New Mexico Geological Society

Downloaded from: https://nmgs.nmt.edu/publications/guidebooks/74

Synopsis of the Nacimiento geologic nexus

Karl E. Karlstrom, Koning Daniel J., Spencer G. Lucas, Larry S. Crumpler, Fraser Goff, Shari A. Kelley, Cameron C. Reed, Nels A. Iverson, and Laura J. Crossey, [eds.]
2024, pp. 105-126. https://doi.org/10.56577/FFC-74.105

in:

Geology of the Nacimiento Mountains and Rio Puerco Valley, Karlstrom, Karl E.;Koning, Daniel J.;Lucas, Spencer G.;Iverson, Nels A.;Crumpler, Larry S.;Aubele, Jayne C.;Blake, Johanna M.;Goff, Fraser;Kelley, Shari A., New Mexico Geological Society 74 th Annual Fall Field Conference Guidebook, 334 p.

This is one of many related papers that were included in the 2024 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual Fall Field Conference that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, and other selected content are available only in print for recent guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

This page is intentionally left blank to maintain order of facing pages.

New Mexico Geological Society Guidebook, 74th Fall Field Conference, 2024, p. 105–126, https://doi.org/10.56577/FFC-74.105

SYNOPSIS OF THE NACIMIENTO GEOLOGIC NEXUS

KARL E. KARLSTROM[1], SPENCER G. LUCAS[2], DANIEL J. KONING[3], LARRY S. CRUMPLER[2], FRASER GOFF[4], SHARI A. KELLEY[3], CAMERON C. REED[1], NELS A. IVERSON[3], AND LAURA J. CROSSEY[1]

[1]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87106, kek1@unm.edu
[2]New Mexico Museum of Natural History and Science, 1801 Mountain Road NW, Albuquerque, NM 87104
[3]New Mexico Bureau of Geology and Mineral Resources, 801 Leroy Place, Socorro, NM 87801
[4]Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, NM 87801

Abstract—This paper provides a summary of the geology of the Nacimiento nexus area. This area is a diffuse intersection among the Colorado Plateau to the west, the Rocky Mountains to the north, and the Rio Grande rift to the east, and it is transected by the Jemez volcanic lineament. This synopsis, and the references provided for this region, may be useful as regional context for students and participants of the New Mexico Geological Society 2024 Fall Field Conference.

INTRODUCTION

The 2024 New Mexico Geological Society (NMGS) Fall Field Conference will investigate the fascinating geology at the juncture of three physiographic provinces and the Jemez lineament. These provinces are the Colorado Plateau, Rio Grande rift, and Southern Rocky Mountains. We informally refer to this area as the Nacimiento nexus, for the Nacimiento Mountains. The Colorado Plateau is a Cenozoic plateau province of rugged topography and deep canyons rather than a single plateau (Kelley, 1955). Its prominent geologic characteristic is that its Paleozoic and Mesozoic strata are still flat-lying (except at the edges of sharp monoclinal bends near uplifts). Its spectacular landscapes were carved by rivers into and through the dominantly flat-lying strata. Regional differential erosion, named the Great Denudation by Dutton (1882), has taken place via cliff retreat and vertical incision–interacting processes that are still active today. Dutton was part of a cadre of America's most famous late-1800s geologists that included J.W. Powell (1875; the first Euro-American scientist to traverse the Grand Canyon and second director of the U.S. Geological Survey [USGS]), G.K. Gilbert (1877; who introduced the concept of dynamic equilibrium of landforms), C. King (first director of the USGS in 1879), and C.D. Walcott (USGS Chief paleontologist and director in 1893/1894). The Great Denudation was attributed to uplift of the western United States. When uplift started in Late Cretaceous time, the sedimentary layer-cake stratigraphy that nonconformably overlies the crystalline basement consisted of (in round numbers) ~1 km of Paleozoic strata and ~2.5 km of Mesozoic strata. With the exception of the landscape that developed in late Paleozoic time during the Ancestral Rocky Mountains (ARM) orogeny, most of the strata were deposited on a low-relief landscape near sea level. The Mesozoic sedimentary succession is capped by deposits related to the development and retreat of the Late Cretaceous Western Interior Seaway. Today's iconic landscapes and the high average elevations of the Colorado Plateau (~6,500 ft or ~ 2 km) and Rocky Mountains (9,800 ft or ~3 km) have been shaped during a ~70-million-year "battle" between episodic uplift and erosion. The basic concept that old rocks are revealed within young landscapes seems simple, but it is an essential starting point for public geoscience education. This concept also presents persistent challenges for seasoned geologists in their efforts to interpret the cumulative history of events in these areas.

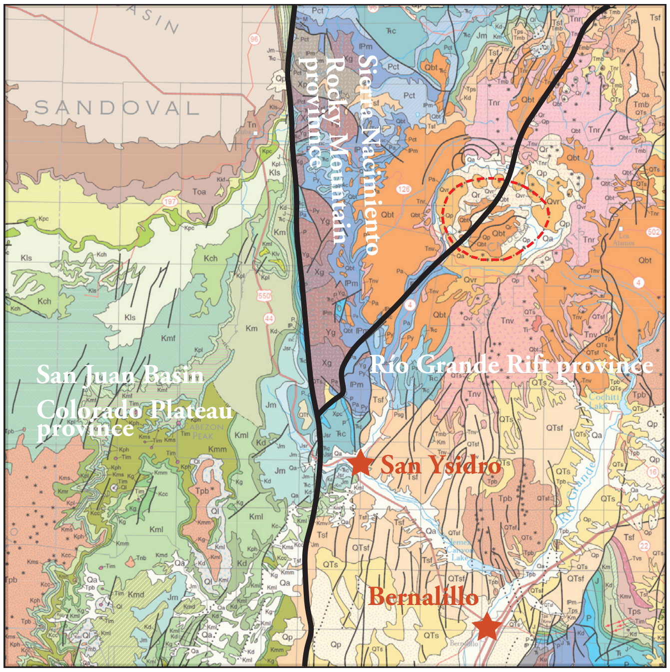

FIGURE 1. The 2024 NMGS Fall Field Conference focuses on the nexus of three geologic provinces: the Colorado Plateau to the west, the Rocky Mountains to the north, and the Rio Grande rift to the east, where all three are crossed by the Jemez lineament with its largest volcanic center, the Valles Caldera, sitting within the crossroads.

New Mexico's young landscapes formed in the Cenozoic. The entire region of Figure 2 was uplifted from sea level in several episodes (Karlstrom et al., 2011; Cather et al., 2012; Karlstrom et al., 2022). (1) The ~90–50 Ma uplift above sea level was driven by flat-slab subduction of the Farallon slab. (2) The ~38–23 Ma uplift and voluminous regional magma-

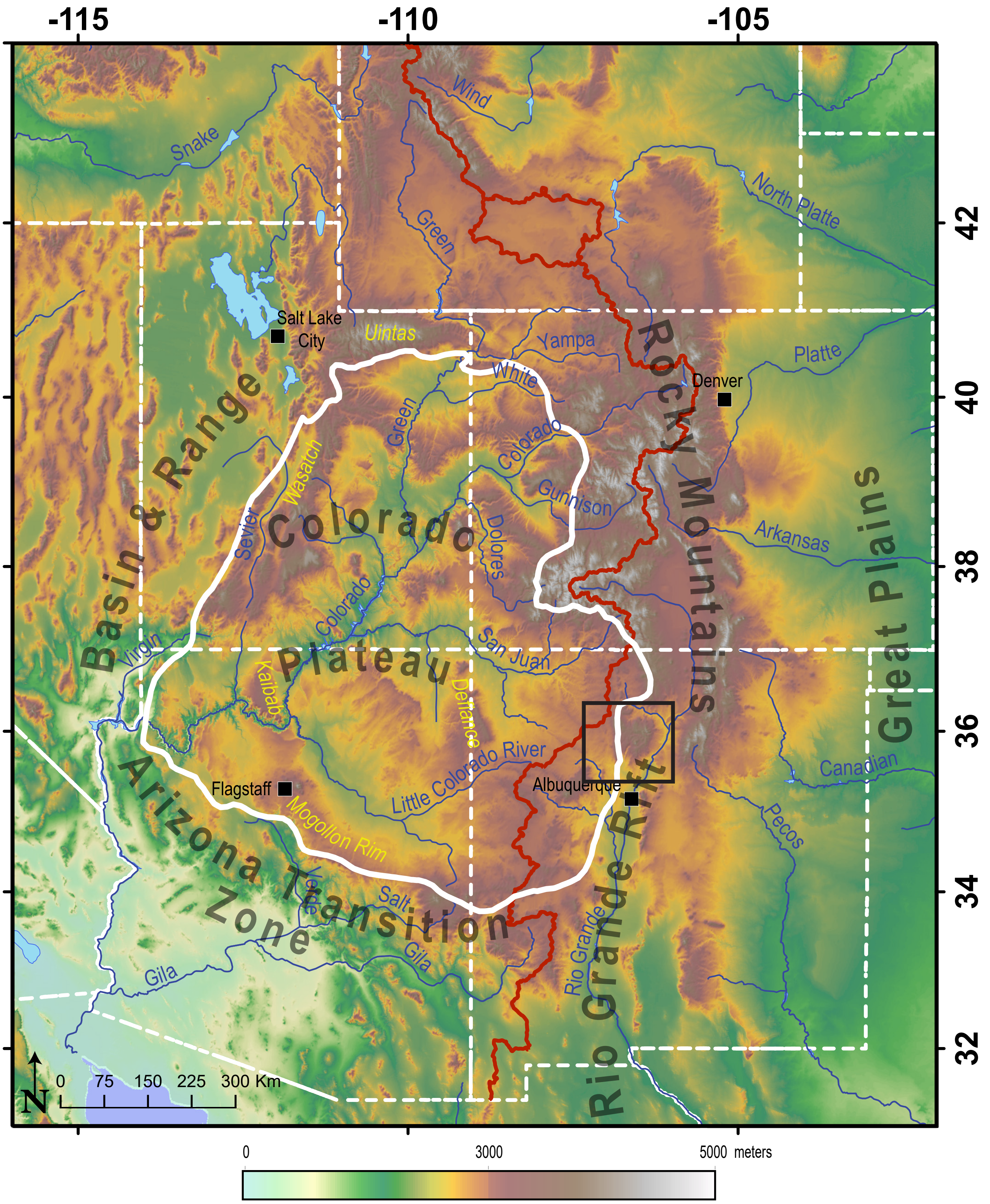

FIGURE 2. The 2024 NMGS Fall Field Conference focuses on the nexus of three geologic provinces (black box). Colorado Plateau province boundaries (Fenneman, 1928) are superimposed on a DEM showing the general bowl shape of the Colorado Plateau. The red line is the continental divide. (Figure adapted with permission from Karlstrom et al., 2022; copyright Annual Reviews.)

tism and ignimbrite flare-ups were driven by diachronous removal (delamination, foundering, dripping off) of the subducted Farallon slab (Humphreys, 1995; Humphreys et al., 2003; Best et al., 2016). (3) Post-20 Ma and ongoing broad differential uplift is being driven by upwelling of buoyant mantle and downwelling of dense mantle (e.g., Levander et al., 2011). The relative importance of each uplift episode in attaining today's elevations in different areas is much debated, but "thirds" is probably not a bad initial concept for the region.

THE BASEMENT

The basement rocks seem to have exerted only a second-order influence on the eventual physiographic boundaries. Thus, the northeast-trending basement boundaries of lithosphere assembly are only cryptically manifested in images of modern physiography (Fig. 2) and deep lithospheric structure (Fig. 3). Northeast-trending boundaries transect the Colorado Plateau (Fig. 3A) and separate Precambrian basement provinces that record the accretion of island arcs to the Archean nucleus from 1.8 to 1.4 Ga, initially across the Archean-Proterozoic suture at the Cheyenne belt (CB of Fig. 3A). This accretion resulted in the building and demise of high mountains and orogenic plateaus. As summarized by Karlstrom et al. (2004) and Hillenbrand et al. (2023a, 2023b), the history of the crystalline basement of New Mexico and Colorado includes accreted 1.75 Ga oceanic island arcs; the ~1.70 Ga Yavapai orogeny, which welded arcs to a southward-growing (present coordinates) Laurentian continent; the ~1.65 Ga Mazatzal orogeny of central and southern New Mexico (Amato et al., 2008; Karlstrom et al., 2016) and southern Colorado (Hillenbrand et al., 2024); and the ~1.45 Ga Picuris orogeny (Daniel et al., 2013). The discovery of 1.5–1.45 Ga sedimentary rocks of the Trampas Group of the Picuris Mountains (Daniel and Pyle, 2006) and the correlative Yankee Joe Formation in Arizona and the Defiance uplift (Doe et al., 2012, 2013) expanded the significance of the 1.45 Picuris orogeny as a regionally important contractional orogeny (Nyman et al., 1994) that constructed an intracratonic orogenic plateau behind a plate convergence zone located to the south (Bickford et al., 2015; Karlstrom et al., 2016; Hillenbrand et al., 2023a, 2023b).

The Nacimiento Mountains area was influenced by these Proterozoic events. Basement rocks of the Nacimiento include representatives of 1.7 Ga and 1.45 Ga granites that intruded volcanic rocks and quartzites that are broadly correlative with the Hondo Group of the Picuris Mountain region (Grambling et al., 2016). Ideas that the Nacimiento Mountains contain the Yavapai-Mazatzal province boundary (Whitmeyer and Karlstrom, 2007) are not supported by Hf isotope data on New Mexico plutons, which show that Yavapai Province basement extends south of the Nacimiento Mountains (Grambling et al. 2016) within a transitional Yavapai-Mazatzal province boundary zone (Shaw et al., 2005). Magnani et al. (2004, 2005) interpreted deep seismic reflection data below the Jemez volcanic lineament as bivergent thrust structures of a Proterozoic suture that may have facilitated the ascent magmas in the Cenozoic. This is one example of how ancient boundaries may have helped shape both modern mantle velocity structure and young physiographic provinces.

SEDIMENTARY STRATA

Regional Phanerozoic stratigraphy also has little manifestation in the Cenozoic physiographic boundaries. For example, as you master the stratigraphy of the nexus, you would not have any inclination based on lithology and extent of stratigraphic units about where to draw the boundaries of the three provinces. Cambrian to Devonian strata are missing in northern New Mexico, likely due to the presence of the transcontinental arch (Amato and Mack, 2012; Holland et al., 2023, but cf. Myrow et al., 2003). During the late Paleozoic (Mississippian, Pennsylvanian, and Permian), the nexus was in the far western tropics of the Pangean supercontinent and was drifting northward across the paleoequator. Mississippian strata in the nexus are locally present as a relatively thin succession (less than 90 m thick) of shallow marine carbonates and siliciclastics of the Arroyo Peñasco Formation as well as the nonmarine red beds of the Log Springs Formation (Krainer and Lucas, 2024). The overlying Pennsylvanian strata have at their base a very local unit, the Lower Pennsylvanian Osha Canyon Formation, only present upstream of Guadalupe Box. The Mississippian strata were deposited on the basement topography of eroded remnants of the transcontinental arch in shallow marine and nonmarine settings.

The ARM orogeny involved tectonism that produced Mississippian/Pennsylvanian/early Permian basement-cored uplifts that were paired with deep sedimentary basins. These were north-northwest-trending, and the major ARM uplifts in New Mexico were the Brazos (Uncompahgre), Sierra Grande (Frontrangia), and Pedernal. The nexus area contained a small ARM uplift called the Peñasco uplift (Woodward, 1996) that exposed basement and influenced local sedimentation in Pennsylvanian time. ARM uplifts were subsequently erosionally beveled and onlapped by Permian strata over much of New Mexico and by Triassic strata near the Colorado border.

