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TECTONICS OF THE SANDIA MOUNTAINS: 50 YEARS AFTER KELLY AND NORTHROP'S MEMOIR

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Abstract—Fifty years after Kelley and Northrop's (1975) Memoir No. 29 on the geology of the Sandia Mountains, we present an updated look at the tectonics of this range based on advances in regional tectonic and geochronologic context. Plate tectonics was not mentioned in the memoir, although it was gaining acceptance as a paradigm after the late 1960s. Precambrian rocks had been mapped, and "basement orogenies" were noted that are now interpreted as a record of the formation of the continental lithosphere of New Mexico. This took place via plate tectonic additions along a long-lived convergent margin of "southern Laurentia" (in present coordinates), with tectonic pulses at approximately 1.75, 1.70, 1.65, and 1.45 Ga. The 1.45-Ga Sandia granite formed by basaltic underplating and lower-crustal partial melting associated with the formation of an orogenic plateau, an overthickened region within the Picuris orogen, which was inboard of the plate margin. The Sandia pluton crystallized at ~10-km (~6-mi) depth in the middle crust and was unroofed between 1.45 Ga and ~300 Ma to form the sub-Pennsylvanian Great Unconformity. Paleozoic structures, tectonics, stratigraphy, and the paleontologic record mark latitudinal shifts of North America during the assembly and breakup of the Pangean supercontinent. The 320–270-Ma Ancestral Rocky Mountains were intracratonic uplifts that resulted from contraction from several sides of the plate during the assembly of Pangea; they reactivated late Proterozoic basement fault zones. Deformation during the ~90–45-Ma Laramide orogeny progressed from west-to-east in New Mexico as a result of flat-slab subduction of the Farallon plate. Embedded oceanic plateaus (e.g., conjugate Shatsky Rise) may help explain Laramide right-lateral transpression in New Mexico. The 38–23-Ma Oligocene ignimbrite flare-up was caused by removal of the Farallon slab, asthenospheric upwelling, and lower-crustal melting. This decoupling led to a transition from contraction to extension roughly along the same east–west direction. The Rio Grande rift initiated by ~25 Ma in response to the breakdown of the subducting Farallon slab and the reactivation of Proterozoic fault zones. Isostatic footwall rebound and erosion of nearly 5 km (3 mi) of overlying strata accompanied 20–17-Ma uplift of the Sandia Mountains and resulted in a high-elevation segment of this eastern rift flank. Complex synextensional rift fill of the Santa Fe Group produced highly variable groundwater aquifers and microseismicity from ongoing east–west crustal extension continues to influence the region.

INTRODUCTION

This paper looks back over 50 years of the New Mexico Geological Society (NMGS) and since the publication of New Mexico Bureau of Mines and Mineral Resources Memoir 29, entitled *Geology of the Sandia Mountains and Vicinity, New Mexico* (Kelley and Northrop, 1975). This memoir was a field-based study that highlighted the spectacular geologic record exposed in the Sandia Mountains and vicinity. It was the culmination of ~75 years of research at the University of New Mexico, initiated by the university's first professor of geology, Clarence Luther Herrick (1858–1904), that contributed to the training of dozens of graduate students and hundreds of undergraduate students. The goal in this article is to expand the regional context for these rocks based on recent literature, especially papers published since the NMGS last met in Albuquerque for the 1999 Fall Field Conference (Pazzaglia and Lucas, 1999). With future students in mind, we highlight continuing research challenges.

New Mexico provides a natural history display of the diverse processes by which Earth's surface responds to uplift and erosional modification. Mountains can be pushed up by plate tectonic forces, as in the Sangre de Cristo Mountains. Mountains can "pop up" isostatically on rift flanks, as seen in the Sandia Mountains. Mountains can be formed by a variety of volcanic processes (e.g., Mount Taylor and the Jemez Mountains) or bowed up by laccolithic intrusions (e.g., Ortiz Mountains). Ancient mountains leave their erosional record in sedimentary rocks such as late Paleozoic successions that have been used to decipher uplifts and basins of the Ancestral Rocky Mountains (ARM). The demise of Proterozoic mountain belts and deep regional erosion led to the formation of the Great Unconformity. Subsequent epeirogenic uplift of Earth's surface formed orogenic plateaus, such as the Colorado Plateau, in response to changes in lithospheric buoyancy.

In Kelly and Northrop (1975), fault geometries and linkages were mapped, described, and compiled into the first comprehensive geologic map of the Sandia Mountains. In their memoir, the term "rift" was used for their Tijeras "rift belt," which included the northeast-trending Tijeras fault zone in Tijeras Canyon. The term "Rio Grande trough" was used for the Rio Grande rift, which involved as much as 10 km (6 mi) of structural relief from the crest to the base of the trough (Kelley and Northrop, 1975; Kelley, 1977). Uplift and subsidence were attributed to faulting and isostatic loading from the rift-filling Santa Fe Formation (now Group). There was essentially no discussion of regional driving forces in the memoir. Over 50 years later, we provide a synthesis and an updated reference list from which students and researchers can further advance

understanding of the geologic history and processes displayed in the Sandia Mountains and throughout New Mexico.

Following the regional synthesis of Kelley and Northrop (1975), geologic investigations of the Sandia Mountains have progressed from reconnaissance-scale mapping toward integrated, process-based studies that place the range within the broader tectonic framework of the Rio Grande rift. Early post-1975 work established the Sandia Mountains as a basement-cored uplift forming the eastern structural margin of the Albuquerque Basin and emphasized the role of Neogene extension in shaping the range (e.g., Kelley, 1977, 1979; Woodward, 1977; Hawley, 1978). Since the 1990s, research has increasingly focused on the interactions among structural inheritance, basin development, and surficial processes.

Regional geologic mapping evolved from early structural frameworks (Kelley and Northrop, 1975; Kelley, 1977; Hawley, 1978) to detailed, multiscale compilations integrating bedrock geology, rift-basin stratigraphy, and structure (e.g., Williams and Cole, 2006; Connell, 2008a). Foundational mapping by Kelley and Northrop (1975) and Kelley (1977) documented the distribution of Proterozoic basement, Paleozoic cover, and major fault systems along the range front. Subsequent 1:24,000-scale mapping by the New Mexico Bureau of Geology and Mineral Resources (e.g., Karlstrom et al., 1994; Connell et al., 1995; Read et al., 1995; Connell, 1996, 1997) refined lithologic, structural, and geomorphic relationships, including delineation of major and subsidiary faults that provide constraints on structural segmentation, displacement, and Pleistocene fault activity.

Key developments since the 1990s have been the recognition of structural inheritance and polyphase deformation as primary controls on the evolution of the Sandia Mountains. Structural and geochronologic studies indicate that Proterozoic basement fabrics influenced Laramide contraction and subsequent extension of the Rio Grande rift (e.g., Lozinsky, 1994; Russell and Snelson, 1994; Kirby et al., 1995; Karlstrom et al., 1999, 2000, 2004; Cather, 2004; Kues and Giles, 2004). These studies interpreted deformation as the reactivation of long-lived crustal weaknesses, with Laramide shortening expressed in basement-involved uplifts and reverse faults later overprinted by extensional structures.

Advances in subsurface geophysics have provided additional constraints on basin geometry and evolution (Cordell, 1979). Early seismic-reflection interpretations suggested an asymmetric basin composed of opposing half-graben subbasins separated by transfer zones (e.g., Russell and Snelson, 1994; May et al., 1994). Subsequent integration of gravity, aeromagnetic, and borehole data led to revised models in which the basin comprises multiple interconnected, predominantly east-tilted subbasins with increasing structural segmentation southward (Grauch et al., 1999; Grauch and Connell, 2013).

Regional syntheses further integrated surface mapping with subsurface data, including well and geophysical datasets, to develop basin-to-range structural and stratigraphic frameworks (e.g., Hawley et al., 1995; Maldonado et al., 1999, 2007; Williams and Cole, 2006; Connell, 2006, 2008a, 2011; Connell et al., 2013; Grauch and Connell, 2013; Ricketts et al., 2015). These compilations highlight the coupling among basement structure, rift-related faulting, syntectonic sedimentation, and Quaternary landscape evolution and provide a foundation for interpreting tectonic, geomorphic, and hydrogeologic processes along the eastern Albuquerque Basin margin (e.g., Hawley et al., 1995; Pazzaglia et al., 1999; Connell et al., 2013; Grauch and Connell, 2013; Ricketts et al., 2015, 2016).

