabriel et al. (Chapter 9) demonstrate that sporadic eruptions from different magmatic sources at 12–13 Ma were closely associated with intense faulting, subsidence, and thick sediment accumulation at the Española Basin margin.

Basin Hydrogeology

Beyond their record of rift processes and evolution, rift basins also host a variety of natural resources such as hydrocarbons, mineral deposits, and groundwater. For example, variations in the depositional environments and facies of basin sediments have important impacts on aquifer storage and water quality for groundwater (e.g., Bartolino and Cole, 2002; Johnson and Bauer, 2012). A number of recent studies have examined variations in geochemical types and ages of groundwater as a function of recharge and permeability variations (Plummer et al., 2004; Manning, 2009). In this volume, Johnson et al. (Chapter 11) present a large set of geochemical and thermal data to examine the evolution of groundwater chemistry in the Santa Fe area of the southern Española Basin. They use modeling and spatial assessment to document recharge and discharge zones and the influence of major north-trending fault zones within the overall east-to-west flow of the groundwater system, and they document upwelling of Na-rich thermal waters in the western part of the basin adjacent to a buried horst. Machette et al. (Chapter 1) summarize evidence for a Pliocene–Pleistocene Lake Alamosa, whose blue clay deposits form an important hydrogeologic confining unit that separates an upper unconfined aquifer and a lower confined aquifer within the northern San Luis Basin.

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Field Trip to Kasha-Katuwe Tent Rocks National Monument

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This document summarizes geological information pertinent to educational interpretation at the monument. It is adapted from an evolving interpretation document prepared for the Bureau of Land Management.

Stop 1:

The geology of Tent Rocks is best expressed in terms of (a) the origin of the Earth materials, and (b) the origin of the landscape.

What is Tent Rocks made of?

The geological materials at Tent Rocks relate to a time of intense, explosive volcanic activity nearby in the southern Jemez Mountains about 6.7-7.0 million years ago (based on isotopic dates of volcanic ash layers). White layers are pumice and ash deposits (called *tuff*) from more than 40 separate eruptions of volcanoes located as close as 1 mile, to as distant as 10 miles from the parking area. The darker gray, tan, and orange layers are sand and gravel washed southward from the volcanoes. The various layers of volcanic and sedimentary material accumulated in a slowly subsiding basin that slid downward along faults to produce the Rio Grande valley.

Nearly all of the fragments at Tent Rocks, whether the pumice and ash in the white volcanic layers or the sand grains to boulders in the sedimentary layers, are composed of a type of volcanic rock called *rhyolite*. Rhyolite lava-flow fragments are abundant in the gravel layers and range in color from light gray to red, commonly with bands of different colored minerals. The rhyolite pumice and ash are snow-white to silvery gray in color.

How did the Tent Rocks landscape form?

Sometime after about 1 million years ago, the Rio Grande valley changed from an area of sediment accumulation to one of erosion. The Rio Grande cut down through the layers of previously deposited sand and gravel, and its tributaries also incised to keep up with the regional lowering of streambed elevation. Gullies at Tent Rocks incised the canyons and also started the formation of the tents. Where the loosely consolidated volcanic and sedimentary layers erode less easily by flowing water and blowing wind, pedestals and teepee-like outcrops project above the more readily eroded deposits.

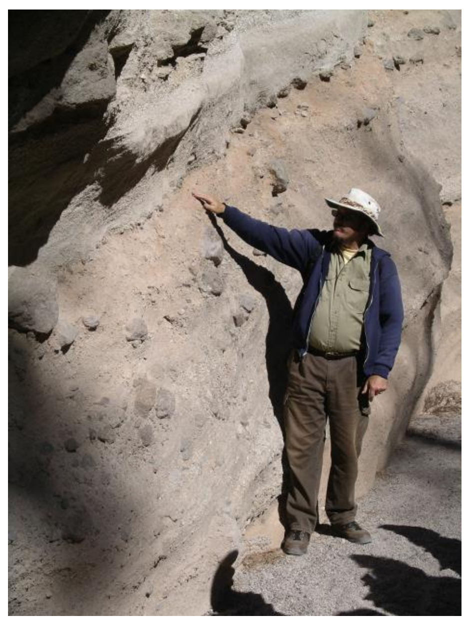
Stop 2:

The site permits contemplating two processes that form the tents.