The ARM orogeny was likely caused by the complex collision of the southern supercontinent of Gondwana and northern supercontinent variously called Euramerica, Laurussia or Laurasia (Kluth and Coney, 1981; Ye et al., 1996; Leary et al., 2017). In the nexus, the first evidence of the ARM orogeny is synorogenic deposits of the Middle Pennsylvanian Sandia Formation—a succession of coarse clastics (quartz sandstone and conglomerate), shale, siltstone and some marine carbonate beds (Lucas and Krainer, 2024). Some of the depositional cycles in Pennsylvanian strata were arguably caused by glacial eustasy (Elrick and Scott, 2010), although tectonism was likely the main driver for local Pennsylvanian sedimentation (Lucas et al., 2013, 2021). Sandia Formation strata are present locally and sporadically across what was the Peñasco uplift that extended ~80 km north-south and ~16 km east-west. That uplift influenced local Middle and early Late Pennsylvanian sedimentation such that diverse Pennsylvanian facies are found sitting on Proterozoic basement in the area surrounding the positive area. However, by very late in the Pennsylvanian

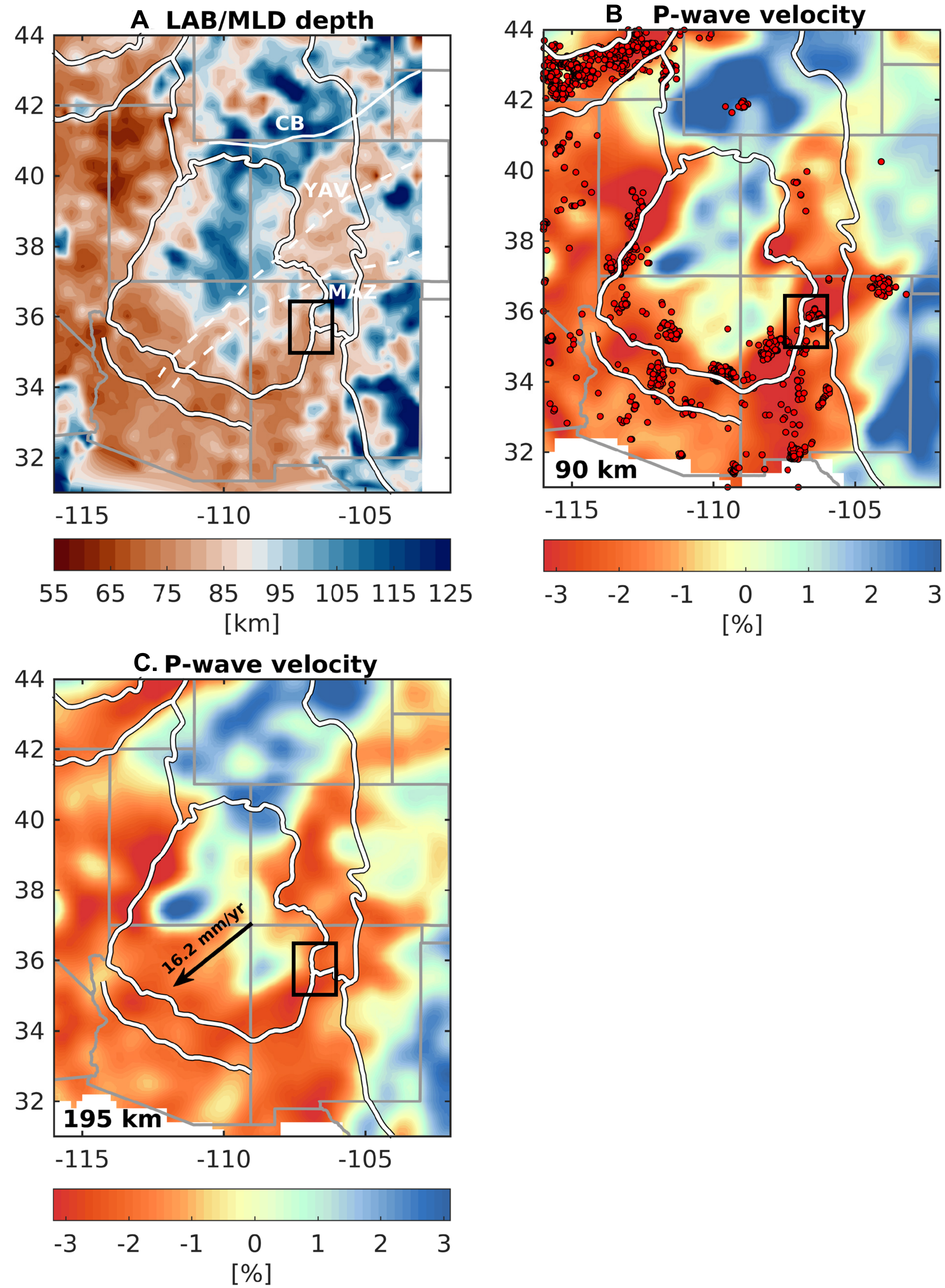

FIGURE 3. Lithospheric-scale properties that delineate the Colorado Plateau region. (A) depth in kilometers to the lithosphere-asthenosphere boundary (LAB) or the mid-lithospheric discontinuity (MLD; Lekic and Fischer, 2014). (B) and (C) P-wave tomography at depths of 90 and 195 km (Schmandt and Lin, 2014). Red dots in B are Quaternary volcanic rocks from NAVDAT (https://www.navdat.org/). The black arrow in C represents North American absolute plate motion direction and velocity of 16.2 mm/yr (Kreemer et al., 2014). The black box is the location of the nexus. CB = Cheyenne belt Archean-Proterozoic suture, YAV = Yavapai province, MAZ = Mazatzal province. (Figure adapted with permission from Karlstrom et al., 2022; copyright Annual Reviews.)

and into the early Permian, the extensive Cutler-Abo fluvial system, which extended across most of northern New Mexico, began to bury the Peñasco uplift, eventually covering it with siliciclastic red beds during Abo Formation deposition in the early Permian (Lucas and Krainer, 2024).

Subsequent Permian deposition over the nexus reflects the aridification that took place after the early Permian collapse of the Gondwana ice sheets, which effectively ended the late Paleozoic ice ages (Marchetti et al., 2022). Thus, the oldest eolianite in the nexus is the lower part of the Yeso Group, the De Chelly Sandstone (long called the Meseta Blanca Member, a local name synonymous with De Chelly). This was New Mexico's first Phanerozoic desert, and it extended from the Four Corners to Placitas and Mesa Lucero in central New Mexico. Subsequent Yeso deposition in the nexus (San Ysidro Formation) reflects a post-desert rise in regional sea level that created an arid coastal plain across much of the state (Lucas and Krainer, 2024).

A second eolianite was deposited later in the early Permian—Glorieta Sandstone, the youngest Paleozoic formation in the nexus. Glorieta Sandstone is equivalent to the Coconino Sandstone of Arizona, and the Coconino-Glorieta erg extended from the Grand Canyon across northern Arizona and into central New Mexico. Prevailing winds were from the northeast, and the New Mexico region was not more than 5° north of the paleoequator by the end of early Permian time. No middle Permian, late Permian, or Early Triassic strata are preserved in the nexus—a hiatus of about 30 million years.

Mesozoic sedimentary rocks exposed in the nexus were mostly deposited as parts of depositional systems larger than the entire state of New Mexico. The oldest are siliciclastic red beds of the Middle Triassic Moenkopi Formation and overlying Upper Triassic Chinle Group. In a simple sense, those units were deposited by rivers that flowed northwesterly across the nexus, headed in uplifts far to the east, southeast, and south. Rocks termed Moenkopi Group or Formation are siliciclastic red beds that were deposited in the Moenkopi back-bulge basin that formed along part of the western margin of Pangea during the Early and Middle Triassic. During the late Early Triassic and earliest Middle Triassic, more than 700 m of siliciclastic red beds (Moenkopi strata) were shed to the north and northwest into this basin; they interfinger with marine carbonates deposited on the Pangean marine shelf and in the arc-trench system to the west. In the nexus, only the youngest (Middle Triassic) strata of the Moenkopi Formation are present as a relatively thin interval of fluvial red beds with local, thin lacustrine limestone.

The Late Triassic Chinle Group depositional basin extended north-south from Idaho to Texas and west-east from eastern Nevada to Nebraska (Lucas, 1993; Lawton, 1994). It formed as a back-bulge basin well east of the continental margin, which was then located in eastern California-western Nevada. The back-bulge basin was east of the volcanic arc and a forebulge in central Nevada. Chinle Group fluvial deposits contain one of the world's most extensive nonmarine fossil records of the Late Triassic, including some of the earliest dinosaurs (Lucas, 1997, 2018).

After a substantial hiatus equivalent to at least all of Early Jurassic time (more than 25 million years), a third desert appeared in the nexus. The Middle Jurassic Entrada Sandstone was part of this erg that extended across eastern New Mexico, northeastern Arizona, and most of Colorado and northern New Mexico into western Oklahoma (Kocurek and Dott, 1983; Blakey et al., 1988). Entrada Sandstone cross-bed dip azimuths indicate winds headed mostly to the southwest, so the erg was still in relatively low latitudes of the zone of prevailing easterlies.

A unique sedimentary unit within the nexus is the Jurassic Todilto Formation, which consists of a thin (<10 m) interval of laminated kerogenic limestone overlain by up to 37 m of gypsum. Todilto Formation deposition took place in a large salina lake that extended from the Four Corners across much of northern New Mexico to an eastern shoreline near Santa Rosa in Guadalupe County (Lucas et al., 1985; Kirkland et al., 1995). Some fish fossils are found in the limestone, but this lake had saline and generally inhospitable water chemistry for fish and invertebrates.

The Middle-Late Jurassic Summerville Formation overlies the Todilto Formation and consists of a stratigraphic interval up to 80 m thick of maroon or grayish red siltstone, silty mudstone, and cross-bedded, fine-grained sandstone. Some of the cross-bedded sandstones in the Summerville interval are eolianites equivalent to a more massive eolianite to the west—the Bluff Sandstone (Anderson and Lucas, 1996). The Bluff Sandstone is the youngest Jurassic eolianite of the Colorado Plateau, and its significance lies in the fact that its cross-beds indicate eastward wind directions. This means that during the time of Bluff sandstone deposition, which is very close to or straddles the Middle-Late Jurassic boundary, the area of the nexus had drifted northward into the zone of prevailing westerly winds (Dickinson, 1989; Lucas et al., 1997).

The Upper Jurassic Morrison Formation overlies Summerville Formation strata across most of northern New Mexico. Morrison Formation deposition took place in a basin that extended north-south from Alberta, Canada, to central New Mexico and west-east from Utah to Nebraska, presaging the location of the Cretaceous seaway (Lawton, 1994). The Nevadan orogeny interacting with the Bisbee rift in southern New Mexico created this basin and an important sub-Cretaceous unconformity when the arc terrane collided with the margin of North America (Chapman and DeCelles, 2021). Fluvial processes deposited the Morrison Formation, first as an extensive river system that flowed eastward, followed by a vast muddy floodplain basin in which river flow was also easterly. Locally, in the nexus and in some other areas of central New Mexico, the uppermost strata of the Morrison Formation, the Jackpile Member, represent a fluvial system, likely Jurassic, but still of uncertain age (Cather et al., 2021; Lucas et al., 2021).

After Jackpile Member deposition, another lengthy hiatus of about 50 million years encompassed much of Early Cretaceous time. The unconformity at the base of the Dakota Sandstone begins the next cycle of deposition (the Greenhorn cycle). It reflects a major tectonic reorganization from a fluvial basin to marine and nearshore deposition in the backarc foreland basin

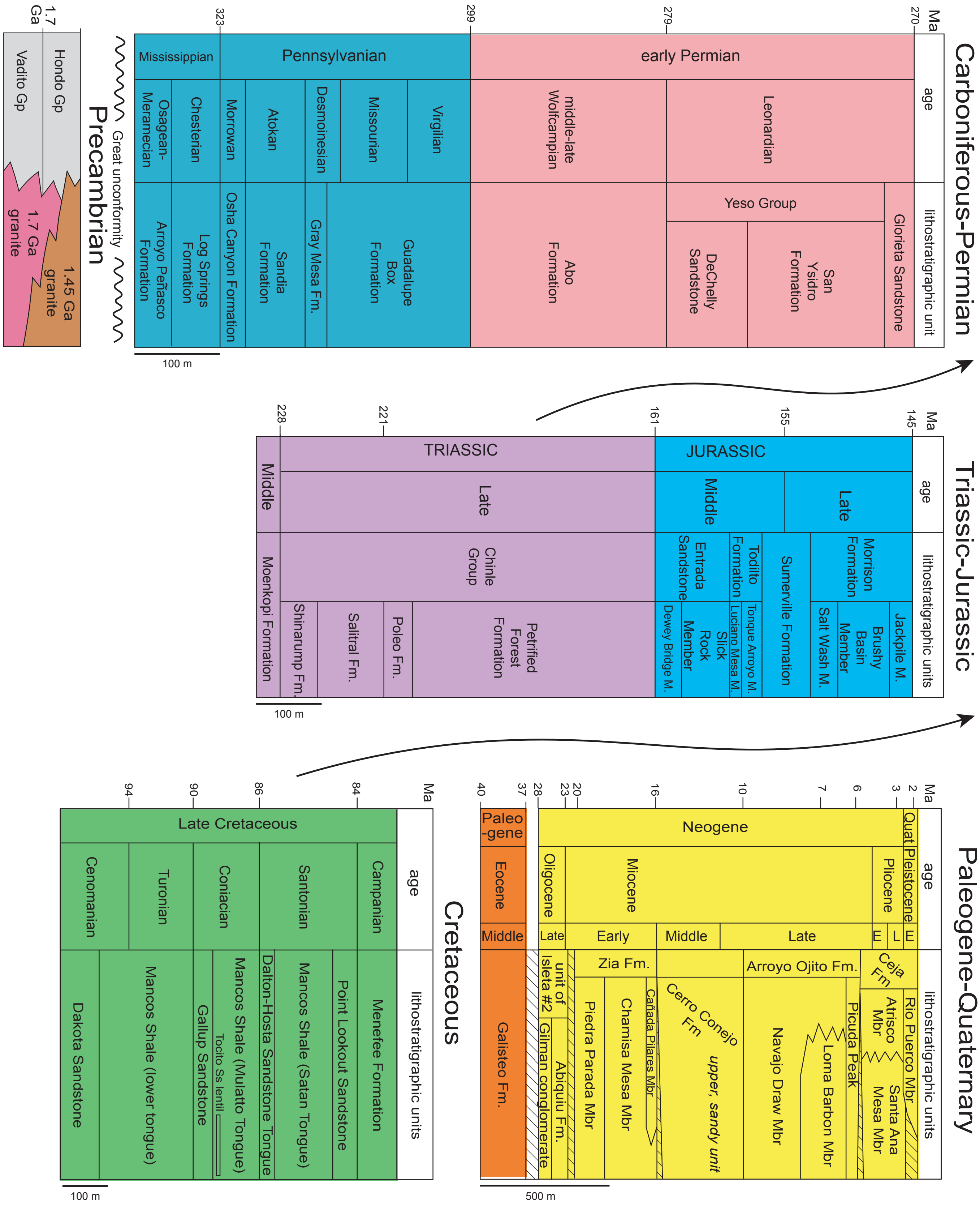

FIGURE 4. Stratigraphy of the Nacimiento nexus area. Calibration of the geologic timescale at the left of each column is from local geochronology plus http:///stratigraphy.org/chart.

of the Late Cretaceous Western Interior Seaway (Mack, 1987; Lawton, 1994). What ensued was the complex set of transgressions and regressions across the western margin of the seaway during most of Late Cretaceous time (Molenaar, 1983).

One topic of this year's Second-Day Field Trip and of next year's (2025) NMGS Fall Field Conference is the southeastern San Juan Basin. This area captures the history of the Cretaceous seaway in strata broadly referred to as Dakota Sandstone, Mancos Shale, and Mesaverde Group, although the actual lithostratigraphic architecture and nomenclature is relatively complex (Molenaar, 1983; Sealey and Lucas, 2019). Sediments of the Cretaceous seaway were deposited in a basin that was dynamically pulled down by shallowing of the Farallon slab (Liu et al., 2010) in a north-south intracratonic seaway with the western coastline alternately moving landward and seaward near the nexus. Sea-level changes on an ice-free planet and the low-relief marine basin caused 100-km-scale transgressive and regressive events that left nearshore, sandstone-dominated sandstones interlayered with offshore, mudstone-dominated strata (Koning, 2024). The black shales (hydrocarbon sources) and shoreline sandstones (hydrocarbon reservoirs) host major oil and gas resources in the San Juan Basin and within the nexus (Hart, 2021). The local last vestige of this seaway occurred in the very late Cretaceous (~75 Ma; Cather, 2004).

An important paleontological record in the nexus region includes information about Permian vertebrates (Lucas et al., 2012). There is little detailed record of the globally important Permo-Triassic extinction because of the disconformity between Permian and Triassic rocks and their dominantly siliciclastic character. Mesozoic sections preserve a globally important record of the evolution of the dinosaur (Lucas, 1997). The San Juan Basin is where the Paleocene Epoch was discovered and named, and it continues to inform our understanding of the early Cenozoic evolution of mammals (Williamson, 1996).

UPLIFT HISTORY

The first stage of regional uplift took place during the Laramide orogeny (Fig. 5) about 80 Ma in the nexus, as shown by thermochronology (cooling ages) in the Nacimiento and Zuni mountains (Kelley et al. 1992; Ricketts et al., 2016; Thacker et al., 2021). Structural relief from uplifted basement-cored blocks to subsiding syntectonic basins exceeded 3 mi (~5 km) for the San Juan Basin (Cather, 2004). Final basin filling is recorded by the Paleocene Nacimiento Formation and the lower Eocene San Jose Formation (Baltz, 1967; Woodward, 1983, 1987; Smith, 1992). The paleolandscape at this time likely comprised rugged, kilometer-high-scale eroding fault blocks amid epeirogenically uplifting but generally still low-elevation basins (Cather et al., 2012).

The Rocky Mountains are unusual in the sense that most of the world's mountain belts and the rest of the North and South American Cordillera are nearer the subduction-related plate boundary, whereas the Rockies are 1000 km inboard. This is interpreted by most workers to be the product of flat-slab subduction transmitting stress from the trench and also from the base of the plate across a wide foreland (e.g. Axen et al., 2018; Thacker et al., 2023). Alternative tectonic models also consider lower crustal flow (McQuarrie and Chase, 2000; Vlaha et al., 2024) and terrane convergence (Maxon and Tikoff, 1996). The cumulative uplift history of the Rocky Mountains involved the same three uplift episodes as the Colorado Plateau, but the Rocky Mountain Laramide uplifts have larger-displacement, reverse-fault-cored Laramide monoclines than those seen on the Colorado Plateau. Both provinces are part of a broad Laramide foreland where both magmatism and deformation swept progressively eastward due to 90–50 Ma slab flattening (Coney and Reynolds, 1997; Livicarri, 1991; Copeland et al., 2017; Thacker et al., 2023).