Thermochronologic studies have further refined our understanding of the timing of the Sandia Mountains uplift. Apatite fission-track and (U–Th)/He data indicate rapid cooling during the early to middle Miocene (~20–17 Ma), followed by slower exhumation rates, consistent with progressive rift-flank uplift and footwall rebound (e.g., House et al., 2003; Ricketts et al., 2015, 2016).

Concurrent work in stratigraphy and basin analysis has improved understanding of tectonic and climatic influences on sedimentation in the adjacent Albuquerque Basin (e.g., Lozinsky, 1994; May et al., 1994; Maldonado et al., 1999, 2007; Connell, 2004, 2008b). Studies of the Santa Fe Group indicate that basin fill reflects interactions among subsidence, sediment supply, and climatic variability (e.g., Connell, 2004, 2008b; Connell et al., 2005, 2013). Integrated geochronologic and stratigraphic analyses show that the deposition of units such as the Ceja and Sierra Ladrones Formations, as well as Quaternary terrace development, was influenced by both tectonic tilting and climate-driven changes in discharge and sediment flux (Cole et al., 2007; Connell, 2008b; Connell et al., 2007, 2013). These studies also identified the development of through-going Rio Grande drainage and subsequent incision after 0.8 Ma as key transitions in the basin's evolution (e.g., Connell et al., 2005, 2013; Repasch et al., 2017). Geomorphic and Quaternary investigations of the Sandia Mountains piedmont document repeated cycles of aggradation, stability, and incision during the Pleistocene, reflecting combined tectonic uplift and climatic variability (e.g., Connell, 1996; Connell and Wells, 1999; Connell et al., 2007, 2013). These studies provide higher-resolution records of the structural and geomorphic evolution along the range front.

Collectively, research since the 1990s has reframed the Sandia Mountains as a structurally complex system shaped by Proterozoic inheritance, Laramide contraction, and Neogene extension (Karlstrom and Humphreys, 1998; Karlstrom et al., 1999). Current interpretations emphasize distributed deformation, basin segmentation, and interactions among tectonics, sedimentation, and climate, establishing the Sandia Mountains and adjacent Albuquerque Basin as an important setting for studying continental rift evolution.

PRECAMBRIAN TECTONICS

The tectonic evolution of Precambrian basement rocks in the Sandia Mountains is now viewed in terms of Proterozoic plate tectonic additions to the Wyoming craton (Condie, 1982; Whitmeyer and Karlstrom, 2007). Figure 1 shows that the Sandia Mountains are within the 1.68–1.60-Ga Mazatzal crustal province. The recognition of the 1.51–1.48-Ga sedimentary successions in the Defiance uplift near the Arizona–New

Mexico border (Doe et al., 2013) and the Picuris Mountains in northern New Mexico (Daniel et al., 2013) demonstrated that 1.5-Ga supracrustal rocks were buried to variable middle-crustal depths during regional deformation and metamorphism at ~1.45 Ga. This has expanded the spatial and temporal extent of Mesoproterozoic deformation and metamorphism beyond the already-known deformation in the aureoles of ~1.4-Ga plutons in the region (Nyman et al., 1994; Kirby et al., 1995). The recognition of metamorphosed supracrustal successions led to questions from some workers about the nature and even

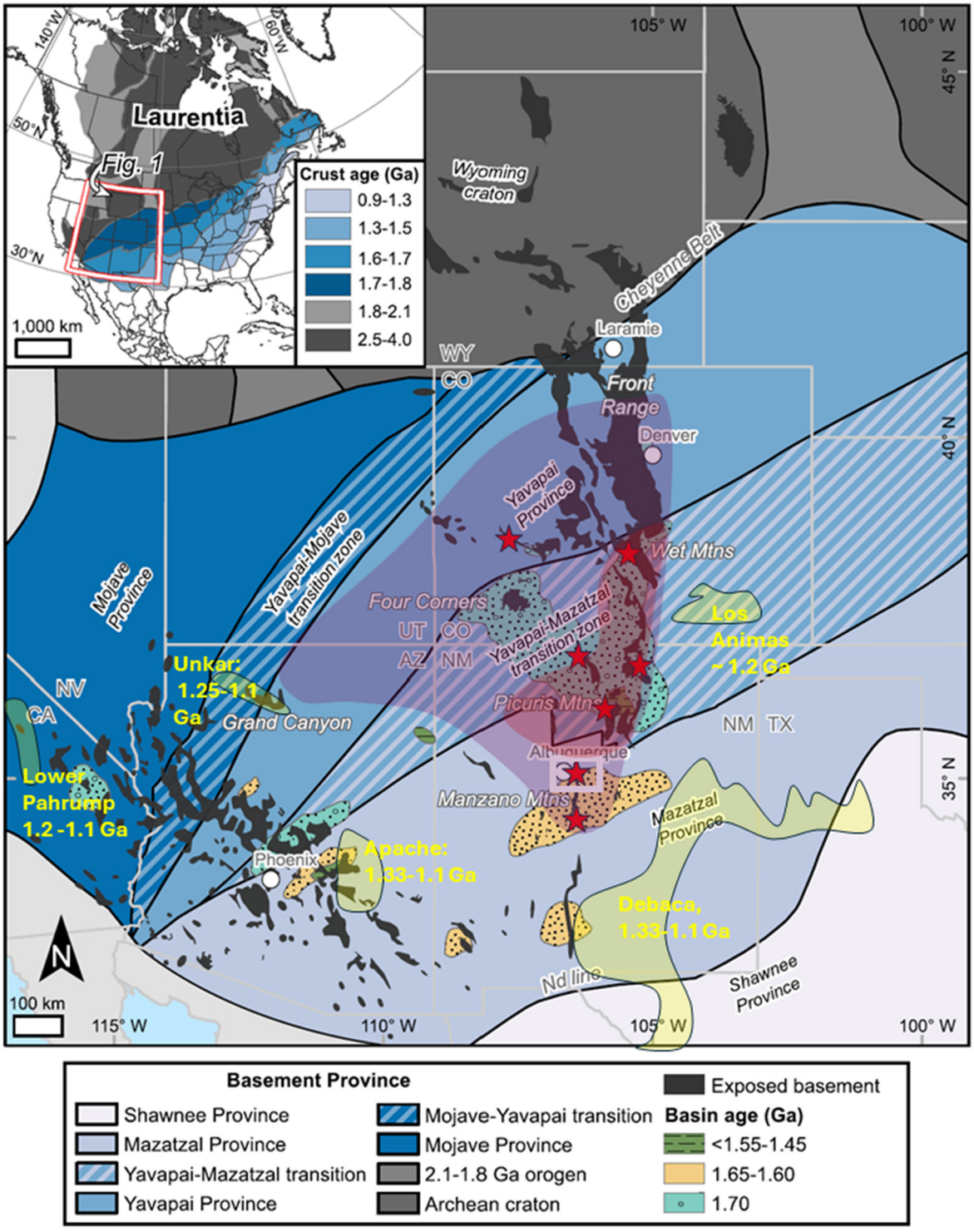


FIGURE 1. Geologic map of Proterozoic crustal provinces (adapted from Hillenbrand et al., 2025, and references therein). The thick white box and red star near Albuquerque indicate the location of the Sandia Mountains. Light purple outline denotes the area of proposed Picuris orogenic plateau, as defined by (1) regions that contain 1.45–1.38-Ga middle-crustal plutons as opposed to shallow-level plutons and rhyolites of this age; (2) regions of 1.45-Ga shear zones representing middle-crustal shortening; (3) areas of highest 1.4-Ga metamorphic grade (dark purple; Shaw et al., 2005), and (4) areas of 1.2–0.8-Ga slow cooling (red stars) as opposed to regions where Mesoproterozoic basement is at the surface by 1.2 Ga and overlain by Mesoproterozoic sedimentary basins (yellow).

the existence of earlier Paleoproterozoic tectonism, such as the Mazatzal orogeny (Arnoff et al., 2016; Jones and Daniel, 2023; Holland and Regan, 2026), reflecting the difficulty of interpreting older deformational events through later deformational fabrics in places like the Picuris Mountains (Hillenbrand et al., 2025). This difficulty can be observed in the Sandia aureole, which we will visit for the 2026 NMGS Field Conference (Connell et al., 2026), where ~1.45-Ga deformation overprints and transposes older fabrics. Petrochronology and in situ dating of metamorphic minerals (Holland et al., 2020; Hillenbrand et al., 2025) help to reveal multiple orogenies in both the Picuris and Manzano Mountains that better calibrate structural studies of long-recognized polyphase (Mazatzal plus Picuris) deformational fabrics (Holcombe and Callendar, 1982; Karlstrom et al., 2016). This, plus other regional work (Amato et al., 2008; Hillenbrand et al., 2026) supports the importance of both 1.65-Ga and 1.45-Ga tectonic events.