(1) Look at the cliff face. It is readily apparent that a large cobble or boulder caps nearly all of the upward-tapering teepees; some large boulders are precariously perched on very narrow pedestals. Geologists call these landscape features *pedestal rocks*, or *hoodoos*. As rainfall and snowmelt runoff streams down the steep outcrops, the water can more readily loosen the sand grains and small pebbles than the larger cobbles and boulders. Over time these larger fragments become more isolated from the surrounding ground surface as the small grains wash away. The sediment directly below the large cobbles and boulders is sheltered from erosion by the overlying cap rock and forms an ever-higher pedestal as surrounding sand and pebbles are carried downslope. Once a pedestal starts to form in this fashion, blowing wind swirls around the feature, carrying away some of the smaller grains comprising the pedestal and sculpting it into a smooth rounded form.

(2) The conical teepees eroded in the white tuff at the base of the cliff (far left) lack cap-rock cobbles and boulders of the sort seen among the sand and gravel layers on the cliff face. One might surmise that there had once been capping cobbles and boulders that have fallen off as the pedestal became more eroded. However, this white layer commonly contains such teepee forms all around Tent Rocks and farther north into the Jemez Mountains and resistant cap rocks are very rare making it likely that these tents formed by a different process than the hoodoos. Clearly, part of the tuff erodes less readily in order to form the high-standing tent rocks. One possibility, suggested from observations elsewhere in the Jemez Mountains, is that parts of the tuff became slightly harder shortly after it deposition. This type of tuff, with many fragments of rhyolite and pumice in addition to dusty ash, forms from very hot, fast-moving avalanches of volcanic debris down the sides of volcanoes. After coming to rest, the deposit is still quite hot (more than 350 ^{o}C, in this case) and hot gases and steam from underlying damp soil rush upward through the tuff toward the surface. Along the way, the hot water vapor reacts with the pumice and ash particles and forms tiny minerals that slightly cement the particles together. This causes part of the tuff to be slightly harder than the rest and, therefore, to remain as higher features as the deposit erodes.

Entrance to the Slot Canyon



Stop 3:

Most layers exposed here consist of sand and gravel eroded from volcanoes a few miles to the north and deposited here by flash-flood-prone streams nearly 6.8 million years ago. Many of the sandier layers are conspicuously more orange in color. These horizons represent buried soils within the sedimentary deposits. Each orange horizon records several thousand years of weathering of the sediment grains, which causes some iron-bearing minerals to form rust-like oxide compounds that account for the orange color. Buried soil horizons are numerous at Tent Rocks and some contain the infilled burrows of rodents and traces of roots.

Several white layers are present on the canyon wall ahead and to the right. Pumice and ash that were explosively ejected by volcanoes and then settled from the sky like snow formed these layers. Pumice and ash particles are *pyroclastic fragments* - derived from the Greek *pyro* (fire) and *clastos* (broken). The deposits here are called *pyroclastic-fall deposits* because they formed by the accumulation of pyroclastic fragments that fell from the sky.

A number of the sand and gravel layers form strong ledges that protrude from the face of the canyon wall. In these layers the sand and gravel fragments are cemented together by a form of quartz, called chalcedony, which precipitated from cooling hot groundwater millions of years ago.