The magnitude and role of right-lateral strike-slip displacement along north-south faults in New Mexico in the Laramide remains controversial (Cather et al., 2006; Woodward et al., 1999; Cather and Karlstrom, 2000). Karlstrom and Daniel (1993), based in part on an important basement piercing point (Miller et al., 1963), suggested that up to 60–75 mi (100–120 km) of right lateral strike slip was distributed across north-south faults that helped localize the Rio Grande rift. These authors suggested ~20 mi (~30 km) across the Nacimiento fault. This was revised to ~12–20 mi (20–33 km) by Cather et al. (2006) and 4–11 mi (6–18 km) by Pollock et al. (2004), the latter agreeing with the 3–12 mi (5–20 km) proposed by Woodward et al. (1997). Recent models propose subduction of the buoyant conjugate Shatsky Rise as part of the subducting Farallon slab beneath western North America during the Laramide (Liu and Gurnis, 2010), and plate motion models that suggest a change from Laramide east-west to northeast-southwest convergence. These models have reinvigorated interest in quantifying the magnitude of right slip across a suite of north-south faults in New Mexico and into southern Colorado. At present, and going back to Baltz (1967), the consensus is that the Laramide right-lateral strike-slip component of displacement across the Nacimiento fault is kilometer-scale and exceeds the vertical component (throw) of the east-up dip-slip displacement.

Paleoelevation proxies for Rocky Mountain-Colorado Plateau uplift history are improving but are not in agreement (Cather et al., 2012; Heitmann et al., 2021). However, the data do support the notion that each of the three uplift episodes contributed substantially to raising the region above sea level. The youngest episode, the post-20 Ma and ongoing mantle-driven epeirogenic surface uplift, helps explain numerous neotectonic and magmatic features of the region (Karlstrom et al., 2008, 2011, 2022). Its ongoing effects are supported by geodetics (Berglund et al., 2012; Murray et al., 2019), seismology (Levander et al., 2011), geodynamic models (Yi and Kapp, 2023), thermochronology (Ricketts et al., 2016; Murray et al. 2019), detrital grain studies from paleoriver deposits indicating young incision (Heizler et al., 2021), and some paleoelevation studies (Leopold and Zaborac-Reed, 2019). A theme of this field conference is that post-20 Ma and ongoing neotectonics are being superimposed on older uplift events to help shape the iconic canyons, plateaus, and landscapes of the region, and additional quantification of uplift rates and magnitudes through time is needed.

Within the Nacimiento nexus, the Nacimiento Mountains

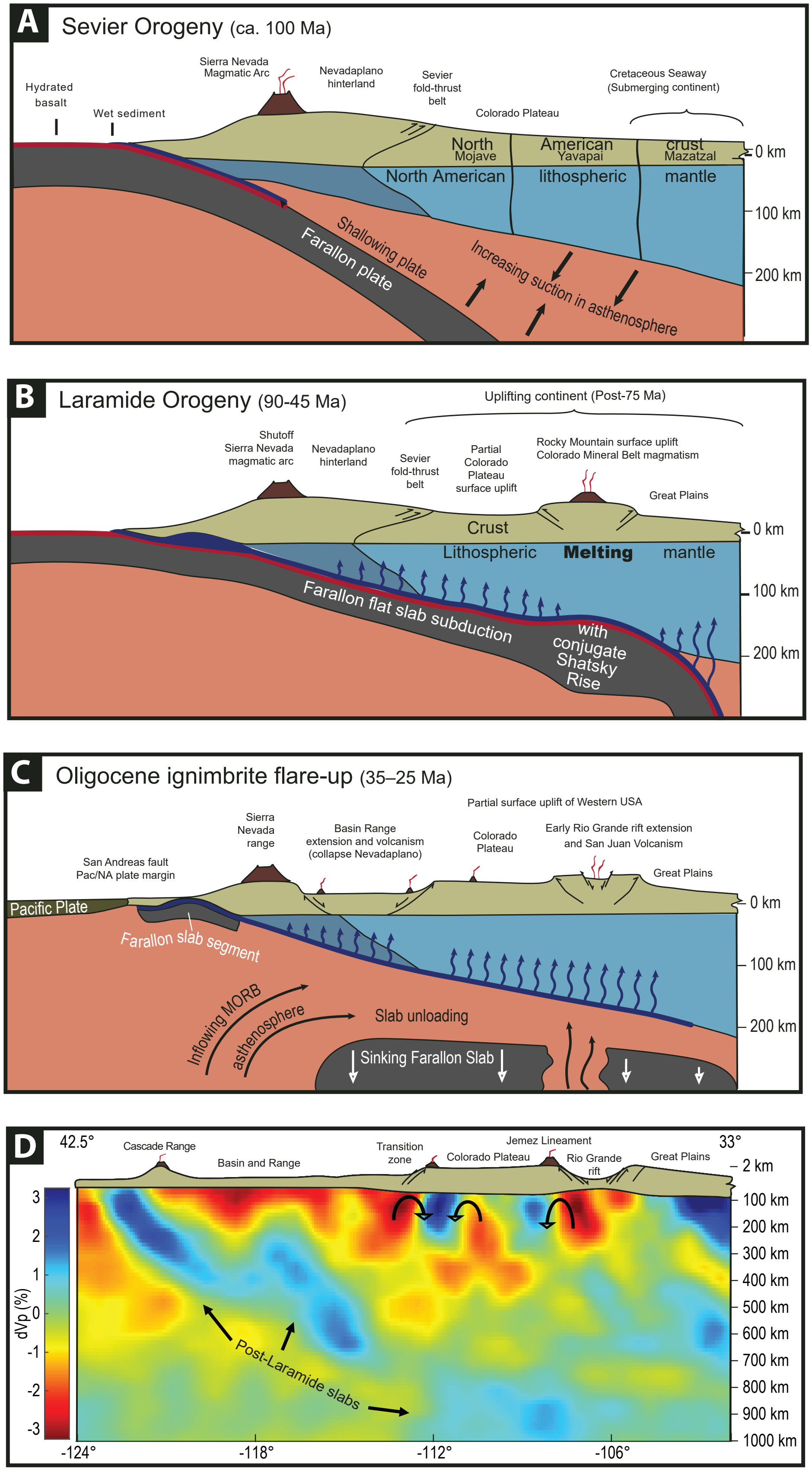

FIGURE 5. Tectonic evolution of the nexus region modified from Humphreys et al. (2003) and Crossey et al. (2016). (A) Sierra Nevada arc. (B) Farallon flat-slab subduction. (C) Removal of the Farallon slab and asthenospheric return flow drives ignimbrite flare-up. (D) Modern mantle tomographic image (cross-section line shown in Fig. 3C) shows ongoing mantle convection with arrows showing downwellings. (Figure adapted with permission from Karlstrom et al., 2022; copyright Annual Reviews.)

are part of the Rocky Mountain physiographic province (Fig. 1). They are similar to the Sangre de Cristo Mountains in being some of the farthest south Laramide arch-basin pairs (Thacker et al., 2023). The Nacimiento Mountains basement-cored block was thrust west over the San Juan Basin of the Colorado Plateau, and the Sangre de Cristo Mountains block was thrust east over the Raton basin of the Great Plains, giving the Rocky Mountains in New Mexico an overall bivergent, regional horst-block-like symmetry that is also seen in the Park and Front Ranges farther north. High-angle reverse faulting is not mechanically favored during horizontal compression (Anderson, 1905), but reverse-slip reactivation of steeply dipping Precambrian normal-slip fault systems is documented for the basement-cored (thick-skin) structures across the Laramide foreland, from the Grand Canyon to the Great Plains (Marshak et al. 2000; Timmons et al., 2001).

Cather (2004) demonstrated a latest Cretaceous influence on subsidence of the San Juan Basin. Baltz (1967) interpreted that deformation along the Nacimiento fault continued during deposition of Paleocene to Eocene strata, although this was questioned by Zellman et al. (2024). Pollock et al. (2004) interpreted thrust-wedge tectonics and strike-slip faulting farther north along the Nacimiento fault system, which commonly interacts with high-angle reverse faulting (Davis and Bump, 2009). Thermochronology of the uplift shows Laramide AFT and AHe cooling ages of 90–45 Ma (Kelley et al., 1992; Ricketts et al., 2016). The northern Nacimiento Mountains cooled earlier due to the erosion of Paleozoic and Mesozoic strata during the Laramide; the southern Nacimiento Mountains cooled during the 35–25 Ma and post-20 Ma uplift episodes. These Rocky Mountain fault blocks, like the Sangre de Cristo Mountains and Front Range, began their journey to the surface in the Laramide, while turtles and crocodiles lived in the adjacent basins that were likely of low elevation (Raynolds et al., 2007).

MAGMATISM

To understand both the volcanism and the tectonism through time in this region, one needs to study the region's nearest plate margin, the base of the plate. Mantle seismic images have gained resolution (Fig. 3) and have been used to infer the role of mantle dynamics during each of the uplift episodes. The volcanic rocks are a direct and datable record of the initially mantle-sourced basaltic magmatism and can provide data about which part of the mantle they come from and the extent of crustal contamination during ascent. Figure 3A is a tomographic image of the depth to the lithosphere-asthenosphere boundary (LAB), which approximates the thickness of the North American plate. This seismic technique (Lekic and Fischer, 2014) images mantle discontinuities that show abrupt velocity decrease with depth, which is characteristic of the LAB in magmatically active areas with high heat flow such as the Basin and Range, Rio Grande rift, and in the rim regions of the Colorado Plateau. Similar discontinuities can also occur within the lithospheric mantle beneath relatively stable areas with lower heat flow such as the core of the Colorado Plateau, Wyoming province, and Great Plains (e.g., Hansen et al., 2013); in these areas, the thickness shown is considered as a minimum lithospheric thickness. Figure 3A reveals a core region of the Colorado Plateau province that is rimmed to the west, south, and east (not the north) by thinner <50-mi- (<80-km-) thick lithosphere. Similarly, figures 3B and 3C show different depth slices through a tomographic model (Schmandt and Lin, 2014). These show that the core region of the Colorado Plateau has a cold, old (Proterozoic), and high-seismic velocity lithospheric keel that extends below 195-km depths.

At all upper-mantle depths, low-seismic-velocity regions occur around the rim of the Colorado Plateau and beneath the Nacimiento nexus. These lower seismic velocities indicate a small percentage of basaltic partial melt along grain boundaries in the mantle peridotite and an overall warmer and more buoyant mantle that is asthenospheric in terms of its ability to flow. Karlstrom et al. (2022) summarized numerous other geophysical and geological images that also suggest that the margins of the Colorado Plateau are weaker and more tectonically active than its core, as shown in the distribution of magmatism in Figure 3B. Low-velocity areas of the mantle may reflect Proterozoic lithospheric mantle that is being hybridized by young, asthenospheric-sourced basalt as it ascends through and helps partially melt lithospheric mantle (Livicarri and Perry, 1993; Reid et al., 2012; Porter and Reid, 2021). The sharp rim-to-core transition that defines the margin of the Colorado Plateau in multiple geophysical and geologic datasets suggests a young and shrinking Colorado Plateau that is uplifting as its edges are being thinned from below by mantle upwelling. In the future, the Colorado Plateau is likely to continue to shrink and merge with surrounding regions of the western United States. This phenomenon also seems to be occurring in the Nacimiento nexus, where extensional faulting is reactivating older faults, and the Rio Grande rift is encroaching into the Colorado Plateau.

New Mexico is the volcano state (Crumpler, 2020) and contains a detailed record of dominantly mantle-sourced Cenozoic volcanism. Laramide magmatism in Arizona and southwestern New Mexico provides the best record of the west-to-east sweep of magmatism that tracked the shallowing of the subducting Farallon slab (Fig. 6; Coney and Reynolds, 1977; Copeland et al., 2017; Thacker et al., 2024). Laramide magmatism also took place along the Colorado Mineral Belt (Fig. 6). The northeast orientation of the Colorado Mineral Belt has been interpreted to have formed above a slab tear in the subducting plate (Chapin, 2012), which is compatible with a lack of directionality of magma propagation (Mutchler et al., 1987). The 38–20 Ma ignimbrite flare-up of the San Juan volcanic field (Lipman, 2021) is superimposed on the Colorado Mineral Belt (Chapin, 2012) and extends south into New Mexico to include the Latir volcanic field. The San Juan volcanic field to the north and Mogollon-Datil volcanic field to the south both likely had extensive volcaniclastic aprons, now eroded, that reached the area of the Nacimiento nexus (Koning and Heizler, 2021). The Ortiz Mountains contain Oligocene shallow-level intrusions that are temporally related to the ignimbrite flare-up. Dacitic-andesitic conglomerate at the base of the Abiquiu Formation (Gilman

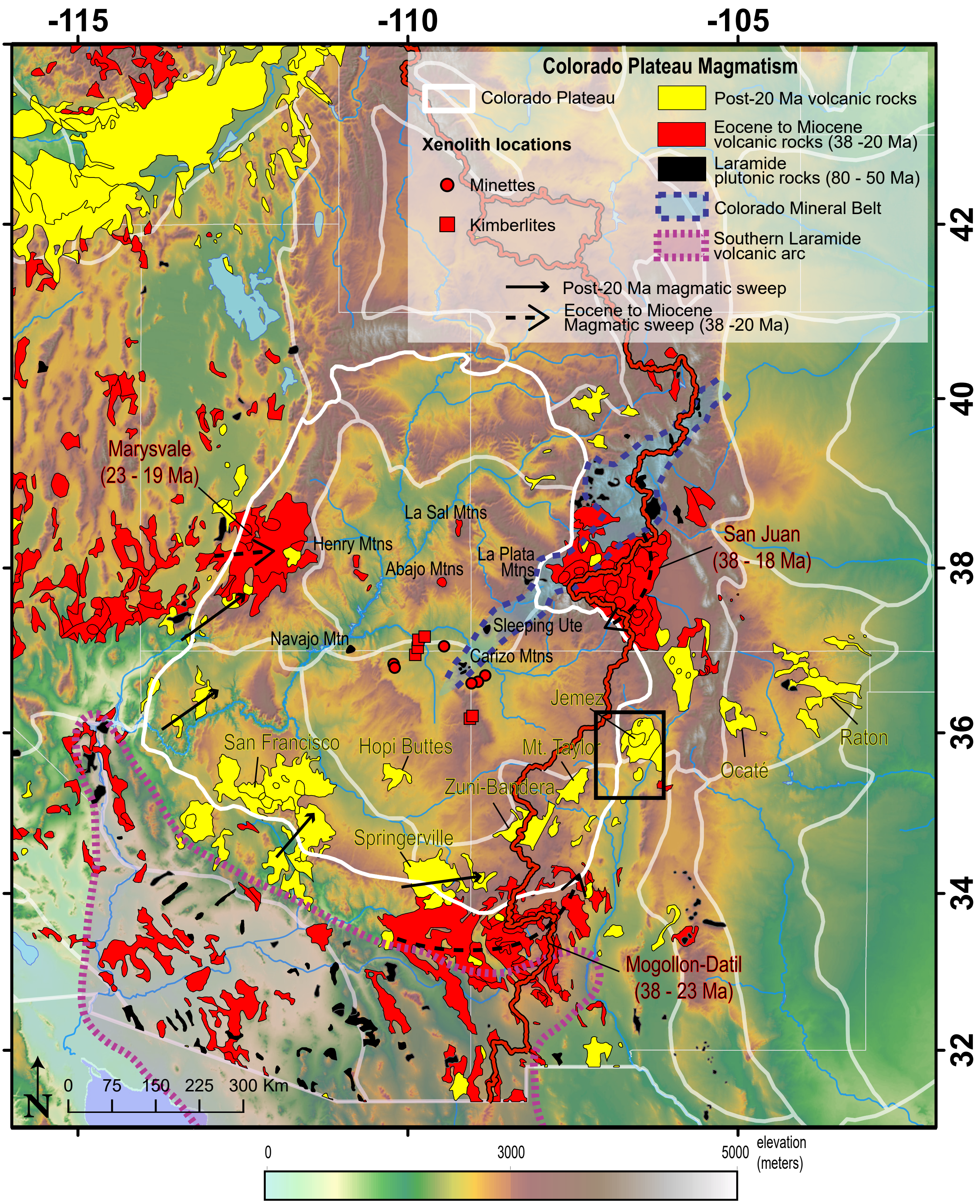

FIGURE 6. Cenozoic volcanism in and surrounding the Colorado Plateau. Purple = locus of southern Laramide volcanic arc; black = Laramide intrusions; red = Oligocene (38–25 Ma) caldera complexes, laccoliths, and diatremes; yellow = Neogene (20–0 Ma) volcanic fields (dominantly basalt). The Oligocene ignimbrite flare-up was when the Colorado Plateau first became geographically delineated; melt extraction from the mantle was likely related to prior hydration and the geometry of the removal of the Farallon slab. (Figure adapted with permission from Karlstrom et al., 2022; copyright Annual Reviews.)