The Picuris orogeny was long-lived based on dating of 1.45–1.38 Ga metamorphic minerals in the Picuris Mountains (Bollen et al., 2022) and regional 1.48–1.35 Ga granitic magmatism (Bickford et al., 2015). The northern and southern aureoles of the Sandia pluton include 1.68–1.60-Ga rocks that are correlated with the Manzano Group (Holland et al., 2020) and associated syntectonic ~1.65-Ga plutons (Brown et al., 1999). Both the northern and southern aureoles of the Sandia pluton record intense ductile deformation near the pluton, involving middle-crustal flow and the transposition of all earlier fabrics during partial melting in the metasedimentary rocks, producing a composite foliation. The most intense ductile flow was adjacent to the crystallizing pluton but predated its final crystallization at 1.45 Ga, as indicated by the relatively weak solid-state deformational fabric in most of the granite (Kirby et al., 1995). Crosscutting northwest-striking tabular pegmatites postdate the ductile deformation and have $^{40}Ar/^{39}Ar$ muscovite ages of 1.45–1.43 Ga (Heizler et al., 2026). At the southern end of the Sandia pluton in Tijeras Canyon, the Seven Springs shear zone deformed and remelted the ~1.65-Ga Cibola granite (Karlstrom et al., 2004) during top-to-the-north shearing, where ductile fabrics are crosscut by pegmatites that yield $^{40}Ar/^{39}Ar$ muscovite ages of 1.45–1.43 Ga. Our interpretation is that the ~10-km (~6-mi) deep middle crust was thermally weakened by the developing magma chamber that concentrated regional deformation before and during 1.45-Ga emplacement (Kirby et al., 1995; Shaw et al., 2005). Major questions about the Picuris orogeny include unraveling the tectonic pulses over its more than 130-million-year (1.48–1.35-Ga) duration and, in the Sandia pluton region, explaining the lack of major basement cooling and unroofing until after ~1.0 Ga (Heizler et al., 2026).

A Picuris orogenic plateau has been hypothesized by Hillenbrand et al. (2023) to have been a region of overthickened crust within the larger Picuris orogeny well inboard (extending ~1,000 km [~621 mi]) from the coeval plate margin that perhaps formed in part through flat-slab subduction followed by slab removal, similar to the modern Colorado Plateau. This is based on estimates of past crustal thickness in parts of northern New Mexico derived from "chemical mohometry" modeling (Luffi and Ducea, 2022). This method applies 41 "chemical mohometers" to calibrate the abundances and ratios of major and trace elements in ancient granodiorites relative to a global dataset of ~35,000 plutonic rock samples from settings with known crustal thicknesses. Results suggest a 30–35-km (19–22-mi)-thick crust between 1.7 and 1.65 Ga (Fig. 2A and 2B) and crust that may have been similarly thin during the deposition of the ~1.5-Ga Trampas Group and correlative basins (Doe et al., 2013; Daniel et al., 2013). Subsequently, the crust over a wide region was thickened to 45–55 km (28–34 mi) during the ~1.45-Ga Picuris orogeny (Fig. 2C). The geometry of this thickened region is not yet well defined by mohometry data alone but may also be constrained by the combination of data shown in Figure 1 (red outline). These include (1) regions that contain 1.45–1.38-Ga middle-crustal plutons (as opposed to shallow-level plutons and rhyolites of this age in the Great Plains); (2) regions of ~1.4-Ga shear zones representing middle-crustal flow and shortening at ~1.45 Ga, such as the Manzano and Picuris thrust belts; (3) areas of highest 1.4-Ga metamorphic grade (red polygon with black outline from Shaw et al., 2005); and (4) areas of 1.2–0.8-Ga slow cooling (red stars) such as the Sandia Mountains, as opposed to regions where Mesoproterozoic basement was exposed at the surface by 1.2 Ga as shown by overlying Mesoproterozoic sedimentary basins (yellow polygons). This crustal thickening was aided by 5–10 km (3–6 mi) of lower-crustal thickening via basaltic underplating (Fig. 2C; Shaw et al., 2005; Crowley et al., 2006; Hillenbrand et al., 2023). The underplating caused lower-crustal partial melting giving rise to "A-type" geochemistry of the Sandia granite and other ferroan granites (Frost et al., 2001). In this petrologic model, the "A" in "A-type" does not stand for anorogenic. Kirby et al. (1995) emphasized this by adding a space between the "n" and the "o" to refer to it as "an orogenic" pluton. This is compatible with a global compilation by Condie et al. (2023), suggesting that most A-type granites occur in accretionary orogens. The "A," however, can stand for anatectic (i.e., lower-crustal partial melting) or anhydrous (rather than subduction related).

Sandia pluton cooling data are consistent with the hypothesis that thick crust in this region persisted and remained magmatically active through basaltic underplating from 1.48 to 1.35 Ga. An analog for this type of regional uplift is the development of an orogenic plateau, such as the Colorado Plateau, through underplating, a combination of upper-crustal and lower-crustal thickening, and the longevity of high topography. The wide extent and relatively low topographic relief of orogenic plateaus (as compared to mountain belts) may reflect a hot, weak lower crust due to underplating. These wide uplifted regions can take tens to hundreds of millions of years to erode to sea level as each increment of regional erosional lowering causes isostatic rebound of as much as half (Lazear et al., 2013), making orogenic plateaus—like icebergs—difficult to remove from the top.

The cooling history of the Sandia pluton also constrains this model and constrains the longevity of the Picuris orogenic plateau. Potassium feldspars in the Sandia granite and its aureole cooled from 175 °C to 250 °C (347 °F to 482 °F) between

1.0 Ga and 0.8 Ga. This cooling reflects partial exhumation from ~6–8 km (~4–5 mi) of crustal depth (assuming a 30 °C/km geothermal gradient). This period was near the end of the broader "Grenville" orogeny, which was concentrated in what is now Texas during the assembly of the supercontinent Rodinia (Karlstrom et al., 2001). A wide foreland region in Arizona and New Mexico received sediment from 1.3 to 1.1 Ga (Fig. 1; Timmons et al., 2001; Mulder et al., 2017). In New Mexico, the 1.3–1.1-Ga Debaca Group is preserved in the subsurface of the Great Plains east of the Rocky Mountains (Amarante et al., 2005). Thermochronology suggests that basement rocks of the Rocky Mountains remained deep and hot from 1.4 to 0.8 Ga, whereas Great Plains rocks of the 1.4-Ga granite–rhyolite province and the Debaca Group were near the surface during much of this time. Regional studies (Karlstrom and Humphreys, 1998) and abrupt thermochronologic changes across the front of the Rocky Mountains (Sanders et al., 2006) suggest east-side-down movement on Mesoproterozoic brittle faults within the Grenville foreland that may have paralleled the eastern edge of the Picuris orogenic plateau and that established the north–south trend of the modern Rocky Mountain front ranges from central Colorado to central New Mexico (Fig. 1). Neoproterozoic near-surface clastic dikes in the Colorado Front Range (Siddoway and Gehrels, 2014) and potential inversion of Front Range structures at ~800 Ma by Neoproterozoic normal faulting (Sanders et al., 2006) was likely related to the breakup of Rodinia (Karlstrom et al., 2000). A continued research challenge is to parse older northeast-, northwest-, and north–south-trending brittle fault systems that appear to have formed a grid-like network of basement weaknesses that ahve been repeatedly reactivated to help localize ARM, Laramide, and Rio Grande rift-flank uplifts.

