San Diego Mountain: A "Rosetta Stone" for Interpreting the Cenozoic Tectonic Evolution of South-Central New Mexico

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Abstract

For more than 65 years, geologists working in southern New Mexico have recognized that the sedimentary and volcanic rocks, unconformities, and structures exposed at San Diego Mountain and in the Tonuco uplift of northern Doña Ana County are keys to interpreting the Cenozoic evolution of the region. When combined with interpretations of outcrops from neighboring mountain ranges, a nearly complete record of major Cenozoic tectonic events can be pieced together, ranging from Laramide deformation to the evolution of the Rio Grande rift.

Laramide contraction in south-central New Mexico produced the large Rio Grande uplift, which may rival some of the Wyoming Laramide uplifts in magnitude and style. Its northwest trend and northeast vergence are consistent with other Laramide uplifts that have been reconstructed across southern New Mexico. Its notable structural relief is confirmed by the thickness of 3.1 km of Paleozoic strata and an unknown amount of Proterozoic rocks that were eroded from its core. The sediments filled the complementary Love Ranch and Potrillo basins to a depth of 0.9–2.0 km, onlapped the uplift, and, in an imperfect way, recorded the erosional unroofing of the Rio Grande uplift. By middle Eocene time, Laramide uplifts were no longer active, were deeply eroded, and were at least partially buried in their own erosional debris.

Intermediate-composition arc volcanism commenced at approximately 46 Ma, and by 37 Ma lava flows and lahar deposits had buried the Laramide structures to depths of as much as 0.6 km. The eruption of 36–34 Ma ignimbrite calderas and the deposition of ignimbrite outflow sheets, often interpreted to herald the onset of extension in southern New Mexico, may also be interpreted to represent the culmination of arc volcanism in a non-extensional stress field—a conclusion reached by other researchers in the southern Cordillera and southern Rocky Mountain regions. The ignimbrite outflow sheets, together with interbedded tuffaceous and fluvial sediment of the Bell Top Formation (36.0–28.6 Ma), accumulated on piedmont slopes adjacent to the Emory caldera and in a broad, shallow paleovalley across south-central New Mexico. Previous interpretations of the Bell Top Formation linked its origin to deposition in an extensional half graben (Mack et al., 1994a) or a volcano-tectonic depression (Seager, 1973), interpretations sometimes cited as evidence for late Eocene onset of extension in the Rio Grande rift. The geometry, facies distribution, low sedimentation rates, and lack of coeval faulting within the Bell Top Formation do not support an extensional setting for the formation. Instead, the outflow tuffs and sediment in the formation are interpreted to have filled a broad, shallow paleovalley and accumulated on a piedmont-slope landscape, both of non-extensional origin.

Initiation of the San Andreas transform may have promoted earliest transtension across the western interior of North America, a hypothesis that is consistent with the onset of regional extension in the Rio Grande rift shortly after 30 Ma. Across south-central New Mexico, the outpouring of the Uvas Basaltic Andesite and Bear Springs Basalt (28 Ma), as well as a change to bimodal volcanism in the Mogollon–Datil volcanic field, mark significant extension. Together with other basaltic andesite units of southern New Mexico and northern Mexico, the basaltic lavas of these formations accumulated to form a broad plateau, fed largely by fissure eruptions. Local fissures, such as the ancestral Cedar Hills fault, probably had sufficient structural relief to produce small alluvial fans. By 27.4 Ma, accelerating extension is suggested by the initiation of a broad, deep basin in northern Doña Ana and southern Sierra counties. The basin was filled with the distal parts of an apron of ash-fall tuff and volcaniclastic sediment more than 0.5 km thick (Thurman Formation) derived from the Mt. Withington caldera located 60 km to the northwest.

The onset of major faulting within the Rio Grande rift, at approximately 26 Ma, is recorded by the thick (1.5 km) "early rift" alluvial-fan and playa (closed basin) deposits exposed at San Diego Mountain and adjacent to the southern Caballo Mountains. The stratigraphy of these deposits, as well as the structures that transect them, indicate that oldest fault blocks within the rift, such as parts of the Caballo uplift, continued to rise throughout the Neogene up to the present. Other fault blocks were initiated at different times—middle Miocene, late Miocene, and perhaps Pliocene. The younger episodes of faulting not only initiated new uplifts but also fragmented all or parts of the older "early rift" closed basins, creating fault blocks such as the Tonuco, Rincon Hills, and Robledo uplifts, among many others. Although folding of middle Paleogene and Neogene rocks is not uncommon in

the southern Rio Grande rift, all is extensional in origin, the product of draping or forced folding of strata across active normal faults. Extreme and perhaps very rapid local extension in the Tonuco uplift area is suggested by a rotated, uplifted, and abandoned low-angle normal fault on the Tonuco horst.

At around 5 Ma, the broken and deeply eroded landscape was buried by “late rift” alluvial fans and fluvial deposits (Camp Rice Formation) associated with the ancestral Rio Grande as it entered southern New Mexico. At 0.8 Ma, this aggradational regime gave way to a degradational one, at least along the Rio Grande corridor. As a result, older structures, such as the Tonuco uplift, were exhumed, the Rio Grande and its tributaries were entrenched into modern valleys, and several generations of terraces along valley sideslopes formed in response to waxing and waning glacial cycles. The “late rift” Plio-Pleistocene deposits remain relatively undeformed, although locally they have been warped and broken along range-boundary faults by Pleistocene fault movements. Locally, Holocene movement has been documented. Broad, epeirogenic uplift of the Rio Grande rift and its flanks (perhaps 800 m or more) has accompanied the evolution of the rift since the late Paleogene.

Introduction

“San Diego Mountain is the Rosetta Stone of south-central New Mexico.” This respectful title has been bestowed upon San Diego Mountain and the surrounding hills by geologists working there over the last 65 years or more. Key outcrops there have provided extraordinary clues about the character of mountain building in the region some 65–50 Ma during the Laramide orogeny, as well as keys to interpreting the tectonic evolution of the Rio Grande rift, which commenced around 24–23 Myr later and continues today. These outcrops provided a kind of hub around which new data from surrounding mountain ranges were gradually attached, eventually leading to an appreciation of not only Laramide and Rio Grande rift tectonic evolution but nearly all Cenozoic events. The focus of this paper is to summarize the most significant features exposed at San Diego Mountain and to show how they became central for understanding the Cenozoic evolution of south-central New Mexico. The discussion will not only confirm interpretations dating back 50 years or more but will also introduce newer ideas and data that have modified earlier views. But first, let us look more closely at San Diego Mountain.

Located in north-central Doña Ana County (Fig. 1), the mountain is actually an imposing, steep-sided bluff, the flat-topped summit (elevation 1,508 m) of which overlooks the Rio Grande floodplain some 305 m below (Fig. 2). Colorful badlands and mesas, rugged canyons, and vein-filled granitic hills surround the mountain on the southern, eastern, and northern sides—all the product of erosion of both a central horst and the surrounding lowland fault blocks.

Figure 3 illustrates the general structural features of the area and Figure 4 summarizes the exposed stratigraphy. The central structure is the Tonuco horst, also referred to as Tonuco uplift. Some 5 km long in a north–northwest direction and 1.2 km wide, the fault block is roughly spindle-shaped, a configuration resulting from the convergence of high-angle, normal boundary faults at both ends of the uplift. Precambrian (Proterozoic) granite and metamorphic rocks form the core of the uplift, although along its eastern side lower Paleozoic as well as Paleogene conglomerate and volcanic rocks overlie the granite unconformably. Significant structures on the horst are two klippen of sedimentary volcanic breccia beds of probable middle Cenozoic age. Judging from the easterly dip of 25° to 30° of lower Cenozoic volcanic rocks on its eastern flank, late Cenozoic uplift of the Tonuco horst was accompanied at some time in its evolution by modest eastward tilting.

Downfaulted strata along both sides of the horst are basin-fill deposits often referred to as “early rift” and “late rift” deposits. Assigned to the Hayner Ranch and Rincon Valley formations (Seager et al., 1971), “early rift” strata range in age from approximately 27–9 Ma, exceed 1.5 km in thickness, are broadly folded and modestly faulted, and were deposited in early, closed basins within the Rio Grande rift. In contrast, “late rift” strata are only 100 m thick, essentially undeformed (except near modern range-boundary faults), and record deposition of an ancestral Rio Grande that flowed through connected rift basins in Plio-Pleistocene time around 5–0.8 Ma. Assigned to the Camp Rice Formation in areas south of Hatch, New Mexico, the formation also includes piedmont-slope deposits adjacent to the ancestral Rio Grande as well as deposits of closed basins beyond Rio Grande drainage divides.

The efforts of several generations of geologists working in south-central New Mexico over the past seven decades or more have stitched together the current understanding of the tectonic evolution of the region. A complete listing would be long indeed, but several studies have proven seminal: Kelley and Silver (1952), Kottlowski (1953), Hawley and Kottlowski (1969), Hawley et al. (1969), Hawley (1970, 1975), Chapin and Seager (1975), Seager et al. (1984), Seager and Mack (1986), Mack et al. (1994c), Seager et al. (1997), Seager and Mack (2003), Mack (2004), and Hawley et al. (2022). Interpretations of outcrops at San Diego Mountain and the Tonuco uplift are based on the mapping of Seager et al. (1971), Seager (1975), and Seager et al. (2021). Other maps of the region the interested reader may find useful are Seager and Hawley (1973), Clemons and Seager (1973), Seager et al. (1975), Seager and Clemons (1975), and Seager et al. (1995).

In the following sections, we will examine Laramide and upper Cenozoic rocks and structures exposed at San Diego Mountain, followed by an effort to show how those features are keys to understanding the broader Cenozoic tectonic evolution of south-central New Mexico. Although middle Cenozoic rocks are largely absent at San Diego Mountain, or at least not exposed, new and older interpretations of these rocks from nearby ranges will be summarized in order to complete the Cenozoic story. Our aim will be to condense the often lengthy published descriptions of various rock units, hoping that the interested reader will use the references cited for additional detail.

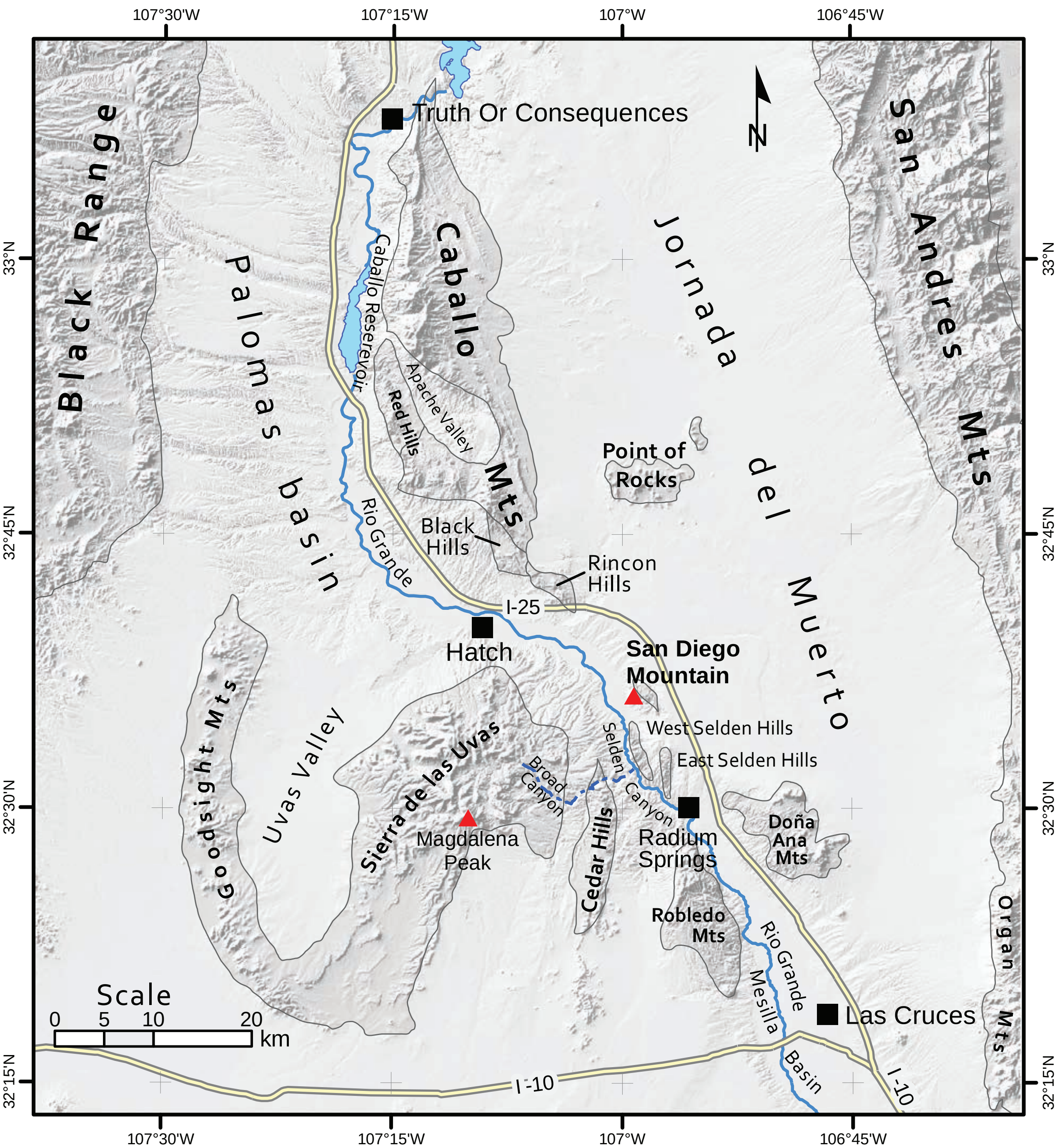


Figure 1. Location map.

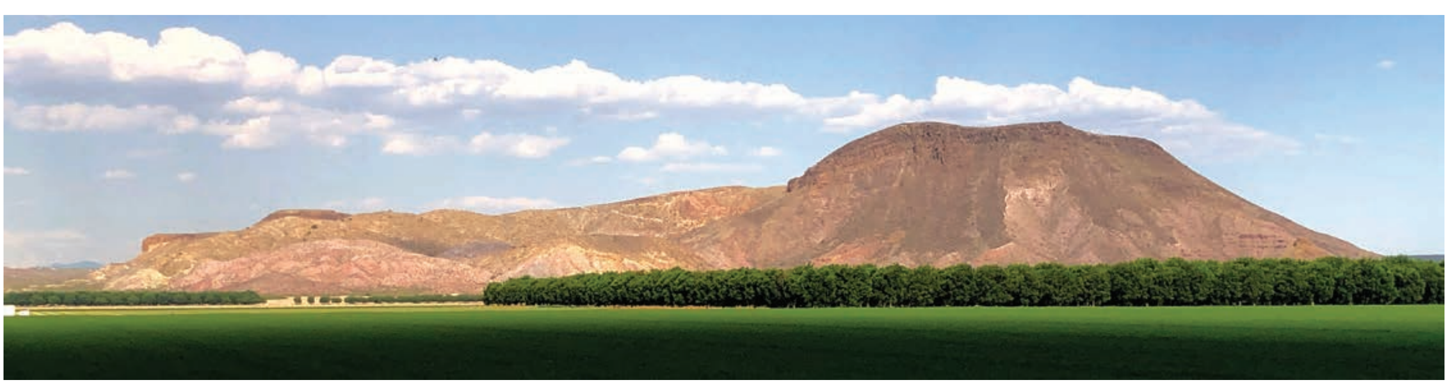


Figure 2. San Diego Mountain. View looks southeast.

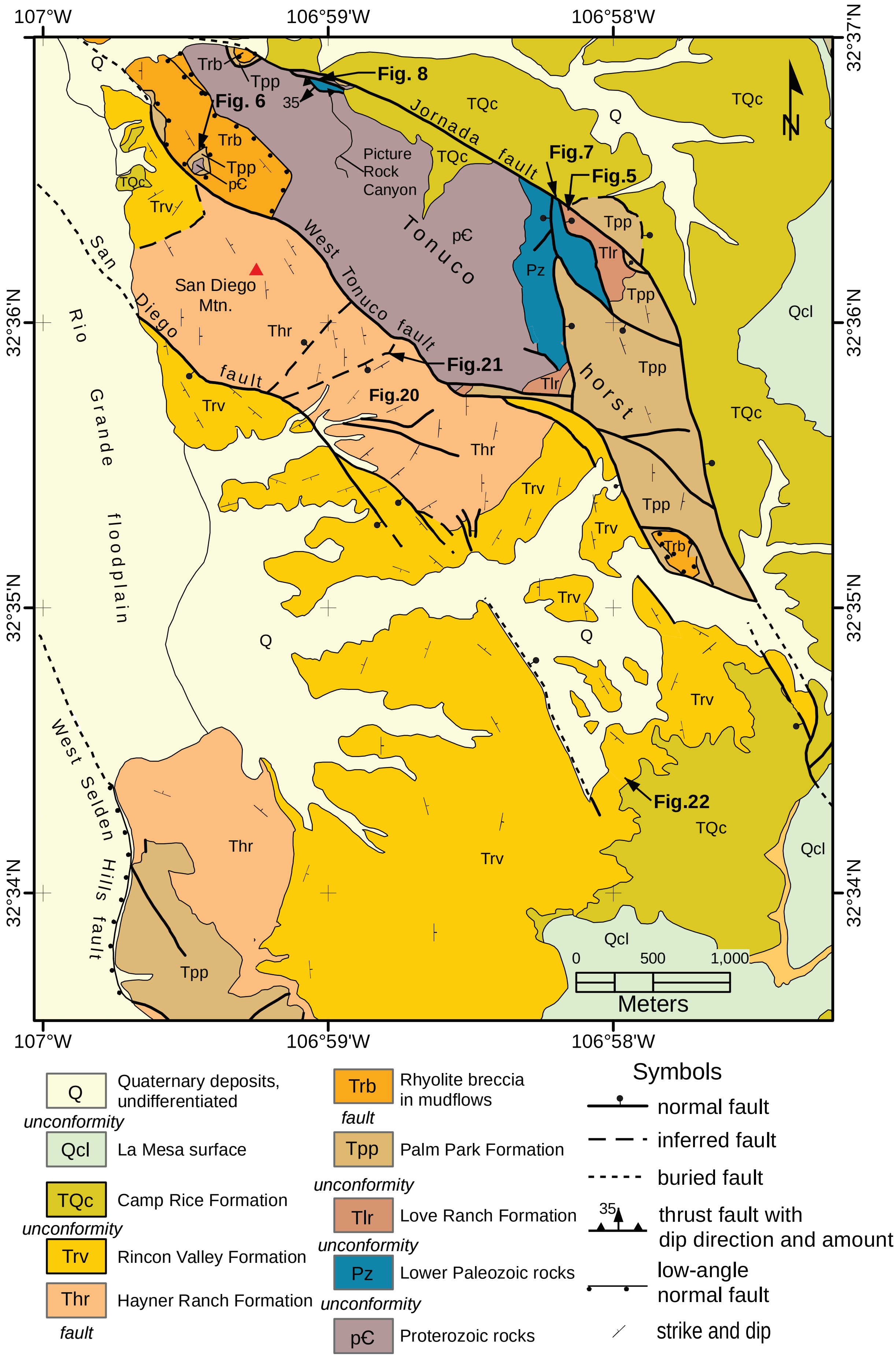


Figure 3. Geologic map of Tonuco uplift (San Diego Mountain) and surrounding area. Note locations of Figures 5–8 and 20–22.