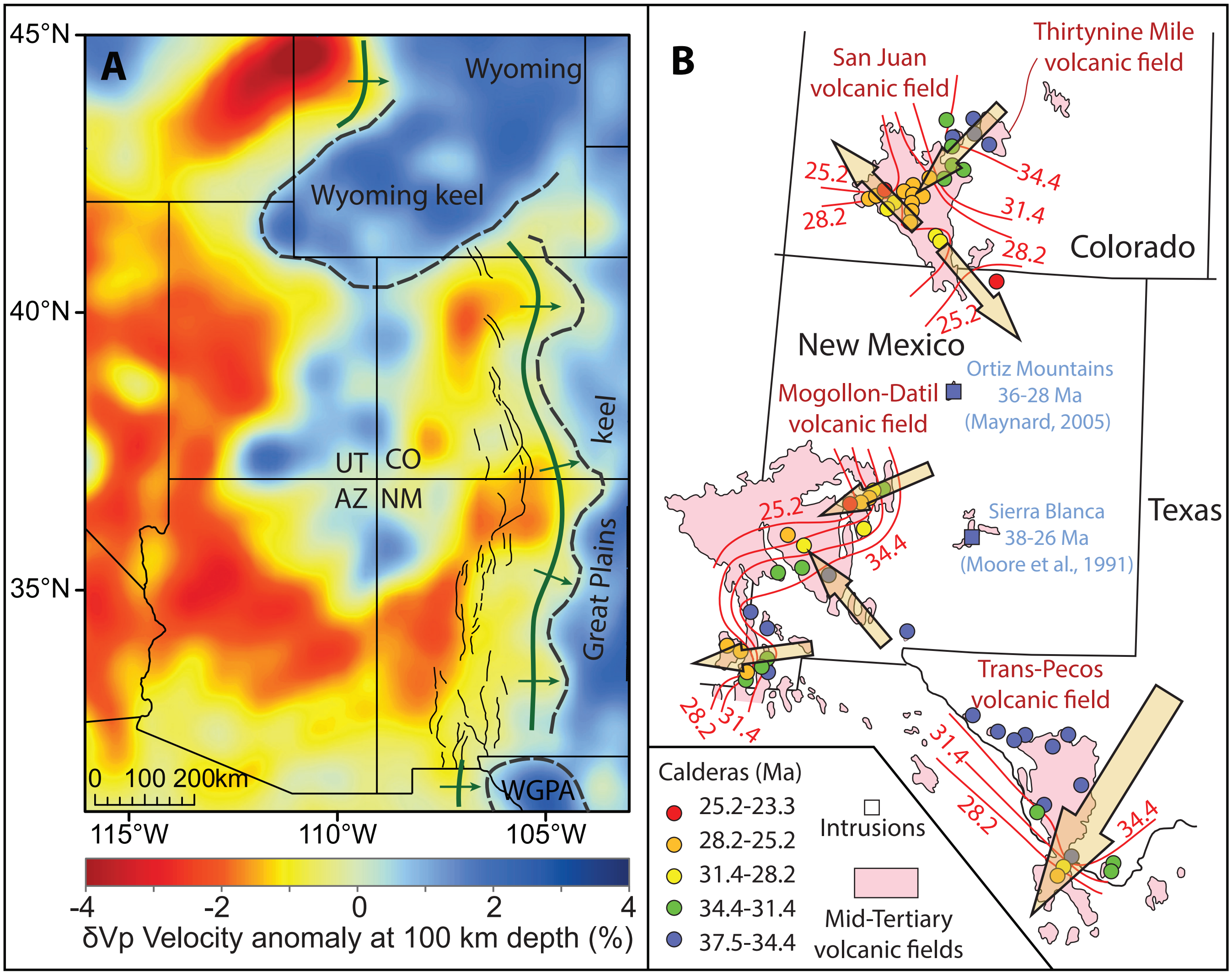

FIGURE 7. (A) Vp velocity anomaly at 100-km depth (Schmandt and Humphreys, 2010). Thick green lines and arrows depict the bend in the Farallon slab as it encountered thicker North American lithosphere. Thick dashed lines outline high-velocity domains. Thin black lines represent main faults in the Rio Grande rift. WGPA = western Great Plains anomaly. (B) Map of large-volume volcanic fields (pink) and distribution of Eocene-Miocene calderas in Colorado, New Mexico, and west Texas, color-coded by age of intracaldera fill (modified from Chapin et al., 2004). Ages are contoured in red, and arrows show interpreted sweep directions of volcanism that tracked the Farallon slab removal.

conglomerate) was likely derived from yet another volcanic center, active 33–28 Ma, that is now buried beneath the northwestern Albuquerque basin (Kelley et al., 2013).

The Jemez lineament is a series of 20 Ma to Quaternary volcanic fields that trends northeast from Arizona to the Great Plains (Fig. 6; Aldrich 1986). These fields overlie a zone of low-velocity mantle that extends from the base of the crust to depths of several hundred kilometers (Schmandt et al., 2012; Schmandt and Lin, 2014). Stable isotopic studies of the Puerco necks xenoliths suggest a long history of lithospheric modification by Farallon slab hydration and slab removal, leading to the origin of Jemez lineament basalts via melting of metasomatized mantle during Rio Grande rift lithospheric thinning and asthenospheric upwelling (Perkins et al., 2006; Porecca et al., 2006). In places there was a switch from lithospheric to asthenospheric basalt derivation through time in a given spot (Livicarri and Perry, 1993). An older idea of a plume track along the Jemez lineament (Suppe et al., 1975) does not seem to be supported because of a lack of directional progression of magmatism in this zone (Dunbar, 2005). However, especially in the southwestern part of the Colorado Plateau, there is a migration of basaltic volcanism toward the core of the Colorado Plateau (Fig. 6; Roy et al., 2009; Crow et al., 2011), with directions and rates that seem to be tracking the ~16 mm/year (absolute plate velocity) transit of the North American plate southwest over warm asthenosphere (Walk et al. 2019; Karlstrom et al., 2022). Crow et al. (2011) noted that within this progression some areas such as the western Grand Canyon evolved from lithospheric-sourced to asthenospheric-sourced basalt through time.

The Jemez Mountains contain New Mexico's supervolcano, with an eruptive ignimbrite volume (680 km^3 from the combined 1.62 and 1.23 Ma eruptions) that is about one-third of its Yellowstone counterpart (~2000 km^3 in this time period; Schmandt et al., 2019, and references therein). The Jemez Mountain volcanic field (JMVF) is located at the intersection of the Jemez lineament with the Rio Grande rift and is the most felsic volcanic center in the Jemez lineament, possibly due to a longer duration of basalt flux from the mantle and longer times for crustal differentiation. Quaternary caldera eruptions occurred twice at 1.62 and 1.23 Ma (Nasholds and Zimmerer, 2022) in overlapping calderas. Resulting pyroclastic Bandelier Tuff outflow sheets typically make up a single cliff containing both the upper 1.23 Ma Tshirege Member and lower 1.62 Ma Otowi Member of the Bandelier Tuff (Goff, 2009). The Jemez Mountains and the Valles Caldera straddle the boundary between the Colorado Plateau and the Rio Grande rift. Deep drill holes in the northwestern caldera penetrated caldera fill on top of Paleozoic/Mesozoic strata, whereas drillholes to the southeast penetrated tuff emplaced on Santa Fe Group rift fill (Goff, 2009). Mapping in the northeastern Jemez Mountains does not show clear connections between the Valles Caldera and the northeast-trending Embudo transfer zone to the northeast (Kelley et al., 2017, unpublished report to the Army Corps of Engineers). However, geochemical studies by Blomgren et al. (2019) suggest a fluid connection between the Valles geothermal system and Ojo Caliente and perhaps to other hot springs in the Taos Plateau region.

Within the Nacimiento nexus, the base of the Bandelier Tuff provides an important datum for estimating Quaternary fault slip and river incision rates (Frankel and Pazzaglia, 2006; Reed et al., 2024). Pyroclastic flows traveled down and overtopped the paleo-San Diego Canyon that is now occupied by the Jemez River. The deepest preserved paleochannels are located on the west side of the modern canyon (Kelley et al., 2003). The resurgent dome (Redondo Peak) in the Valles Caldera represents rapid uplift of the caldera floor after ~1.25 Ma evacuation and refilling of much of the magma chamber. Subsequently, a necklace of rhyolite lava domes developed on the ring fracture in a counterclockwise progression from 1.1 Ma to 400 ka. A series of caldera lakes developed and drained (Fawcett et al., 2011) with evolving volcanic topography. The most recent volcanism included the ~70 ka Banco Bonito flows and El Cajete pumice (Nasholds and Zimmerer, 2022). New seismic data reinforce previous imaging showing the presence of a shallow (1–3 km) magma chamber beneath Redondo Peak (Wilgus et al., 2023), and a modern geothermal system is present in the western caldera. The Third-Day Field Trip discusses this dormant but still-active supervolcano with an active downstream outflow of the geothermal plume recorded at Soda Dam, Jemez Springs, and Twin Mounds (McGibbon et al., 2018). A similar outflow is inferred to the north along the Embudo fault system (Blomgren et al., 2019).

RIO GRANDE RIFT

The entire western United States is being uplifted in the youngest episode, and the plate is thinning via upper crustal extension in the Basin and Range/Rio Grande rift provinces by ductile stretching in the deeper crust and by replacement and modification of lithospheric mantle by warmer and more buoyant asthenospheric mantle (van Wijk et al., 2010, 2018). This plate thinning is particularly pronounced in the Rio Grande rift province. The Rio Grande rift is one of the classic intracontinental rifts in the world (another famous one being the East African rift); it extends ~1000 km from northern Colorado into northern Mexico. In the north half of New Mexico, the Rio Grande rift comprises a series of right-stepping half-graben basins linked by northeast-trending transfer zones (Kelley, 1982).

Within the Nacimiento nexus, the main rift features are two sub-basins in the larger Albuquerque basin: the relatively symmetrical Santo Domingo sub-basin to the northeast and the asymmetric (deepening to the east) Calabacillas basin to the southwest (Connell, 2008a). These basins are filled by synrift, sand-dominated sediment called the Santa Fe Group. The Ziana structure, envisioned as an anticline (Kelley, 1977) or horst block (Koning and Personius, 2002), is located ~5 mi (~8 km) west of Bernalillo and is crossed (in the subsurface) on all three days of this field conference. West-southwest of the Ziana structure, the Calabacillas basin ramps down to the south and is bounded on the west by the north-south San Ysidro-Jemez fault system. Where preserved on either side of the fault (e.g., 12 mi [~20 km] south of San Ysidro), lowermost Santa Fe Group strata are offset 1000–1500 ft (300–450 m; Koning et al., 2024). This is minor compared to the 3.7 mi (6 km) of stratigraphic offset of the faults on the east side of the Calabacillas sub-basin (East Heights and Sandia fault zones in Connell, 2008a). Even with their small displacements, the San Ysidro-Jemez fault and other nearby faults (e.g., Sand Hill fault) effectively serve as the boundary between the Colorado Plateau and the Rio Grande rift. As a demonstration of how the nexus is a place of interconnectedness between the geologic provinces, east-down movement along these western border faults provides local windows of recharge into the deep Santa Fe Group aquifer from bedrock aquifers in the Colorado Plateau (Connell, 2011).

Chapin and Seager (1975) argued that pre-existing crustal flaws related to earlier Laramide and ARM deformations localized the rift, and Marshak et al. (2020) invoked still older, Late Precambrian fault weaknesses. As a compatible model to a prior zone of weakness, Ricketts et al. (2016) suggested that the Rio Grande rift became localized above the break-off of the frontal bend of the Farallon slab (Fig. 7). Steeper subduction and slab tears to the north and south influenced slab segmentation similar to the modern-day Andes. Slab removal via drips and delamination took place under the San Juan (Hansen et al., 2014), Mogollon-Datil, and Trans-Pecos volcanic complexes to drive these 38–23 Ma ignimbrite flare-ups and related surface uplift. Breaking of the remaining slab near its frontal bend (Fig. 8) is interpreted to have driven the 25–10 Ma synchronous opening of the rift inferred from thermochronologic data (Landman and Flowers, 2012; Ricketts et al., 2016).

The Santa Fe Group in the northwestern Albuquerque basin consists of three stratigraphic packages (Fig. 4; Connell, 2008b). The lowest is dominated by sandstone, with lesser mudstone-rich intervals, of the Zia (20–16 Ma) and Cerro Conejo 14.8–10 Ma) Formations. These formations are separated by a disconformity in exposures, but how far south-southwestward the disconformity extends in the subsurface is uncertain. The middle stratigraphic package, the Arroyo Ojito Formation (10–6 Ma), is marked by the presence of conglomeratic and clayey mudstone beds within predominately sandstone. Overlying a prominent unconformity (the Rincones Surface of Connell et al., 2013), sediment remains relatively coarse (mainly sand and variable gravel) in the upper package, the Ceja Formation (5–1.5 Ma; Connell, 2008b; Connell et al., 2013). In the Jemez River valley below the confluence of San Diego and Guadalupe Canyons, below the Santa Fe Group lie 50–62 m of white to tan, medium-grained sandstone interbedded with ash-fall deposits, one of which is 20.62 +/- 0.02 Ma (Kelley et al., 2013). These light-colored, tuffaceous strata are assigned to the Abiquiu Formation and are underlain by the Gilman Conglomerate, with clast ages ranging from 28.6–29.5 Ma (Kelley et al., 2013).

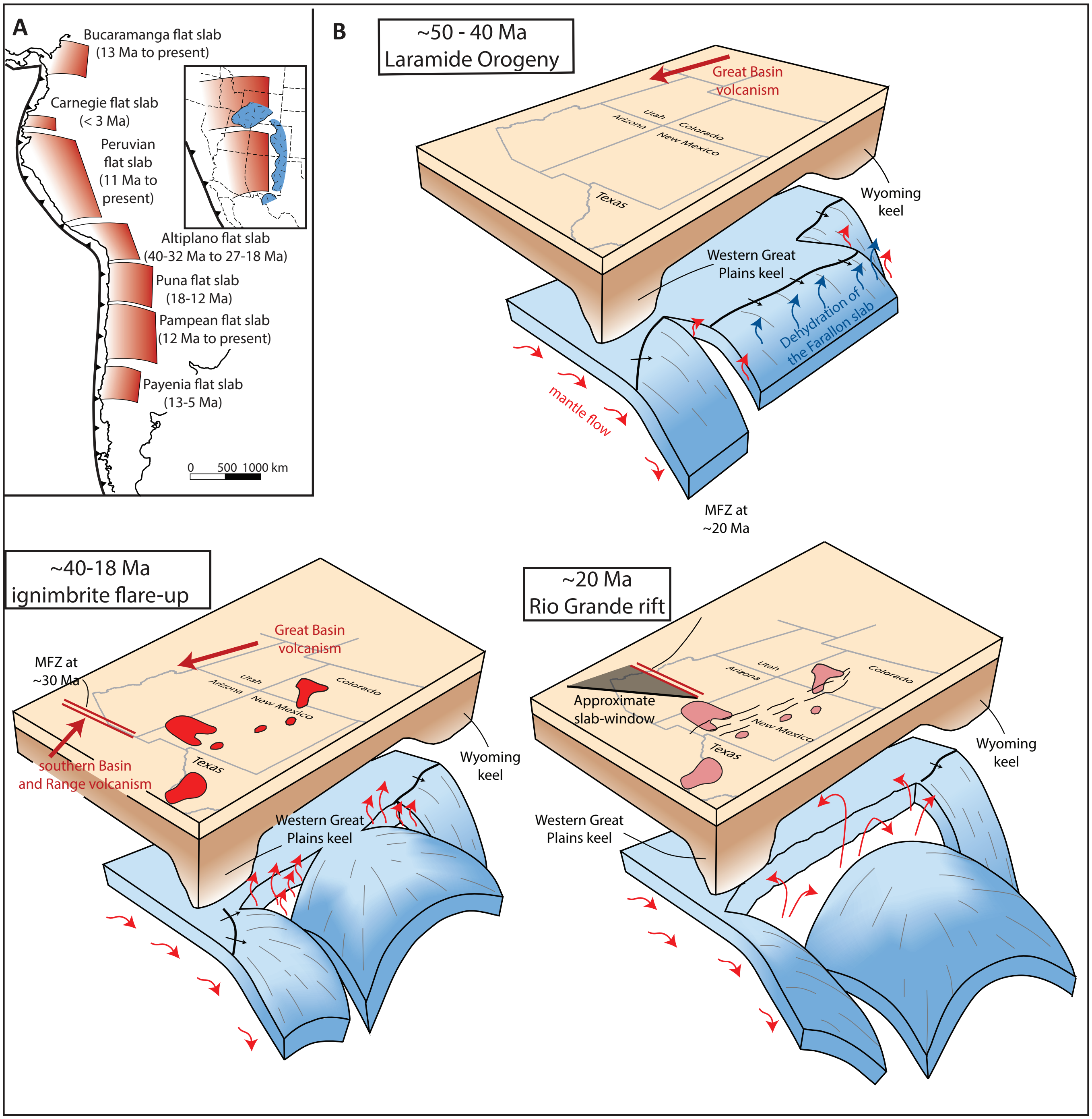

FIGURE 8. (A) Size comparison of the proposed flat-slab segment extending from the Wyoming craton to the western Great Plains anomaly (inset) to different flat-slab segments in South America (the latter modified from Ramos, 2009). (B) Proposed evolution of the Rio Grande rift and relationship to the Laramide orogeny and ignimbrite flare-up in Colorado, New Mexico, and west Texas. Flat-slab subduction in the Laramide was followed by slab tears and delamination during the ignimbrite flare-up and slab break-off to cause Rio Grande rifting.