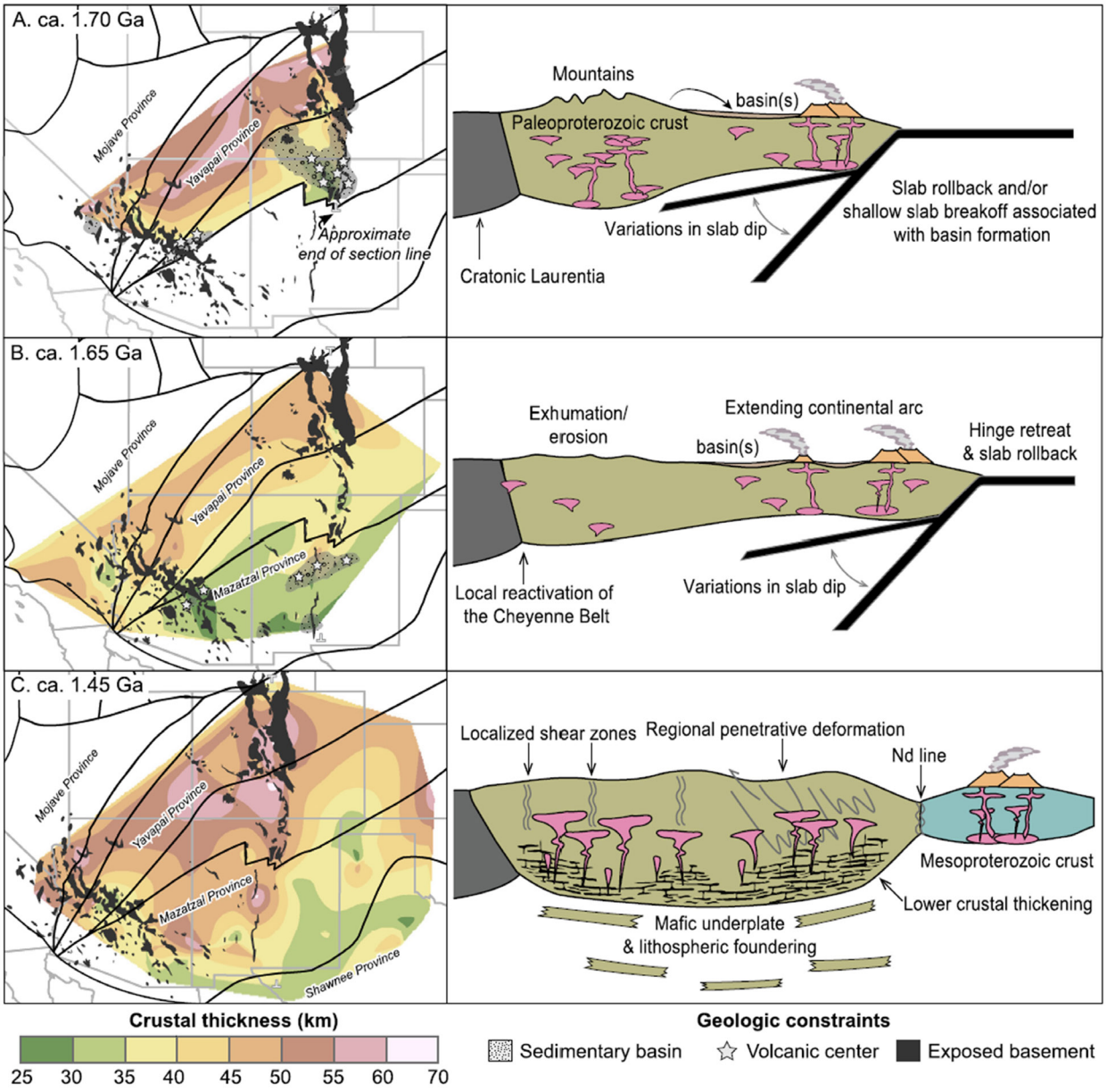


FIGURE 2. Maps of crustal thickness (left) and schematic plate tectonic cross-sections (right, modified from Shaw et al., 2005) of Proterozoic orogens through time based on "chemical mohometry" (Hillenbrand et al., 2023).

PALEOZOIC ROCKS AND TECTONICS

Transcontinental Arch

The existence of an early Paleozoic Transcontinental Arch that was emergent during the Cambrian Sauk marine transgressions has been hypothesized based on the absence of Cambrian and lower Paleozoic strata in northern New Mexico and parts of southern Colorado (Amato and Mack, 2012). It is variably drawn as a northeast-trending highland (Rocky Mountain Atlas, 1972; Amato and Mack, 2012; Sweet et al., 2021) with northwest-trending segments in some versions (Carlson, 1999; Holland et al., 2023), and parts of it may have been emergent.

The Sandia Mountains do not include strata older than Middle Pennsylvanian resting on the Proterozoic basement, except for some very local and thin Mississippian strata. This is the case at least as far south as Socorro, New Mexico. South of the latitude of Truth or Consequences, New Mexico, upper Cambrian to Mississippian strata are present between Proterozoic basement and Middle Pennsylvanian strata. The question is whether such strata were deposited farther north and removed by erosional truncation during the Pennsylvanian, whether the Transcontinental Arch was a highland during much of the Paleozoic across which deposition did not take place, or whether some combination of these occurred.

Bachman (1968) noted that none of the lower-middle Paleozoic strata in southern New Mexico (all of marine origin) show a "landward transition in lithology" northward. Furthermore, most of these lithostratigraphic units have variable thickness across southern New Mexico, although there is a general northward thinning of some units and the truncation of all lower and middle Paleozoic strata no farther north than southern Socorro County, which is >125 km (>78 mi) south of the Sandia Mountains. In southern New Mexico, three substantial unconformities in the lower-middle Paleozoic section shed light on this time interval. (1) At the base of the Cable Canyon Sandstone (Montoya Group), upper-Middle Ordovician strata rest on Lower Ordovician strata, representing a hiatus of nearly 25 million years. (2) At the base of the Percha Formation, upper-Middle Devonian strata rest on Upper Ordovician strata, representing a hiatus of about 60 million years. And (3) At the base of the Red House/Sandia Formations, Middle Pennsylvanian strata rest on Upper Devonian strata, representing a hiatus of about 55 million years. Various workers (Kelley and Silver, 1952; Kottlowski, 1960; Bachman, 1968; Seager and Mack, 2003; Lucas et al., 2023) concluded that thickness changes and truncation of the lower-middle Paleozoic units northward can be explained as the result of erosional truncation under one or more unconformities rather than as a continuous Transcontinental Arch. Kelley and Silver (1952, fig. 16) invoked epeirogenic movements along a hinge line north of the Caballo Mountains in Sierra County as the tectonic force behind the pre-Montoya and pre-Percha unconformities.

The most substantial unconformity, from a stratigraphic viewpoint, is the pre-Pennsylvanian unconformity, which marks the onset of the ARM. This unconformity overlies all lower-middle Paleozoic strata that were present as far north as Socorro County. Thus, the thinning and removal of lower and middle Paleozoic strata northward can be attributed to at least three unconformities, two likely driven by epeirogeny, and the last driven by the ARM orogeny. Yet it remains unclear just how far north the lower-middle Paleozoic strata were deposited.

The timing and geometry of the Transcontinental Arch and regional Paleozoic depositional patterns remain active research topics (e.g., Myrow et al., 2003; Hantsche et al., 2021) that continue to be tested through detrital zircon studies of Cambrian rocks that indicate potential fluvial pathways around or through Cambrian uplifts. Both "Grenville-age" (1.2–1.0-Ga) zircons and Cambrian-age detrital grains from well-dated magmatic sources can help resolve sediment dispersal patterns (e.g., Holland et al., 2023; Muhlbauer et al., 2025). We speculate that 1.1-Ga plume-related uplift of a northeast-trending transcontinental arch within the Grenville foreland may have taken place due to rapid movement of Laurentia over a plume that impacted the base of the plate at 1098 Ma to form the southwestern Laurentia large igneous province and then spread to the midcontinent rift region (i.e., Duluth complex) by 1094 Ma (Mohr et al., 2024). Such an uplift may later have been segmented by northwest- and north-trending fault systems that developed after ~1.1 Ga, creating a basement fault network in the southwestern United States (Marshak et al., 2000; Timmons et al., 2001, 2005).

Ancestral Rocky Mountain Orogeny

The Sandia Mountains preserve little record of tectonic events between 0.8 Ga and 300 Ma, except that nearly 5 km (3 mi) of crystalline basement was removed by erosion during this time, forming the sub-Pennsylvanian Great Unconformity. The 320–270-Ma Ancestral Rocky Mountains (e.g., Dickinson and Lawton, 2003) were a set of uplifts ringed by facies changes within Pennsylvanian strata: mostly arkose near unroofed basement rocks, giving way to carbonates and shales in distal parts of fault-bounded depositional basins that reflect the fact that during much of the Pennsylvanian, New Mexico was in the Pangean equatorial tropics as an archipelago of islands surrounded by shallow seaways. These facies patterns reflect now-eroded mountain uplifts of unknown height documented within the sedimentary basin record. The deepest troughs in New Mexico, where the most subsidence took place, include the Taos trough, where more than 3 km (>2 mi) of Pennsylvanian strata are preserved.