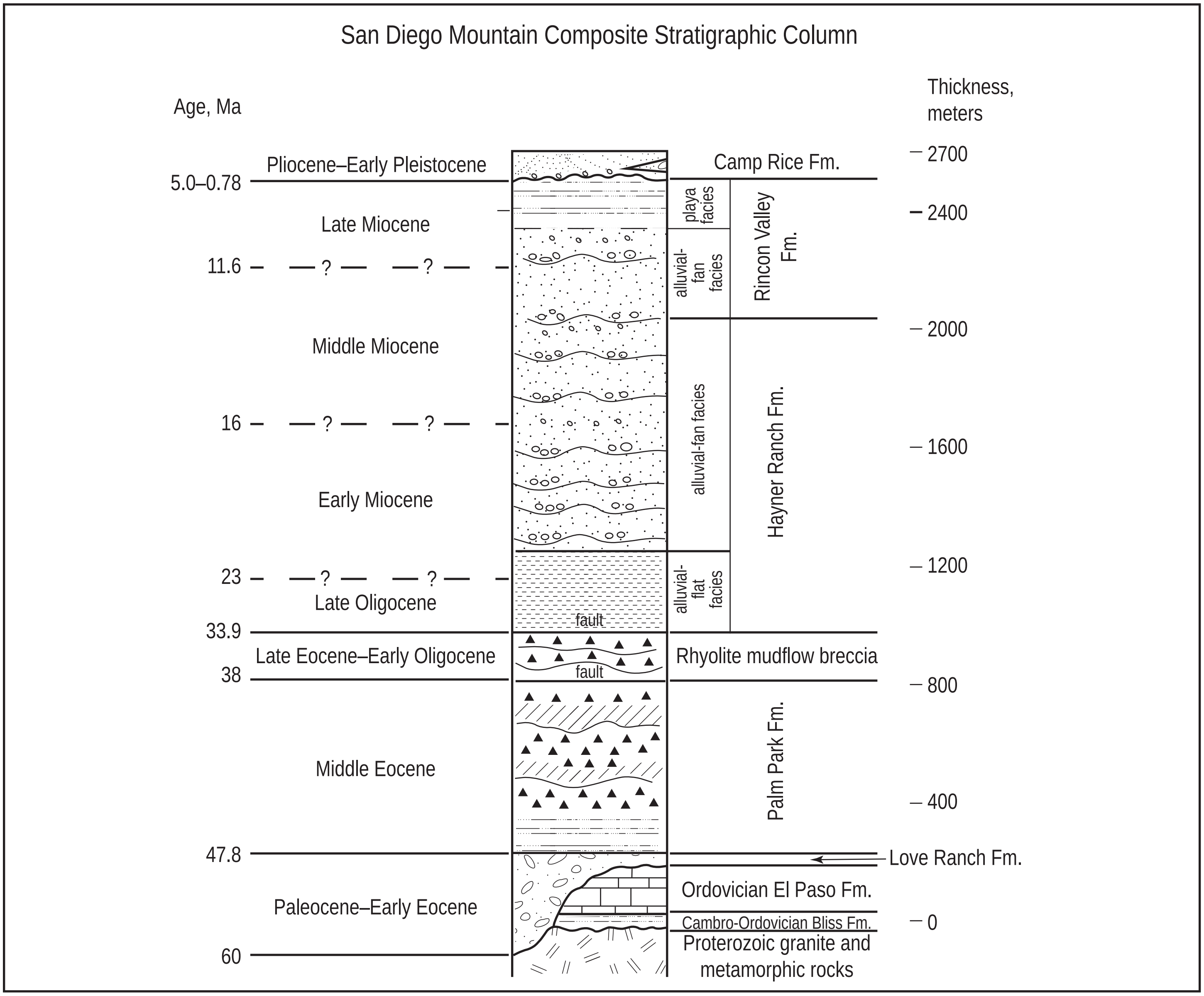


Figure 4. Composite stratigraphic column of the San Diego Mountain area.

Laramide Rocks and Structures, Tonuco Uplift

Three outcrops in the Tonuco uplift are keys to appreciating the character of Laramide deformation in south-central New Mexico. Two of the three are exposures of the Love Ranch Formation (Figs. 5 and 6), which is generally regarded as the sedimentary record of the erosion and burial of Laramide uplifts in the region (Kottlowski et al., 1956; Seager et al., 1997). Although undated directly, a latest Cretaceous to middle Eocene age is based on its stratigraphic position above the McRae Formation (75–73 Ma) near Truth or Consequences and beneath volcanic and volcaniclastic rocks of the Palm Park Formation (45–35.7 Ma) in south-central New Mexico (Lucas, 2015; Amato et al., 2017; Creitz et al., 2018). Both deformed syntectonic and relatively undeformed post-tectonic Love Ranch strata have been identified, the former generally associated with major thrust faults and the latter with onlap onto eroded uplift margins or with deposition in complementary basins beyond the effect of uplift-bounding thrust faults (e.g., Seager, 1981; Seager et al., 1997). Thickness of the Love Ranch Formation varies dramatically, ranging from essentially absent on the topographically high parts of eroded Laramide uplifts to 1.5 km or more in complementary basins. Thin, relatively undeformed Love Ranch outcrops on the Tonuco uplift are consistent with deposition on an eroded Laramide uplift.

In the northwestern corner of the Tonuco uplift, exposed in an erosional window through a Neogene low-angle normal fault, the Love Ranch Formation nonconformably overlies Precambrian granite and underlies the Palm Park Formation (Fig. 6). Only 1–2 m thick, the Love Ranch strata consist largely of cemented granitic grus, together with scattered, rounded cobbles of granite and Paleozoic limestone. Clearly, the nonconformity documents uplift and erosion of the entire pre-existing Paleozoic and Cretaceous section, which is more than 3.1 km thick in the Caballo Mountains only 15–20 km to the north.

This outcrop indicates that erosion during Laramide tectonism also cut into Precambrian rocks by an unknown but perhaps substantial amount.

A second outcrop of Love Ranch strata, located along the east-central flank of the Tonuco uplift, is equally informative. Here, an angular unconformity separates Love Ranch conglomerate from underlying Bliss and silicified El Paso strata. Locally, the base of the Love Ranch clastic rocks overlaps the two formations and was deposited on Precambrian granite and metamorphic rocks. As much as 50 m thick, the formation is overlain, probably unconformably, by volcaniclastic strata of the Palm Park Formation. Clasts within the Love Ranch Formation range up to 2 m in diameter and consist largely of El Paso limestone (Fig. 5), although clasts of Bliss and Precambrian rocks are conspicuous where the formation was deposited on those formations.

Figure 5. Talus or proximal-fan deposits of the Love Ranch Formation, eastern flank of Tonuco uplift. Formation consists entirely of El Paso Formation limestone blocks up to 1.5 m in length and overlies vertical El Paso strata. See Figure 3 for location.

Figure 6. Yellowish-brown Precambrian granite overlain by purple volcaniclastic rocks of the Palm Park Formation, northeastern Tonuco uplift. Soft, gray slope between the two rock units is Love Ranch Formation. Only 1–2 m thick, it consists mainly of lithified grus containing cobbles of granite and lower Paleozoic rocks. The outcrop is inferred to be 100–200 m above the thrust fault of Figure 8. View looks east. See Figure 3 for location.

Beneath the Love Ranch conglomerate, eroded El Paso and Bliss beds dip moderately to steeply eastward, 20° to 60° more steeply than overlying Love Ranch and Palm Park strata. Locally, silicified, tightly folded El Paso strata form the core of a northeast-verging, overturned anticline with an amplitude of at least 100 m (Fig. 7). After removing approximately 30° of late Cenozoic tilt, the axial surface of the fold would dip nearly 30° southwest. Again, the relationships require erosion of nearly 3 km of Paleozoic and Mesozoic strata from a significant Laramide uplift, followed by onlap and burial of the structure by Love Ranch alluvial-fan deposits.

The third key outcrop in the Tonuco horst provides evidence for the cause of uplift and erosion. An apparently major thrust fault is well exposed in Picture Rock Canyon near the northern end of the Tonuco uplift (Fig. 8). The thrust fault has carried sheared and altered Precambrian granite over silicified El Paso (?) limestone. Striking approximately N 45° W, the fault dips 30° southwest. Removal of approximately 30° of younger eastward tilting of the Tonuco fault block indicates that the fault dipped southwest near 60° when it was active. Corrugations and shear-sense criteria suggest dominantly dip-slip motion on the fault with a slight sinistral obliquity. Projected into the subsurface along strike, the fault would underlie at modest depth (100–150 m) the unconformities and overturned fold described above.

Collectively, the outcrops in the Tonuco horst may be used to reconstruct a small part of a major northwest-trending Laramide uplift, which verged northeastward and was raised along its northeastern flank by movement on a thrust fault that dipped 60° southwest. Sufficient structural and topographic relief was eventually attained so that a minimum thickness of about 3 km of Paleozoic and Cretaceous strata and an unknown amount of Precambrian rock were removed by erosion from the core of the uplift. By 46 Ma, the uplift was at least partially buried by relatively thin deposits of Love Ranch grus, talus, and paleovalley fill. Volcanic rocks of the Palm Park Formation then deeply buried the uplift during the middle Eocene.

Rio Grande Uplift, Love Ranch and Potrillo Basins

The outcrops in the Tonuco uplift became the nucleus around which a broader understanding of Laramide deformation in south-central New Mexico evolved. Mapping in adjacent ranges revealed contractional structures, unconformities, and outcrops of Love Ranch Formation that might be fitted with those in the Tonuco uplift to reveal a major Laramide structure, named the Rio Grande uplift, and its two complementary basins, the Love Ranch basin to the north and the Potrillo basin to the south (Fig. 9; Seager, 1983; Seager and Mack, 1986; Seager et al., 1986, 1997). While it is not the purpose of this paper to detail all evidence that supports the interpretation illustrated in Figure 9, essential data from three areas are worth summarizing.

Figure 7. Overturned, nearly recumbent core of anticline in silicified El Paso Formation, eastern flank of Tonuco horst. Fold is inferred to be 100–200 m above thrust fault of Figure 8. Dashed line follows bedding. View is toward the north-northeast. See Figure 3 for location.

Figure 8. Thrust fault exposed in Picture Rock Canyon. Precambrian granite in the cliff above the thrust overlies silicified lower Paleozoic rocks forming the slope below the fault. View looks south. See Figure 3 for location.

The Bear Peak fold and thrust belt, located in the southern San Andres Mountains (Seager, 1981), is interpreted to be an eastern segment of the northern edge of the Rio Grande uplift. Seismic reflection studies (Keller et al., 1986) show that the Bear Peak structures extend westward from the San Andres outcrops into the subsurface of the eastern reaches of the Jornada basin. That is not to say that the structures there and at San Diego Mountain are continuous across the intervening Jornada del Muerto, but that the zone of faulting and uplift may be semi-continuous, modified in places by culminations or minimums of uplift along its length. Trending west–northwest, the Bear Peak structure is huge, locally preserving in its hanging wall an overturned anticline and within its footwall an overturned, thrust-faulted syncline. Both verge north–northeast. Within the syncline, both syn- and post-tectonic Love Ranch fanglomerate, more than 600 m thick, were derived from Permian strata in the hanging wall of the uplift and deposited on Cretaceous strata in the footwall. These represent proximal fan alluvium deposited at the margin of both the Rio Grande uplift and Love Ranch basin (Kottlowski et al., 1956; Seager, 1981).

Farther northwest, in the Caballo Mountains, outcrops of the Love Ranch Formation, as well as contractional structures, provide constraints on the geometry of both the Rio Grande uplift and Love Ranch basin. In the southern part of the range, a significant percentage of Love Ranch clasts consists of Precambrian granite, increasing in size and volume southward. Because the conglomerate overlies Paleozoic rocks in most places in the southern part of the range, a source of granite is required south, presumably from a deeply eroded uplift now buried beneath the modern Hatch Valley or beneath the northern reaches of the Sierra de las Uvas. Consequently, the basement uplift and thrust fault exposed at San Diego Mountain might be extended northwestward beneath these features as Figure 9 illustrates. A corollary to this interpretation is that the Love Ranch strata in the southern Caballo Mountains are alluvial-fan deposits, derived at least partly from the exposed Precambrian core of the Rio Grande uplift to the south. Geophysical data (Kleinkopf et al., 2002), as well as unconformities between Love Ranch and various Paleozoic formations (Seager, 1994; Seager and Mayer, 1988), indicate the Rio Grande uplift might be projected farther westward across the Rio Grande rift into the southern Black Range.

The unconformity between Love Ranch strata and underlying Paleozoic rocks in the southern Caballo region may be used to infer a structurally lower "structural bench" located adjacent to the main uplift (Fig. 9). Nearly 700 m of Cretaceous strata were removed by erosion from this bench before it was buried by Love Ranch fanglomerate, which spread northward from the source area to the south, as noted above. Major fault-propagation folds and thrust-faulted Paleozoic strata define the eastern and northern margin of the bench in the eastern and central Caballo area (Seager and Mack, 1986, 2003).

Essential features of the Love Ranch basin are displayed by outcrops of the Love Ranch Formation in the east-central part of the Caballo range, extending into the Jornada del Muerto basin (Seager, 1995; Seager et al., 1997). As much as 900 m thick within the basin, the formation contains alluvial-fan, fluvial, and alluvial-flat facies, the latter recording the final stages of the filling of the basin near its center. Erosional "unroofing" of the Rio Grande uplift is also recorded by the clast content of the basin fill, albeit in an imperfect way. Finally, broad folds in lower parts of the basin fill apparently are syndepositional, the shallower expression of more severe shortening in Paleozoic rocks at depth (Seager et al., 1997). Upper parts of the basin fill are undeformed by Laramide deformation.

The erosional truncation of Precambrian through Permian rocks southward from the Tonuco uplift may be interpreted to indicate that the Rio Grande uplift was a thrust-bounded, basement-cored block, tilted southward several degrees (Fig. 10).

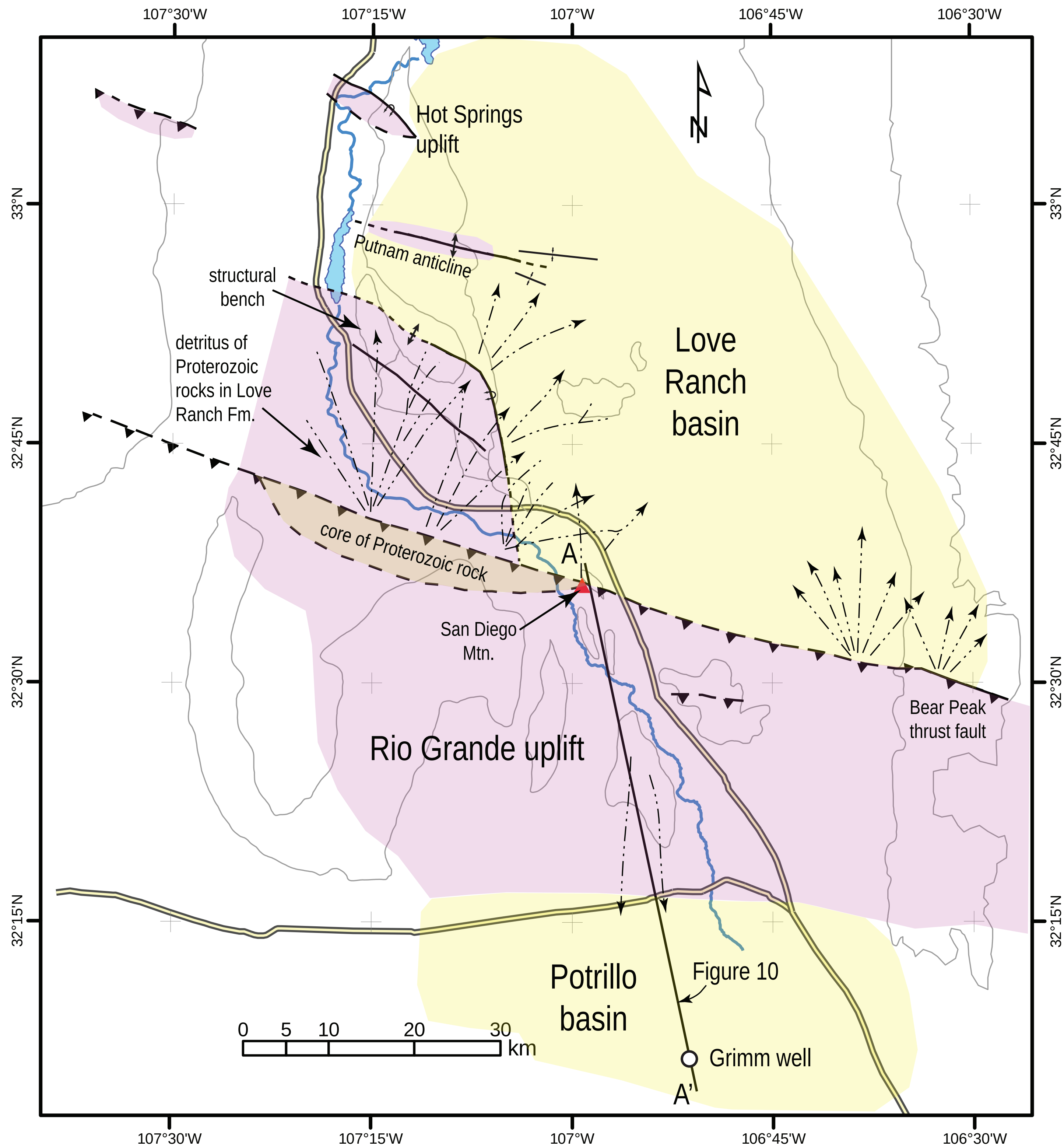


Figure 9. Interpreted tectonic map of Laramide Rio Grande uplift, Love Ranch basin, and Potrillo basin.

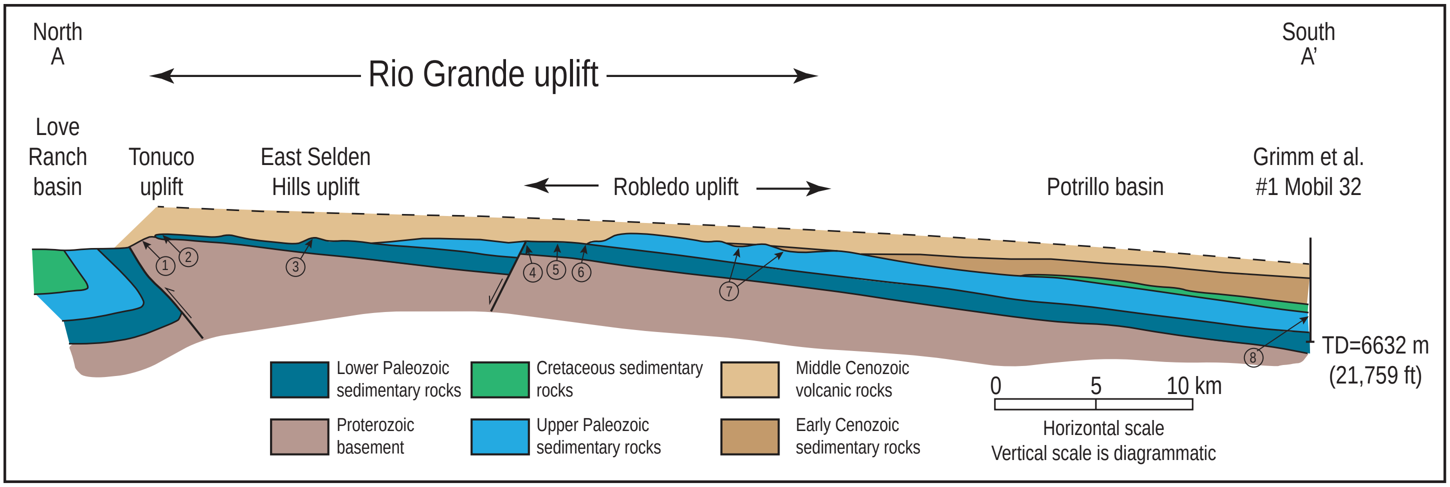


Figure 10. Interpreted N–S cross section of Rio Grande uplift based on exposed unconformities, structures, and subsurface data from the Grimm et al. No. 1 Mobil well. Circled numbers refer to outcrops on which the reconstruction is based: (1) Palm Park Formation nonconformable on Precambrian granite, (2) Love Ranch Formation unconformable on lower Paleozoic strata, (3) Palm Park Formation unconformable on Silurian dolomite, (4) Laramide (?) normal fault intruded by 35 Ma rhyolite (Kottlowski et al., 1969), (5) Palm Park Formation unconformable on Devonian shale, (6) Love Ranch Formation unconformable on Mississippian strata, (7) south-draining channel-fill of Love Ranch Formation on lower Permian strata, and (8) Paleogene sedimentary rocks overlying Cretaceous strata. See Figure 9 for location of cross section.