Look around in the loose sandy floor of the wash, and you will find small pieces of black, translucent to transparent obsidian, just a few millimeters across. "Apache Tears" are small pieces of rhyolite obsidian that are found in the sand and gravel layers and have eroded to accumulate along the trails and the bottoms of the washes. Apache-tear obsidian is found in many places in the western United States and the term originates from an occurrence near Superior, Arizona. One legend holds that the Apache tears found there represent the hardened tears shed by Apache women as their beloved warriors jumped over a cliff to their death rather than be captured by U.S. cavalry in the late 1880's. Geologically, Apache tears are known to form from the natural weathering of black obsidian. Obsidian is a natural glass and readily absorbs water from rainfall. As the water is absorbed within the glass it expands and cracks. Water enters along the cracks and hydrates more, previously dry obsidian. The obsidian progressively hydrates inward from cracks. The hydrated obsidian is highly fractured because of expansion after absorbing water and this allows light to readily penetrate into the ordinarily opaque, black obsidian. This lighting along the fractures renders the rock a bright, pale gray; and forms perlite. Perlite is used in the manufacture of building insulation (New Mexico is the country's leader in perlite production, from mines near Socorro and Taos). Obsidian converts to perlite by the hydration process and if that process has not gone to completion, small nuggets of obsidian may remain, enveloped in perlite. Because the highly fractured perlite is very friable, this outer gray coating readily washes or blows away, liberating the small, commonly translucent obsidian tears.

Close examination of rocks on the northern part of the Cave Loop Trail and along the summit ridge on the Canyon Trail show obsidian tears still encased in perlite. These sites, as wells as dense accumulations of Apache tears in alluvium. Although this is a national monument, the BLM does not strongly object to collection of a *few tears*, if desired.

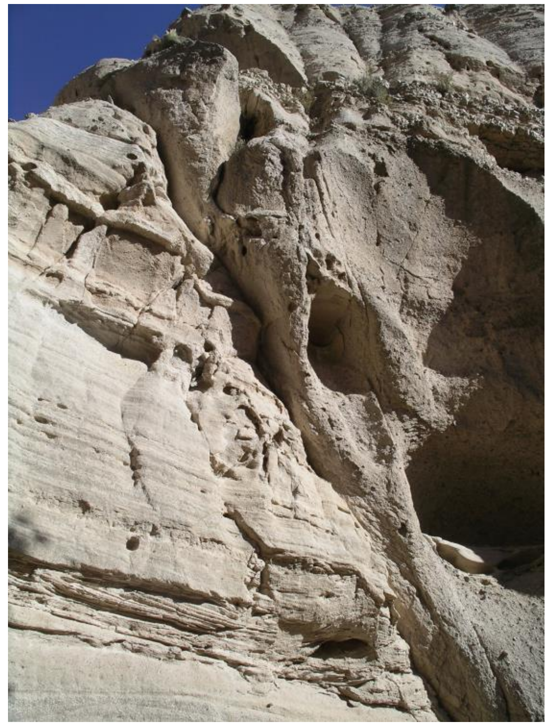
Stop 4:

Near old fence-rail holes in canyon wall

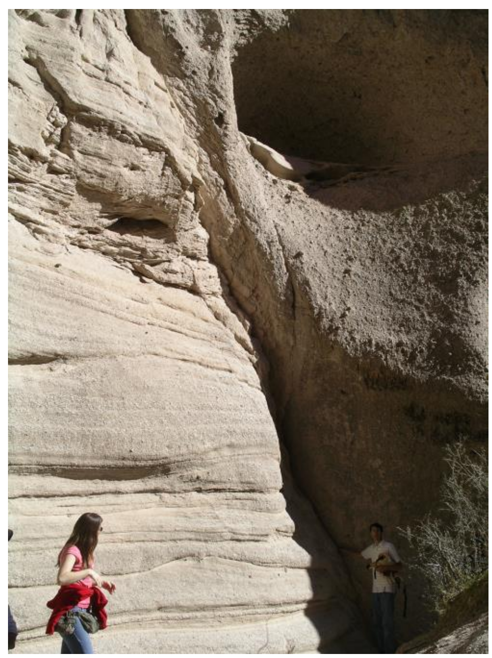
The thick white layer exposed on both sides of the canyon at eye level consists of randomly mixed pieces of pumice, blocks of rhyolite, and small grains of ash. This pyroclastic deposit did not form from grains settling out of the sky but originated, instead, from a fast-moving, hot, ground-hugging avalanche of material explosively ejected from a nearby volcano. This phenomenon is a *pyroclastic flow* and is the deadliest hazard of active volcanoes. Pyroclastic flows move at speeds in excess of 150 mph and can travel more than 100 miles. The pyroclastic-flow deposit seen here was the result of a relatively small event where the flow traveled about 5 miles.