The Sandia Mountains were the site of fluviodeltaic to shallow-marine deposition during Middle Pennsylvanian time and received sediment of the Sandia Formation primarily from the Pedernal uplift to the southeast. Soreghan et al. (2012) define the Sandia Mountains as a minor uplift, similar to the Nacimiento Mountains. Lucas et al. (2026) note that the thickness and lithofacies distribution of the Sandia Formation in the Sandia Mountains suggest the presence of a small, local depositional basin that was likely adjacent to a local uplift during part of the Middle Pennsylvanian. Thus, in the northern part of the range, from Sandia Peak to South Sandia Peak, the Sandia

Formation is relatively thick, up to ~90 m (295 ft). Coarse-grained siliciclastic sediments (conglomerate and sandstone) occur mainly near the base, and the bulk of the Sandia Formation contains thick (~10-m [~33-ft]) beds of shallow-marine limestone and covered intervals that probably represent marine shale or siltstone intervals. These thicker Sandia Formation successions indicate deposition in a structural depression ("Sandia basin") that subsided during the Atokan. Thicker Sandia successions are also present farther east, at Tejano Canyon (104 m [341 ft] in thickness) and along the Tejano Highway (124 m [407 ft] in thickness at the Doc Long Picnic Area), indicating that this upper Paleozoic "Sandia basin" continued to the east.

Toward the south-southeast (Cedro Peak), the Sandia Formation thins to 65 m (213 ft) at Carlito Spring, and, in the northern Manzanita Mountains, to 50–55 m (164–180 ft) southwest of Tijeras and 8 m (26 ft) at Cedro Peak (Lucas et al., 2021). This suggests that in the Cedro Peak area and east of Cedro Peak, a structural high was present from which coarse-grained siliciclastic material was transported toward the northwest (Carlito Spring), west (Szabo sections), and southwest (Sol se Mete). The thickness of the Sandia Formation increases from Sol se Mete south to 70 m (230 ft) at Priest Canyon and more than 100 m [328 ft] in the Los Pinos Mountains. Thus, during the Atokan, an approximately east–west-trending, small "Sandia basin" developed that later subsided, likely along normal faults that bounded the basin to the north ("Placitas high") and south-southeast ("Cedro Peak high").

MESOZOIC EROSION AND TECTONICS

A regional sub-Cretaceous unconformity bevels Mesozoic strata in the southern Colorado Plateau. Chapman and DeCelles (2021) proposed that interaction between the Cordilleran foreland forebulge to the west and uplift from Jurassic rifting in the Bisbee basin to the south generated more than 1.5 km (1 mi) of Late Jurassic and Early Cretaceous uplift and southward beveling of Mesozoic strata, such that Cretaceous strata rest on progressively older units toward the southern highlands (Dickinson, 2013). Ongoing detrital sanidine studies of the Jackpile Member of the Morrison Formation are in progress to potentially determine whether it is Cretaceous or Jurassic (Cather, 2021; Lucas, 2021; Lucas et al., 2025), and hence whether the sub-Dakota disconformity represents a 25- or 50-million-year lacuna in northern New Mexico (Lucas et al., 2025).

Laramide Orogeny

The ~90–45-Ma Laramide orogeny involved the formation of basement-involved structural uplifts/arches with adjacent subsided basins that partitioned the Cordilleran foreland basin system east of the Sevier fold-thrust belt. Laramide-style deformation is considered to have resulted from flat-slab subduction (Dickinson and Snyder, 1978), similar to that of shallow slab segments in the modern Andes. Shallowing of the flat-slab beneath southern Arizona and New Mexico was marked by eastward-migrating magmatism in the Cordilleran magmatic arc (Coney and Reynolds, 1977). Eastward-migrating deformation is indicated by thermochronology and stratigraphic thicknesses showing the onset of arch exhumation and basin subsidence ~90–70 Ma that in New Mexico started ~80–75 Ma at the Arizona–New Mexico border region and progressed eastward to the Sangre de Cristo arch and Raton basin by ~75–70 Ma (Fig. 3; Thacker et al., 2022). Progressive deformation continued until ~45 Ma at least in central New Mexico. The source of Laramide stresses likely involved a combination of a plate margin end-load (Livaccari and Perry, 1993; Axen et al., 2018), basal tractions between the Farallon plate and overriding North American plate (Heller and Liu, 2016; Copeland et al., 2017), or gravitational potential energy from collapsing highlands (Livaccari, 1991) of the Nevadaplano and Arizonaplano. Subduction of oceanic plateaus and their effects on tectonics have

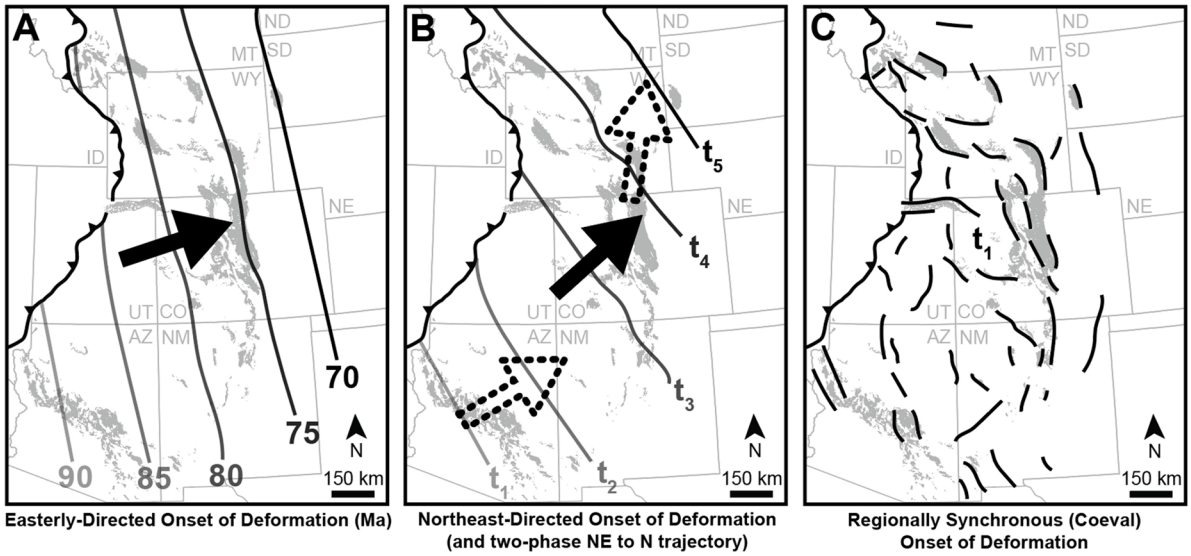


FIGURE 3. Models for timing of onset of Laramide deformation (Thacker et al., 2022). A) West-to-east sweep due to flat slab subduction (Thacker et al., 2022, and references therein). B) Northeast-directed shortening from passage of an oceanic plateau such as the conjugate Shatsky Rise (e.g., Heller and Liu, 2010). C) Regionally synchronous onset of deformation (Dickinson et al., 1988) and/or regionally continuous long-lived reactivation of structures.

also been considered (e.g., conjugate Shatsky Rise; Liu et al., 2010; Humphreys et al., 2015; Heller and Liu, 2016).

Although largely oriented northwest–southeast, Laramide-style structures exhibit a complex array of trends, including east–west, northeast–southwest, and north–south. This variable trend can be explained in part by continued contractional reactivation of preexisting fault systems (Mesoproterozoic to ARM) that were in favorable orientations to relieve Laramide compressional stress directed west-southwest to east-northeast (Fig. 3). The result was that many Laramide features across the Rocky Mountain region, and especially in New Mexico, have complex map traces with jogs between segments (e.g., Defiance arch) that reflect linkage of older reactivated structures. Unambiguous dextral motion is recorded in many Laramide structures across New Mexico.

The magnitude of Laramide dextral deformation in the state is debated, with some papers suggesting a predominance of Laramide dextral strain (Karlstrom and Daniel, 1993; Bauer and Ralser, 1995; Cather, 1999, 2004; Cather et al., 2006) and others suggesting that dextral strain was due to west southwest–east northeast shortening that was oblique to variable structural orientations (Erslev, 2001; Pollock et al., 2004; Thacker, 2025). Sinistral strain on Laramide features in New Mexico has also been suggested, including on the Zuni arch (Thacker, 2020; Davis et al., 2022). Cather (1999) suggested 40–60 km (25–37 mi) of dextral strike separation across what is now the Rio Grande rift in New Mexico. Cather et al. (2006) also suggested 55–90 km (34–56 mi) of overall dextral strike separation of magnetic anomalies across a series of north–south faults that span the Rio Grande rift, with ARM and Laramide dextral slip possible.