Thin Love Ranch or Palm Park beds overlie Precambrian or lower Paleozoic rocks at the Tonuco uplift, Fusselman Dolomite (Silurian) in the East Selden Hills (located a few kilometers south of the Tonuco uplift), and, in succession, Percha Shale (Devonian) and Mississippian and Permian rocks in the Robledo Mountains. The Permian strata are overlain by fluvial Love Ranch conglomerate, deposited in incised, south-flowing channels (Seager and Mack, 1986). Still farther south, lower Cenozoic basin fill, more than 2.1 km thick and correlative with the Love Ranch Formation, was drilled in the Grimm et al. No. 1 Mobil well (Thompson, 1982). These strata help define the Potrillo basin, the hanging wall dip-slope basin along the southern margin of the Rio Grande uplift (Fig. 10). Lahar and lava flows of the Palm Park Formation eventually buried the Rio Grande uplift and its complementary basins between 46 and 35.7 Ma, based on chronologies compiled by Crietz et al. (2018) and Lucas (2015).

Burial of Laramide Structures, Tonuco Uplift

Nowhere is the burial of a Laramide uplift better illustrated than on the Tonuco horst where lahars and lavas of the Palm Park Formation (Kelley and Silver, 1952) were emplaced on the Precambrian rock core of the Rio Grande uplift (Figs. 3 and 6), as well as across the eroded cuestas or hogbacks of lower Paleozoic strata along its flanks (Seager et al., 1971; Seager, 1975). Approximately 600 m thick, the volcanic rocks are entirely intermediate in composition. Lavas and clasts within lahars are porphyritic in texture and calc-alkaline in composition (McMillan, 2004). Andesite porphyry flows, gradational into lahars, comprise much of the upper 240 m of the formation. Locally, fluvial sandstone and mudstone are interpreted to be "run-out" deposits from the distal parts of lahars. Except for an enigmatic sequence of rhyolite breccia beds, no younger middle Cenozoic rocks are exposed on or adjacent to the Tonuco uplift.

The rhyolite breccia beds are unique in the region. Bounded by faults at both base and top, they comprise a cyclical sequence of breccia and red mudstone beds at least 200 m thick. Breccia beds commonly occupy shallow channels and consist of angular, cobble- to pebble-sized clasts of gray to red, flow-banded rhyolite supported by a matrix of red mudstone. These grade upward into red mudstone. Breccia/mudstone pairs average 6–7 m in thickness. In view of their composition, texture, and the graded nature of the bedding, the strata are interpreted to be distal mudflow deposits derived from flow-banded rhyolite dome complexes.

While the mudflow-breccia deposits are clearly younger than volcanic rocks of the Palm Park Formation, which underlie them on a low-angle normal fault (Fig. 4), their precise stratigraphic position is uncertain. Based on their proximity (5–10 km) to the flow-banded rhyolite domes of the Cedar Hills vent zone, the angularity of the clasts, and overall lithologic similarity to the rhyolite that forms these domes, we interpret the breccia to be the product of mudflows derived from one or more of the domes during or shortly after their emplacement. If true, the breccia beds date to around 35 Ma (the age of the domes) and are a member of the Bell Top Formation (see below).

Burial of Laramide Structures, Regional Perspective

At least partially buried by conglomerate of the Love Ranch Formation, Laramide uplifts were eventually completely buried by volcanic rocks of the Palm Park Formation, then more deeply hidden by the sedimentary and volcanic rocks of the Bell Top Formation, Uvas Basaltic Andesite, Thurman Formation, and "early rift" basin fill. Although unconformities separate these formations locally, one can piece together from different locales—particularly the Caballo Mountains and Sierra de las Uvas—a seemingly conformable sequence of these rock units more than 3.6 km thick. Each formation offers insight into the tectonic evolution of south-central New Mexico during the middle and late Cenozoic, a time span extending from 46 Ma to approximately 10 Ma.

Palm Park Formation

Beyond the Tonuco uplift, across nearly all of south-central New Mexico, lahars and lavas of the Palm Park and correlative Rubio Peak formations (Elston, 1957) accumulated to an average thickness of 600 m or more, completely burying the last remnants of the early Paleogene (Laramide) topography. These lahars and lavas constructed a nearly featureless plain or low plateau, presumably surmounted in places by stratovolcanoes or other volcanic edifices. Clemons (1979) mapped the intrusive "roots" of an apparent stratovolcano, as well as partially exhumed dome-flow complexes, in the Goodsight Mountains, and Seager (unpublished) recognized a Rubio Peak cinder cone on the eastern flank of the Black Range. An unusually thick (ca. 1.5 km) section of Rubio Peak Formation reported by Elston (1957) along the southwestern flank of the Black Range and Emory caldera may indicate proximity to an eroded volcano. The distribution of lavas and textural variations in associated lahars suggest the possibility of a volcanic edifice now buried beneath the southern Jornada del Muerto (Creitz, 2017) and adjacent to both the Organ and Doña Ana calderas (Seager, 1981; Seager and Mack, 2018). The semiconcordant granodiorite pluton in the Cookes Range (38.8 Ma; Loring and Loring, 1980) might be part of a Rubio Peak magma chamber, or not. Between these areas, however, evidence for the remains of volcanoes within the Palm Park Formation is missing.

In a broad area from the Caballo Mountains southward to Interstate 10 and beyond, lahar and associated fluvial and cienega strata are the nearly exclusive components of the Palm Park Formation. Across broad parts of this region distal lahar facies prevail, some interbedded with fluvial sandstone and conglomerate. Individual lahar deposits generally range from 0.5 to 5 m in thickness and contain clasts of pebble to small boulder size. There are striking local exceptions. In general, the lahars in this region appear to have been deposited on relatively low-gradient slopes—on lowlands perhaps tens of kilometers from their source. Local hot-spring deposits contain palm fossils, suggesting subtropical, lowland environments of deposition during the middle Eocene in south-central New Mexico. We suggest these lowlands subsequently became the floor of the Goodsight–Cedar Hills paleovalley and piedmont slope.

Bell Top Formation and Goodsight–Cedar Hills paleovalley

Formerly regarded as a volcano-tectonic depression (Seager, 1973) and later as an "early rift" half graben (Mack et al., 1994b), the Goodsight–Cedar Hills paleovalley (Fig. 11) is now envisioned as a broad, shallow topographic lowland on the south, merging northward into eastward-sloping piedmonts. Some 35 km wide by 70 km long, the northward-trending paleovalley corresponds closely to the middle Eocene lowlands on which Palm Park lahars accumulated. Geologic mapping and stratigraphic studies indicate that volcanic highlands of eroded Rubio Peak volcanoes and an evolving Emory caldera (Elston et al., 1975) probably bordered the paleovalley and piedmont slopes on the west, whereas its eastern limit is partially defined by a cluster of around 35 Ma rhyolite dome/flow complexes, named the Cedar Hills vent zone (Seager, 1973; Seager and Clemons, 1975). Between latest Eocene (35.7 Ma) and early Oligocene (28.7 Ma) time, a succession of rhyolitic ash-flow tuff outflow sheets, minor basaltic andesite flows, ash-fall tuff, and tuffaceous sedimentary rocks filled the paleovalley or were deposited on the neighboring piedmont slopes. Named the Bell Top Formation by Kottlowski (1953), the formation is as much as 480 m thick near the center of the paleovalley. Oldest dated Bell Top rock units (35.7 Ma), located near the inferred axis of the paleovalley, are essentially the same age as youngest Palm Park strata (36.5–35.7 Ma; Lucas, 2015), indicating that at least locally the two formations may be conformable. The Bell Top Formation has been described in detail by Seager (1973), Clemons (1975, 1976, 1979), and Mack et al. (1994b, 1998a). Figure 12 summarizes the general stratigraphy and ages of the Bell Top Formation, and Figure 13 shows the distribution of various Bell Top rock units within a cross section through the southern part of the paleovalley.

The half-graben model of Mack et al. (1994b) was based largely on the distribution of sedimentary facies and flow-direction indicators in the Bell Top Formation. They interpreted the eastern, faulted footwall uplift to be composed largely of rhyolitic rocks of the Cedar Hills vent zone, whereas the hanging wall-dip slope was formed by inferred eastward-dipping Rubio Peak rocks of an ancestral Goodsight Mountains. The "keel" and deepest part of the asymmetric half graben was located adjacent to the footwall uplift, as required by a half-graben model. The half-graben model is important because it would support the interpretation that regional extension prevailed in south-central New Mexico at the onset of ignimbrite eruptions around 36 Ma, continuing to the present.

In our view, several key aspects of the Bell Top Formation are inconsistent with a half-graben model. We interpret the formation as documenting the progressive filling of a broad, southern paleovalley segment and deposition on a perhaps even broader northern piedmont-slope segment, both non-extensional in origin and tectonically stable throughout the late Eocene until around 30 Ma.

At least the southern part of the Goodsight–Cedar Hills paleovalley is symmetrical, its lowest reaches lying near the valley center as Figure 13A illustrates. This is especially evident from the thickness variation in fluvial sedimentary units. Near 220 m thick along the paleovalley axis, sedimentary units thin progressively toward both borders, essentially pinching out against the highlands on either side (Fig. 13A). They do not thicken eastward as a half-graben model would predict, and there is no evidence that a Bell Top-age normal fault exists along the eastern side of the valley, nor is one needed.

Clast composition and size are also consistent with deposition in a symmetrical paleovalley. Flow-banded rhyolite is the predominant clast in fluvial conglomerate across the southeastern part of the valley.

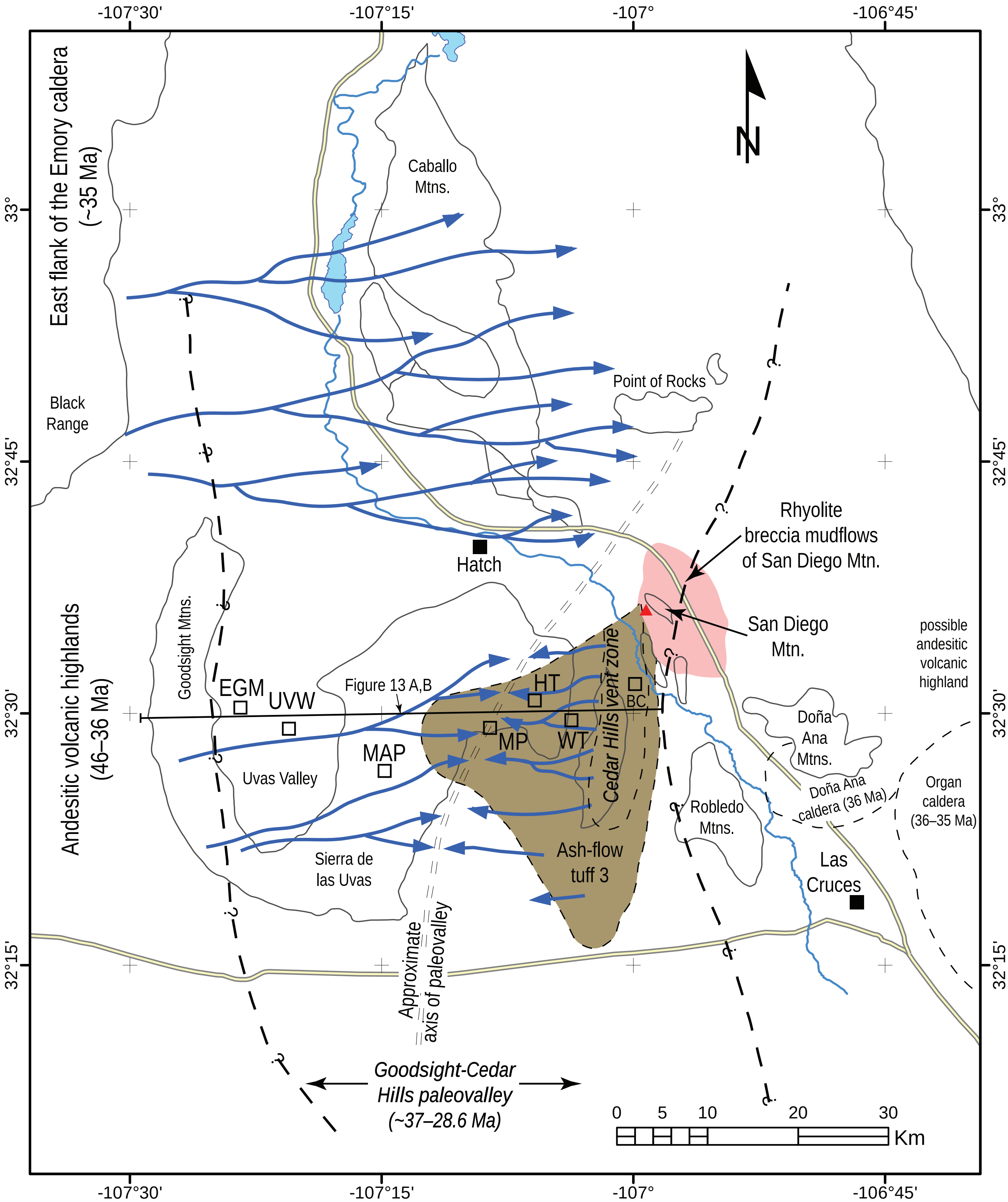


Figure 11. Interpretive map of Goodsight–Cedar Hills paleovalley based on known extent of Bell Top Formation. Abbreviations refer to measured-section data points on which the Figure 13 cross section is based. MP: Magdalena Peak, HT: Hersey tank, WT: Ward tank; BC: Broad Canyon, MAP: Massacre Peak, UVW: water well in Uvas Valley, and EGM: Eastern Goodsight Mountains. "Volcanic highlands" refers to possible location of Palm Park volcanic center (Creitz, 2017).

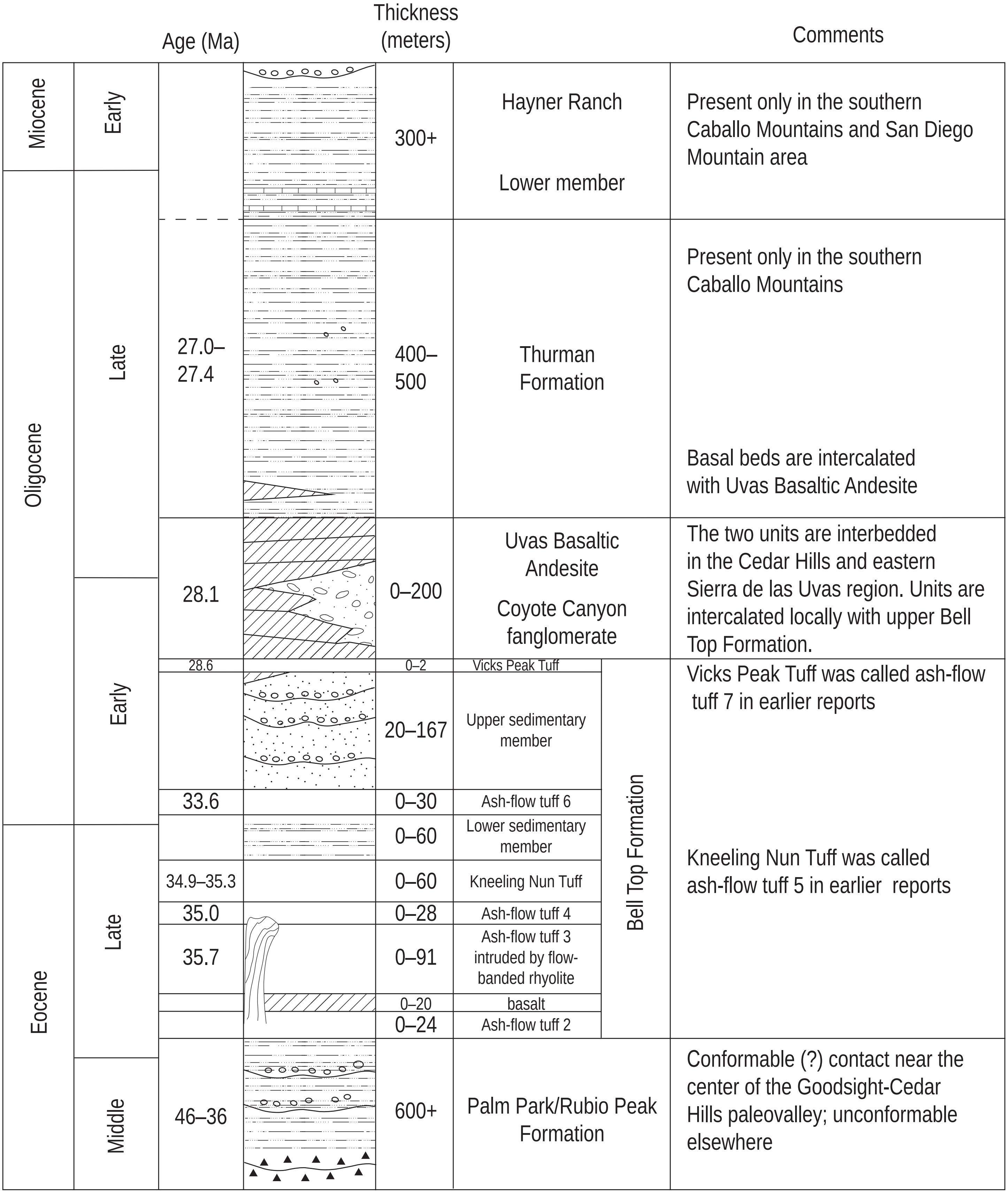
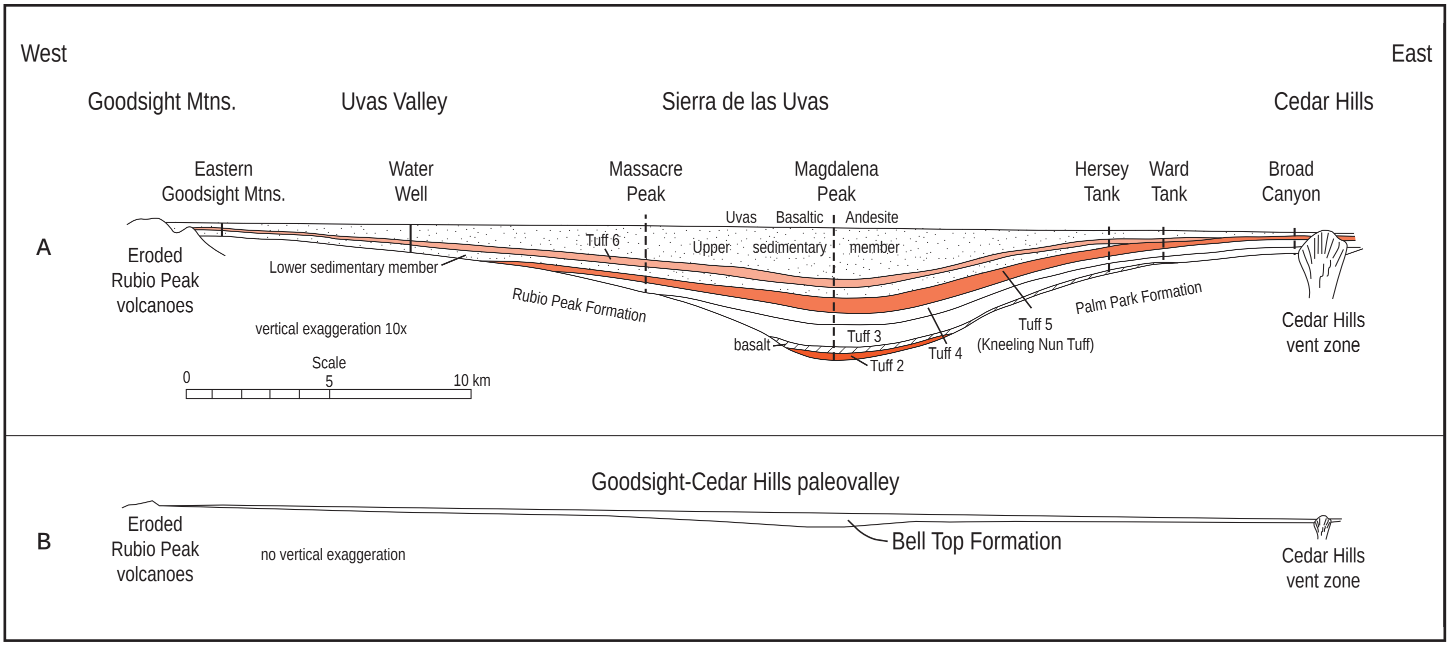


Figure 12. Composite stratigraphic column of Eocene–Oligocene volcanic and volcaniclastic rocks in Sierra de las Uvas, Cedar Hills, and southern Caballo Mountains. Different ages of the Kneeling Nun Tuff (34.9 Ma and 35.3 Ma) are from McIntosh et al. (1991) and Syzmanowski et al. (2019), respectively.