The path along the wash moves out of loose sand and into a narrow chute eroded into the white pyroclastic-flow deposits.

Fault and crossbedding



(image above is the top part of the fault, image below is the lower part of the fault)



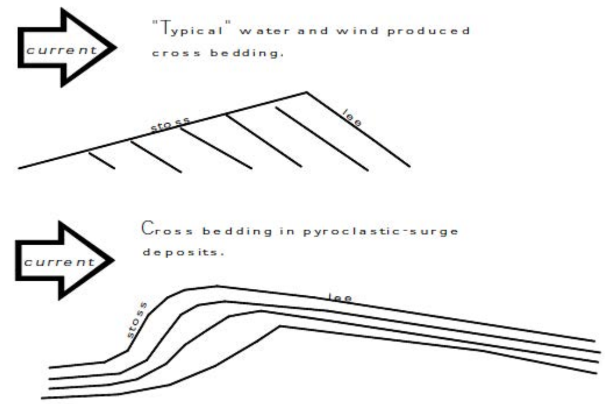
Stop 5

This is but one of many faults that are visible at Kasha Katuwe Tent Rocks. Faults are fractures along which rocks move relative to one another in response to stresses in the Earth's crust. Movement of rocks along faults generates earthquakes. The faults at Tent Rocks relate to the stretching of crust in New Mexico that began about 25 million years ago and continues to the present. As the crust stretched, faults form that caused some areas to slide downward and others to rise upward. The Rio Grande follows a series of down-dropped fault blocks.

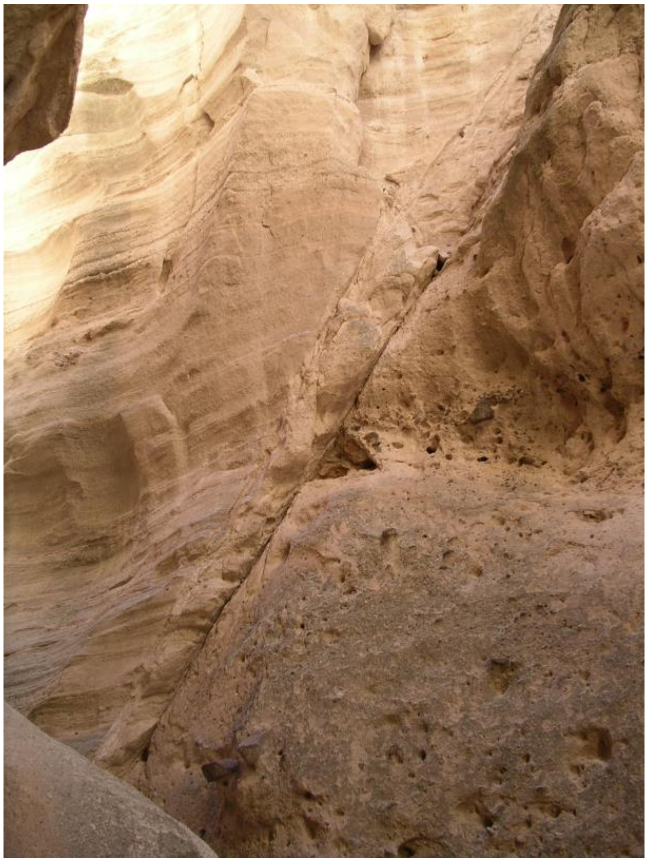
This is a normal fault (down to the southeast). It is a splay off of the much larger Pajarito fault, which is just on the other side of the ridge east of the slot canyon. The Pajarito fault has moved about 100 m in just the last million years. It is possible to match up layers to determine that there is about 30 m of displacement of the exposed tuff layers. The thick white pyroclastic-flow layers on the hanging wall correlate to the middle of a sequence of white tuff layers visible high on the canyon wall in the footwall.