A nexus concept presented at the 2024 NMGS Fall Field Conference (Karlstrom et al., 2024) was that Laramide reverse/dextral transpressional faulting along the Nacimiento fault zone have been reactivated by normal faulting associated with the Rio Grande rift, with increasing reactivation to the south, toward the location of the second-day field trip area for the 2026 NMGS Fall Field Conference (Koning et al., 2026). These frontal Nacimiento Mountains structures were proposed by Baltz (1967) to have significant right-lateral transpression that lasted into the Eocene time of San Jose Formation deposition. Laramide ancestry and Miocene reactivation were proposed by Slack and Campbell (1976) as an explanation for the Puerco fault zone and the right-step from the Nacimiento uplift south to the Lucero uplift on the west side of the rift. The northeast–southwest Tijeras–Cañoncito fault system east and northeast of the Sandia Mountains also shows multiple phases of reactivation, with Precambrian, Pennsylvanian, Cretaceous–Paleogene, and Quaternary movement (Lisenbee et al., 1979). Within the Rio Grande rift in northern New Mexico, tens-of-kilometer-scale right lateral displacement of Precambrian thrusts and folds were proposed by Miller et al. (1963), and this concept was extended to include a series of north–south structures that offset magnetic anomalies (Karlstrom and Daniel, 1993; Cather et al., 2006), suggesting that the Rio Grande rift reactivated an earlier zone of Laramide transpressional faults that, in turn reactivated the ARM and late Precambrian faults.

East-trending regional piercing lines formed by stratigraphic pinchouts, truncations, and facies changes of Paleozoic and Mesozoic strata help constrain the Laramide right-lateral offset along the eastern side of the Colorado Plateau, but magnitudes have been alternatively interpreted as 5–20 km ([3–12 mi]; Molenaar, 1983; Woodward et al., 1997; Lucas et al., 2000) versus 20–33 km (12–21 mi) for the Sand Hill–Nacimiento fault system and 40–60 km across what is now the Rio Grande rift (Cather, 1999). Workers agree that the magnitude of Laramide strike separation exceeds the dip separation across at least some Laramide north–south faults in New Mexico, such as the Nacimiento fault system (Cather et al., 2006).

The reactivation hypotheses relate to the Sandia–Los Pinos rift flank on the east side of the Albuquerque Basin (Karlstrom et al., 1999) because what is now the rift flank uplift occupies the same north–south structural position as the Colorado Front Range at the transition from the Great Plains to the Rocky Mountains. The Montosa fault on the east side of the Manzano Mountains has the same reverse fault/monocline geometry as Front Range structures (but smaller displacement) and is thought to have moved at ~45 Ma based on thermochronology (Ricketts et al., 2016). Laramide cooling ages are also preserved in many New Mexico uplifts at high elevations where rocks had cooled to <50–100 °C before Rio Grande rift extension began (e.g., Ricketts et al., 2016).

CENOZOIC DEPOSITS AND TECTONICS

An "ignimbrite flare-up" produced Oligocene caldera complexes in the 38–23-Ma San Juan Mountains to the north and the 37–24-Ma Mogollon–Datil volcanic field to the south. Hansen et al. (2013) found that the highest peaks in the San Juan Mountains are underlain by thin crust in Colorado and suggested that about half of the isostatic support of modern topography could be provided by buoyant mantle. They invoked crustal delamination of the restitic roots of the San Juan volcanic field to explain this (also proposed by Lipman, 2021). Figure 4 (Ricketts et al., 2016) suggests that observed magmatic progressions in these volcanic fields record the direction of delamination/removal of the Farallon slab (Humphreys, 1995) leading to the bending and breaking of the frontal Farallon slab and formation of the rift above the bend. This helps to explain the change in stress field from contractional (during slab coupling) to early extension (after slab removal). Farmer et al. (2008) proposed a massive whole-crustal magmatic overturn due to lower-crustal melting focused at these two sites, which depleted a larger intervening region of lower-crustal melt. East of the Sandia Mountains, Oligocene sills in the Ortiz Mountains and Cerillos Hills represent smaller volumes of these melts that were intruded as laccoliths (Maynard, 2005), similar to Colorado Plateau laccoliths rather than the large caldera complexes. Several workers have proposed a component of Oligocene epeirogenic surface uplift of the Rocky Mountain–Colorado Plateau region (Spencer, 1996; House et al., 2003; Roy et al., 2009; Karlstrom et al., 2011; Cather et al., 2012). This was one of three main pulses of surface uplift of this region (Karlstrom et al., 2022) and, as a speculative estimate, was responsible for

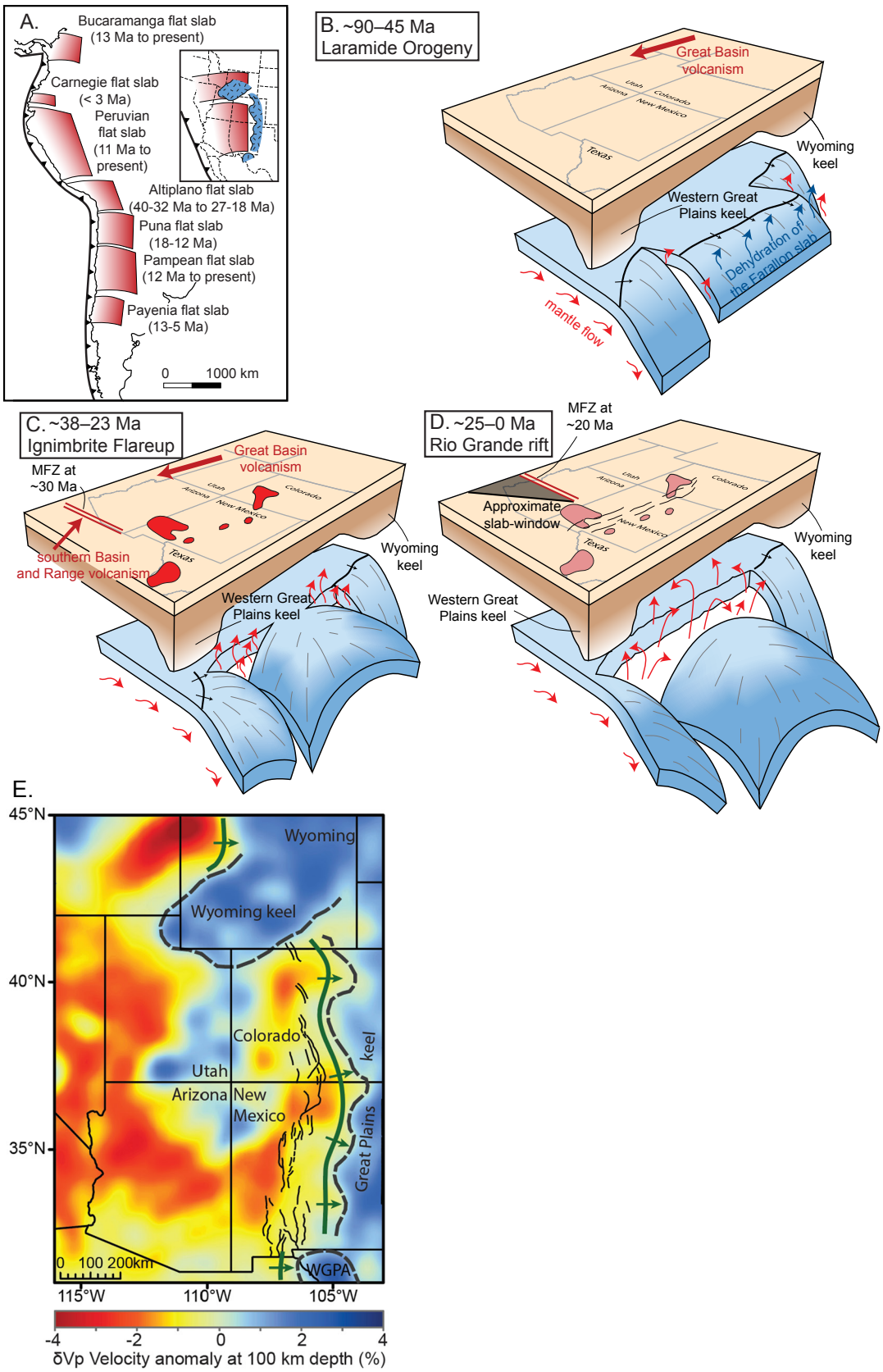


FIGURE 4. Model for the evolution of the Rio Grande rift (modified from Ricketts et al., 2016). A) South America is a modern analog for variable slab dip in the western U.S. Cordillera during the Cenozoic. B) The Farallon flat slab extended to eastern New Mexico before it bent to higher dips. C) Partial removal of the Farallon plate and asthenospheric upwelling formed the San Juan Mountains and Mogollon–Datil caldera complexes. D) Break at the bend in the downgoing Farallon plate localized the Rio Grande rift. E) Wyoming and West Texas high-velocity (blue) mantle anomalies may be Precambrian in age (Ricketts et al., 2016) and/or underplated oceanic plateaus (Humphreys et al., 2015; Axen et al., 2018).

about one-third of the total surface uplift of the Rocky Mountains and the Colorado Plateau region from sea level during the Late Cretaceous to modern average elevations of 3 km (2 mi) and 2 km (1 mi), respectively. Different paleo-elevation proxies and studies yield distinct histories, so resolving the surface uplift history (i.e., elevation of the Earth's surface relative to sea level) remains an important research topic (Heitmann et al., 2021).