Figures 13A and 13B. East–west cross sections through Goodsight–Cedar Hills paleovalley. Figure 13A, with 10× vertical exaggeration, shows distribution of Bell Top rock units within the paleovalley along the line of cross section. Figure 13B, without vertical exaggeration, illustrates how broad and shallow the paleovalley was. See Figure 11 for location of cross section.

Flow-direction indicators confirm that these clasts were derived from rhyolite domes of the Cedar Hills vent zone along the valley's eastern flank (Mack et al., 1994b). In contrast, intermediate-composition volcanic clasts largely comprise fluvial conglomerate beds on the western slopes of the paleovalley. Their source, again suggested by flow-direction indicators (Mack et al., 1994b), is interpreted to be exposures of eroded andesitic (Rubio Peak Formation) highlands that formed the southwestern edge of the paleovalley. Along the basin axis, in the vicinity of present-day Magdalena Peak (MP; Fig. 11) and well west of the half graben "keel" of Mack et al. (1994b), a mix of clast types exists in the paleovalley's thickest sedimentary beds. In a general way throughout the basin, clast size increases from pebble, cobble, and lesser boulders along the paleovalley axis to prevailingly cobble and boulder clasts toward its margins.

The distribution of successively younger ash-flow tuffs also suggests the southern part of the paleovalley was filled from its axial region outward (Fig. 13A). Ash-flow tuff 2 and a thin basalt flow—the oldest units of the Bell Top sequence—are confined to the center and presumably lowest part of the valley. In a general way, as younger ash-flow tuffs spilled into the valley from outside sources, they spread as thin (20–50 m) sheets across successively wider and higher parts of the valley floor, progressively onlapping valley sideslopes and filling the paleovalley. In this way, a hiatus between Bell Top and Palm Park units becomes more significant as successively younger Bell Top units are inset against Palm Park or Rubio Peak rock units on the valley sideslopes, best illustrated along the western flank of the paleovalley (Fig. 13A).

Ash-flow tuff 3 is an exception to this process. Interpreted to have erupted from the Cedar Hills vent zone, tuff 3 then avalanched westward into the paleovalley where it ponded, accumulating to 90 m thick along the basin center (Fig. 11). Flow-banded rhyolite dome/flow complexes in the Cedar Hills vent zone intruded and are essentially the same age as ash-flow tuff 3 (ca. 35.7 Ma); they are interpreted to be the remaining, devolatilized magma, emplaced as rhyolite domes shortly after the eruption of ash-flow tuff 3. The domes largely blocked the eastward spread of tuff 4, the Kneeling Nun Tuff, and tuff 6 as indicated by the pinchout of the tuffs against the western flanks of the domes (Seager and Clemons, 1975). Erosion of the domes locally produced mudflow deposits such as those preserved at San Diego Mountain, and tuffaceous rocks associated with the rhyolite domes contain fossil palms, suggesting that subtropical lowland environments persisted from the middle Eocene into the late Eocene in south-central New Mexico.

The vertical exaggeration in Figure 13A may be misleading in terms of the relief on the paleovalley floor. The same cross section with no vertical relief (Fig. 13B) has a width-to-depth ratio of 70:1 (where the Bell Top Formation is thickest), illustrating how broad and shallow the paleovalley really was. Using the maximum thickness of the sedimentary units near the center of the paleovalley (approximately 220 m) and the ages of the tuffs that enclose them (35.0 and 28.6 Ma), we estimate a rate of sedimentation along the paleovalley axis to have been approximately 30 m/Myr. This rate is significantly lower than our estimates for the late Oligocene and Miocene sedimentation rates in "early rift" basins of the Rio Grande rift (90 to 1,000 m/Myr).

Outcrops of the Bell Top Formation in the southern Caballo Mountains and Point of Rocks hills (Fig. 11) tell a somewhat different story. Only Kneeling Nun Tuff, tuff 6, thin Vicks Peak Tuff, and associated fluvial sediments spread into this region, suggesting that by around 35 Ma the lowest, perhaps topographically closed parts of the southern paleovalley had been filled, permitting subsequent ash flow sheets to spread into the northern parts. Most importantly, distinctive rounded clasts of proximal outflow and intracaldera Kneeling Nun Tuff are conspicuous within upper Bell Top fluvial conglomerate at these localities (Mack et al., 1994b). These clearly indicate that upper Bell Top fluvial systems drained the eastern slopes of the Emory caldera. At this latitude, the symmetrical Goodsight–Cedar Hills paleovalley may have merged into low-gradient piedmont slopes of Bell Top age draining from the Emory caldera an unknown distance eastward.

From the above evidence and interpretations, we view the Bell Top Formation as filling a broad, very shallow and symmetrical paleovalley and an adjacent piedmont slope. Both paleovalley and piedmont-slope depositional settings were seemingly stable for 8 Myr, except for the eruption of tuff 3 and emplacements of rhyolite domes near 35.7 Ma. And the succession of ash-flow tuff sheets that entered the paleovalley either ponded along the closed part of its axis or spread widely across the landscape as uniformly thin sheets, encountering no terrane of extensional origin. In our view the "Goodsight–Cedar Hills half graben" should no longer be cited as evidence of middle Cenozoic extension in south-central New Mexico.

Uvas Basaltic Andesite

Flows of Uvas Basaltic Andesite (Kottlowski, 1953) quickly buried the Goodsight–Cedar Hills paleovalley, spreading far beyond its boundaries (Fig. 14). Ranging in thickness from 150 to 250 m, the flows (and correlative flows of Bear Springs Basalt; Elston, 1957) were emplaced over a brief span of time at around 28 Ma (as demonstrated by ages of both underlying and overlying rocks; Fig. 12). Near the center of the paleovalley, basaltic andesite flows intertongue with underlying sedimentary strata of the Bell Top Formation, but along the western margin of the paleovalley and across the Cedar Hills vent zone, the base of the Uvas is strikingly unconformable on Rubio Peak or Palm Park formations or on various members of the Bell Top Formation. A thick, southward-building apron of tuffaceous sedimentary rocks, the Thurman Formation (Figs. 12 and 14; Kelley and Silver, 1952), locally blocked the northward movement of Uvas flows in the central Caballo area (Seager and Mack, 2003). The absence of Uvas flows at San Diego Mountain and adjacent areas to the south probably resulted from erosion of the formation from very early fault blocks within an incipient Rio Grande rift (see below).

Uvas Basaltic Andesite flows issued from a variety of vents. Swarms of basaltic andesite dikes, exposed in the eastern Caballo Mountains, are considered to be of Uvas age (Seager and Mack, 2003). One dike merges upward into a basal Uvas Basaltic Andesite flow, and another has yielded a 26.8 ± 0.68 Ma $^{40}Ar/^{39}Ar$ age (Esser and McIntosh, 2003). Such dikes probably fed fissure eruptions. The general north–northwesterly trend of many dikes suggests that east-northeast-west-southwest extension prevailed during these fissure eruptions. Numerous small plugs, the eroded remnants of a maar, and two cinder cones (Fig. 14) are also associated with Uvas flows (e.g., Clemons and Seager, 1973; Seager et al., 1975).

One cinder cone, located in lower Broad Canyon and within the Cedar Hills vent zone (Figs. 14 and 15), lies astride and was broken by the latest Miocene Cedar Hills normal fault, inviting speculation that the cone was constructed in late Oligocene time on a fissure or incipient fault—a precursor to the late Miocene fracture. Uvas Basaltic Andesite flows associated with this cone are interbedded with the Coyote Canyon Fanglomerate Member (Seager and Clemons, 1975). Derived from adjacent domes of flow-banded rhyolite (Figs. 14 and 15), the Coyote Canyon Fanglomerate is as much as 100 m thick. Perhaps late Oligocene uplift on an ancestral Cedar Hills fissure or fault was sufficient to briefly accelerate or renew erosion of the 35 Ma domes while Uvas flows were emplaced along their flanks. If so, this is evidence of the earliest faulting (near 28 Ma) associated with the southern Rio Grande rift.

Thurman Formation

Finally, the Thurman Formation (Kelley and Silver, 1952) deserves a bit more attention (Fig. 12). The Thurman Formation intertongues with and overlies Uvas Basaltic Andesite in the central and southern Caballo Mountains except, as noted above, where Uvas flows pinch out at the base of the formation; at that location, the Thurman Formation unconformably overlies the Bell Top Formation. Dated at 27.4–27.0 Ma (Boryta and McIntosh, 1994; W. McIntosh, personal communication *in* Mack et al., 1994c), the age of the Thurman Formation correlates with the timing of the eruption of the Mt. Withington caldera (Deal, 1973) located 60 km northwest. Fall-out tuff, tuffaceous sandstone, conglomeratic sandstone, and mudstone comprise much of the formation (Fig. 16), interpreted to be the product of both sheet flood and mudflow processes (Kieling, 1993). The fine-grained nature of the strata suggests that the formation represents distal parts of a huge alluvial apron that spread far southward from the caldera (McIntosh et al., 1991; Kieling, 1993). Thickness of the formation exceeds 500 m in the southern Caballo Mountains; its deposition over a period of 0.4 Myr (1,250 m/Myr) supports the conclusion that the formation was deposited in a subsiding basin in late Oligocene time, perhaps the earliest indication of basin formation in the Rio Grande rift (Fig. 14). The formation grades upward into conglomeratic fluvial sandstone and increasingly proximal fanglomerate of the Hayner Ranch Formation, which provides a remarkable record of the initiation and early growth of fault blocks in the Caballo Mountains and the complementary Hayner Ranch half graben, both major structures in the Rio Grande rift.

The early West Selden Hills uplift

Before returning to the Tonuco uplift, we want to alert the reader that, with the exception of the "red rhyolite breccia" mudflow deposits, all of the Bell Top, Uvas, and Thurman formations are missing from the Tonuco uplift. All three formations, or parts of them, likely were deposited across the Tonuco area, but they are almost entirely missing east of the West Tonuco and West Selden Hills fault zones.

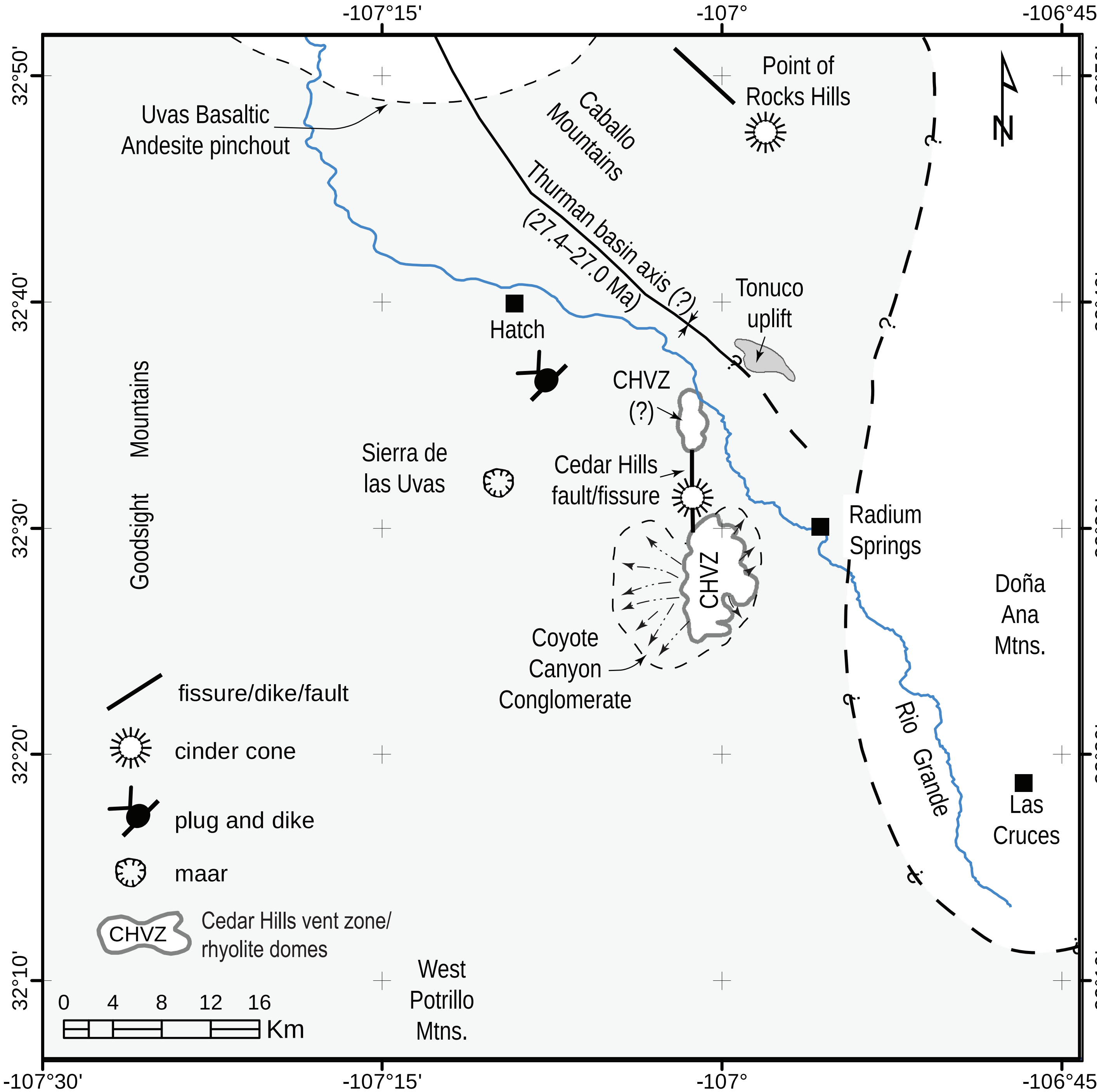


Figure 14. Paleotectonic map showing known and inferred limits of Uvas Basaltic Andesite flows and associated eruptive vents (ca. 28 Ma). Note Cedar Hills cinder cone, Coyote Canyon alluvial fans, and inferred Thurman basin (27.4–27.0 Ma), the latter of which developed after emplacement of Uvas Basaltic Andesite flows.

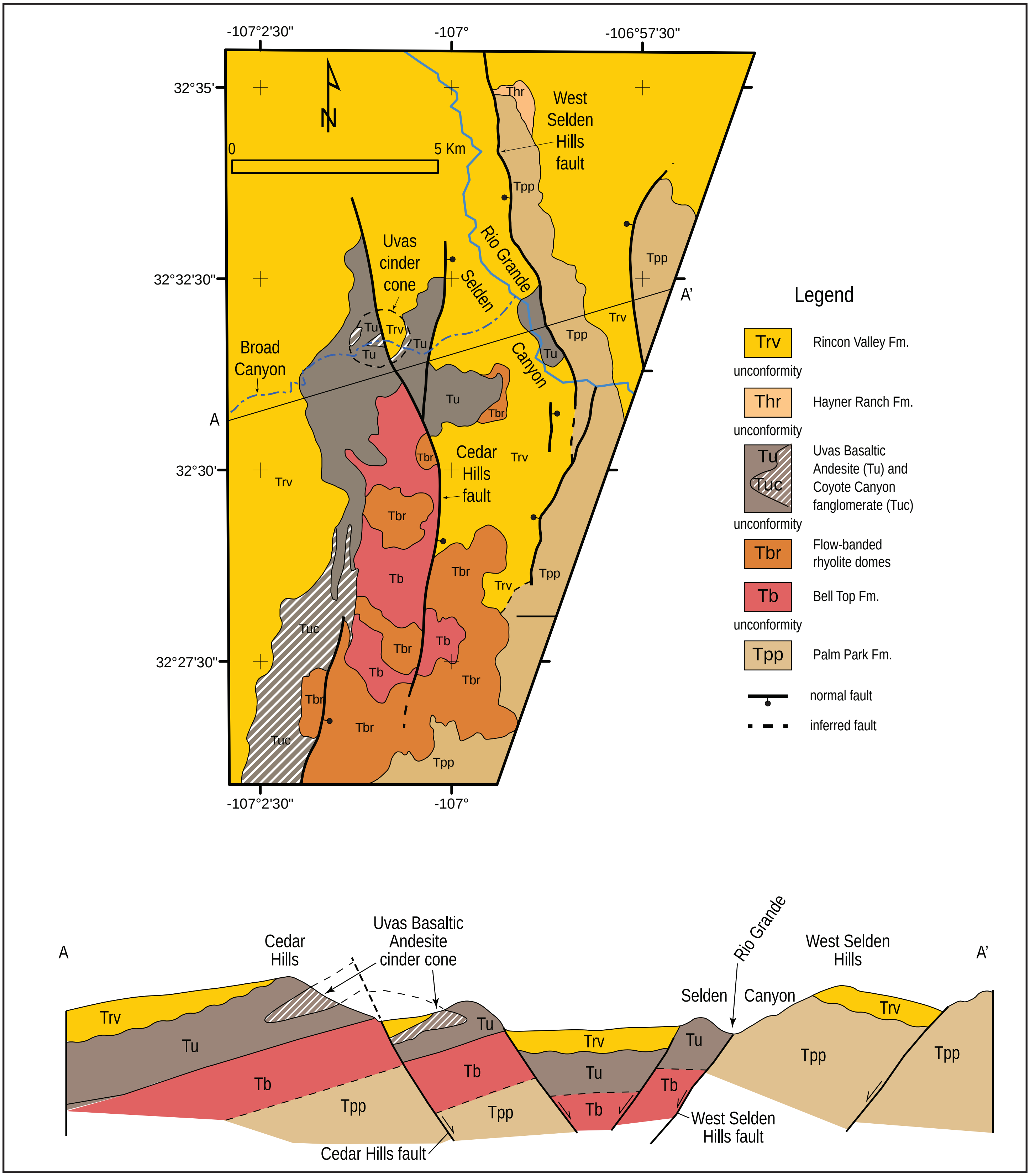


Figure 15. Simplified map and cross section of Selden Canyon area illustrating two “early rift” structures and the late Miocene transfer zone described in the text. The Uvas Basaltic Andesite cinder cone, apparently constructed on an incipient Cedar Hills fault or fissure, suggests initiation of that fault as early as Oligocene time. Nascent uplift along the fault or fissure may have produced the Coyote Canyon Fanglomerate, which interfingers with basaltic andesite flows south of the cinder cone and was derived from flow-banded rhyolite domes adjacent to the fault. Stratigraphic relations across the West Selden Hills fault suggest pre- or syntectonic Hayner Ranch (late Oligocene to early Miocene) movement along that fault, resulting in the erosion of Uvas and Bell Top rock units from the footwall prior to onlap of Hayner Ranch fanglomerate. Latest Miocene faulting has resulted in the present structure illustrated in cross section A—A’ (vertical exaggeration approximately 2.5×), drawn along Broad Canyon. Mack and Seager (1995) suggest that the arched structure accommodated the transfer zone between the oppositely dipping West Robledo/East Selden Hills fault zone and Ward Tank faults (see Fig. 27 for location of these faults).