The pale-tan tuff layers exposed in the footwall of the fault were produced by pulsating, staccato explosions from a volcano about 1 mile to the northwest, which erupted 6.92 million years ago. There were dozens of explosive blasts, each of which hurled a fast moving cloud of ash and debris in all directions and piled it up in dunes (represented by the wavy layers). This phenomenon is called a *pyroclastic surge* and is similar to a pyroclastic flow although there are some important differences in the details of their fluid mechanics. The explosions that produced these pyroclastic-surge deposits were caused by the energetic interaction of rising magma with groundwater; hence, this type of eruption is called a *hydromagmatic eruption*.

The surge layers are cross bedded. The rapidly moving blast current creates dunes, much like those formed by wind blowing in a desert or water flowing across a sandy streambed. Cross bedding forms when the dunes move with the current.



The diagram shows that the surge-produced cross bedding seen at B is different than more commonly seen eolian and fluvial cross bedding. Typical sedimentary cross beds only preserve slanted strata that accumulated on the sloping lee (downcurrent) side of the moving dune; the stoss side is a site of erosion or sediment transport. Surge cross bedding commonly looks different because of the high velocity of the blast current and the very high rates of particle sedimentation. Not only is there deposition on the lee, but there is also deposition on the stoss. Furthermore, through time the dune builds and migrates into the current (i.e., antidune). When looking at the surge cross bedding, the eye focuses first on the steeper, S-shaped stoss-side cross beds, but these actually face up current, rather than downcurrent. The cross bedding seen here shows that the surges moved southeast. Geologists have used measurements of the surge dunes to determine that the volcano that experienced this eruption was about 1 mile to the northwest (centered near the junction of Colle and Peralta Canyons on the Rivera property near the northern boundary of the monument).



Stop 6:

The thick bedded and very massive deposits exposed here are on the footwall of another fault that slices up the canyon walls. The massive deposits formed during earlier stages of the same explosive eruption that produced the cross-bedded surge deposits. The exact processes responsible for forming the massive, rather than cross-bedded layers are not clearly deciphered from the rocks. It is possible, however, that these deposits originated from surges that deposited fragments so quickly that dunes could not form.

Into the wide amphitheater

The canyon widens considerably upslope of the fault at C. Cross bedding and volcanic-bomb sags are present on the high cliffs on either side of the trail. Clasts in the pyroclastic-surge deposits at trail level are mostly volcanic, but there are also some other things to notice.

- A few clasts are nonvolcanic, including quartzite.
- The nonvolcanic clasts, and many of the volcanic pebbles, are very well rounded, suggesting derivation from stream gravel.
- There are many pink, angular clasts of poorly lithified siltstone.

These clasts are derived from old Rio Grande channel gravels and floodplain muds that are located beneath the volcanic vent for these surge deposits, which is only about a mile to the NW.

Stop 7:

As the Rio Grande valley has subsided along faults during the last 25 million years, a deep trough called the Rio Grande rift progressively filled with sediment washed from flanking mountains. The pore spaces between the sediment grains are filled with water at depth, and this groundwater is a critical water resource for all communities along the valley. The part of the rift-valley fill that contains abundant water is called an *aquifer*. The best quality aquifer is found in the especially porous sediment deposited by the Rio Grande over the last 10 million years, as opposed to less-porous sediment washed into the valley from its east and west margins.