Rio Grande Rift

The Rio Grande rift extends north–south over 1,000 km (621 mi) from central Colorado to southern New Mexico, where it merges with the wider Basin and Range extensional province (e.g., Hawley, 1978). It is one of the two most famous continental rifts in the world, the other being the East African Rift. Questions often asked about the Rio Grande rift include the following: (1) What controlled its location? (2) When did it form? (3) Are there low-angle normal faults as in the Basin and Range? (4) Is it still active? and (5) Will it develop into an ocean basin? In the context of uncertainties about paleo-elevation, it remains unclear to what extent the rift flanks gained elevation versus the corresponding basin bottoms losing elevation, but the result is the spectacular modern ~10-km (~6-mi) vertical displacement of the Great Unconformity between Sandia Crest and deeper parts of the Albuquerque Basin. These questions are briefly addressed below.

Why is it here?

Two crustal-scale factors that concentrate plate extension into narrow rift zones are reactivation of earlier zones of weakness (Li et al., 2026) and crustal weakening due to magmatism (Brune et al., 2023; Ajala et al., 2024). Kinematic (strain) models for the Rio Grande rift include clockwise rotation of the Colorado Plateau block (Cather, 1999; Murray et al., 2019) and oblique extension (Abbey and Niemi, 2020; Kelsch et al., 2025) that became localized along reactivated earlier fault zones. Dynamic (stress) models link these movements to underlying asthenospheric upwelling, for example, due to lithosphere delamination at the inboard eastern extent of the Farallon flat slab before it descended into the asthenosphere at steeper angles (Ricketts et al., 2016) and/or edge-driven mantle convection at the edge of the Colorado Plateau lithosphere (van Wijk et al., 2010, 2018). Decades of "chicken-and-egg" debates about active (mantle-driven) versus passive (plate-stress-driven) rifting have evolved into more specific discussions of how these forcings interact temporally and spatially (Brune et al., 2023).

When was it formed?

Thermochronology of the rift flanks suggests synchronous "opening" based on the timing of exhumation of rift flanks at ~25–10 Ma for the entire north–south extent of the Rio Grande rift (Landman and Flowers, 2013; Ricketts et al., 2016; Abbey and Niemi, 2020; Gavel et al., 2021). To its north and south, the rift is bounded by two keels of high-velocity (cold, dense) mantle, suggesting deep influences (Fig. 4). Ricketts et al. (2016) suggested that these preexisting mantle anomalies influenced Farallon slab dynamics, whereas Axen et al. (2018) suggested that thrust-style deformation "bulldozed" the upper mantle in front of the Farallon slab to create the mantle low velocity anomalies. The two models are not mutually exclusive and are difficult to test because the age(s) of the presumed mantle anomalies (Proterozoic versus Laramide) are not known.

Once formed by its synchronous north–south opening ~25–20 Ma (Fig. 4), Rio Grande rift fault segments lengthened and became linked together across accommodation zones from ~20 to ~5 Ma to become a connected system of rift basins (Abbey and Niemi, 2020). Concepts and complexities of segmented rift flank uplifts, isostatic rebound to form low-angle normal faults, and rift accommodation zones have all been refined in the Rio Grande rift. The right-stepping geometry of the rift will be evident during both the first and second days of the 2026 NMGS field trip (Connell et al., 2026; Koning et al., 2026), on both the active (Sandia Mountains) and less active (Puerco fault zone) sides of the Albuquerque Ba (e.g., Grauch and Connell, 2013). Geometries of half-graben subbasins and accommodation zones between basins and subbasins can form in homogeneous sandbox experiments (e.g., McClay et al., 2002), so the half-graben subbasin geometry may or may not have been influenced by preexisting right-stepping geometry of Laramide fault zones (Slack and Campbell, 1976).

Low-angle normal faults?

Basin and Range extension can progress to core complexes, leading to low-angle normal faults (LANFs) where the crust was originally thickest (Coney and Harms, 1984) and where extension was greatest (>100%; Wernicke and Axen, 1998). Ricketts et al. (2015) suggest that the Sandia Mountains and Ladron Peak may have formed by a similar process, but at ~30–40% crustal extension, based on observations of rift-flank uplifts. LANFs are reported in the Sandia Mountains (with fault dips of ~20–40°) on the footwall of the highest-elevation eastern rift flank that is mirrored by the deepest parts of the adjacent rift basins (Ricketts et al., 2015, fig. 7). Younger, large-magnitude, high-angle normal faults located toward the center of the basin, the Rio Grande fault system of Russell and Snelson (1994) or the Eubank fault system (Connell, 2008a; Ricketts et al., 2015), may have facilitated footwall unroofing and dip shallowing. Available age constraints suggest that LANF segments in the Sandia Mountains and Ladron Peak are older than the currently active intrabasinal faults. These observations support a model in which LANF segments originated at a higher (~60°) fault dip and became progressively shallower as extension continued.

Low-temperature thermochronology in the Sandia Mountains suggests that the rift flank cooled quickly ~20–17 Ma due to erosion of nearly 5 km (3 mi) of strata off the top of the range (Fig. 4C), with resulting isostatic footwall uplift that produced the east dip of ~20° on the range crest (Roy et al., 1999).

The Mesozoic rocks near Juan Tabo Boulevard, which we will see on the first day of the 2026 Field Conference (Connell et al., 2026), are a key locality, as these strata are surrounded by Sandia granite, are fault-bound, and may be underlain by a LANF (Van Hart, 1999). This outcrop can be interpreted as a klippe that can be portrayed by a restorable cross section (Fig. 5). Cross-sections with only upper-crustal high-angle fault geometries (Kelley and Northrop, 1975; Russell and Snelson, 1994; Grauch and Connell, 2013) are only partially restorable at crustal scale without allowing some degree of low-angle fault slip near the brittle–ductile transition, as shown on Figure 5 and as imaged seismically in Russell and Snelson (1994).

Other LANF localities in the Sandia Mountains region include the Diamond Tail fault in the Hagan basin, which dips 20° and is inferred to have had its dip shallowed during the uplift of the Sandia block and tilting of Hagan basin section (Black, 1979; Roy et al., 1999), and the Ranchos fault to the north of the Sandia uplift, with a dip of 20–30° and dip-oriented slickenlines (Ricketts et al., 2015). Ricketts et al. (2015) referred to both the Sandia Mountains on the east side of the Albuquerque basin and Ladron Peak on the west side as "embryonic core complexes". The overprinting of older normal faults by later high-angle faults explains the isostatic lowering of fault dips of the older faults, but may also account for the faceted bedrock cliffs and mid-level "benches" paralleling the Sandia Mountains.

Is the rift still active?

Ongoing Global Positioning System (GPS) measurements of regional extension is broadly distributed across northern New Mexico, with extensional movements (relative to a fixed point in the mid-continent) of 1–2 mm/year (Murray et al., 2019). The GPS-measured rates do not seem to be higher in areas near or across faults of the Rio Grande rift, suggesting that the rift is no longer a major locus of crustal extension. However, extension rates near travertine-depositing springs in the Belen area are similar to rates during the Miocene (Ricketts et al., 2014), suggesting that weakening by carbonic fluids, perhaps related to the Socorro magma body (Williams et al., 2013), may enhance seismicity and fluid movement along pre-existing faults.

Will the rift become a mid-ocean ridge?