Figure 16. Upper part of Thurman Formation exposed in the Rincon Hills. View looks northwest.

Three kilometers south of the Tonuco uplift, at the northern end of the West Selden Hills (Fig. 1), Uvas, Bell Top, and possibly Thurman rock units were removed by late Oligocene or earliest Miocene erosion from the footwall of the West Selden Hills fault block (Fig. 15). At this location, Uvas flows and Bell Top ash-flow tuff 3 are still preserved in the hanging wall of the West Selden Hills fault but are missing (presumably eroded) from the footwall (Fig. 15). Fanglomerate of the upper Oligocene or lowest Miocene Hayner Ranch Formation unconformably onlapped Palm Park strata and the eroded remnants of Bell Top tuffs on the footwall. Thus, this ancestral West Selden Hills fault block is among the earliest to have been active in the southern Rio Grande rift. If this uplift and erosion extended a few kilometers farther north, it would account for the missing formations on the much younger Tonuco uplift and would predict their absence in the adjacent subsurface.

As we have seen, the "red rhyolite breccia" mudflow deposits may be correlative with the Cedar Hills rhyolite domes (35 Ma). These "red rhyolite breccia" beds are the only record on the Tonuco uplift of events that happened between 39.5 and 27.0 Ma, the ages of the Palm Park and Thurman formations, respectively. Following this missing time interval, however, the Tonuco uplift displays a remarkable sedimentary account of the late Oligocene and Miocene initiation and evolution of the Rio Grande rift.

"Early Rift" Deposits, Tonuco Uplift

Besides revealing key aspects of Laramide tectonics in south-central New Mexico, San Diego Mountain's "Rosetta Stone" offers an extraordinary insight into the evolution of the southern Rio Grande rift. The understanding stems from remarkable outcrops of both "early rift" (27–9 Ma) and "late rift" (5.0–0.8 Ma) basin fill, faulted down around the perimeter of the Tonuco horst, as well as from instructive exposures of both high-angle and low-angle normal faults. We first summarize essential features of "early rift" basin fill, then discuss rift structures, and end with a brief account of "late rift" basin fill and associated faults.

"Early rift" deposits at San Diego Mountain were first described and named by Hawley et al. (1969; Seager et al., 1971). They recognized that the conglomeratic strata exposed there are part of the Santa Fe Group, the general name assigned to deposits of Rio Grande rift basins throughout the length of the rift. Oldest parts of the "early rift" basin fill were named Hayner Ranch Formation, whereas conformably overlying parts were assigned to the Rincon Valley Formation (Fig. 4). The base of the Hayner Ranch Formation is no older than 27 Ma, the age of the Thurman Formation, which gradationally underlies Hayner Ranch strata in the Rincon Hills (Fig. 1). The 9.6 Ma Selden Basalt (Seager et al., 1984), interbedded with the Rincon Valley Formation, provides an approximate upper age for the two formations (Seager et al., 1984). Based on these dates, the Hayner Ranch Formation is no older than late Oligocene, ranging to middle Miocene, whereas the Rincon Valley Formation is probably middle to late Miocene. Together, the formations comprise the fill of the Hayner Ranch basin, a half graben with the Caballo Mountains forming the footwall uplift and an ancestral Sierra de las Uvas forming the hanging wall ramp. (Figs. 17 and 18A; Mack et al., 1994c). In addition, the Rincon Valley Formation documents the early rise of the Sierra de las Uvas uplift and subsidence of the Rincon Valley half graben (Figs. 18B and 19).

Hayner Ranch basin, Hayner Ranch Formation

Downfaulted along the southern and western margins of the Tonuco horst are superb outcrops of the Hayner Ranch Formation. In the slopes of San Diego Mountain alone, a thickness of nearly 300 m of the formation is exposed (Fig. 2). And along the southern flank of the uplift, broadly folded Hayner Ranch strata nearly 1.1 km thick have been sculpted by erosion into a series of colorful hogbacks and strike valleys (Fig. 20).

The Hayner Ranch Formation can be roughly divided into two parts. The lower part is at least 300 m thick, its base not exposed. Bright red siltstone, shale, and mudstone are the predominant rock types (Fig. 21), but at least two beds of freshwater algal limestone, each 1–2 m thick, are interbedded in the lowest part of the section (Fig. 12). As we shall see, the limestone beds are helpful in establishing the late Oligocene to early Miocene age of the Hayner Ranch Formation. Alluvial-flat environments and spring-fed cienegas, ponds, or small lakes are indicated by these strata.

As much as 800 m thick, the upper part of the Hayner Ranch Formation at San Diego Mountain is red to grayish-purple conglomerate, conglomeratic sandstone, and interbedded mudstone (Figs. 20 and 21). Collectively, sedimentary structures, grain size, and texture are consistent with deposition by fluvial or arroyo systems or by sheet floods on the mid to distal parts of alluvial fans (Kieling, 1994). Conglomerate clasts are exclusively middle Cenozoic volcanic rocks, including abundant Palm Park, Uvas Basaltic Andesite, and Bell Top ash-flow tuffs. Transport-direction indicators suggest a northerly source, interpreted to be an ancestral Caballo footwall uplift that supplied middle Cenozoic volcanic detritus to the mid or distal parts of these fans (Mack et al., 1994c).

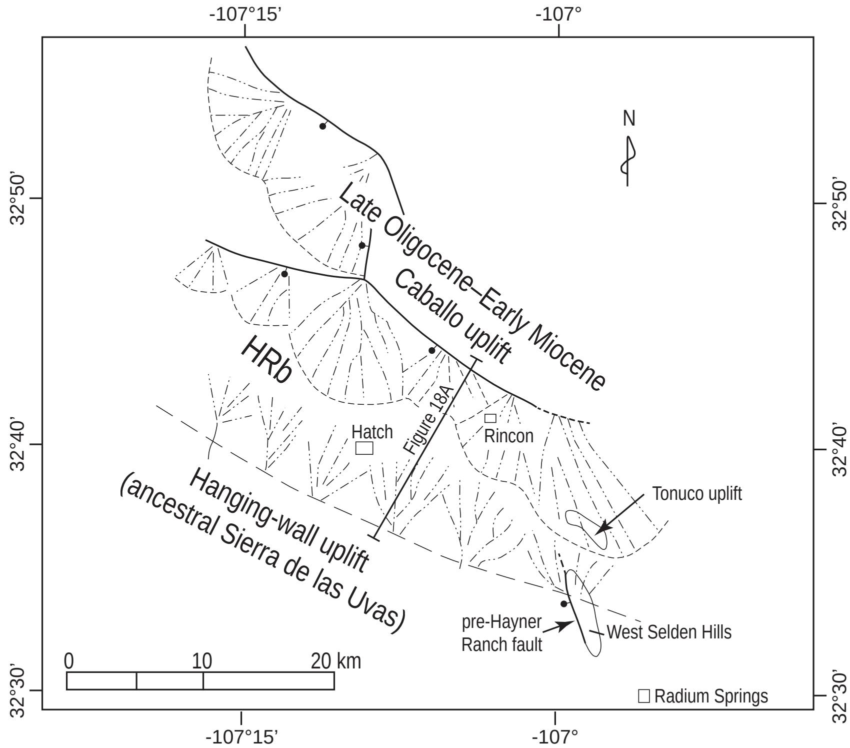
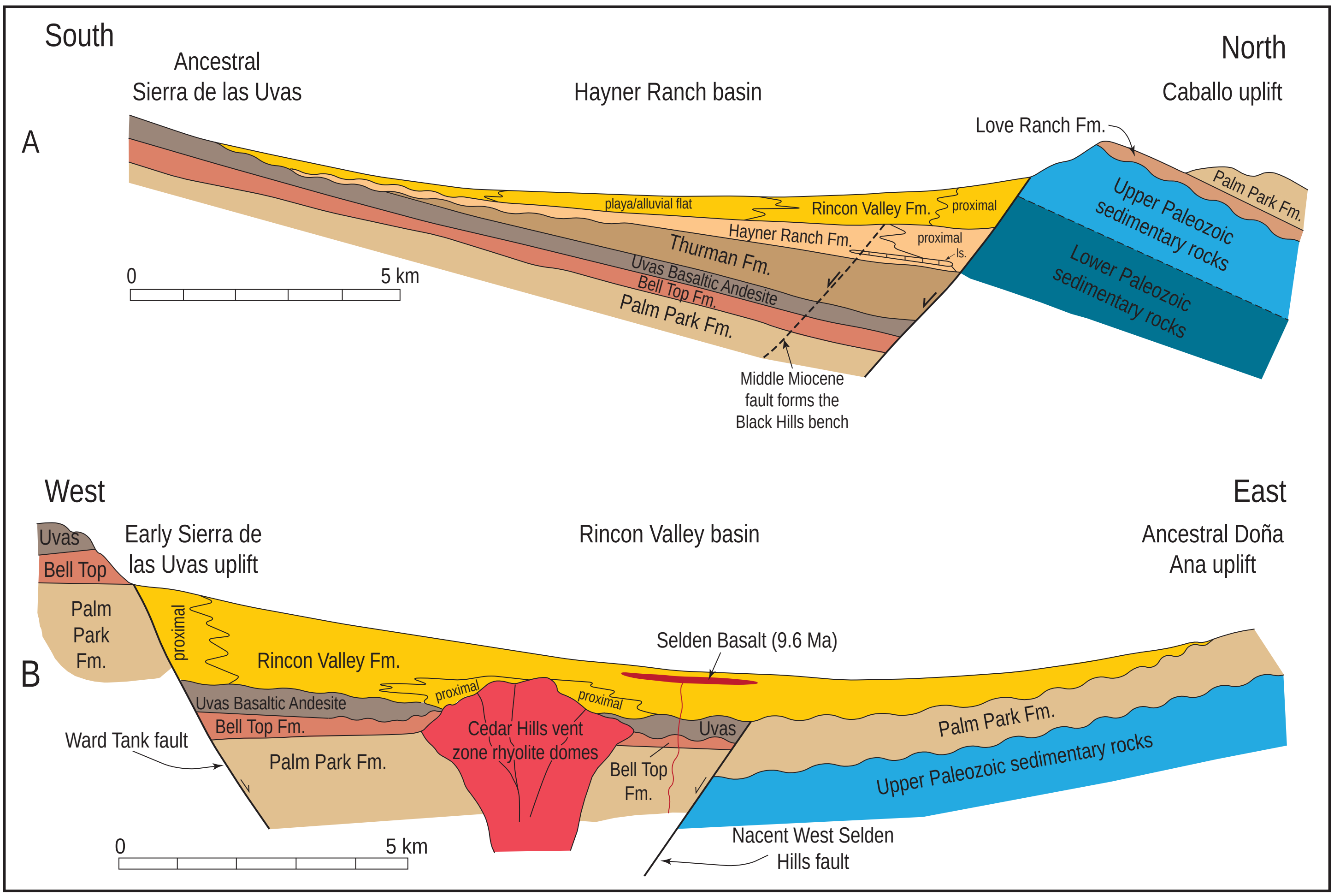


Figure 17. Tectonic map of Hayner Ranch basin (HRb). Note location of cross section of Figure 18A.



Figures 18A and 18B. Diagrammatic cross sections of Hayner Ranch and Rincon Valley basins before latest Miocene breakup (around 9 Ma). Note the location of cross section 18A on Figure 17 and the location of cross section 18B on Figure 19. "Ls" in Figure 18A refers to limestone marker beds near base of Hayner Ranch Formation. Vertical scale is exaggerated and diagrammatic to illustrate the important stratigraphic and structural relationships in each basin.

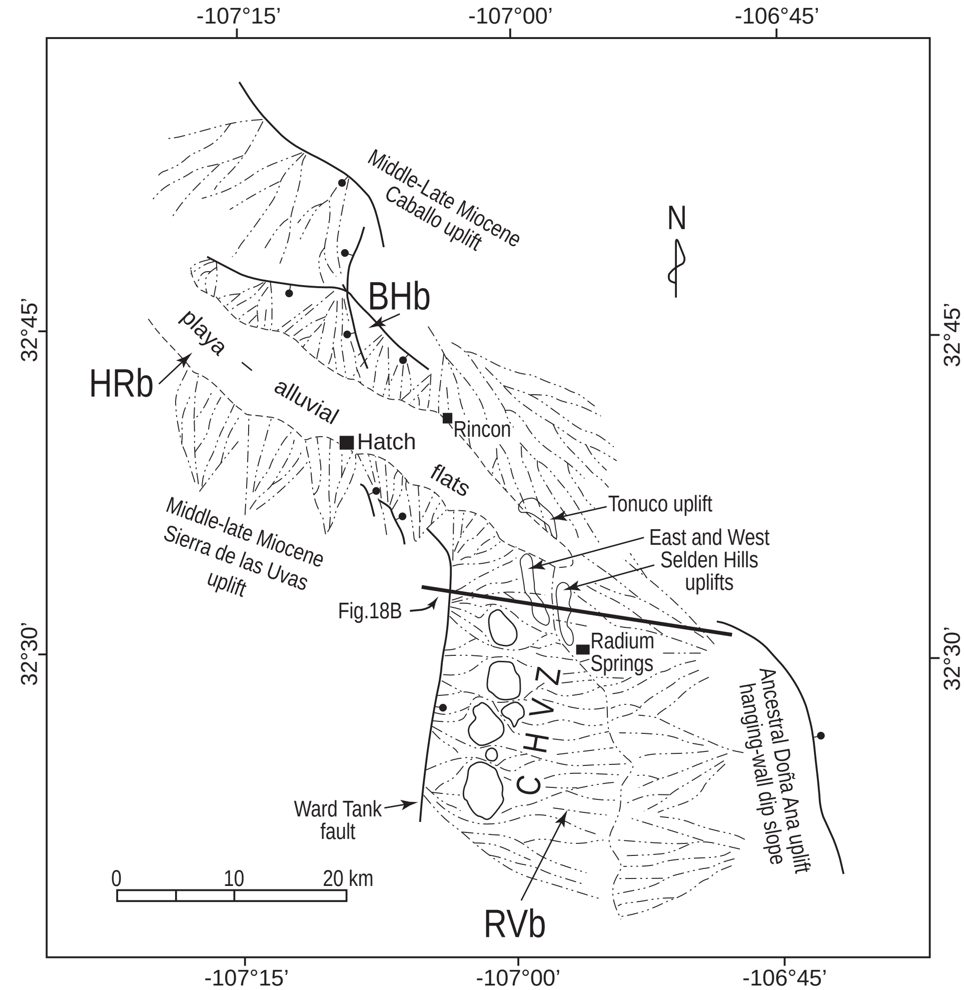


Figure 19. Tectonic map of Hayner Ranch basin (HRb) and Rincon Valley basin (RVb) during late Miocene time. CHVZ is eroded remnants of Cedar Hills vent zone (flow-banded rhyolite domes) and BHb is the Black Hills bench. Note location of cross section of Figure 18B.

Figure 20. Hogbacks of Hayner Ranch fanglomerate, south side of San Diego Mountain. Precambrian rocks in the Tonuco horst form ridge on skyline. View looks east. See Figure 3 for location.

Figure 21. Alluvial-flat red beds near the base of the Hayner Ranch Formation, south side of San Diego Mountain. Cliff at upper right in shadow is basal bed of 800-m-thick section of Hayner Ranch "early rift" fanglomerate that overlies the alluvial-flat facies. Ridge on skyline is Precambrian granite in the Tonuco horst. See Figure 3 for location.

Hayner Ranch basin, Rincon Valley Formation

Conformably overlying the Hayner Ranch Formation in outcrops south of San Diego Mountain is the Rincon Valley Formation. At least 400 m thick, the formation's original thickness is unknown owing to the erosion surface that truncates its upper strata.

Two distinctive facies comprise the Rincon Valley Formation. The lower 250 m of the formation is essentially a continuation of the Hayner Ranch Formation. Interbedded tan to gray conglomerate, conglomeratic sandstone, and mudstone prevail. Sedimentary structures, bedding, sorting, and clast size differ little from the underlying Hayner Ranch strata, all consistent with deposition on the mid to distal portions of an alluvial fan (Kieling, 1994). Again, directional indicators suggest a northerly source. The most important distinction between the two formations is the clast content. Clasts in the Rincon Valley Formation include as much as 25% Paleozoic and Cretaceous pebbles, cobbles, and occasional boulders, clasts missing altogether from the Hayner Ranch Formation. Especially significant are clasts of Permian Yeso limestone and Cretaceous Dakota sandstone, clasts whose only possible nearby source is the eastern flank of the Caballo uplift. These Paleozoic and Cretaceous clasts suggest that, by middle to late Miocene time, uplift and erosion of Caballo fault blocks had exposed Paleozoic and Cretaceous strata whose clasts were delivered to alluvial fans of the Rincon Valley Formation (Mack et al., 1994c).

The fanglomerate of the lower Rincon Valley Formation grades abruptly upward into pink gypsiferous mudstone, claystone, and siltstone, which comprise a second facies of the formation. At least 150 m thick, this facies documents sedimentation on alluvial flats (Fig. 22) and playas at the toes of alluvial fans and near the basin center. Locally, as in Figure 22, a lobe of distal alluvial-fan gravel overlies the alluvial-flat/playa facies. Part of the younger Rincon Valley basin story, these fan deposits are addressed below. In general, however, the playa/alluvial-flat facies logs the conclusion of "early rift" sedimentation.