Large sediment clast

Take a careful look along the right side of the wash just before making the big left-hand (westward) turn. Depending on how much dust is on the outcrop, you should be able to see swirling black sandy stripes and rumpled pink siltstone layers in the otherwise massive surge deposits. With a few moments of staring, you can see that there is a large block of stratified sediment, nearly 3 meters long and about 1.5 meters high, enclosed in the massive surge deposits. This is a single large block of the aquifer excavated by the explosions. Sandy layers with rounded pebbles represent channel deposits, interleaved with siltstones that represent bar-top or slackwater deposition in abandoned channels.

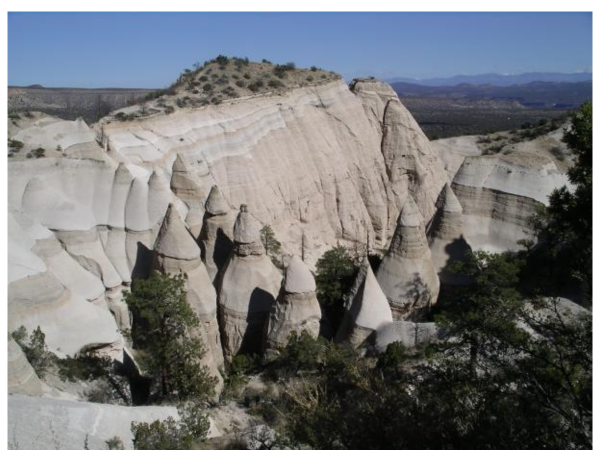
Smaller blocks of the same sort of material are commonly seen along the upcoming sinuous part of the trail. You will also see somewhat more lithified red sandstone fragments. These are *not* pieces of pre-Tertiary red beds. Instead, they are pieces of the aquifer material that baked in close proximity to the rising magma. When the steam explosions blew out the aquifer sediments, both baked (metamorphosed) sediment close to the magma and unaltered layers farther from the magma were ejected.

Stop 8:

Starting the Ascent

The slot canyon ends in a box, and the path climbs up to the south. This used to be a long, steep scramble, but now it is an improved trail with steps.

Looking back down toward the northeast from part way up the slope, there is a great view of 8, almost perfectly conical tents. This is the most photographed view at Tent Rocks. These tents are in the same pyroclastic-flow layers pointed out near the parking area.



Lunch Stop with a View

Those afraid of heights will not want to venture out to the very point, but good safe views for lunch are present all along this southward pointing ridge prong.

Some *background* to things seen from here (be selective of what to present, depending on student questions; mostly people will want to eat lunch):

Looking into the slot canyon. From this ridge you can look down into the slot canyon you just hiked up through. Particularly impressive are the 3D views of the visited faults and the great views of cross bedding in the surge deposits.

Taking in the view. Physiographic and geologic features seen in a panorama starting to the north and moving clockwise:

a) The Jemez Mountains form the northern skyline. These mountains are eroded, overlapping volcanoes, mostly active between 12 and 5 million years ago. The highest point on the near skyline to the NNW is Bearhead Peak, a rhyolite volcano that was the source for many of the pyroclastic deposits at Tent Rocks. The Jemez Mountains experienced two truly huge eruptions at about 1.6 and 1.2 million years ago. Each eruption ejected about 300 km^3 of pumice and ash, deposited by pyroclastic flows that rushed radially in all directions from the center of the mountains and as pyroclastic fall as far distant as central Kansas. So much magma was rapidly evacuated from the subterranean magma chamber that the roof of the chamber collapsed to form a huge elliptical depression nearly 12 miles across. The margin of this caldera depression forms the far skyline. Eruptions within the caldera continued until 60,000 years ago and earthquakes reveal the continued presence of magma below the caldera that may erupt at sometime in the future. The presence of this shallow magma accounts for the many popular hot springs in the Jemez Springs - La Cueva area. The now peaceful caldera features large marshy meadows and forested rhyolite volcanoes within the Valles Caldera National Preserve.