Although oceanic spreading centers generally initiate within continents, the possible progression of the Rio Grande rift to form a seaway floored by new oceanic crust, like the modern Red Sea rift, seems unlikely because extension rates have waned since Miocene time. The Rio Grande rift is, however, linked to a broader region of extension in the Basin and Range province, so this will depend on the future evolution of far-field plate tectonic forcings in western North America, such as the San Andreas–Gulf of California–Cascadia system, as well as on mantle processes that are thinning western North America.

Neotectonics

There are no Pleistocene basalts in the Sandia–Manzano uplift, and young basaltic magmatism in the adjacent Rio Grande rift follows north–south dike structures in the Albuquerque Basin, such as the ~200 ka Albuquerque Volcanoes

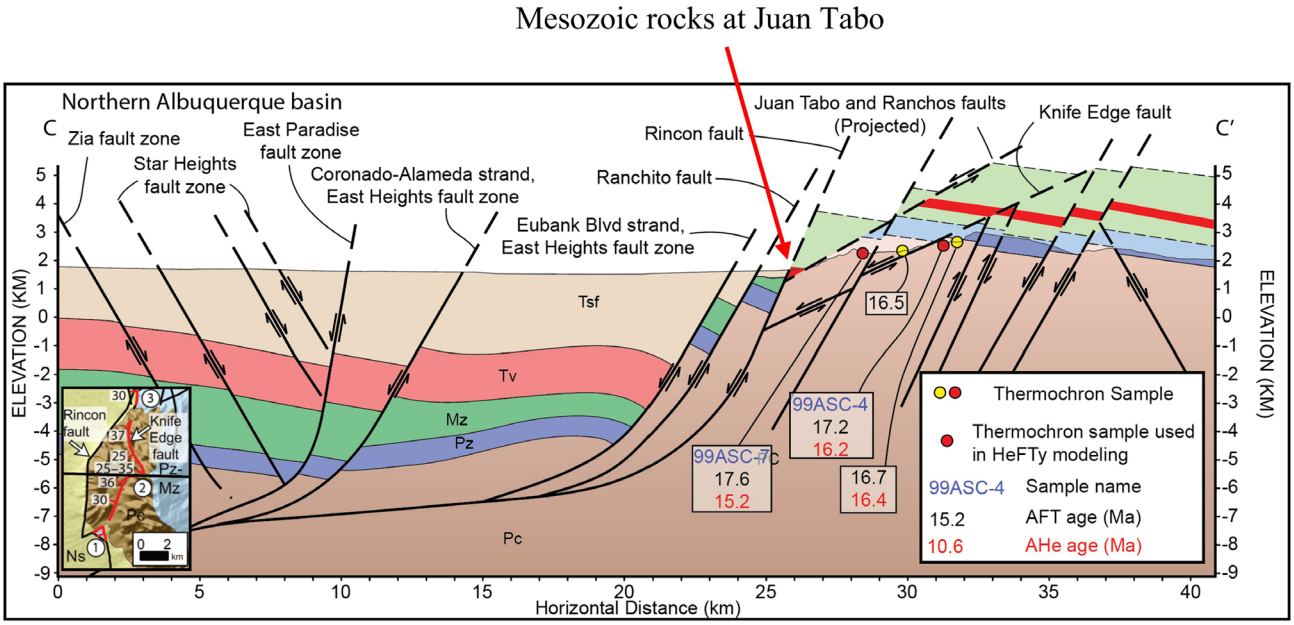


FIGURE 5. East–west cross-section through uppermost Triassic and Jurassic strata visited on the first day of the 2026 NMGS Fall Field Conference (Connell et al., 2026), interpreted as underlain by a low-angle normal fault (e.g., Van Hart, 1999) in the footwall of a younger, large-magnitude, high-angle normal fault system (Eubank fault system, Connell, 2008a). Low-temperature thermochronology in the Sandia Mountains suggests that the rift flank was uplifted ~20–17 Ma (Ricketts et al., 2015), with isostatic rebound driving footwall uplift and observed east-dipping strata east of the range crest (Roy et al., 1999). AFT = apatite fission-track thermochronometry; AHe = apatite (U–Th)/He thermochronometry; pC = Proterozoic; Pz = Paleozoic; Mz = Mesozoic (also shown in red); Tv = Paleogene; Tsf = Santa Fe Group synrift fill.

(Singer et al., 2008). Both GPS data and extension direction inferred from seismic and geologic indicators suggest that the Rio Grande rift has been undergoing east–west extension over the past several million years.

Differential uplift across the Jemez lineament has been inferred from differential bedrock incision in terrace straths of rivers that cross the lineament. From northeast to southwest, studies proposed neotectonic epeirogenic uplift of the Jemez lineament include Cather et al. (2012), Nereson et al. (2013), Repasch et al. (2017), Channer et al. (2015), and Anderson et al. (2021). In each of these studies, from the Great Plains to the Mogollon highlands of Arizona, the hypothesis is that 100-m-scale Quaternary differential uplift of Earth's surface, driven by deeper crustal or mantle forcings, causes rivers to incise more rapidly (tens to hundreds of meters per million years) above uplifting areas than above adjacent subsiding or non-uplifting areas. The extent to which the Rio Grande, Rio Chama, and Rio Puerco incision rates have been influenced by the Jemez lineament (Repasch et al., 2017), as well as by magmatism of the Socorro magma body, is debatable (e.g., Sion et al., 2020) and incompletely resolved.

Neotectonic influences on groundwater have been termed hydrotectonics (Crossey et al., 2024) and include fault-bounded aquifer subbasins with distinct hydrochemistry, fault- and damage-zone conduits for recharge, vertical transport between semi-confined aquifers via fractures, and upwelling geothermal fluids along faults. Low-magnitude seismicity can promote fluid transport and aquifer connections, motivating the establishment of better seismic networks. Concept papers include discussion of the use of noble gases in springs to identify even small volumes of fluids into the groundwater system from mantle sources (Newell et al., 2005; Karlstrom et al., 2013; Crossey et al., 2016). Many of the springs with quantifiable mantle inputs were initially identified from surface travertine deposits that reveal CO_2-oversaturated groundwaters and upward CO_2 leakage along faults that have existed for hundreds of thousands to millions of years (Ricketts et al., 2014).

How and where hydrotectonic concepts apply to the Sandia Mountains and Rio Grande rift are ongoing research questions. For the Sandia Mountains, Crossey et al. (2026) describe subtle hydrochemical differences in fault-bounded springsheds. Stable isotopes indicate that these springs are dominantly recharged by "upper world" meteoric water, but even at these high elevations, the travertine-depositing Las Huertas spring has inputs along its longitudinal profile where external CO_2 is introduced along the Ellis and Las Huertas fault systems (Townsend, 2023). Groundwater data suggest that this component of the external CO_2 is not derived from the dissolution of carbonate or gypsum in the Sandia Mountains aquifer systems, but rather from deeper sources (Crossey et al., 2016, 2026).

CONCLUSIONS

A theme of this review is that the structural inheritance of Proterozoic crustal weaknesses has occurred in response to changing far-field stresses at the edge of the plate. A wide Picuris orogenic plateau inboard of the active plate margin at 1.45 Ga is proposed to have developed from convergence with a long-lived margin of southern North America (in present coordinates) and to have formed not only the thrust belts of the Manzano and Picuris Mountains but also the north–south boundary that would become the Rocky Mountain front and Rio Grande rift. This has some similarities to the plate tectonic model in figure 10E of Daniel et al. (2013, but not their models 10A–10D) but also incorporates mafic underplating due to lithosphere removal, reminiscent of Shaw et al. (2005) and similar to the Cenozoic ignimbrite flare-up of the Colorado Plateau region (Karlstrom et al., 2022). Intracratonic reactivation of Proterozoic fault systems helps to explain the Phanerozoic uplift patterns observed in the ARM, Laramide, and Rio Grande rift.

Ongoing research is needed to test the reactivation hypothesis for each time frame. Collaborative studies, as conducted by Kelley and Northrop (1975), when combined with new tools such as petrochronology, thermochronology, and detrital sediment studies, can be used to refine uplift histories and sediment dispersal patterns. These techniques, combined with improved geophysical imaging and modeling, fundamental geologic field work, and refined structural mapping, offer abundant opportunities for the next generation of researchers.

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Mountain short-horned lizard (*Phrynosoma hernandesi*). Photograph courtesy of Celestyn Brożek.



Northern flank of the Sandia Mountains, from Placitas. Photography courtesy of Sean Connell.