Figure 22. Alluvial-flat deposits in upper Rincon Valley Formation. Banded, upper part of cliff is a lobe of alluvial-fan conglomerate, derived from an ancestral Doña Ana uplift. Light-colored beds at the skyline are Camp Rice fluvial deposits unconformably above the slightly tilted Rincon Valley strata. View looks southeast from a point 2 km south of San Diego Mountain. See Figure 3 for location.

"Early Rift" Deposits, Regional Perspective

At and near San Diego Mountain, outcrops of the Hayner Ranch and Rincon Valley formations were keys to realizing that some "early rift" basins in the Rio Grande rift are no longer a part of the modern landscape, and that their clast content recorded the initiation and early evolution of the rift (e.g., Seager and Hawley, 1973; Chapin and Seager, 1975). Ongoing studies and mapping in adjacent areas (e.g., Seager et al., 1975, 1984, 1995; Kieling, 1994) gradually broadened the geologic data and insights that the San Diego Mountain strata provide, leading to identification of the "early rift" Hayner Ranch and Rincon Valley basins (Mack et al., 1994c).

Hayner Ranch basin

As Figures 17 and 18A illustrate, the Hayner Ranch basin is interpreted to be a northwest-trending half graben that extended some 30 km from the vicinity of San Diego Mountain to the southern Palomas basin. Fault blocks of the Caballo uplift formed the footwall uplift, whereas an ancestral Sierra de las Uvas is interpreted to have made up the hanging-wall dip slope (Mack et al., 1994c). As at San Diego Mountain, and throughout its length, the basin was filled with fluvial, alluvial-fan, and playa deposits of the Hayner Ranch and Rincon Valley formations. Nearly 1.5 km thick, the two formations record a rate of sedimentation in the half graben of around 90 m/Myr between 27 and around 9 Ma.

The central outcrops on which reconstruction of the Hayner Ranch basin is based are located in the Rincon Hills, canyons draining southward from the Caballo Mountains toward the Rio Grande north and northeast of the village of Hatch, the Black Hills, badlands along the floodplain of the Rio Grande, and foothills of the Sierra de las Uvas (Fig. 1).

Outcrops in the Rincon Hills are especially informative (Seager and Hawley, 1973). Algal limestone beds exposed there near the base of the Hayner Ranch Formation are correlative with those located near the base of the formation at San Diego Mountain. In the Rincon Hills, however, interbedded fluvial clastic rocks grade downward into uppermost Thurman strata dated near 27 Ma (W. McIntosh, personal communication *in* Mack et al., 1994c), demonstrating that oldest "early rift" deposits in the Hayner Ranch Formation are probably late Oligocene in age. Basal fluvial strata are 200–300 m thick and likely correlate with alluvial-flat red beds at the base of the Hayner Ranch Formation at San Diego Mountain. The different facies may be interpreted to mean that late Oligocene fluvial systems in the Rincon Hills region drained southward from an incipient Caballo uplift and graded to alluvial-flat environments in the San Diego Mountain area. Fanglomerate first appears 200–300 m above the base of the Hayner Ranch Formation, both in the Rincon Hills (proximal facies) and at San Diego Mountain (mid-fan to distal-fan facies), suggesting that by perhaps 26–25 Ma, uplift of Caballo fault blocks was well underway. Using apatite-fission track thermochronology, Kelley and Chapin (1997) conclude that uplift of the Caballo fault blocks was well established by 15 Ma.

The half-graben geometry of the Hayner Ranch basin is confirmed by three sets of data. First is the distribution of facies within the basin. Proximal boulder fanglomerate of the Hayner Ranch Formation is exposed in a 2-km-wide belt between the Rincon Hills and the canyons north of Hatch (Fig. 23); this facies lies adjacent to footwall uplifts of Caballo fault blocks. Basinward, the same canyons expose mid-fan facies within the conformably overlying Rincon Valley Formation (Fig. 24), and in badlands adjacent to the Rio Grande floodplain, playa and alluvial-flat sedimentary rocks cap the Rincon Valley Formation from west of Hatch eastward to San Diego Mountain. Second is the onlap of basin fill onto Uvas Basaltic Andesite that formed an inferred hanging-wall dip slope on the southern side of the basin. South of Hatch at one locality on this dip slope, Hayner Ranch boulder beds fill a northward-draining paleovalley incised into Uvas Basaltic Andesite, and overlying Rincon Valley basin fill onlaps far up onto the hanging-wall dip slope of the basin (Mack et al., 1994c). South of San Diego Mountain in the West Selden Hills, similar onlap of basal Hayner Ranch fanglomerate onto eroded Palm Park Formation is believed to define the basin's southern margin there (see "Early West Selden Hills uplift"). At both localities, the onlap of basin fill onto middle Cenozoic volcanic rocks created a major unconformity that is missing from the deeper parts of the Hayner Ranch basin near the Caballo uplift (Fig. 18A). Third, except locally, all basin-fill deposits dip gently northward toward the Caballo footwall uplift, consistent with a northward-deepening half graben. Collectively, the data support the conclusion that during its lifespan from early Oligocene to late Miocene, the Hayner Ranch basin functioned as a half graben as Figures 17 and 18A portray.

As they do at San Diego Mountain, clasts in the Hayner Ranch and Rincon Valley formations record the progressive uplift and erosion of the Caballo footwall fault blocks from late Oligocene to late Miocene. Clasts in the Hayner Ranch Formation are almost entirely derived from Palm Park, Bell Top, and Uvas Basaltic Andesite, formations exposed in the Caballo Mountains footwall during the late Oligocene to middle Miocene. A transition zone, approximately 100 m thick between the Hayner Ranch and overlying Rincon Valley formations, contains distinctive, rounded, and case-hardened clasts of Paleozoic and Precambrian rocks recycled from emerging exposures of Love Ranch Formation in the footwall escarpment. Clasts of upper Paleozoic rocks increase upward in the Rincon Valley Formation, evidence that by middle to late Miocene time, Upper Paleozoic rocks comprised much of the footwall escarpments. The lack of first-cycle lower Paleozoic and Precambrian rocks within the Rincon Valley Formation indicates that uplift and erosion had yet to expose those rocks. By Pliocene time, however, they were widely exposed and deeply eroded, as evidenced by clasts in "late rift" fan deposits of the Camp Rice Formation. Not surprisingly, clasts of Cretaceous rocks are not present in the Rincon Valley Formation, except at San Diego Mountain, because they were completely eroded during the Laramide orogeny from the "structural bench" of the Rio Grande uplift; that bench subsequently became the footwall (Caballo) uplift of the Hayner Ranch basin. Finally, the content of only middle Cenozoic volcanic rocks as clasts in the Rincon Valley Formation along the southwestern flank of the Hayner Ranch half graben confirms that only those rocks were exposed in the hanging-wall dip slope throughout the life span of the half graben.

As we have noted, the Hayner Ranch and Rincon Valley formations are prevailingly conformable throughout the basin. However, in outcrops in the Black Hills (Fig. 1), a striking unconformity separates them (Seager and Hawley, 1973). The unconformity is interpreted to have formed from basinward

Figure 23. Proximal boulder fanglomerate of Hayner Ranch Formation exposed in a canyon north of Hatch, New Mexico. Clasts are Bell Top ash-flow tuff and Uvas Basaltic Andesite. Hat for scale. Outcrop is approximately 0.5 km south of Caballo uplift escarpment, which today exposes only lower and upper Paleozoic strata.

Figure 24. Mid-fan facies, Rincon Valley Formation, exposed in Rincon Hills. Red color is due to clasts of red sandstone of the Abo Formation (Permian).

stepping of faulting during the middle Miocene, tilting and erosion of Hayner Ranch fanglomerate from the uplifted (Black Hills) bench (Figs. 18A and 19), and subsequent burial of the bench by Rincon Valley fan deposits (Mack et al., in press). Basinward stepping of faulting at the same time may also have initiated the Apache Valley graben and the Red Hills fault blocks (Fig. 1; Seager and Mack, 2003).

Besides recording the culmination of sediment aggradation in the Hayner Ranch basin, the Rincon Valley Formation chronicles the initiation and growth of a new basin. Here named Rincon Valley basin ("Southern Rincon Valley half graben/basin" in Mack et al., 1994c), it lies south of but overlaps the northern margin of the Hayner Ranch basin (Figs. 18B and 19).

Rincon Valley basin

Like the Hayner Ranch basin, the Rincon Valley basin was a half graben (Fig. 18B). Unlike the Hayner Ranch basin, the Rincon Valley basin trended northerly, its orientation controlled by the course of the Ward Tank fault, the major boundary fault of the Sierra de las Uvas (Fig. 19). Thus, an incipient Sierra de las Uvas fault block formed the footwall of the half graben along its western margin, whereas 12 km to the east, the hanging-wall dip slope is interpreted to have been an ancestral Doña Ana uplift (Mack et al., 1994c). Growth of the half graben was accompanied by deposition of alluvial fans of the Rincon Valley Formation, which spread both eastward from the footwall and westward from the hanging-wall uplifts (Fig. 18B). A middle to late Miocene age for the basin is indicated by the Rincon Valley Formation's stratigraphic position above the Hayner Ranch Formation, by the major unconformity at its base, and by the 9.6 Ma Selden Basalt interbedded near the middle or top of the formation. Fragmented by faulting in latest Miocene time, the basin no longer exists, except for its rock record.

Whereas the Rincon Valley Formation is mostly conformable with underlying Hayner Ranch strata in the Hayner Ranch basin, it is strikingly unconformable with underlying rock units within the Rincon Valley basin. A basal conglomerate buried paleotopography across much of the western part of the basin, including paleocanyons incised in Bell Top or Uvas rocks. Farther east, the formation overlapped deeply eroded Palm Park or Hayner Ranch strata exposed in the footwall of the West Selden Hills fault (Figs. 15 and 18B), and merged with fan deposits that spread westward from the ancestral hanging-wall dip slope of the Doña Ana uplift. Because the constructional top of the formation is nowhere preserved, the total thickness of the Rincon Valley Formation is uncertain; 300 m or more is generally evident across the basin.

Clast size, provenance, and paleocurrent indicators were used by Mack et al. (1994c) and Kieling (1994) to recognize four sedimentary facies within the Rincon Valley half graben. A narrow, proximal alluvial-fan to talus facies accumulated adjacent to the Ward Tank fault (Figs. 25 and 26). Composed largely of meter-sized blocks of Uvas Basaltic Andesite and Bell Top ash-flow tuffs, the facies indicates that those formations were exposed in a steep footwall scarp adjacent to the fault (today those formations cap mesas 5 km or more west of the Ward Tank fault). This facies grades quickly eastward into a mid-fan facies composed of the same clasts, as well as clasts of flow-banded rhyolite derived from the eroded stubs of Bell Top rhyolite domes (illustrated in Fig. 18B as Cedar Hills vent zone domes). The Selden Basalt is interbedded with this facies in Selden Canyon (Figs. 1 and 18B). A significant aspect of this facies is the absence of clasts of Paleozoic rocks adjacent to the Robledo Mountains, an uplift in which Paleozoic rocks are widely exposed today. The easternmost facies in the basin contains distinctive clasts of metamorphic and Paleozoic rocks derived from an ancestral Doña Ana uplift, inferred to be the hanging-wall dip slope of the Rincon Valley half graben.

Figure 25. Talus or proximal-fan deposits of the Rincon Valley Formation in hanging wall of Ward Tank fault in Broad Canyon. Fault is located near base of outcrop. Clasts are entirely Uvas Basaltic Andesite and Bell Top ash-flow tuffs. Hat for scale. View looks north.

Figure 26. Talus or proximal-fan deposits in hanging wall of Ward Tank fault. Fault passes at base of cliffs and continues along base of the upturned, massive bluffs of fanglomerate across the canyon. Yellowish-brown beds to the right of bluffs are in a sliver of vertical Bell Top tuff, and to the right (west) of them is Palm Park Formation in the footwall of the fault. View looks south.

A fourth facies, typical of the overlapping northern margin of the Rincon Valley basin and southern and southeastern margin of the Hayner Ranch basin, is distinguished by clasts of mixed provenance, including the Doña Ana and Sierra de las Uvas uplifts (Mack et al., 1994c). A few kilometers south of San Diego Mountain, this facies represents fan lobes that prograded locally across the youngest playa and alluvial-flat sediments in the Hayner Ranch basin (Fig. 22).

Uppermost strata of the Rincon Valley Formation, whether they be playa deposits of the Hayner Ranch basin or alluvial-fan deposits of the Rincon Valley basin, mark the end of the life span of those closed basins. In latest Miocene time, they were segmented or at least modified by an extraordinary interval of faulting that altered the landscape dramatically.

Breakup of "Early Rift" Basins, Tonuco Uplift

Sometime between 9.6 Ma, the age of the Selden Basalt, and 5.0 Ma, the age of oldest "late rift" strata of the Camp Rice Formation, "early rift" basins were broken into several fault blocks by high-angle normal faults (Fig. 27; Chapin and Seager, 1975; Seager et al., 1984; Mack et al., 1994c). Because of the substantial thickness (50 m or more) of Rincon Valley fanglomerate that overlies Selden Basalt flows, we estimate this period of faulting to be latest Miocene (9–5 Ma).

Again, the Tonuco uplift best illustrates this interval of basin disruption and the initiation of a new generation of fault blocks. Uplift of the Tonuco horst was accompanied by folding and faulting of rocks as young as the Rincon Valley strata, whereas "late rift" sedimentary rocks that partially buried the uplift are nearly undeformed. These relationships establish an age of 9–5 Ma for initiation and most of the growth of the Tonuco horst.

The spindle-shaped Tonuco horst (Fig. 3) rose through an approximately 2.4-km-thick section of Cenozoic volcanic and sedimentary rocks, including mid- to distal-fan and playa sediments in the Hayner Ranch basin. Within that 4–5 Myr period in the late Miocene, Proterozoic rocks, formerly exposed in the core of the Laramide Rio Grande uplift, were re-exposed at the surface, and the whole Cenozoic section was removed by erosion from the horst. Along the western and southern sides of the Tonuco horst, mid- to distal-fan deposits of the Hayner Ranch and Rincon Valley formations were downfaulted against Precambrian rocks; outcrops of all three rock units form much of the modern landscape. Movement on normal faults along the boundaries of the uplift is clearly responsible for this remarkable uplift and erosion. However, evidence suggests uplift of the Tonuco horst evolved through three semi-continuous episodes of normal faulting (Fig. 28).

An early stage of uplift of the Tonuco horst is implied by two outcrops of a low-angle normal fault, one at the northwestern corner and the other at the southeastern corner of the horst (Fig. 3). The fault in these exposures strikes northwesterly and dips 10° to 35° southwest. Hanging-wall rocks above the fault consist entirely of rhyolite mudflow breccia (Bell Top Formation?), which dips 25° to 70° degrees southwest and was translated to the southwest. Footwall rocks are Precambrian granite and Palm Park volcanic rocks in the northwestern exposure (Fig. 29), and Palm Park rocks alone in the southeastern outcrop. At both outcrops, the low-angle fault is truncated by the steep (except locally) West Tonuco normal fault, which forms the western and southern boundary of the modern horst (Fig. 3). As they approach the West Tonuco fault, the rhyolite breccia beds above the low-angle fault, as well as the fault itself, steepen dramatically, apparently a drag effect caused by subsequent down-to-the-west movement along the West Tonuco fault.

Notably important are the facts that the low-angle normal fault is located within and adjacent to the footwall of the West Tonuco fault, both faults dip southwest, both are parallel in strike direction, and both are downthrown to the southwest; these relationships suggest the faults are kinematically related. Furthermore, if 25° to 30° of eastward tilt (Fig. 3) of the horst is removed, the low-angle fault is restored to its original attitude—a northwest-striking, high-angle normal fault, movement on which could have raised the Tonuco block early in its history (Fig. 28A). Continued uplift and eastward tilting of the fault block gradually flattened the fault, causing it to no longer be able to accommodate extensional strain (Fig. 28B). At that point, new high-angle faults formed, the West Tonuco and San Diego faults (Fig. 30), movement on which could permit extension and uplift to progress (Figs. 28B and 28C). We tentatively conclude that the low-angle fault was initiated around 9 Ma as a high-angle normal fault, to be replaced by the West Tonuco and San Diego faults as the original fault was rotated to a low-angle position. A similar evolution of rift faults elsewhere has been well documented (e.g., Proffett, 1977; Chamberlin, 1983; Ricketts et al., 2015).

It is difficult to understand how uplift of a horst could be accompanied by significant tilting in one direction, eastward in this case. We speculate that movement on the low-angle fault and subsequently on the West Tonuco and probably the San Diego fault was accompanied by eastward rotation of the fault block, perhaps into a speculative Hayner Ranch boundary fault located east of the horst as Figure 27 suggests (T. Lawton, personal communication, 2022). Later, a newly formed Jornada fault broke the eastern part of the tilted fault block, creating the eastern boundary of the Tonuco horst (Fig. 28C). If this interpretation is correct, the three faults document three stages in the growth of the Tonuco horst.

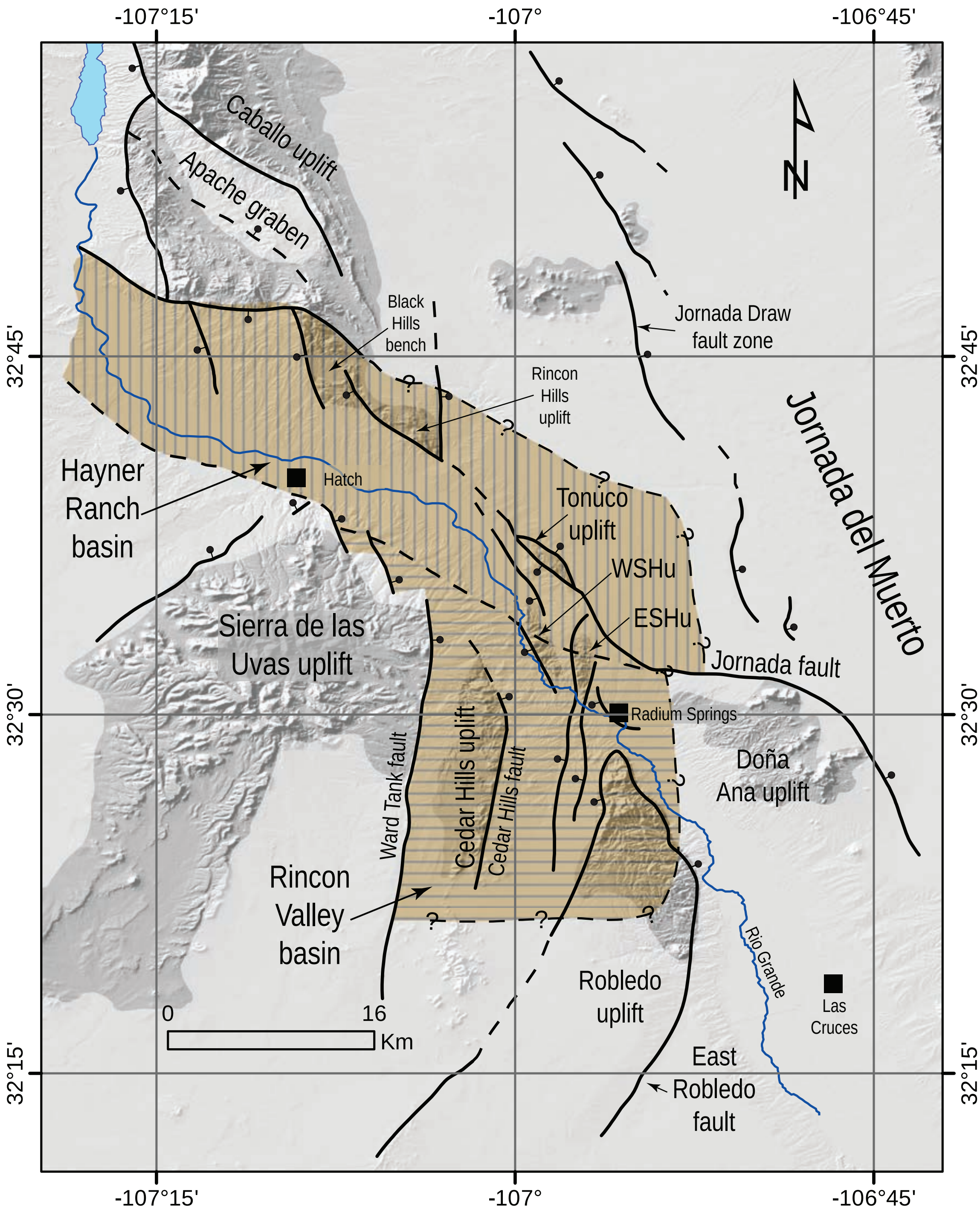


Figure 27. Latest Miocene fault blocks that broke up the "early rift" Hayner Ranch and Rincon Valley basins. Jornada Draw fault zone is interpreted to have been initiated in Plio-Pleistocene time (Seager and Mack, 1995). WSHu = West Selden Hills uplift, ESHu = East Selden Hills uplift.