b) To the north-northeast one can see the San Miguel Mountains (with flat-topped St. Peter's Dome) forming the southeastern corner of the Jemez Mountains. In front of the mountains are conspicuous flat-topped mesas of pink-gray, orange and brown tuff. This is the Bandelier Tuff, the product of the two eruptions at 1.6 and 1.2 Ma that formed the Valles caldera. The Bandelier Tuff also forms the honeycombed pinkish-gray rock seen through the saddle above the box canyon that you walked through earlier. The large-displacement Pajarito fault intervenes between these relatively young volcanic rocks and the 6.8-7.0 million-year-old rocks that you hiked through in the canyon. You are on the uplifted side of the fault.

c) To the northeast, beyond the tips of the Bandelier Tuff mesas, the Rio Grande cuts a deep canyon, mostly hidden from this perspective, through 2.5-4 million year old lava flows erupted between the Jemez Mountains and Santa Fe. This volcanic area, called the Cerros del Rio, includes more than a dozen small volcanoes and cinder cones forming the many hills just east of the Rio Grande. Looking beyond the Cerros del Rio you can see the Santa Fe Range of the Sangre de Cristo Mountains on the skyline. The Santa Fe Range is a rock uplift on the east side of the Rio Grande valley and consists mostly of rocks that are 1.6-1.7 billion years old.

d) To the east, the pointed top of Tetilla Peak marks the southernmost volcano of the Cerros del Rio, below which the ground surface drops abruptly across the La Bajada escarpment beyond Cochiti Lake. The La Bajada escarpment marks the location of a large fault. In this area, the Rio Grande is located near the center of rift basin, a block of crust dropped down along faults. The La Bajada fault marks the east side of the basin and the Pajarito fault, located just beyond the ridge above the slot canyon, forms the western side of the basin.

e) To the southeast are the many cone-shaped peaks of the Cerrillos Hills followed toward the south by the Ortiz Mountains, San Pedro Mountains, and South Mountain. These features are the highly eroded roots and exposed, solidified magma chambers for volcanoes that were active between 28 and 36 million years ago. Hot groundwater solutions circulating around the magma chambers deposited gold, turquoise and lead ores that have been valuable exploited resources for more than 1000 years.

f) To the south is the stair-stepped profile of the Sandia Mountains rising immediately to the east of Albuquerque. The steep western escarpment is composed of 1.4-1.6 billion year old rocks that originally formed more than 8 miles below the ground surface. The crest of the range is composed of layers of limestone and other sedimentary strata that accumulated in warm, tropical shallow sea about 300 million years ago. A major rift fault uplifted the Sandia Mountains and downdropped the area of the city of Albuquerque. Closer and to the right (west) of the Sandia Mountains is Santa Ana Mesa, capped by lava flows erupted about 2.5-2.7 million years ago. The largest of the many small shield volcanoes that erupted this lava forms a low-sloping cone.

g) A conspicuous forested mesa extending toward the southeast forms the southwestern skyline. This mesa is capped by stream gravel that is about 2 million years old and marks the highest surface across which streams flowed before the Rio Grande and its tributaries began downcutting and eroding the valley. If you look carefully, you will see that there are actually two parallel mesas, one slightly lower than the other is. The same gravel deposit caps both mesa surfaces and the difference in their elevations represents the offset along a fault that cuts the old landscape surface.

Why is Tent Rocks here? From this vantage point it is clear that the steep cliffs, slot canyons, and pedestal rocks are only found in a very small area. Looking southward across Peralta Canyon one sees rounded hills cloaked in juniper, piñon and brush with virtually no rock outcrops. Geologic mapping shows that the same layers are present in those hills as are seen at Tent Rocks.