Tectonism and climate have influenced the deposition of the Santa Fe Group. Thickness variations of the Gilman conglomerate and syn-depositional faulting and folding in the upper, transitional units of this conglomerate and the basal Abiquiu Formation indicates early Miocene activity along the Jemez fault system. For younger Santa Fe Group strata, long-term stratal accumulation rates reflect subsidence along rift normal faults. In the northwestern Albuquerque basin, published undecompacted sedimentation rates were 83 m/Ma between 14.8 and 10 Ma (Tedford and Barghoorn, 1999) and 125 m/Ma between 10 and 6 Ma (Connell et al., 2013). These two rates are from different fault-bounded blocks, and one cannot necessarily infer that 14.8–10 Ma tectonic activity was lower than 10–6 Ma activity. The presence of the Cerro Conejo-Zia disconformity argues that, locally, fault subsidence exceeded depositional rates between 16 and 15 Ma, causing an offlap of the basin margin. Stratal accumulation rates decrease notably in the Plio-Pleistocene (van Wijk et al., 2018), with coarse sediment deposition over the Rincones paleosurface inferred to have been driven primarily by climatic factors (Connell et al., 2013).

NEOTECTONICS

One theme of this field conference is examining the history of fault reactivations manifested in the region. Proterozoic ancestry for nexus faults is conjectural, except to note that Mesoproterozoic fault-bounded basins occur in the subsurface of the region, such as the 1.1 DeBaca basin to the east (e.g., Amarante et al., 2005) and the San Andres basin in southern Colorado (Timmons et al., 2005). The Pennsylvanian Peñasco uplift was the precursor to the Laramide Nacimiento Mountains, but the locations and nature of Ancestral Rockies age faults remain poorly understood because of later reactivations.

Figure 9 shows a new view of fault reactivations, segmentation, and proposed naming of faults in the nexus region. Refined mapping and naming of the segmentation within the USGS-named fault zones are important because the segment boundaries often reflect different reactivation histories and can control seismic hazards and the geometry of fluid conduits. The Nacimiento fault had Laramide contractional and strike-slip movement, as detailed above. This fault zone can be seen from satellite images as a straight line that continues toward the western boundary of the Albuquerque basin. First-Day Field Trip stops near the south extent of the mapped Nacimiento fault zone suggest that extensional reactivation (inversion) of Laramide monoclinal structures helps explain the southward continuation of the Nacimiento fault zone in several segments through the Tierra Amarilla anticline (Bailey et al., 2024). A Laramide ancestry of basement-cored sections of the San Ysidro-Jemez faults system is also suggested for several locations based on the pairing of fault-adjacent anticlines and synclines that are characteristic of Laramide monoclines. The basement exposure in the Soda Dam area is also interpreted to reflect Laramide reverse faulting (Jean et al., 2024). Late Quaternary movement on the southern Nacimiento fault zone was proposed by Formento-Trigilio and Pazzaglia (1996). These studies and observations suggest that the southern Nacimiento Mountain block is undergoing Quaternary uplift relative to both the San Juan Basin and Rio Grande rift, with east-up displacement on the Nacimiento fault (Formento-Trigilio and Pazzaglia, 1998) and the east-down movement distributed across one or several north-south faults including the San Ysidro and Jemez faults (Reed et al., 2024). South of U.S. Highway 550, the Laramide faults become progressively more strongly inverted by normal slip related to Rio Grande rift extension, which conceals but often does not erase their original reverse throw. Small-scale gypsum veins along the Nacimiento fault that we see in the core of the Tierra Amarilla anticline remind us of the right-lateral strike-slip component in this zone.

The modern river network (Fig. 1) that is carving our "young landscapes" is another focus of this field conference. Neogene uplift of the Rocky Mountain region is hypothesized to have promoted downward integration of the Colorado River from the Rockies at 11 Ma to the Gulf of California by 5 Ma (Karlstrom et al., 2011; Crow et al., 2023). On the east side of the continental divide, the Rio Chama and Rio Grande were integrated together by ~4 Ma, and the combined river system worked its way southward through internally drained lake- and playa-filled sub-basins of the Rio Grande rift to reach the sea at the Gulf of Mexico only in the past 1 million years (Galloway, 2000, 2004, 2011; Connell et al., 2005; Repasch et al., 2018). Within the nexus, the Jemez River has re-incised San Diego Canyon in the past 1.2 Ma. Terrace flights exposed around the southern tip of the Nacimiento Mountains and up the Jemez River to Soda Dam contain the Lava Creek B (Yellowstone) ash of 630 ka. Other terraces are cemented by travertine that provides U-series dates that are used to constrain differential bedrock incision, which, in turn, quantifies Quaternary fault slip over the same intervals (Reed et al., 2024).

Travertines are freshwater carbonate deposits from carbonic springs. These are prevalent in the nexus region and a topic for the field conference (Cron et al., 2024; Jean et al., 2024). A travertine lexicon includes terms like "lower-world" waters for the carbonic springs, "xenowhiffs" for the foreign trace gases including high CO_2 and mantle helium (^3He) entrained in the groundwater system, and "chemical volcanoes" for the constructional mounds and fissure ridge deposits. The term "continental smokers" refers to carbonic springs, hot springs, and fumaroles that vent mantle-derived fluids in continental settings and exhibit many of the same processes of heat and mass transfer and ecosystem niche differentiation that are also seen in black and white smokers of mid-ocean ridges (Crossey et al., 2016). The travertines of the nexus, the Rio Grande rift, and the broader western U.S. region overlie low-velocity mantle domains and are an important indicator of mantle-to-surface connections and Quaternary neotectonics (e.g., Ricketts et al., 2015). The lithospheric-scale pathways for the ascent of mantle-derived fluids include upwelling asthenosphere, partial melt in the mantle, basaltic sill and dike magmatism in the crust, a CO_2-rich carrier gas for volatiles, fault networks with significant fracture permeability due to multiple reactivations and ongoing extension, and travertine deposition at spring vents due to CO_2 degassing. These springs and fluids are a product of

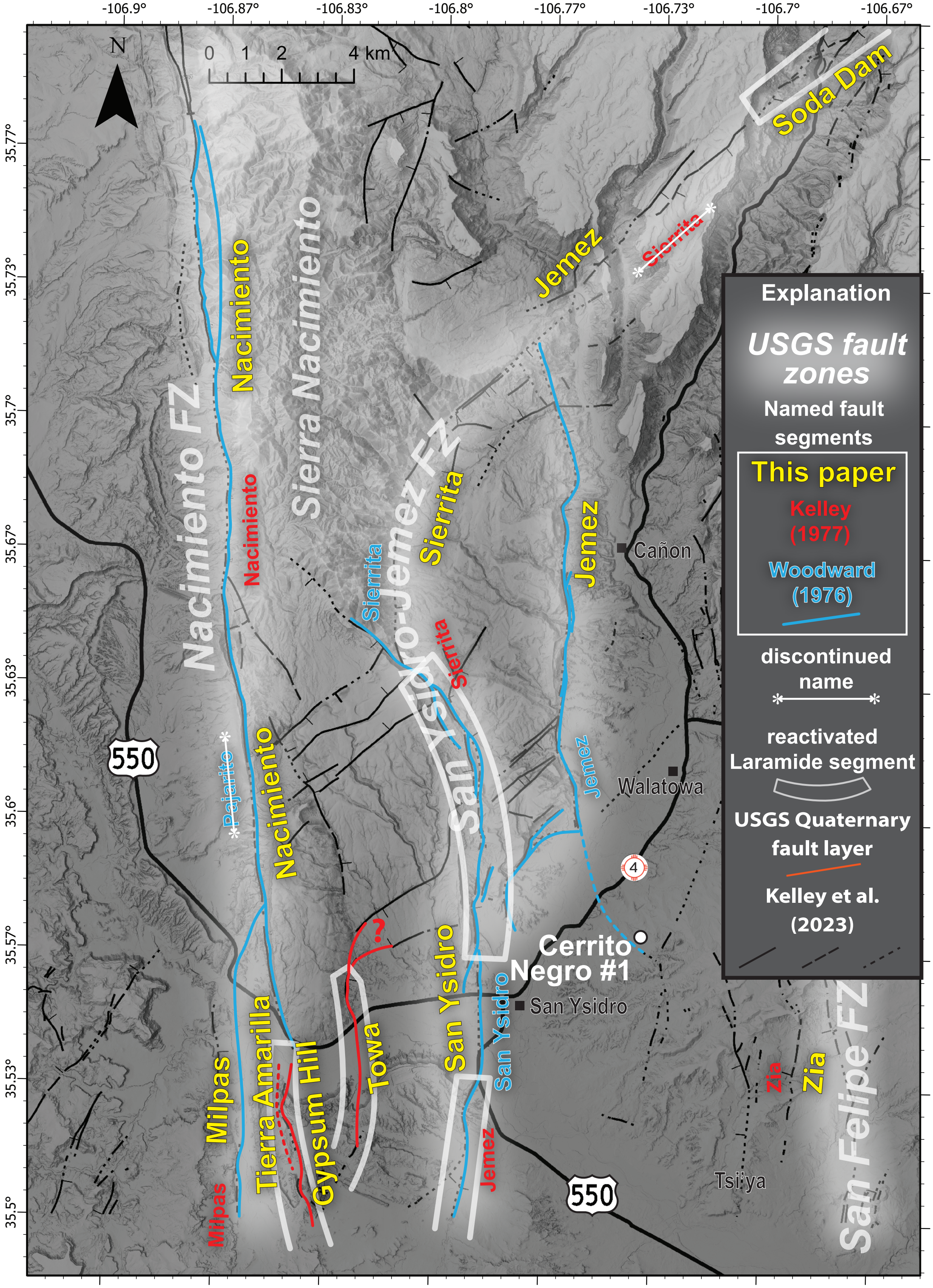

FIGURE 9. Faults of the southern Nacimiento region. Yellow letters are the recommended names of the faults in this paper based on naming history and proposed segmentation. These can be combined with the names of regional fault zones (white letters) used by the USGS (n.d.). Blue letters are names from Woodward (1976), red letters are names from Kelley (1977), and strike-throughs are names recommended to be discontinued. White boxes are Laramide contractional and strike-slip fault segments that have been reactivated during Rio Grande rift and ongoing extension. The Towa structure is discussed in the text.

neotectonism because the CO_2 is deeply derived and ascends on fault conduits. They are also a cause of neotectonism because the carbonic fluids create high pore-fluid pressure that can decrease effective normal stress and promote reactivation of faults.

These springs also cause degradation of water quality when lower-world waters mix with upper-world (meteoric) recharge. This mixing is evident and quantifiable in surface water mixing, as reported by Crossey et al. (2012) for the Jemez River, where geothermal inputs at Soda Dam degrade water quality—an effect that makes water unsafe to drink at low river stages. The same type of mixing takes place in groundwater but is more cryptic and often masked in Rio Grande rift aquifers. Evidence for groundwater mixing of lower-world waters in Rio Grande rift groundwater include the hydrochemical variations in well fields and calcite cementation along faults, in Santa Fe Group sandstones, and in your water heater.

New Mexico has also produced great wealth from the oil and gas within the San Juan Basin. These oil, mineral, and water resources make a direct connection between our geoheritage and human needs for water and energy. Papers in this volume explore critical mineral resources in the region and their importance (McLemore, 2024).

CONCLUSION

New Mexico provides an exceptionally well-exposed geologic record of nearly 2 billion years of Earth's history. This record can be summarized in three main chapters, with one major chapter missing. Chapter 1, the basement rocks, records the formation of North American crust and mantle lithosphere between 1.8 and 1.4 Ga. This lithospheric assembly created high mountains (~1.7 Ga) and an orogenic plateau (~1.45 Ga) as volcanic arcs collided with an evolving southward-growing (in today's coordinates) Laurentian continent. One or more missing chapters (the Great Unconformities) record the erosional demise of those mountains to exhume middle crustal basement rocks. Chapter 2, recorded by Paleozoic and Mesozoic strata, are a record of changing sedimentary environments in a near-sea-level continent from about 1.0 Ga to 66 Ma. The fossils entombed in these sediments record the biological evolution of life on Earth. Chapter 3 records the formation of the modern landscapes during three uplift episodes, Neogene volcanic activity, and focused extension in the Rio Grande rift. The three uplift episodes took place during the 90–45 Ma Laramide formation of the Rocky Mountains, the 38–23 Ma Cenozoic magmatism of the ignimbrite flare-up, and the post-20 Ma uplift. Unlike orogenic (mountain building) uplifts, each of these were epeirogenic (plateau building; Eaton, 2008) uplifts involving broad regions that were elevated by mantle-driven changes in plate buoyancy. West-east extension after 30 Ma created the north-trending Rio Grande rift. Normal faulting during this time, particularly after 20 Ma, created the space for multi-kilometer-thick deposition of Santa Fe Group in the Albuquerque basin and created imposing, rift-flank uplifts such as the Sandia Mountains. Post-20 Ma extension interacted with the northeast-trending Jemez lineament to produce the Jemez volcanic field, which has erupted felsic, intermediate, and mafic lavas and tephras since 11 Ma, in addition to voluminous, ignimbrite-producing eruptions at 1.62 and 1.23 Ma (Otowi and Tshirege members of the Bandelier Tuff).

One conclusion of the 2024 NMGS Fall Field Conference is that the post-20 Ma uplift is ongoing and is helping to expose the nearly 2-billion-year-long older geologic stories. Iconic mountain, canyon, and plateau landscapes are being continually reshaped by erosion that is responding to both the cyclical climatic shifts and surface uplift. The uplift process reflects interacting forcings of mantle convection, crustal and mantle magmatism, faulting, and river incision. Pick your chapter or process of greatest interest, and continue to learn about the others as well. For questions about where the southern end of the Rocky Mountains, the eastern edge of the Colorado Plateau, or the western edge of the Rio Grande rift are, the nexus region shows that the boundaries are transitional. The Colorado Plateau and Rio Grande rift boundary could be defined at faults that bound the western edge of Santa Fe Group rift-fill sediments (e.g., some segments of the San Ysidro-Jemez fault), but reactivation of older Laramide faults in the nexus region shows that ongoing crustal extension is also affecting the easternmost Colorado Plateau. The boundaries of the Rocky Mountains are generally drawn at the "break in slope," but the nexus shows that one such mountain uplift, the Nacimiento uplift, is undergoing block uplift at its southern tip (north of the highway), whereas the Tierra Amarilla area (south of the highway) is collapsing via extensional slip on older faults. Covered uplifts within the Rio Grande rift such as the Ziana anticline and Sierra uplift (Cather, 1983) may also have been shaped by collapse and reactivation of older Rocky Mountain fault blocks. The Jemez lineament has it all: Proterozoic ancestry, upwelling mantle, and presently dormant but potentially active magmatism. The Nacimiento geologic nexus region is an excellent place to refine our understanding of the interaction of these geologic features and processes.

ACKNOWLEDGMENTS

We thank Steve Cather, Steve Reynolds, and Kevin Hobbs for reviews that improved this paper.

REFERENCES

Aldrich, M.J., 1986,Tectonics of the Jemez Lineament in the Jemez Mountains and Rio Grande Rift: Journal of Geophysical Research, v. 91, no. B2, p. 1753–1762, https://doi.org/10.1029/JB091iB02p01753

Amarante, J.F.A., Kelley, S.A., Heizler, M.T., Barnes, M.A., Miller, K.C., and Anthoney, E.Y., 2005, Characterization and age of the Mesoproterozoic Debaca Sequence in the Tucumcari Basin, New Mexico, *in* Karlstrom, K.E., and Keller, G.R., eds., The Rocky Mountain Region: An Evolving Lithosphere: Tectonics, Geochemistry, and Geophysics: American Geophysical Union Geophysical Monograph 154, p. 185–200.

Amato, J.M., and Mack, G.H., 2012, Detrital zircon geochronology from the Cambrian-Ordovician Bliss Sandstone, New Mexico: Evidence for contrasting Grenville-age and Cambrian sources on opposite sides of the Transcontinental Arch: Geological Society of America Bulletin, v. 124, p. 1826–1840, https://doi.org/10.1130/B30657.1

Amato, J.M., Boullion, A.O., Serna, A.M., Sanders, A.E., Farmer, G.L., Gehrels, G.E., and Wooden, J.L., 2008, Evolution of the Mazatzal province and the timing of the Mazatzal orogeny: Insights from U-Pb geochronology and geochemistry of igneous and metasedimentary rocks in southern New Mexico: Geological Society of America Bulletin, v. 120, p. 328–346, https://doi.org/10.1130/B26200.1

Anderson, E.W., 1905, The dynamics of faulting: Transactions of the Edinburgh Geological Society, v. 8, p. 387–402, https://doi.org/10.1144/transed.8.3.387

Anderson, O.J., and Lucas, S.G., 1996, Stratigraphy and depositional environments of Middle and Upper Jurassic rocks, southeastern San Juan Basin, New Mexico, *in* Goff, F., Kues, B.S., Rogers, M.A., McFadden, L.D., and Gardner, J.N., eds., Jemez Mountains Region: New Mexico Geological Society Guidebook 47, p. 205–210, https://doi.org/10.56577/FFC-47.205

Aslan A., Karlstrom, K.E., Kirby, E., Heizler, M.T., Granger, D.E., Feathers, J.K., Hanson, P.R., and Mahan, S.A., 2019, Resolving time-space histories of Late Cenozoic bedrock incision along the Upper Colorado River, USA: Geomorphology, v. 347, 106885, https://doi.org/10.1016/j.geomorph.2019.106855

Axen, G.J., van Wijk, J.W., and Currie, C.A., 2018, Basal continental mantle lithosphere displaced by flat-slab subduction: Nature Geoscience, v. 11, p. 961–964, https://doi.org/10.1038/s41561-018-0263-9

Bailey, J.M., Karlstrom, K.E., Reed C., and Heizler, M.T., 2024, Structural geology of the Tierra Amarilla anticline, New Mexico, *in* Karlstrom, K.E., Koning, D.J., Lucas, S.G., Iverson, N.A., Crumpler, L.S., Aubele, J.C., Blake, J.M., Goff, F., and Kelley, S.A., eds., Geology of the Nacimiento Mountains and Rio Puerco Valley: New Mexico Geological Society Guidebook 74 (this volume), p. 281–289.