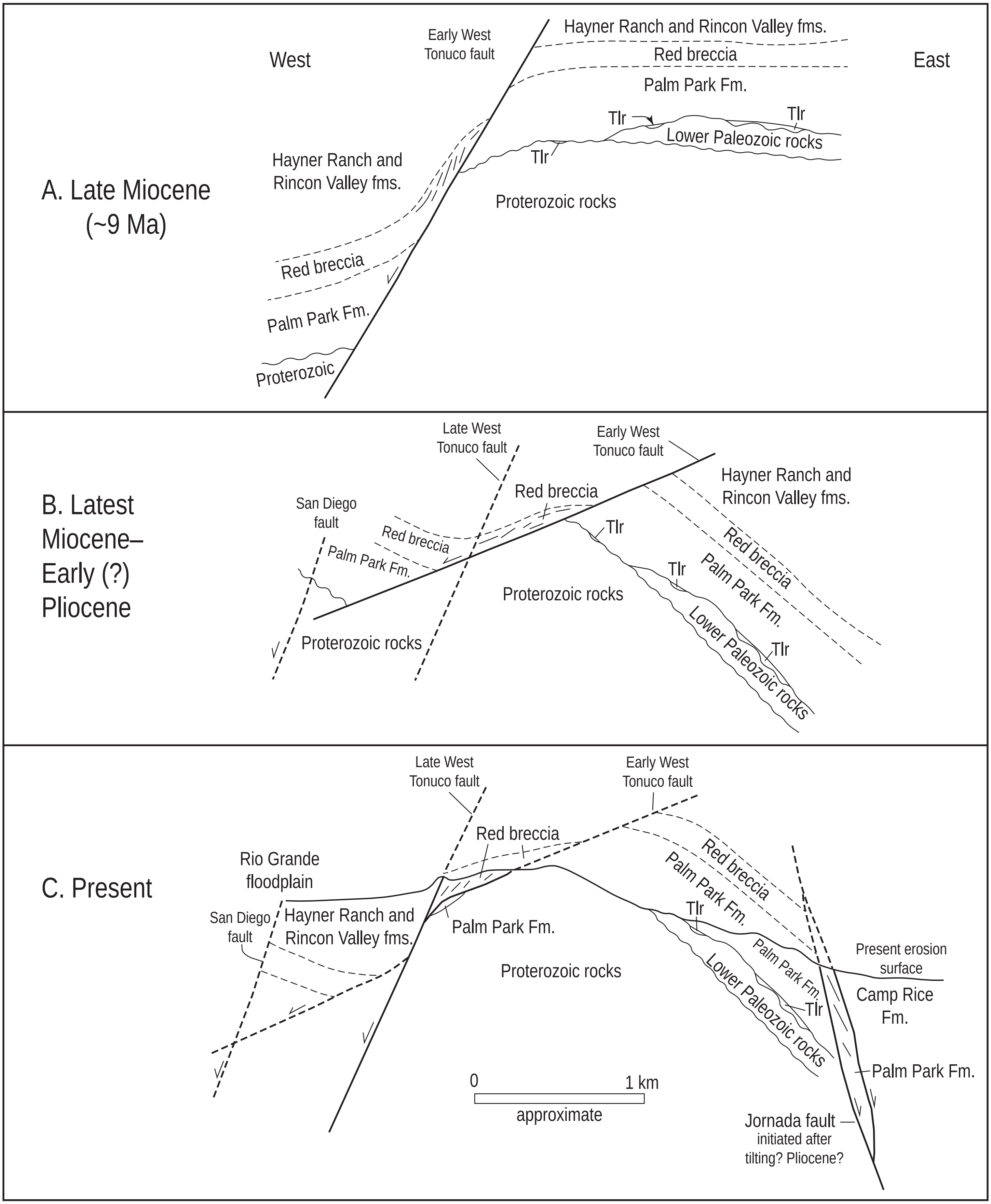


Figure 28. Possible evolution of the Tonuco horst. A: Initial uplift of the Tonuco fault block is accompanied by forced folding of sedimentary rocks across the fault. B: Eastward rotation of the fault block flattens original boundary fault, making it incapable of accommodating continuing strain. Two new high-angle faults (West Tonuco and San Diego faults) replace the inactive one and accommodate further uplift of the fault block. The inactive fault remains on the uplift as a low-angle normal fault. C: The Jornada fault is initiated; movement on it transforms the tilted fault block into a horst. Tlr = Love Ranch Formation.

Figure 29. Low-angle normal fault exposed on northwestern part of Tonuco uplift. West-dipping rhyolite breccia beds above the fault overlie purple Palm Park volcaniclastic rocks below the fault. Yellow outcrop is Precambrian granite, nonconformable beneath Palm Park strata. Location is the same as Figure 6, but looking north.

Figure 30. Jornada fault. Light-colored fluvial sandstone of the Camp Rice Formation is faulted against Precambrian granite, the latter in the hanging wall of the thrust fault of Figure 8. View looks west at mouth of Picture Rock Canyon.

Breakup of "Early Rift" Basins, Regional Perspective

Late Miocene segmentation of "early rift" basins extended well beyond the San Diego Mountain area (Fig. 27). This faulting everywhere deformed the Rincon Valley fan and playa deposits in both the Hayner Ranch and Rincon Valley basins. Like the Tonuco uplift, many of the intrabasin uplifts rose through central to distal parts of the "early rift" basins. Except for the low-angle fault on the Tonuco uplift, all of the intrabasin faults are high-angle normal faults with stratigraphic separation ranging from tens of meters to 2 km or more along the West Tonuco and other faults. Horsts, grabens, tilted fault blocks, and half grabens—all were a product of the fragmentation of the basins. Even unbroken parts of basins were deformed by modest tilting of basin deposits that rotated toward footwall faults. Movements along the boundary faults of the Caballo and Sierra de las Uvas uplifts also broke or otherwise deformed Rincon Valley strata, demonstrating that older uplifts continued to grow even as younger structures were initiated within the "early rift" basins. Broad uplift probably accompanied breakup of the "early rift" basins. Even today, the region between the southern Caballo and Robledo mountains is a structurally high, faulted corridor along which the Rio Grande follows.

Much of the Hayner Ranch basin was broken by normal faulting that stepped basinward from the Caballo uplift. The Rincon Hills, Red Hills, Apache graben, and other smaller structural benches, as wells as the Tonuco uplift, are examples (Fig. 27; Seager and Mack, 2003).

Similarly, the Rincon Valley basin was fragmented by normal faulting. The Robledo horst, one of the major uplifts in south-central New Mexico, rose through the eastern parts of the basin, breaking through the Rincon Valley Formation.

In the Selden Canyon area, the eastward-tilted East and West Selden Hills and westward-tilted Cedar Hills uplifts form a broad, faulted arch (Fig. 15), interpreted by Mack and Seager (1995) to be a transfer zone between overlapping, oppositely dipping segments of the West Robledo/East Selden Hills and Ward Tank faults (Fig. 27). If so, breakup of the Rincon Valley basin and uplift of the Selden Canyon area is a product of the extension created by the transfer of throw between these two major fault zones.

Uplift and disruption of the "early rift" basins 9–5 Ma dramatically altered geological processes that had been operating continuously or haltingly throughout the latest Oligocene and much of the Miocene. Drainage patterns of early closed basins were modified, gradually reorganized, and adjusted to new fault-block topography. Sedimentation in the early closed basins progressively ceased as sediment was moved by new drainage systems into basins not affected by the uplift and fragmentation of the older ones, and an erosional regime was initiated. "Early rift" basin deposits were stripped away over large areas, leaving no record of the last stage of basin fill in the Rincon Valley Formation. The latest Miocene fault blocks were eroded as they rose, with erosion digging deep into older rocks, even to the Precambrian rock core of the Rio Grande uplift, which is exposed now on the Tonuco uplift. As we have seen, a thickness of approximately 2.4 km of middle to upper Cenozoic rocks was removed by erosion from the Tonuco uplift in late Miocene time, lesser amounts elsewhere.

Interestingly, no sedimentary record of this late Miocene (9–5 Ma) interval of faulting and erosion is exposed in south-central New Mexico. Presumably it is hidden within some of the deeper, unbroken, more continuously subsiding basins in the region, probably conformable with underlying Rincon Valley deposits and overlying "late rift" sediments. The Palomas, Jornada del Muerto, and southern Mesilla basin are good candidates for where the latest Miocene sedimentary record might be preserved. At any rate, by the end of the Miocene, the broad, closed "early rift" basins were replaced by a rough and broken landscape, a landscape that would soon be buried by the "late rift" deposits of the Camp Rice Formation. A striking angular unconformity now separates the deformed and eroded older rocks from the relatively undeformed Camp Rice strata.

"Late Rift" Deposits, Camp Rice Formation

From the Hatch area southward into Texas, "late rift" deposits are assigned to the Camp Rice Formation (Strain, 1966). Radiometric ages of basalt, tephra, pumice-clast conglomerate, and mammalian remains and reversal magnetostratigraphy have established its age from near 5.0 to 0.78 Ma (e.g., Hawley et al., 1969; Bachman and Mehnert, 1978; Mack et al., 1993, 1996, 1998b). Where it is exposed in south-central New Mexico, the base of the formation is a conspicuous unconformity (Fig. 22).

Much of our understanding of the Camp Rice Formation is based on the pioneering work of Kottlowski (1958), Ruhe (1964), and Strain (1966), the latter having named the formation, as well as Hawley and Kottlowski (1969) and Hawley (1975, 1981), among others. More recent studies, including Mack and Seager (1990), Mack and James (1993), and Mack et al. (1994a, 1996, 1998b), have added further insights into the formation's importance. A thorough review of both older and recent studies of the formation is presented in Mack et al. (2006).

The formation is especially significant because it documents the entry into southern New Mexico of an "ancestral" Rio Grande, a river system that linked Rio Grande rift basins to the north with the basins in south-central New Mexico and westernmost Texas (Ruhe, 1962; Hawley et al., 1969; Mack et al., 2006; Repasch et al., 2017; Ridl et al., 2019). In southern New Mexico, the river spilled into four intermontane basins and buried lowest parts of the basins with fluvial sediment in the process. At the same time, piedmont-slope deposits, including widespread alluvial fans, spread toward the river system, interfingering with the fluvial deposits. Thus, different facies of the Camp Rice Formation were deposited across a broad swath of south-central New Mexico, even across the Jornada, southern Tularosa, and northern Hueco basins, which today are without through-going drainage.

Alluvial-fan facies in the Camp Rice Formation, as well as the faults that transect them, bear witness to the continuing rise of fault-block uplifts in the southern Rio Grande rift throughout the Pliocene and the early part of the Pleistocene. Their clast content invariably reflects rock units exposed today in footwall escarpments or in hanging-wall dip slopes. But we shall restrict our account of the Camp Rice Formation to its special relevance near San Diego Mountain and adjacent areas.

Outcrops of the Camp Rice Formation near San Diego Mountain are almost entirely fluvial in origin, deposited by the ancestral Rio Grande. Best exposed in the bluffs south (Fig. 22), east, and north of the mountain, the fluvial sediment includes multistory deposits of sand, gravelly sand, sandstone, and interbedded floodplain clay and silt lenses, approximately 100 m thick. Soil carbonate is well-developed in many horizons in the sequence and indicates periods of landscape stability, particularly on floodplain sediment. Locally, fluvial deposits onlap the eastern part of the Tonuco horst and are also faulted against it (Fig. 30). Thin piedmont-slope deposits, derived from the Tonuco horst, intertongue with the fluvial deposits along the east side of the uplift, and a few remnants of pediment gravel occur on the uplift itself. The constructional top of the deposits, the La Mesa surface, survives now as the floor of the Jornada del Muerto basin east of the uplift. It is underlain by stage IV soil carbonate as much as 1 m thick (Gile et al., 1981). When this surface is projected over the Tonuco uplift, it is clear that much of the Tonuco horst and all of the surrounding "early rift" strata were buried by fluvial deposits by 0.78 Ma. In fact, onlap of the fluvial deposits onto the horst can be viewed in the eastern wall of Picture Rock Canyon (Fig. 3). By 0.78 Ma, surrounded by a fluvial plain of braided channels and floodplains, San Diego Mountain was a low, flat-topped island awash in a sea of sand and gravel (Seager et al., 2021).

Similarly, the low-lying Rincon Hills were partly buried by fluvial strata, but farther south, the structurally and topographically high corridor created by the latest Miocene fault blocks restricted the course of the ancestral Rio Grande. A thickness of only 10–15 m of fluvial Camp Rice strata was deposited across the "transfer zone" of fault blocks in the Selden Canyon area and west of the Robledo Mountains (Seager et al., 1975, 2008). Apparently, these channels represent a short-lived excursion by the river from its main course east of San Diego Mountain into the Mesilla and Jornada del Muerto basins. These thin fluvial deposits were quickly buried by thin Camp Rice piedmont-slope and pediment veneers that spread eastward from the Sierra de las Uvas.

Huge Camp Rice alluvial fans built basinward from all of the major fault blocks in the southern Rio Grande rift, and many have been sufficiently dissected by younger drainage to reveal their internal architecture (e.g., Seager and Mack, 2003). Particularly instructive are the well-exposed fans that are faulted against the eastern footwall of the Robledo uplift. As much as 60 m thick adjacent to the East Robledo fault (Fig. 27), the proximal fan gravels are interbedded with fluvial deposits. Mack and Seager (1990) concluded that repeated fault movements along the East Robledo fault during the Pliocene and early Pleistocene are recorded by tongues of fan gravel within the fluvial sediment. Furthermore, subsidence of the hanging wall continually forced the course of the Rio Grande toward the footwall of the Robledo uplift, where it remains today.

Post-Camp Rice Deposits

Whereas the Camp Rice Formation documents an aggradation stage in the evolution of the southern Rio Grande rift basins, a general degradation regime has existed for the last 0.78 Myr, at least along the course of the Rio Grande (Ruhe, 1962; Hawley and Kottlowski, 1969; Hawley et al., 1976; Hawley, 1981). Repeated episodes of downcutting and backfilling have produced a stepped sequence of terraces along sidewalls of the Rio Grande valley throughout its length. As many as five terraces have been recognized (e.g., Keyes, 1907; Ruhe, 1967; Gile et. al, 1981; Sion et al., 2020), each the constructional surface of backfilled sediment. Today, the Rio Grande is entrenched approximately 100 m below the La Mesa surface, the constructional top of the Camp Rice Formation. The broad Hatch and Mesilla valleys, the narrow Selden Canyon, the exhumation of the Tonuco uplift, and the incision of numerous tributary canyons to the Rio Grande through Camp Rice strata into older bedrock—all are a consequence of the river's entrenchment over the last 0.78 Ma (Repasch et al., 2017). And climate appears to be a crucial factor in shifting the Rio Grande to a degradation regime (Metcalf, 1967; Hawley and Kottlowski, 1969; Hawley et al., 1976).

According to Gile et al. (1981) and Mack et al. (2006), ice volumes in the northern hemisphere, as well as climatic oscillations of 0.1-Myr glacial–interglacial cycles (Repasch et al., 2017), increased around 0.95–0.80 Ma to a critical threshold. As a result, waxing and full glacial periods promoted a high ratio of water runoff to sediment load, resulting in episodes of river entrenchment. In contrast, waning glacial and interglacial intervals saw high sediment loads being moved by an underfit river, causing deposition on valley floors.

Although the Rio Grande removed huge volumes of sediment from its inner valley during the middle and late Pleistocene, broad alluvial fans continued to aggrade on piedmont slopes, particularly adjacent to major uplifts, such as the Caballo and Sierra de las Uvas uplifts. Because fans were always graded to the level of the river's floodplain, several generations of fans formed, almost all inset below Camp Rice fans, and younger fans inset below older ones, a result of the river's progressive lowering of the local base level.

Uplift of major fault blocks in south-central New Mexico continued through the Pleistocene, even into the late Holocene. This is most evident from piedmont scarps that offset alluvial fans as young as late Holocene (e.g., Gile, 1987; Machette, 1998) and by deformed Camp Rice strata, as well as the La Mesa surface. Fault scarps, as much as 10 m in height, transect Camp Rice fans along the range-boundary faults of the Caballo and Sierra de las Uvas uplifts and elsewhere. Camp Rice strata are often dragged or tilted against these active faults; even the La Mesa surface is locally deformed, a good example being the broad warping of the surface along the Jornada fault between the Tonuco and Doña Ana uplifts, transected by Interstate 25 just north of the town of Radium Springs (Fig. 27). Collectively, the deformation indicates that the Rio Grande rift has continued to be active in the last 5 Myr and up to the present, but perhaps has slowed relative to the remarkable deformation that reorganized rift structure from 9–5 Ma.

Summary and Discussion

Outcrops of Laramide structures, sedimentary rocks, and unconformities at San Diego Mountain and adjacent ranges demonstrate that Laramide shortening in south-central New Mexico resulted in uplift of a huge basement-cored block uplift, named the Rio Grande uplift. Its west–northwest trend and northeastward vergence are consistent with most of the other Laramide block uplifts in southern New Mexico, suggesting northeastward-directed shortening of the crust (Seager, 2004). Overall, the geometry of the Rio Grande uplift and its adjoining deep basins resembles in style, and perhaps in dimensions and structural relief, some of the Laramide uplifts and basins of the Wyoming foreland. Furthermore, growth of the Rio Grande uplift correlates temporally with the evolution of Wyoming's Laramide basins and uplifts, i.e., latest Cretaceous to early Eocene.