So, why is the most picturesque scenery found only here? In order to stand in steep slopes and cliffs, rock materials have to be consolidated to some extent. In order to erode the canyons and form the tent rocks, the materials must be easily eroded. This apparent paradox can be resolved only by considering that the sedimentary and volcanic layers at Tent Rocks are sufficiently consolidated to form steep slopes while not being so consolidated that they cannot be readily eroded. This "just right," or Goldilocks circumstance is what makes Tent Rocks so unique.

As you look around the amphitheater and slot-canyon walls you notice hard ledges among the rock layers that project a short distance beyond the outcrop face and cast shadows. The ledge-forming layers began as poorly consolidated beds of sand and tuff.

The ledge-forming layers were particularly porous and became preferred pathways for movement of groundwater before streams eroded the amphitheater. The ground water originated in the volcanic Jemez Mountains to the north and was heated by subterranean magma. The water moved southward along large faults, especially the Pajarito fault, which is present just east of the ridge bounding the east side of the Tent Rocks amphitheater. The water moved along the fault and then laterally along porous layers. The water cooled as it traveled farther from the volcanic heat source. When hot the water had dissolved silica from the volcanic rocks that it passed through. As it cooled, the silica was precipitated as microscopic quartz crystals, called chalcedony, which cemented the particles in the porous layers to make solid rock.

There are enough hard, cemented ledges to provide sufficient structural integrity to the outcrops to form steep cliffs. At the same time, most of the rock materials remain sufficiently soft to be easily eroded. The restricted nature of the steep cliffs, slot canyons, and pedestal rocks at Tent Rocks results from proximity to a large fault along which warm water spread laterally and cemented some rock layers with minerals that precipitated as the water cooled.

Note about return hike: You have two options when leaving this spot, both of which involve backtracking through the slot canyon to point A on the map. If time is short then it is probably best to just continue backtracking to the parking area. If time and interest permit, then do the Cave Loop Trail. There's some up and down on this trail, and lots of Apache Tears.

The Cave

The cave is excavated in silvery gray volcanic ash erupted 6.8 million years ago. If you look closely you can see that there are two distinct beds of ash. The lower bed, with diffuse nearly horizontal layers within it, is slightly more resistant to erosion and forms a bench inside the cave. This bed represents the accumulation of ash that fell out of the sky from a high plume of ash and vapor that had been explosively propelled many miles into the air above a nearby volcano (pyroclastic-fall deposit). The thicker upper bed, with diffuse layers inclined downward to the east (right) is the deposit of a dune of ash that was blown around by the wind. This bed is very soft and was easily excavated to make the cave with the ash-fall bed forming the bench.

The history of this cave remains to be sorted out. Archaeologists call these little caves, *caveats* (cave-ate), and they are common in association with ancient pueblo settlements throughout the Jemez Mountains. It is likely, however, that this is a relatively recent (19th or early 20th century) excavation by livestock herders. If you stand at the base of the cliff and look downslope to the south you will notice a square area that lacks any piñon or juniper trees, and instead contains lots of sagebrush, chamisa, and cholla. This difference in vegetation suggests disturbance by humans and may outline a former corral.

Continue looping around the Tent Rocks amphitheater on the trail. The trail crosses a wash emerging from a canyon that drains the northwest part of Tent Rocks. This canyon is on private land, so refrain from allowing trip participants to wander in that direction. There is, however, great Apache Tear collecting in the sand of the wash.

"Teepee Garden"

Here, the trail passes between conical tents eroded in pyroclastic-flow deposits (the same deposits seen between A and B, and the same ones containing conical tents visible on the ascent near F). These tents lack capstones and probably form by differential erosion of tuff that was locally indurated by minerals condensing from rising gases when the deposits cooled.

Trace this thick white layer across the outcrop face above the trail to the north-northwest, and you will see it displaced downward to the north along a fault. The fault coincides with a narrow ravine, which can be traced upward to the top of the cliff.