Baltz, E.H., 1967, Stratigraphy and regional tectonic implications of part of Upper Cretaceous and Tertiary rocks, east-central San Juan Basin, New Mexico: U.S. Geological Survey Professional Paper 552, 101 p., https://doi.org/10.3133/pp552

Best, M.G., Christiansen, E.H., de Silva, S., and Lipman, P.W., 2016, Slab-rollback ignimbrite flareups in the southern Great Basin and other Cenozoic American arcs: A distinct style of arc volcanism: Geosphere, v. 12, p. 1097–1135, https://doi.org/10.1130/GES01285.1

Berglund, H.T., Sheehan, A.F., Murray, M.H., Roy, M., Lowry, A.R., Nerem, S., and Blume, F., 2012, Distributed deformation across the Rio Grande Rift, Great Plains, and Colorado Plateau: Geology, v. 40, p. 23–26, https://doi.org/10.1130/G32418.1

Bickford, M.E., Van Schmus, W.R., Karlstrom, K.E., Mueller, P.A., and Kamenov, G.D., 2015, Mid-continent Mesoproterozoic granite-rhyolite provinces revisited: Evidence from new SHRIMP U-Pb ages, zircon saturation temperatures, and Hf isotopic compositions: Precambrian Research, v. 265, p. 286–312, https://doi.org/10.1016/j.precamres.2014.11.024

Blakey, R.C., Peterson, F., and Kocurek, G., 1988, Synthesis of late Paleozoic and Mesozoic eolian deposits of the western interior of the United States: Sedimentary Geology, v. 56, p. 3–125, https://doi.org/10.1016/0037-0738(88)90050-4

Blomgren, V., Crossey, L.J., Karlstrom, K.E., and Fischer, T., 2019, Hot spring hydrochemistry on opposite sides of the Rio Grande rift in northern New Mexico and a geochemical connection between Valles Caldera and Ojo Caliente: Journal of Volcanology and Geothermal Research, v. 387, 106663, https://doi.org/10.1016/j.jvolgeores.2019.106663

Cather, S.M. 1983, Laramide Sierra uplift—Evidence for major prerift uplift in central and southern New Mexico:, *in* Chapin, C.E., and Callender, J.F., eds., Socorro Region II: New Mexico Geological Society Guidebook 34, pp. 99–101, https://doi.org/10.56577/FFC-34.99

Cather, S.M., 2004, Laramide orogeny in central and northern New Mexico and southern Colorado, the geology of New Mexico, a geologic history: New Mexico Geological Society Special Publication, p. 203–248.

Cather, S.M., 2021, Jurassic stratigraphic nomenclature for northwestern New Mexico, *in* Frey, B.A., Kelley, S.A., Zeigler, K.E., McLemore, V.T., Goff, F., and Ulmer-Scholle, D.S., eds., Geology of the Mount Taylor Area: New Mexico Geological Society Guidebook 71, p. 251–258, https://doi.org/10.56577/FFC-71

Cather, S.M., Karlstrom, K.E., Grauch, V.J.S., Heizler, M., and Timmons, J.M., 2006, A palinspastic reconstruction of Proterozoic basement-related aeromagnetic features in north-central New Mexico: Implications for Mesoproterozoic to late Cenozoic tectonism: Geosphere, v. 2, p. 229–323, https://doi.org/10.1130/GES00045.1

Cather, S.M., Chapin, C.E., and Kelley, S.A., 2012, Diachronous episodes of Cenozoic erosion in southwestern North America and their relationship to surface uplift, paleoclimate, paleodrainage, and paleoaltimetry: Geosphere, v. 8, p. 1177–1206, https://doi.org/10.1130/GES00801.1

Chapin, C.E., 2012, Origin of the Colorado Mineral Belt: Geosphere, v. 8, p. 28–43, https://doi.org/10.1130/GES00694.1

Chapin, C.E., Wilks, M., and McIntosh, W.C., 2004, Spacetime patterns of Late-Cretaceous to present magmatism in New Mexico—Comparison with Andean volcanism and potential for future volcanism, *in* Cather, S.M., McIntosh, W.A., and Kelley, S.A., eds., Tectonics, Geochronology, and Volcanism in the Southern Rocky Mountains and the Rio Grande Rift: New Mexico Bureau of Geology and Mineral Resources Bulletin 160, p. 13–40.

Chapman, J.B., and DeCelles, P.G., 2021, Beveling the Colorado Plateau: Early Mesozoic rift-related flexure explains erosion and anomalous deposition in the southern Cordilleran foreland basin: Tectonics, v. 40, e2020TC006517, https://doi.org/10.1029/2020TC006517

Coney, P.J., and Reynolds, S.J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403–406, https://doi.org/10.1038/270403a0

Connell, S.D., 2004, Geology of the Albuquerque Basin and tectonic development of the Rio Grande rift, north-central New Mexico, *in* Mack, G.H., and Giles, K.J., eds., The Geology of New Mexico, A geologic history: New Mexico: New Mexico Geological Society Special Publication 11, p. 359–388.

Connell, S.D., 2008a, Geologic map of the Albuquerque-Rio Rancho metropolitan area and vicinity, Bernalillo and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources Geologic Map 78, scale 1:50,000.

Connell, S.D., 2008b, Refinements to the stratigraphic nomenclature of the Santa Fe Group, northwestern Albuquerque basin, New Mexico: New Mexico Geology, v. 30, no. 1, p. 14–35.

Connell, S.D., Hawley, J.W., and Love, D.W., 2005, Late Cenozoic drainage development in the southeastern basin and range of New Mexico, southeasternmost Arizona, and western Texas, *in* Lucas, S.G., Morgan, G.S., and Zeigler, K.E., eds., 2005, New Mexico's Ice Ages, New Mexico Museum of Natural History and Science Bulletin 28, p. 125–150.

Connell, S.D., Smith, G.A., Geissman, J.W., and McIntosh, W.C., 2013, Climatic controls on nonmarine depositional sequences in the Albuquerque Basin, Rio Grande rift, north-central New Mexico, *in* Hudson, M.R., and Grauch, V.J.S., eds., New Perspectives on Rio Grande Rift Basins: From Tectonics to Groundwater: Geological Society of America Special Paper 494, p. 383–425, https://doi.org/10.1130/2013.2494(15)

Copeland, P., Currie, C.A., Lawton, T.F., and Murphy, M.A., 2017, Location, location, location: The variable lifespan of the Laramide orogeny: Geology, v. 45, n. 3, p. 223–226, https://doi.org/10.1130/G38810.1

Cather, S.M., Karlstrom, K.E., Grauch, V.J.S., Heizler, M., and Timmons, J.M., 2006, A palinspastic reconstruction of Proterozoic basement-related aeromagnetic features in north-central New Mexico: Implications for Mesoproterozoic to late Cenozoic tectonism: Geosphere, v. 2, p. 229–323, https://doi.org/10.1130/GES00045.1

Cather, S.M., Chapin, C.E., and Kelley, S.A., 2012, Diachronous episodes of Cenozoic erosion in southwestern North America and their relationship to surface uplift, paleoclimate, paleodrainage, and paleoaltimetry: Geosphere, v. 8, p. 1177–1206, https://doi.org/10.1130/GES00801.1

Chapin, C.E., 2012, Origin of the Colorado Mineral Belt: Geosphere, v. 8, p. 28–43, https://doi.org/10.1130/GES00694.1

Chapin, C.E., Wilks, M., and McIntosh, W.C., 2004, Spacetime patterns of Late-Cretaceous to present magmatism in New Mexico—Comparison with Andean volcanism and potential for future volcanism, *in* Cather, S.M., McIntosh, W.A., and Kelley, S.A., eds., Tectonics, Geochronology, and Volcanism in the Southern Rocky Mountains and the Rio Grande Rift: New Mexico Bureau of Geology and Mineral Resources Bulletin 160, p. 13–40.

Chapman, J.B., and DeCelles, P.G., 2021, Beveling the Colorado Plateau: Early Mesozoic rift-related flexure explains erosion and anomalous deposition in the southern Cordilleran foreland basin: Tectonics, v. 40, e2020TC006517, https://doi.org/10.1029/2020TC006517

Coney, P.J., and Reynolds, S.J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403–406, https://doi.org/10.1038/270403a0

Connell, S.D., 2004, Geology of the Albuquerque Basin and tectonic development of the Rio Grande rift, north-central New Mexico, *in* Mack, G.H., and Giles, K.J., eds., The Geology of New Mexico, A geologic history: New Mexico: New Mexico Geological Society Special Publication 11, p. 359–388.

Connell, S.D., 2008a, Geologic map of the Albuquerque-Rio Rancho metropolitan area and vicinity, Bernalillo and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources Geologic Map 78, scale 1:50,000.

Connell, S.D., 2008b, Refinements to the stratigraphic nomenclature of the Santa Fe Group, northwestern Albuquerque basin, New Mexico: New Mexico Geology, v. 30, no. 1, p. 14–35.

Connell, S.D., Hawley, J.W., and Love, D.W., 2005, Late Cenozoic drainage development in the southeastern basin and range of New Mexico, southeasternmost Arizona, and western Texas, *in* Lucas, S.G., Morgan, G.S., and Zeigler, K.E., eds., 2005, New Mexico's Ice Ages, New Mexico Museum of Natural History and Science Bulletin 28, p. 125–150.

Connell, S.D., Smith, G.A., Geissman, J.W., and McIntosh, W.C., 2013, Climatic controls on nonmarine depositional sequences in the Albuquerque Basin, Rio Grande rift, north-central New Mexico, *in* Hudson, M.R., and Grauch, V.J.S., eds., New Perspectives on Rio Grande Rift Basins: From Tectonics to Groundwater: Geological Society of America Special Paper 494, p. 383–425, https://doi.org/10.1130/2013.2494(15)

Copeland, P., Currie, C.A., Lawton, T.F., and Murphy, M.A., 2017, Location, location, location: The variable lifespan of the Laramide orogeny: Geology, v. 45, n. 3, p. 223–226, https://doi.org/10.1130/G38810.1

Cron, B., Crossey, L.C., Karlstrom, K.E., Polyak, V., Asmerom, Y., and McGibbon, C, 2024, Geochemistry and microbial diversity of CO_2-rich springs and U-series dating of travertine from the Tierra Amarilla anticline, New Mexico, *in* Karlstrom, K.E., Koning, D.J., Lucas, S.G., Iverson, N.A., Crumpler, L.S., Aubele, J.C., Blake, J.M., Goff, F., and Kelley, S.A., eds., Geology of the Nacimiento Mountains and Rio Puerco Valley: New Mexico Geological Society Guidebook 74 (this volume), p. 225–235.

Crossey, L.J., Karlstrom, K.E., Schmandt, B., Crow, R., Coleman, D., Cron, B., Takacs-Vesbach, T.D., Dahm, C., Northup, D.E., Hilton, D.R., Ricketts, J.R., and Lowry, A.R., 2016, Continental smokers couple mantle degassing and unique microbiology within continents: Earth and Planetary Science Letters, v. 435, p. 22–30, https://doi.org/10.1016/j.epsl.2015.11.039

Crossey, L.J., Sherson, L.R., Jochems, A.P., Harding, J.J., Woolsey, E., Karlstrom, K.E., Ali, A.-M. , Person, M.A., Halihan, T., and Dahm, C.N., 2012, The water quality challenge: Using new technology to track tectonic salinity sources to surface and ground water: Geological Society of America Abstracts with Programs, v. 44, no. 6, p. 5.

Crow, R., Karlstrom, K.E., Asmerom, Y., Schmandt, B., Polyak, V., and DuFrane, S.A., 2011, Shrinking of the Colorado Plateau via lithospheric mantle erosion: Evidence from Nd and Sr isotopes and geochronology of Neogene basalts: Geology, v. 39, p. 27–30, https://doi.org/10.1130/G31611.1

Crow, R., Schwing, J., Karlstrom, K.E., Heizler, M., Pearthree, P., House, P.K., Dulin, S., Janeke, S.U., Stelten, M., and Crossey, L.J., 2021, Refining the age of the Colorado River: Geology, v. 49., https://doi.org/10.1130/G48080.1

Crumpler, L.S., 2020, The land of a thousand volcanoes: El Palacio, v. 125, p. 24–39.

Daniel, C.G., and Pyle, J.M., 2006, Monazite-xenotime thermochronometry and Al_2SiO_5 reaction textures in the Picuris Range, northern New Mexico, USA: New evidence for a 1450–1400 Ma orogenic event: Journal of Petrology, v. 47, p. 97–118, https://doi.org/10.1093/petrology/egi069

Daniel, C.G., Pfeifer, L.S., Jones, J.V., III, and McFarlane, C.M., 2013, Detrital zircon evidence for non-Laurentian provenance, Mesoproterozoic (ca. 1490–1450 Ma) deposition and orogenesis in a reconstructed orogenic belt, northern New Mexico, USA: Defining the Picuris orogeny: Geological Society of America Bulletin, v. 125, no. 9–10, p. 1423–1441, https://doi.org/10.1130/B30804.1

Davis, G.H., and Bump, A.P., 2009, Structural geologic evolution of the Colorado Plateau in the backbone of the Americas' shallow subduction, plateau uplift, and ridge and terrane collision, *in* Kay, S.M., Ramos, V.A., and Dickinson, W.R., eds., Geological Society of America Memoir, v. 204, p. 99–124, https://doi.org/10.1130/2009.1204(05)

Dickinson, W.R., 1989, Tectonic setting of Arizona through geologic time, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic Evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 1–16.

Doe, M.F., Jones, J.V., III, Karlstrom, K.E., Thrane, K., Frei, D., Gehrels, G., and Pecha, M., 2012, Basin formation near the end of the 1.6-1.45 Ga tectonic gap in southern Laurentia: Mesoproterozoic Hess Canyon Group of Arizona an implications for 1.5 Ga supercontinent configurations: Lithosphere, v. 4, no. 1, p. 77–88, https://doi.org/10.1130/L160.1

Doe, M.F., Jones, J.V. III, Karlstrom, K.E., Dixon, B., Gehrels, G., and Pecha, M., 2013, Using detrital zircon ages and Hf isotopes to identify 1.48-1.45 Ga sedimentary basins and fingerprint sources of exotic 1.6-1.5 Ga grains in southwestern Laurentia: Precambrian Research, v. 231, p. 409–421, https://doi.org/10.1016/j.precamres.2013.03.002

Dunbar, N.W., 2005, Quaternary volcanism in New Mexico: New Mexico Museum of Natural History and Science Bulletin 28, p. 95–106.

Dutton, C.E., 1882, Tertiary History of the Grand Canon District; with atlas: Department of the Interior, Monographs of the United States Geological Survey, Volume II: 263 p.,

Eaton, G.P., 2008, Epeirogeny in the southern Rocky Mountains region: Evidence and origin: Geosphere, v. 4, p. 764–784, https://doi.org/10.1130/GES00149.1

Elrick, M., and Scott, L.A., 2010, Carbon and oxygen isotope evidence for high-frequency (104-105 yr) and My-scale glacio-eustasy in Middle Pennsylvanian cyclic carbonates (Gray Mesa Formation), central New Mexico: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 285, p. 307–320, https://doi.org/10.1016/j.palaeo.2009.11.023

Fawcett, P. J., et al., 2011, Extended megadroughts in the southwestern United States during Pleistocene interglacials, Nature, v. 470, p. 518–521, https://doi.org/10.1038/nature09839

Fenneman, N.M., 1930, Physiographic Provinces of the United States: Washington, D.C., U.S. Geological Survey.

Formento-Trigilio, M.L., and Pazzaglia, F.J., 1996, Quaternary stratigraphy, tectonic geomorphology, and long-term landscape evolution of the southern Sierra Nacimiento, *in* Goff, F., Kues, B.S., Rogers, M.A., McFadden, L.D., and Gardner, J.N., eds., Jemez Mountains Region: New Mexico Geological Society Guidebook 47, p. 335–345, https://doi.org/10.56577/FFC-47.335

Frankel, K.L., and Pazzaglia, F.J., 2006, Mountain fronts, base-level fall, and landscape evolution: Insights from the southern Rocky Mountains: Geological Society of America Special Paper 398, p. 419–434.

Galloway, W.E., 2005, Gulf of Mexico Basin depositional record of Cenozoic North American drainage basin evolution, *in* Blum, M.D., Marriott, S.B., and LeClair, S.F., eds, Fluvial Sedimentology VIII: Malden, MA, International Association of Sedimentologists Special Publication 5, p. 409–423, https://doi.org/10.1002/9781444304350.ch22

Galloway, W.E., Ganey-Curry, P.E., Li, X., and Buffler, R.T., 2000, Cenozoic depositional history of the Gulf of Mexico basin: American Association of Petroleum Geologists Bulletin, v. 84, no. 11, p. 1743–1774, https://doi.org/10.1306/8626C37F-173B-11D7-8645000102C1865D

Galloway, W.E., Whiteaker, T.L., and Ganey-Curry, P., 2011, History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico basin: Geosphere, v. 7, no. 4, p. 938–873, https://doi.org/10.1130/GES00647.1

Gilbert, G.K., 1877, Geology of the Henry Mountains: U.S. Geological Survey Monograph, 160 p., https://doi.org/10.3133/70038096

Goff, F., 2009, Valles Caldera: A Geologic History: Albuquerque, University of New Mexico Press, 128 p.

Grambling, T.A., Karlstrom, K.E., Holland, M.E., and Grambling, N.L., 2016, Proterozoic magmatism and regional contact metamorphism in the Sandia-Manzano Mountains, New Mexico, USA, *in* Frey, B.A., Karlstrom, K.E., Lucas, S.G., Williams, S., Zeigler, K., McLemore, V., and Ulmer-Scholle, D.S., eds., The Geology of the Belen Area: New Mexico Geological Society Guidebook 67, p. 169–176, https://doi.org/10.56577/FFC-.169

Hansen, S.M., Dueker, K.G., Stachnik, J.C., Aster, R.C., and Karlstrom, K.E., 2013, A rootless Rockies—Support and lithospheric structure of the Colorado Rocky Mountains inferred from CREST and TA seismic data: Geochemistry, Geophysics, and Geosystems, v. 14, p. 2670–2695, https://doi.org/10.1002/ggge.20143

Heitmann, E.O., Hyland, E.G., Schoettle-Greene, P., Brigham, C.A.P., and Huntington, K.W., 2021, Rise of the Colorado Plateau: A synthesis of paleoelevation constraints from the region and a path forward using temperature based elevation proxies: Frontiers in Earth Science, v. 9, https://doi.org/10.3389/feart.2021.648605

Heizler, M.T., Karlstrom, K.E., Albonico, M., Hereford, R., Beard, L.S., Cather, S.M., Crossey, L.J., and Sundell, K.E., 2021, Detrital sanidine ^{40}Ar/^{39}Ar dating confirms <2 Ma age of Crooked Ridge paleoriver and subsequent deep denudation of the southwestern Colorado Plateau: Geosphere, v. 17, https://doi.org/10.1130/GES02319.1

Hillenbrand, I., Williams, M.L., Karlstrom, K.E., Gilmer, A.K., Lowers, H.A., Jercinovic, M.J., Suarez, K.A., and Souders, A.K., 2023a, Monazite and xenotime petrochronologic constraints on four Proterozoic tectonic episodes and ca. 1705 Ma age of the Uncompahgre Formation, southwestern Colorado: Geosphere, v. 19, no. 4, p.1057–1079 https://doi.org/10.1130/GES02631.1

Hillenbrand, I.W., Karlstrom, K.E., Williams, M.L., Gilmer, A., Premo, W., and Davis, P., 2023b, Geochemical evidence for evolving Proterozoic crustal thickness and orogenic styles in southwestern Laurentia: Earth and Planetary Science Letter, v. 622, https://doi.org/10.1016/j.epsl.2023.118417

Hillenbrand, I.W., Gilmer, A.K., Williams, M.L., Karlstrom, K.E., Souders, A.K., Jercinovic, M.J., Vazquez, J., and Premo, W.R., 2024, Heterogeneous multi-stage accretionary orogenesis of the Yavapai Province, southwest USA—Evidence from the Gunnison block: Precambrian Research, v. 401, https://doi.org/10.1016/j.precamres.2023.107256

Holland, M.E., Mohr, M., Schmitz, M., Madronich, L., and Karlstrom, K., 2023, Source-to-sink tandem geochronology reveals tectonic influences on the Cambrian Transcontinental Arch of Laurentia: Terra Nova, v. 36, no. 2, p. 161–169, https://doi.org/10.1111/ter.12692

Humphreys, G., 1995, Post-Laramide removal of the Farallon slab, western United States: Geology, v. 23, p. 987–990, https://doi.org/10.1130/0091-7613(1995)023<0987:PLROTF>2.3.CO;2

Humphreys, E., Hessler, E., Dueker, K., Farmer, G.L., Erslev, E., and Atwater, T., 2003, How Laramide-age hydration of the North American Lithosphere by the Farallon slab controlled subsequent activity in the western United States: International Geological Reviews, v. 45, p. 575–595, https://doi.org/10.2747/0020-6814.45.7.575

Jean, A., Crossey, L.J., Karlstrom, K.E., Polyak, V., and Asmerom, Y, 2024, Uranium-series geochronology of travertine from Soda Dam, New Mexico: A Quaternary record of episodic spring discharge and river incision in the Jemez Mountains, *in* Karlstrom, K.E., Koning, D.J., Lucas, S.G., Iverson, N.A., Crumpler, L.S., Aubele, J.C., Blake, J.M., Goff, F., and Kelley, S.A., eds., Geology of the Nacimiento Mountains and Rio Puerco Valley: New Mexico Geological Society Guidebook 74 (this volume), p. 257–270.

Karlstrom, K.E., and Daniel, C.G., 1993, Restoration of Laramide right lateral strike slip in northern New Mexico using Proterozoic piercing points: Tectonic implications from the Proterozoic to the Cenozoic: Geology, v. 21, no. 12, p. 1139–1142, https://doi.org/10.1130/0091-7613(1993)021<1139:ROLRLS>2.3.CO;2

Karlstrom, K.E., Amato, J.M., Williams, M.L., Heizler, M., Shaw, C.A., Read, A.S., and Bauer, P., 2004, Proterozoic tectonic evolution of the New Mexico region, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society Special Publication 11, p. 1–34.

Karlstrom, K.E., Williams, M.L., Heizler, M.T., Holland, M.E., Grambling, T.A., and Amato, J.M., 2016, U-Pb Monazite and ^{40}Ar/^{39}Ar data supporting polyphase tectonism in the Manzano Mountains: A record of both the Mazatzal (1.66-1.60 Ga) and Picuris (1.45 Ga) Orogenies, *in* Frey, B.A., Karlstrom, K.E., Lucas, S.G., Williams, S., Zeigler, K., McLemore, V., and Ulmer-Scholle, D.S., eds., The Geology of the Belen Area: New Mexico Geological Society Guidebook 67, p. 177–184.

Karlstrom, K.E., Crow, R., Crossey, L.J., Coblentz, D., and van Wijk, J., 2008, Model for tectonically driven incision of the less than 6 Ma Grand Canyon: Geology, v. 36, p. 835–838, https://doi.org/10.1130/G25032A.1

Karlstrom, K.E., et al., 2011, Mantle-driven dynamic uplift of the Rocky Mountains and Colorado Plateau and its surface response: Toward a unified hypothesis: Lithosphere, v. 4, no. 1, p. 3–22, https://doi.org/10.1130/L150.1

Karlstrom, K.E., Wilgus, J., Thacker, J.O., Schmandt, B., Coblentz, D., and Albonico, M., 2022, Tectonics of the Colorado Plateau and its margins: Annual Reviews of Earth and Planetary Sciences, v. 50, p. 295–322, https://doi.org/10.1146/annurev-earth-032320-111432

Kelley, S.A., Chapin, C.E., and Corrigan, J., 1992, Late Mesozoic to Cenozoic cooling histories of the flanks of the northern and central Rio Grande rift, Colorado and New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 145, 39 p., https://geoinfo.nmt.edu/publications/monographs/bulletins/145/

Kelley, S.A., Kempter, K. A., Goff, F., Rampey, M., Osburn, B., and Ferguson, C. A., 2003, Preliminary geologic map of the Jemez Springs 7.5-minute quadrangle: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map 73, scale 1:24,000, https://doi.org/10.58799/OF-GM-73

Kelley, S.A., et al., 2013, Geologic map of the Los Alamos 30 x 60-minute quadrangle study area, Los Alamos, Santa Fe, and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Digital Geologic Map 298, scale 1:24,000, https://doi.org/10.58799/OF-GM-298

Kelley, S.A., Koning, D., Jochems, A., Mansell, M, and Zimmerer, M., 2017, Hillslope sediment volumes and geologic mapping, Santa Clara Canyon, northeastern Jemez Mountains, New Mexico: unpublished report and 1:10,000 scale geologic map submitted to the Army Corp of Engineers, 9 p.

Kelley, V.C., 1955, Regional Tectonics of the Colorado Plateau and Relationship to the Origin and Distribution of Uranium: University of New Mexico Publication in Geology, no. 5, 120 p.

Kelley, V.C., 1977, Geology of the Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 33, 59 p., https://doi.org/10.58799/M-33

Kelley, V.C., 1982, The right-relayed Rio Grande rift, Taos to Hatch, New Mexico, *in* Grambling, J.A., and Wells, S.G., eds., Albuquerque Country II: New Mexico Geological Society Guidebook 33, p. 147–151, https://doi.org/10.56577/FFC-33.147

Kirkland, D.W., Denison, R.E., and Evans, R., 1995, Middle Jurassic Todilto Formation of northern New Mexico and southwestern Colorado: Marine or nonmarine?: New Mexico Bureau of Mines and Mineral Resources Bulletin 147, 37 p., https://doi.org/10.58799/B-147

Kluth, C.F., and Coney, P.J., 1981, Plate tectonics of the Ancestral Rocky Mountains: Geology, v. 9, p. 10–15, https://digitalcommons.usf.edu/kip_articles/4327

Kocurek, G., and Dott, R.H., Jr., 1983, Jurassic paleogeography and paleoclimate of the central and southern Rocky Mountains region, *in* Reynolds, M.W., and Dolly, E.D., eds., Mesozoic Paleogeography of the West-Central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Rocky Mountain Paleogeography Symposium 2, p. 101–116.

Koning, D.J., 2024, Comparison of the sedimentologic and stratigraphic characteristics of the Point Lookout vs. Gallup sandstones near Cabezon, New Mexico, *in* Karlstrom, K.E., Koning, D.J., Lucas, S.G., Iverson, N.A., Crumpler, L.S., Aubele, J.C., Blake, J.M., Goff, F., and Kelley, S.A., eds., Geology of the Nacimiento Mountains and Rio Puerco Valley: New Mexico Geological Society Guidebook 74 (this volume), p. 201–217.

Koning, D.J., and Personius, S.F., 2002, Geologic map of the Bernalillo NW quadrangle, Sandoval County, New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map 2404, scale 1:24,000, https://doi.org/10.58799/OF-GM-41

Koning, D.J., Heizler, M., and Jochems, A., 2021, Clues from the Santa Fe Group for Oligocene-Miocene paleogeography of the southeastern Colorado Plateau near Grants, NM, *in* Frey, B., Kelley, S.A., Zeigler, K.E., McLemore, V.T., Goff, F., and Ulmer-Scholle, D.S., eds., Geology of the Mount Taylor Area: New Mexico Geological Society Guidebook 71, p. 267–280, https://doi.org/10.56577/FFC-71.267

Krainer, K., and Lucas, S.G., 2024, New observations and tectonic inferences on Mississippian-Lower Pennsylvanian strata in the Sierra Nacimiento-San Pedro Mountains-Jemez Mountains, north-central New Mexico, *in* Karlstrom, K.E., Koning, D.J., Lucas, S.G., Iverson, N.A., Crumpler, L.S., Aubele, J.C., Blake, J.M., Goff, F., and Kelley, S.A., eds., Geology of the Nacimiento Mountains and Rio Puerco Valley: New Mexico Geological Society Guidebook 74 (this volume), p. 157–170.

Kreemer, C., Blewitt, G., and Klein, E.C., 2014, A geodetic plate motion and global strain rate model: Geochemistry, Geophysics, and Geosystems, v. 15, p. 3849–3889, https://doi.org/10.1002/2014GC005407

Landman, R.L., and Flowers, R.M., 2012, (U-Th)/He thermochronologic constraints on the evolution of the northern Rio Grande rift, Gore Range, Colorado, and implications for rift propagation models: Geosphere, v. 9, p. 170–187, https://doi.org/10.1130/GES00826.1

Lawton, T.F., 1994, Tectonic setting of Mesozoic sedimentary basins, Rocky Mountain region, United States, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., eds., Mesozoic systems of the Rocky Mountain region, USA: Denver, Rocky Mountain Section of the Society of Economic Paleontologists and Mineralogists, p. 1–25.

Leary, R.J., Umhoefer, P., Smith, M.E., and Riggs, N., 2017, A three-sided orogen: A new tectonic model for Ancestral Rocky Mountain uplift and basin development: Geology, v. 45, p. 735–738, https://doi.org/10.1130/G39041.1

Lekić, V., and Fischer, K.M., 2014, Contrasting lithospheric signatures across the western United States revealed by Sp receiver functions: Earth and Planetary Science Letters, v. 402, p. 90–98, https://doi.org/10.1016/j.epsl.2013.11.026

Leopold, E.B., and Zaborac-Reed, S., 2019, Pollen evidence of floristic turnover forced by cool aridity during the Oligocene in Colorado: Geosphere, v. 15, no. 1, p. 254–294, https://doi.org/10 .1130/GES01689.1

Levander, A., Schmandt, B., Miller, M.S., Liu, K., Karlstrom, K.E., Crow, R.S., Lee, C.-T.A., and Humphreys, E.D., 2011, Continuing Colorado Plateau uplift by delamination-style convective lithospheric downwelling, Nature, v. 472, p. 461–65, https://doi.org/10.1038/nature10001

Lipman, P.W., 2021, Raising the West: Mid-Cenozoic Colorado-plano related to subvolcanic batholith assembly in the Southern Rocky Mountains (USA)?: Geology, v. 49, https://doi.org/10.1130/G48963.1

Liu, L., Gurnis, M., Seton, M., Saleeby, J., Müller, R.D., and Jackson, J.M., 2010, The role of oceanic plateau subduction in the Laramide orogeny: Nature Geoscience, v. p. 353–357, https://doi.org/10.1038/ngeo829

Livaccari, R.F., and Perry, F.V., 1993, Isotopic evidence for preservation of Cordilleran lithospheric mantle during the Sevier-Laramide orogeny, western United States: Geology, v. 21, p. 719–722, https://doi.org/10.1130/0091-7613(1993)021<0719:IEFPOC>2.3.CO;2

Lucas, S.G., 1993, The Chinle Group: revised stratigraphy and chronology of Upper Triassic nonmarine strata in the western United States: Museum of Northern Arizona Bulletin 59, p. 27–50.

Lucas, S.G., 1997, Upper Triassic Chinle Group, western United States: A nonmarine standard for Late Triassic time, *in* Dickins, J.M., Yang, Z., Yin, H., Lucas, S.G. and Acharyya, S.K., eds., Late Palaeozoic and Early Mesozoic Circum-Pacific Events and Their Global Correlation: Cambridge, Cambridge University Press, p. 209–228, https://doi.org/10.1017/CBO9780511564413.024

Lucas, S.G., 2018, Late Triassic terrestrial tetrapods: Biostratigraphy, biochronology and biotic events, *in* Tanner, L.H., ed., The Late Triassic World: Topics in Geobiology 46, p. 351–405, https://doi.org/10.1007/978-3-319-68009-5_10

Lucas, S.G., 2021, Jurassic stratigraphy of the southeastern Colorado Plateau, west-central New Mexico: 2020 synthesis, *in* Koning, D.J., Hobbs, K.M., Phillips, F.M., Nelson, J., and Cather, S.M, eds., Socorro Region III: New Mexico Geological Society Guidebook 72, p. 241–250.

Lucas, S. G. and Krainer, K., 2024, Upper Paleozoic stratigraphy around the Sierra Nacimiento, San Pedro Mountains and Jemez Mountains, northern New Mexico, *in* Karlstrom, K.E., Koning, D.J., Lucas, S.G., Iverson, N.A., Crumpler, L.S., Aubele, J.C., Blake, J.M., Goff, F., and Kelley, S.A., eds., Geology of the Nacimiento Mountains and Rio Puerco Valley: New Mexico Geological Society Guidebook 74 (this volume), p. 141–156.

Lucas, S.G., Kietzke, K.K., and Hunt, A.P., 1985, The Jurassic System in east-central New Mexico, *in* Lucas, S.G., and Zidek, J., eds., Santa Rosa-Tucumcari Region: New Mexico Geological Society Guidebook 36, p. 213–243, https://doi.org/10.56577/FFC-36.213

Lucas, S.G., Heckert, A.B., Estep, J.W., and Anderson, O.J., 1997, Stratigraphy of the Upper Triassic Chinle Group, Four Corners region, *in* Anderson, O.J., Kues, B.S., and Lucas, S.G., eds., Mesozoic Geology and Paleontology of the Four Corners Region: New Mexico Geological Society Guidebook 48, p. 81–108, https://doi.org/10.56577/FFC-48.81

Lucas S.G., Harris, S.K., Spielmann, J.A., Berman, D.S., Henrici, A.C., Krainer, K., Rinehart, L.F., DiMichele, W.A., Chaney, D.S., and Kerp, H., 2012, Lithostratigraphy, paleontology, biostratigraphy, and age of the upper Paleozoic Abo Formation near Jemez Springs, northern New Mexico, USA: Annals of Carnegie Museum, v. 80, p. 323–350, https://doi.org/10.2992/007.080.0403

Lucas, S.G., Barrick, J.E., Krainer, K., and Schneider, J.W., 2013, The Carboniferous-Permian boundary at Carrizo Arroyo, central New Mexico, USA: Stratigraphy, v. 10, p. 153–170, https://doi.org/10.29041/strat.10.3.02

Lucas, S.G., Krainer, K., Allen, B.D., Barrick, J.E., and Vachard, D., 2021, The Carboniferous System in the Manzano Mountains, New Mexico: New Mexico Museum of Natural History and Science Bulletin 84, p. 17–87.

Mack, G.H., 1987, Mid-Cretaceous (late Albian) change from rift to retroarc foreland basin in southwestern New Mexico: Geological Society of America Bulletin, v. 98, p. 507–514, https://doi.org/10.1130/0016-7606(1987)98<507:MLACFR>2.0.CO;2

Magnani, M.B., Miller, K.M., Levander, A., and Karlstrom, K.E., 2004, The Yavapai-Mazatzal boundary: A long-lived tectonic element in the lithosphere of southwestern North America: Geological Society of America Bulletin, v. 116, p. 1137–1142.

Magnani, M.B., Levander, A., Miller, K.M., Eshete, T., Karlstrom, K.E., 2005, Seismic investigations target the Yavapai-Mazatzal transition zone and the Jemez lineament, *in* Karlstrom, K.E., and Keller, G.R., eds., The Rocky Mountain Region—An Evolving Lithosphere: Tectonics, Geochemistry, and Geophysics: American Geophysical Union Geophysical Monograph 154, p. 227–238, https://doi.org/10.1029/154GM16

Marchetti, L., et al., 2022, The Artinskian warming event: An Euramerican change in climate and the terrestrial biota during the early Permian: Earth-Science Reviews, v. 226, 103922, https://doi.org/10.1016/j.earscirev.2022.103922

Marshak, S., Karlstrom K., Timmons, J.M., 2000, Inversion of Proterozoic extensional faults: An explanation for the pattern of Laramide and Ancestral Rockies intracratonic deformation, United States: v. 28, no. 8, p. 735–738, https://doi.org/10.1130/0091-7613(2000)028<0735:IOPEFA>2.3.CO;2

McGibbon, C., Crossey, L.C., Karlstrom, K.E. and Grulke, T., 2018, Carbonic springs as distal manifestations of geothermal systems, highlighting the importance of fault pathways and hydrochemical mixing: Example from the Jemez Mountains, New Mexico: Applied Geochemistry, v. 98, p. 45–57, https://doi.org/10.1016/j.apgeochem.2018.08.015

McLemore, V.T., Owen, E.J., and Newcomer, J., Critical minerals in sediment-hosted stratabound copper deposits in the Nacimiento and Zuni Mountains, northwestern New Mexico: Preliminary Results, *in* Karlstrom, K.E., Koning, D.J., Lucas, S.G., Iverson, N.A., Crumpler, L.S., Aubele, J.C., Blake, J.M., Goff, F., and Kelley, S.A., eds., Geology of the Nacimiento Mountains and Rio Puerco Valley: New Mexico Geological Society Guidebook 74 (this volume), p. 307–317.

McQuarrie, N., and Chase, C., 2000, Raising the Colorado Plateau: Geology, v. 28, p. 91–94.

Miller, J.P., Montgomery, A., and Sutherland, P.K., 1963, Geology of part of the Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 11, 106 p.

Molenaar, C.M., 1983, Major depositional cycles and regional correlations of Upper Cretaceous rocks, southern Colorado Plateau and adjacent areas, *in* Reynolds, M.W., and Dolly, E.D., eds., Mesozoic paleogeography of west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, Rocky Mountain Paleogeography Symposium 2, p. 201–224.

Murray M.H., and Sheehan A.F., 2019, Active deformation near the Rio Grande Rift and Colorado Plateau as inferred from continuous Global Positioning System measurements: Journal of Geophysical Research, Solid Earth, v. 124, p. 2166–2183, https://doi.org/10.1029/2018JB016626

Mutschler, F.E., Larson, E.E., and Bruce, R.M., 1987, Laramide and younger magmatism in Colorado—New petrologic and tectonic variations on old themes: Colorado School of Mines Quarterly, v. 82, no. 4, p. 1–47.

Myrow, P.M., Taylor, J.F., Miller, J.F., Ethington, R.L., Ripperdan, R.L., and Allen, J., 2003, Fallen arches: Dispelling myths concerning Cambrian and Ordovician paleogeography of the Rocky Mountain region: Geological Society of America Bulletin, v. 115, p. 695–713, https://doi.org/10.1130/0016-7606(2003)115<0695:FADMCC>2.0.CO;2

Nasholds, M.W.M., and Zimmerer, M.J., 2022, High-precision ^{40}Ar/^{39}Ar geochronology and volumetric investigation of volcanism and resurgence following eruption of the Tshirege Member, Bandelier Tuff, at the Valles Caldera: Journal of Volcanology and Geothermal Research, v. 431, 107624, https://doi.org/10.1016/j.jvolgeores.2022.107624

Nyman, M.W., Karlstrom, K.E., Kirby, E., and Graubard, C., 1994, 1.4 Contractional orogeny in western North America: Evidence from ca. 1.4 Ga plutons: Geology, v. 22, p. 901–904, https://doi.org/10.1130/0091-7613(1994)022<0901:MCOIWN>2.3.CO;2

Perkins, G.B., Sharp, Z.D., and Selverstone, J., 2006, Oxygen isotope evidence for subduction and rift-related mantle metasomatism beneath the Colorado Plateau–Rio Grande rift transition: Contributions to Mineralogy and Petrology, v. 151, p. 633–650.

Pollock, C.J., Stewart, K.G., Hibbard, J.P., Wallace, L., and Giral, R.A., 2004, Thrust wedge tectonics and strike-slip faulting in the Sierra Nacimiento, New Mexico: New Mexico Bureau of Geology and Mineral Resources Bulletin 160, p. 97–111.

Porreca, C., Selverstone, J., and Samuels, K., 2006, Pyroxenite xenoliths from the Rio Puerco volcanic field, New Mexico: Melt metasomatism at the margin of the Rio Grande rift: Geosphere, v. 2, p. 333–351.

Porter, R., and Reid, M., 2021, Mapping the thermal lithosphere and melting across the continental US: Geophysical Research Letters, v. 48, e2020GL092197, https://doi.org/10.1029/2020GL092197

Powell, J.W., 1875, Exploration of the Colorado River of the West and its Tributaries: Washington, D.C., U.S. Government Printing Office, 291 p., https://doi.org/10.3133/70039910

Ramos, V.A., 2009, Anatomy and global context of the Andes: Main geologic features and the Andean orogenic cycle, *in* Kay, S.M., Ramos, V.A., and Dickinson, W.R., eds., Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision: Geological Society of America Memoir 204, p. 31–65, https://doi.org/10.1130/2009.1204(02)

Raynolds, R.G., Johnson, K.R., Ellis, B., Dechesne, M., and Miller, I.M., 2007, Earth history along Colorado's Front Range: Salvaging geologic data in the suburbs and sharing it with the citizens: GSA Today, v. 17, no. 12, https://doi.org/10.1130/GSAT01712A.1

Reed, C.C., Karlstrom K.E., Rodriguez, B., Iverson, N.A., Heizler, M.T., Rose-Coss, D., Crossey, L.C., Cox, C., Jean, A., Polyak, V., and Asmerom, Y., 2024, Differential river incision due to Quaternary faulting on the Rio Salado-Jemez system at the million-year timescale, *in* Karlstrom, K.E., Koning, D.J., Lucas, S.G., Iverson, N.A., Crumpler, L.S., Aubele, J.C., Blake, J.M., Goff, F., and Kelley, S.A., eds., Geology of the Nacimiento Mountains and Rio Puerco Valley: New Mexico Geological Society Guidebook 74 (this volume), p. 237–256.

Reid, M.R., Bouchet, R.A., Blichert-Toft, J., Levander, A., Liu, K., Miller, M., and Ramos, F., 2012, Melting under the Colorado Plateau, USA: Geology, v. 40, p. 387–390, https://doi-org.libproxy.unm.edu/10.1130/G32619.1

Repasch, M., Karlstrom, K.E., and Heizler, M., 2017, Birth and evolution of the Rio Grande fluvial system in the last 8 Ma: Progressive downward integration and interplay between tectonics, volcanism, climate, and river evolution: Earth-Science Reviews, v. 168, p. 113–164, https://doi.org/10.1016/j.earscirev.2017.03.003

Ricketts, J., Karlstrom, K.E., Crossey, L.J., and Prievisch, A., 2014, Persistent Quaternary extension in the Rio Grande rift at elevated strain rates: Interaction between magmatism, fluid-enhanced paleoseismicity, and travertine deposition documented in central New Mexico: Lithosphere, v. 6, p. 3–16, https://doi.org/10.1130/L278.1

Ricketts, J.W., Kelley, S.A., Karlstrom, K.E., Schmandt, B., Donahue, M.S., and van Wijk, J., 2016, Synchronous opening of the Rio Grande rift ~20-10 Ma supported by apatite (U-Th)/He and fission-track thermochronology, and evaluation of possible driving mechanisms: Geological Society of America Bulletin, v. 128, p. 397–424, https://doi.org/10.1130/B31223.1

Roy, M., Jordan, T.J., and Pederson J., 2009, Colorado Plateau magmatism and uplift by warming of heterogeneous lithosphere: Nature, v. 459, p. 978–982, https://doi.org/10.1038/nature08052

Schmandt, B., and Lin, F., 2014, P and S wave tomography of the mantle beneath the United States: Geophysical Research Letters, v. 41, p. 6342–6349, https://doi.org/10.1002/2014GL061231

Schmandt, B., Dueker, K., Humphreys, E., Hansen, S., 2012, Hot mantle upwelling across the 660 beneath Yellowstone: Earth and Planetary Science Letters, v. 331, p. 224–236.

Schmandt, B., Jiang, C., and Farrell, J., 2019, Seismic perspectives from the western U.S. on magma reservoirs underlying large silicic calderas: Journal of Volcanology and Geothermal Research, v. 384, p. 158–178.

Sealey, P.L., and Lucas, S.G., 2019, Late Cretaceous (Cenomanian-Campanian) ammonite systematic paleontology and biostratigraphy, southeastern San Juan Basin, Sandoval County, New Mexico: New Mexico Museum of Natural History and Science Bulletin 80, 245 p.

Shaw, C.A., and Karlstrom, K.E., 1999, The Yavapai-Mazatzal crustal boundary in the southern Rocky Mountains: Rocky Mountain Geology, v. 34, no.1, p. 37–52.

Shaw, C.A., Karlstrom, K.E., and Heizler, M.T., 2005, Mid-crustal temperatures during ca. 1.4 Ga metamorphism in the southwestern United States: A regional synthesis of ^{40}Ar/^{39}Ar data, *in* Karlstrom, K.E., and Keller, G.R., eds., The Rocky Mountain Region—An Evolving Lithosphere: Tectonics, Geochemistry, and Geophysics: American Geophysical Union Geophysical Monograph 154, p. 163–184.

Smith, L.N., 1992, Stratigraphy, sediment dispersal and paleogeography of the lower Eocene San Jose Formation, San Juan Basin, New Mexico and Colorado, *in* Lucas, S.G., Kues, B.S., Williamson, T.E., and Hunt, A.P., eds., San Juan Basin IV: New Mexico Geological Society Guidebook 43, p. 297–309, https://doi.org/10.56577/FFC-43.297

Smith, R.L., Bailey, R.A., and Ross, C.S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey IMAP 571, https://doi.org/10.3133/i571

Suppe, J., Powell, C., and Berry, R., 1975, Regional topography, seismicity, Quaternary volcanism, and the present-day tectonics of the western United States: American Journal of Science, v. 275-a, p. 397–436.

Tedford, R.H., and Barghoorn, S., 1999, Santa Fe Group (Neogene), Ceja del Rio Puerco, northwestern Albuquerque Basin, Sandoval County, New Mexico, *in* Pazzaglia, F.J., Lucas, S.G., and Austin, G.S., eds., Albuquerque Country: New Mexico Geological Society Guidebook 50, p. 327–335.

Thacker, J O., Kelley, S.A., and Karlstrom, K.E., 2021, Cretaceous–Recent low-temperature cooling history and tectonic analysis of the Zuni Mountains, west-central New Mexico: Tectonics, v. 40, e2020TC006643, https://doi.org/10.1029/2020TC006643

Thacker J.O., Karlstrom, K.E., Kelley, S.A., Crow, R.S., and Kendall, J.J., 2023, Late Cretaceous time-transgressive onset of Laramide arch exhumation and basin subsidence across northern Arizona–New Mexico, USA, and the role of a dehydrating Farallon flat slab: Geological Society of America Bulletin, v. 135, no. 1–2, p. 389–406, https://doi.org/10.1130/B36245.1

Timmons, M.J., Karlstrom, K.E., Dehler, C.M., Geissman, J.W., and Heizler, M.T., 2001, Proterozoic multistage (~1.1 and ~0.8 Ga) extension in the Grand Canyon Supergroup and establishment of northwest and north-south tectonic grains in the southwestern United States: Geological Society of America Bulletin, v. 113, no. 2, p. 163–180.

Timmons, J.M., Karlstrom, K.E., Heizler, M., Bowring, S.A., and Crossey, L.C., 2005, Tectonic inferences from the 1254-~1100 Ma Unkar Group and Nankoweap Formation, Grand Canyon: Intracratonic deformation and basin formation during protracted Grenville orogenesis: Geological Society of America Bulletin, v. 117, p. 1573–1595, https://doi.org/10.1130/B25538.1

U.S. Geological Survey, n.d., Quaternary fault and fold database of the United States, https://www.usgs.gov/natural-hazards/earthquake-hazards/faults, accessed February 2024.

vanWijk, J.W., Baldridge, W.S., van Hunen J., Goes, S., Aster, R., Coblentz, D.D., Grand, S.P., and Ni, J., 2010, Small-scale convection at the edge of the Colorado Plateau: Implications for topography, magmatism, and evolution of the Proterozoic lithosphere: Geology, v. 38, p. 611–614, https://doi.org/10.1130/G31031.1

vanWijk, J., Koning, D., Axen, G., Coblentz, D., Gragg, E., and Sion, B., 2018, Tectonic subsidence, geoid analysis, and the Miocene-Pliocene unconformity in the Rio Grande rift, southwestern United States: Implications for mantle upwelling as a driving force for rift opening: Geosphere, v. 14, p. 684–709.

Vlaha, D.R., Zuza, A.V., Lin, C., and Harlaux, M., 2024, Hot Cordilleran hinterland promoted lower crust mobility and decoupling of Laramide deformation: Nature Communications, v. 15, https://doi.org/10.1038/s41467-024-48182-8

Walk, C.J., Karlstrom, K.E., Crow, R.S., and Heizler, M.T., 2019, Birth and evolution of the Virgin River fluvial system: ~1 km of post–5 Ma uplift of the western Colorado Plateau: Geosphere, v. 15, p. 1–24, https://doi.org/10.1130/GES02019.1

Whitmeyer, S., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, v. 3, no. 4, p. 220–259, https://doi.org/10.1130/GES00055.1

Wilgus, J., Schmandt, B., Maguire, R., Jiang, C., and Chaput, J., 2023, Shear velocity evidence of upper crustal magma storage beneath Valles Caldera: Geophysical Research Letters, v. 50, no. 5, e2022GL101520, https://doi.org/10.1029/2022GL101520

Williamson, T.E., 1996, The beginning of the age of mammals in the San Juan Basin, New Mexico: Biostratigraphy and evolution of Paleocene mammals of the Nacimiento Formation: New Mexico Museum of Natural History and Science Bulletin 8, 141 p.

Woodward, L.A., 1987, Geology and mineral resources of Sierra Nacimiento and vicinity, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 42, 84 p.,

Woodward, L.A., 1996, Paleotectonics of the late Paleozoic Peñasco uplift, Nacimiento region, New Mexico, *in* Goff, F., Kues, B.S., Rogers, M.A., McFadden, L.D., and Gardner, J.N., eds., Jemez Mountains Region: New Mexico Geological Society Guidebook 47, p. 107–113.

Woodward, L.A., and Ruetschilling, R.L., 1976, Geology of San Ysidro quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources Geologic Map 37, scale 1:24,000, https://doi.org/10.58799/GM-37

Woodward, L.E. DuChene, H.R., and Martinez, R., 1977, Geology of Gilman quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources Geologic Map 45, scale 1:24,000, https://doi.org/10.58799/GM-45

Woodward, L.A., Anderson, O.J., and Lucas, S.G, 1997, Mesozoic stratigraphic constraints on Laramide right slip on the east side of the Colorado Plateau: Geology, v. 25, p. 843–846.

Woodward, L.A., Anderson, O.J., and Lucas, S.G., 1999, Late Paleozoic right-slip faults in the Ancestral Rocky Mountains, *in* Pazzaglia, F.J., Lucas, S.G., and Austin, G.S., eds., Albuquerque Country: New Mexico Geological Society Guidebook 50, p. 149–153, https://doi.org/10.56577/FFC-50.149

Ye, H., Royden, L., Burchfiel, C., and Schuepbach, M., 1996, Late Paleozoic deformation of interior North America: The greater Ancestral Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 80, p. 1397–1432.

Yi, J.J.Y., and Kapp, P., 2023, Basin record of a Miocene lithosphere drip beneath the Colorado Plateau: Nature Communications, v. 14, no. 1, https://doi.org/10.1038/s41467-023-40147-7

Zellman, K.L., Plink-Björklund, P., Spangler, L., 2023, Progradational to retrogradational styles of Palaeogene fluvial fan successions in the San Juan Basin, New Mexico: Basin Research, v. 36, https://doi.org/10.1111/bre.12823

Zimmerer, M.J., Lafferty, J., and Coble, 2016, The eruptive and magmatic history of the youngest pulse of volcanism at Valles Caldera: Implications for successful dating late Quaternary eruptions: Journal of Volcanology and Geothermal Research, v. 310, p. 50–57, https://doi.org/10.1016/j.jvolgeores.2015.11.021