Laramide deformation across the western U.S. is generally accepted to be the result of low-angle subduction of the Farallon Plate (Dickinson and Snyder, 1978; Bird, 1988; Dickinson et al., 1988). Hypotheses to explain low-angle subduction fall into three categories: increased rate of convergence between the Farallon and North American plates (Jurdy, 1984; Engebretson et al., 1984); subduction of young, buoyant lithosphere as the Farallon/Kula Plate spreading center approached the subduction zone (Engebretson et al., 1985); and subduction of a buoyant oceanic plateau (Livaccari et al., 1981), more recently designated the conjugate Shatsky Rise oceanic plateau (Liu et al., 2010; Heller and Liu, 2016; Copeland et al., 2017). The role that the flat slab played to impart contraction of western North America ≥1,000 km from the Cretaceous–Paleogene plate margin remains a point of discussion. Two current end-member models that may account for inboard contraction are basal traction (Dickinson and Snyder, 1978; Bird, 1984, 1998; Heller and Liu, 2016; Copeland et al., 2017; Lawton, 2019) and plate margin end load (Livaccari and Perry, 1993; Axen et al., 2018; Jackson et al., 2019). Other models consider segmentation or deformation of the slab (e.g., Saleeby, 2003).

Shallow subduction seemingly had two major effects in south-central New Mexico. First, traction or coupling between the subducting slab and the overlying crust initiated intraplate, northeasterly directed compression, resulting in uplift of basement-cored blocks and subsidence of yoked basins, such as the Laramide Rio Grande uplift and Love Ranch and Potrillo basins. Second, volcanism was nearly shut down between 73 and 46 Ma, although some "late Laramide" intrusives were emplaced in the Silver City region around 60–55 Ma (McMillan, 2004; Amato et al., 2017) along the southern boundary of a Laramide segment (Saleeby, 2003).

Outcrops at San Diego Mountain and elsewhere across southern New Mexico also show that the Rio Grande uplift was deeply eroded into Precambrian basement along its northeastern margin and buried, first by its own debris (the Love Ranch Formation) and, after 46 Ma, by thick lavas of intermediate composition and associated lahar deposits of the Palm Park and Rubio Peak formations. The widespread unconformity that separates those formations from the deformed and eroded underlying rocks

(Fig. 31) demonstrates that Laramide deformation had ceased long before 46 Ma. This contrasts with recent conclusions that Laramide tectonism in southwestern New Mexico continued into the Oligocene (Copeland et al., 2011, 2017) as late as 30.9 ± 0.5 Ma (Tomlinson et al., 2013).

Hinge rollback or some other kind of foundering of the Farallon Plate probably resulted in the cessation of Laramide compression long before 46 Ma (e.g., Coney and Reynolds, 1977; Humphreys, 1995; Dickinson, 2009). By 46 Ma, the formerly shallowly dipping Farallon Plate had steepened sufficiently to once again interact with the asthenosphere, thereby triggering arc volcanism, recorded by calc-alkaline lavas and lahars of the Palm Park and Rubio Peak formations. Emplaced between 46 and 36 Ma, the chemistry and mineral composition of the lahars and lavas are consistent with those of continental arcs (McMillan, 2004; Chapin et al., 2004a; Creitz et al., 2018). Although the exact locations of arc volcanoes in southern New Mexico are difficult to identify, owing mostly to younger deformation and burial over wide areas, thick lava sequences, very coarse-grained lahars, cinder cones, and intrusive/extrusive complexes may be interpreted in places to represent the remnants of andesitic eruptive centers (Fig. 11). Lahars associated with these volcanic highlands spread widely, accumulating to as much as 600 m thick in inter-volcano lowlands, such as the future Goodsight–Cedar Hills paleovalley. Fossil evidence indicates that the lowlands supported subtropical flora, suggesting relatively low elevations (500 m or less?) between volcanic edifices, an environment that persisted throughout the late Eocene.

During the late Eocene and early Oligocene, the Goodsight–Cedar Hills paleovalley was gradually filled with a thickness of nearly 500 m of outflow ash-flow tuff sheets and both syn- and post-eruptive volcanic sediment, all assigned to the Bell Top Formation. Collectively, the width-to-depth ratio of the paleovalley (70:1), the low sedimentation rate (ca. 30 m/Myr),

Figure 31. Angular unconformity between red beds in the Abo Formation (Permian) and basal beds of Palm Park strata, Broad Canyon. The steep dip of Abo beds resulted from deformation within the Laramide Rio Grande uplift, whereas the shallow west dip in Palm Park beds is a result of Miocene uplift and west tilting of the Sierra de las Uvas fault block. View looks north.

the geometry and composition of the basin fill, and the absence of faulting along its margins are consistent with progressive filling—over a span of 8 Myr—of a tectonically stable intermontane valley rather than an active half graben as Mack et al. (1994b) proposed.

The northern part of the paleovalley is less well understood. It may simply be a broad piedmont slope extending eastward from the eastern slopes of the Emory caldera, buried by the youngest outflow tuffs, fluvial conglomerate, and sandstone of the Bell Top Formation.

The Bell Top outflow tuffs, as well as the circa 36 Ma ignimbrites of the Emory, Organ, and Doña Ana calderas, represent the "ignimbrite flare up" of Coney (1978) in south-central New Mexico. Closely following and perhaps somewhat overlapping earlier andesitic arc volcanism, the "ignimbrite flare up" is viewed by some geoscientists as a brief transition into an extensional regime, even as the beginning of the Rio Grande rift (Cather, 1990; Mack et al., 1994b, 1994c; McMillan, 1998; McMillan et al., 2000; Mack, 2004; Chapin et al., 2004b; Copeland et al., 2011; Ricketts et al., 2016; Hampton et al., 2018). Others, working in both New Mexico and across the western Cordillera, cite evidence that the "ignimbrite flare up" was accompanied by little or no regional extension (e.g., Lipman et al., 1978; Chamberlin, 1983; Best et al., 2016). And in the northern Sierra Madre Occidental, Bryan and Ferrari (2016) conclude that significant extension, marked by the eruption of basaltic andesite (SCORBA of Cameron et al., 1989), began around 29 Ma *during* a major pulse of ignimbrite volcanism.

Based on our analysis of the character of the Bell Top Formation, extension in south-central New Mexico was either nonexistent or weak during both preceding arc volcanism and the "ignimbrite flare up," and remained so until about 30–28 Ma. The slow rate of sedimentation (30 m/Myr) in the Goodsight–Cedar Hills paleovalley; the widespread and thin outflow sheets of ash-flow tuff like the Kneeling Nun Tuff, which apparently encountered no topography of extensional origin; the near absence of basalt; and the amagmatic character of the region between 33.6 and 28.6 Ma seem consistent with a non-extending crust until near 30 Ma.

As elsewhere across the southern Cordillera of North America, middle to late Eocene volcanism spanning southern New Mexico represents a style of arc volcanism that resulted from steepening, rollback, and perhaps foundering of the Farallon Plate together with delamination of lithospheric mantle (Lipman et al., 1972; Coney, 1978; Lipman, 1980; Best and Christiansen, 1991; Best et al., 2016). Whereas middle Eocene stages of slab steepening formed the familiar arc of intermediate-composition volcanoes (Palm Park/Rubio Peak) well inland of the trench, we view the "ignimbrite flare up" in south-central New Mexico to be its culminating event.

Among others, Best et al. (2016), Syzmanowski et al. (2019), and Lipman et al. (2022) have suggested a stepped process by which large volumes of eruptible silicic magma may form in continental arcs: (1) basaltic magma is produced by partial melting of the foundering slab and/or decompression melting of upwelling mantle above or inboard of the slab; (2) the rise of basaltic magma may partially melt a nonextending, hydrated crustal lithosphere; (3) the diapir-like rise of mixed mafic and silicic melt eventually accumulates in magma chambers at relatively shallow depths; and (4) after 1–2 Myr or more of "incubation and maturation," large volumes of silicic magma are erupted explosively as ignimbrite.

By early Oligocene time (ca. 30 Ma), volcanism in the Mogollon–Datil volcanic field, as well as in the northern Sierra Madre Occidental, became increasingly bimodal basalt/rhyolite (Chapin et al., 2004a, fig. 2; Bryan and Ferrari, 2013), which these authors interpret to indicate the onset, or dramatic acceleration, of crustal extension. Gavel et al. (2021) arrived at the same conclusion from their thermochronological studies in the southern Rio Grande rift. The flood basalts of the Uvas Basaltic Andesite and Bear Springs Basalt are also convincing evidence that a strong extensional regime was established across southern New Mexico by 28 Ma. Numerous dikes, some of which merge upward into flows, suggest that fissures were a common mode of eruption. The prevailing northwesterly trend of dikes indicates that east-northeast-west-southwest directed extension prevailed near 28 Ma. Like the upper Eocene ash-flow tuffs, flows of basaltic andesite spread across broad areas, even far into Mexico (Cameron et al., 1989), without "encountering" significant extensional topography, building instead a widespread plateau-like surface reminiscent of the Columbia Plateau of the Pacific Northwest. Locally, however, fissure eruptions may have evolved into incipient fault blocks, as suggested by the cinder cone and Coyote Canyon Fanglomerate exposed in the Cedar Hills (Figs. 14 and 15).

According to McMillan (1998) and McMillan et al. (2000), the Uvas Basaltic Andesite, Bear Springs Basalt, and other basaltic andesite of the Mexican border region (SCORBA basalts of Cameron et al., 1989) originated by partial melting of slightly hydrated lithosphere. Transfer of heat to the lithosphere was a result of a rising asthenosphere that replaced the rolled back or foundering Farallon slab. Thus, the back-arc position of south-central New Mexico during the early to middle Oligocene fostered both magmatism and extensional stresses (Lipman, 1980, 1981; Seager et al., 1984).

Earliest signs that extension might have produced broad sagging of the upper crust come from the Thurman Formation in the southern Caballo Mountains. As much as 500 m thick, the formation was deposited between 27.4 and 27.0 Ma, a rate of sedimentation (1,250 m/Myr) that suggests deposition was accommodated by significant extension and subsidence of the crust. We suspect this subsiding basin (Fig. 14) might be a precursor to the major late Oligocene and Miocene "early (Rio Grande) rift" half grabens of south-central New Mexico.

By late Oligocene (26–25 Ma), extension in the southern Rio Grande rift was well underway, a conclusion long recognized (e.g., Hawley et al., 1969; Chapin and Seager, 1975; Seager et al., 1984) and consistent with recent studies (Ricketts et al., 2016; Gavel et al., 2021). Uplift of the Caballo Mountains and complementary subsidence of the "early rift" Hayner Ranch basin was in progress, as well as nascent movement along the West Selden Hills fault (Fig. 15). By middle Miocene, basinward-stepping faults began to break up the Hayner Ranch basin, forming the Black Hills bench (Seager and Hawley, 1973; Mack et al., in press), as well as the Red Hills and Apache graben blocks (Figs. 1 and 15; Seager and Mack, 2003). At the same time, initial uplift of the Sierra de las Uvas and Doña Ana uplift is recorded by the alluvial-fan deposits of the Rincon Valley Formation, which accumulated in the new "early rift" Rincon Valley basin. Sedimentation rates in the "early rift" basins were approximately 90 m/Myr. Eruption of alkali-olivine basalt at 9.6 Ma, including the Selden Basalt within the Rincon Valley basin, probably signals a critical thinning of the lithosphere and decompressional, partial melting of a rising asthenosphere wedge.

A possible culmination of rifting in late Miocene time (9–5 Ma) resulted in the complete segmentation of the Rincon Valley basin and further breakup of the Hayner Ranch basin, including the rise of the Tonuco horst through a thickness of nearly 2.4 km of Cenozoic rocks. An exceptional amount and perhaps rate of extension may have accompanied uplift of the Tonuco horst, indicated by the uplifted and rotated low-angle normal fault in the range. Similar low-angle faults in other ranges of southern New Mexico demonstrate that the rotation and abandonment of early formed range-boundary faults was not uncommon (e.g., Chamberlin, 1983; Kelley and Matheny, 1983; Seager and Mack, 1994; Ricketts et al., 2015). Throughout the latest Oligocene and most of the Miocene (a span of nearly 18 Myr), earliest uplifts, such as the Caballo fault blocks, continued to rise at least semi-continuously, recorded by the deposits of the Hayner Ranch and Rincon Valley formations and by apatite fission-track data (Kelley and Chapin, 1997).

Widespread and deep erosion followed the latest Miocene fragmentation of the Hayner Ranch and Rincon Valley basins, and around 5 Ma an "ancestral" Rio Grande entered south-central New Mexico. By 0.78 Ma, fluvial and alluvial-fan deposits of the Camp Rice Formation accumulated to near 100 m thick (or much more at basin centers), burying lower parts of the former topography. By their clast content, the fan deposits record the continuing uplift and erosion of fault blocks to essentially their present contours. Whereas the Camp Rice Formation documents an aggradation stage in the development of southern Rio Grande rift basins, the middle and late Pleistocene is characterized by a degradation regime, driven by climatic changes. Entrenchment of the Rio Grande into its present valley, beginning around 0.78 Ma, was distinguished by alternating periods of downcutting and backfilling, driven by glacial cycles, and resulted in a spectacular series of stepped terraces along the valley sideslopes.

Unlike Laramide contractional deformation in south-central New Mexico, which produced narrow zones of overturned and thrust-faulted strata, late Cenozoic deformation was characterized by homoclinal dips, the result of simple isostatic uplift and tilting of fault blocks or by rotation of strata into listric faults. Extensional folds do exist and they are well developed in some of the fault blocks of the Caballo Mountains (Seager and Mack, 2003). In every case of folding of middle Eocene and younger rocks, the folding is a product of draping or forced folding associated with normal faults, or with simple drag adjacent to such faults. A good example is the Sierra de las Uvas dome, a product of westward tilting of the uplift and broken, eastward-dipping forced folds associated with normal faults along its eastern flank.

Fault movements have certainly continued over the last 5 Myr. Pleistocene or younger movements are indicated by locally warped or tilted Camp Rice and Palomas strata as well as by piedmont scarps that displace fan surfaces as young as late Holocene (Gile, 1987; Machette, 1987). While most scarps can be attributed to renewed displacement along pre-existing faults, new faults, such as the Jornada Draw fault (Fig. 27), perhaps were initiated as late as the latest Pliocene or early Pleistocene (Seager and Mack, 1995).

Debate about the origin of forces driving the acceleration of extension about 30 Ma and transition into full continental rifting near 27–26 Ma has continued for more than 45 years. Ricketts et al. (2016) critique the various models, which include collapse of over-thickened crust at the end of the Laramide orogeny (e.g., Cordell, 1978; Eaton, 1986; Coney, 1987; Axen et al., 1993), rotation of the Colorado Plateau away from the Great Plains (Hamilton, 1981; Chapin and Cather, 1994), shear and transtension created in the western United States by the initiation of right-lateral movement on the San Andreas fault system (Dokka and Ross, 1995; Dickinson and Wernicke, 1997), and, finally, a group of models that would relate the evolution of the rift to upwelling mantle behind or around and above the rollback, delamination, or other fragmentation of the Farallon Plate or lithosphere, following the Laramide orogeny (e.g., Coney and Reynolds, 1977; Dickinson and Snyder, 1979; Humphreys, 1995, 2009; Moucha et al., 2008; van Wijk et al., 2008; Ricketts et al., 2016). The latter group of models suggests "active" extension beginning in the late Eocene with the "ignimbrite flare up" and continuing through the continental rifting process. In contrast, "passive" rifting is largely transtensional and would follow the development of the San Andreas fault system near 30 Ma. In this regard, the apparent acceleration or initiation of extension in southwestern New Mexico and northern Mexico near 30 Ma might support the transtension model. Alternatively, mantle upwelling and transtension may have operated together after 30 Ma (Coney, 1987).

Whatever the ultimate cause of extension leading to the Rio Grande rift, one important result has been epeirogenic uplift along its entire length, from Colorado to southern New Mexico (Eaton, 2008). Eaton (1986, 1987) referred to the uplift as "Alvarado Ridge" and later as "the epeirogen" (Eaton, 2008). Although Eaton (2008) suggests that as much as 2,000 m of uplift affected the northern part of the epeirogen, we estimate at least 800 m of epeirogenic uplift since the late Eocene in southern New Mexico. Eaton (2008) concludes that uplift resulted from thinning of the lithosphere in response to 20–25 Myr of extension, rise of the asthenosphere accompanied by crustal heating, and inflation of the crust by low-density, middle Cenozoic plutons.

Conclusions

Our goal in this paper is to review geologic evidence for the tectonic evolution of south-central New Mexico during the Cenozoic era, and to show how important the outcrops at San Diego Mountain (Fig. 32) are in understanding that story. Equally important are the splendid outcrops in adjacent ranges like the Caballo Mountains and Sierra de las Uvas, which expose an essentially continuous rock record of south-central New Mexico's tectonic evolution between about 46 to 9 Ma. Choosing between geodynamic models of Laramide, middle Cenozoic, or rift evolution is not our intent. The conclusions we present below are meant to focus on a group of new insights or interpretations—or to restate old ones—that may be of value in designing future geodynamic models for the southern New Mexico border region.

1. The Laramide uplifts and basins in south-central New Mexico were comparable in size and style to those of Wyoming and are approximately the same age.
2. Laramide basement-cored block uplifts were deeply eroded, locally to basement, and at least partly buried by their own debris by 46 Ma, probably a few Myr earlier. That is, the Laramide orogeny in south-central New Mexico was essentially no longer active before 46 Ma.
3. The "ignimbrite flare up" in south-central New Mexico may represent a culmination of andesitic arc volcanism around 36–35 Ma.
4. The Goodsight–Cedar Hills "depression" is a broad, shallow, late Eocene to early Oligocene paleovalley and piedmont slope, not a volcano-tectonic depression nor an "early rift" half graben. Sedimentation rates (30 m/Myr or less) in the paleovalley were much lower than in the rift basins that followed in the late Oligocene and Miocene.
5. Between 36 and about 30 Ma, south-central New Mexico experienced either a neutral stress state or very weak extensional strain.
6. Accelerating extension, beginning around 30 Ma, was followed by eruption of the 28 Ma flood basalts of the Uvas Basaltic Andesite and Bear Springs Basalt. Local fissures may have developed into the earliest fault blocks of the Rio Grande rift, suggested by the Coyote Canyon Fanglomerate.
7. The thick Thurman Formation may record the earliest Rio Grande rift basin in south-central New Mexico at 27.4–27.0 Ma; sedimentation rate in the basin exceeded 1,000 m/Myr.
8. Fault uplift of Rio Grande rift ranges and subsidence of "early rift" half grabens in south-central New Mexico were in progress by 26–25 Ma. Sedimentation rates in "early rift" half grabens were around 90 m/Myr.

9. By 9.6 Ma, extensional thinning of the lithosphere was sufficient to permit asthenosphere-derived basalt to be erupted.

10. A culmination of rifting 9–5 Ma resulted in uplift and fragmentation of "early rift" basins. Involving an area of more than 1,400 km^2, the deformation involved both basinward stepping of faulting as well as rifting within an important fault transfer zone.

11. Fault uplifts and basins were initiated at different times within the southern Rio Grande rift: late Oligocene, middle Miocene, late Miocene, and probably Pliocene. At least segments of early uplifts, like the Caballo uplift, rose semi-continuously from late Oligocene to the present as recorded in the deposits of the Hayner Ranch, Rincon Valley, and Camp Rice formations, and by Pleistocene and Holocene piedmont scarps.

12. Low-angle normal faults, such as the structure on the Tonuco horst, are not uncommon in the southern Rio Grande rift, and some may be interpreted to be early range-boundary faults that have been rotated, abandoned, and uplifted to become part of the uplift's footwall structure. As elsewhere in the Basin and Range province, these faults may indicate local, large amounts, and perhaps rapid rates of extension.

13. Folds in volcanic and sedimentary rocks younger than 46 Ma are a product of draping, forced folding, or simple drag and are always associated with exposed or inferred upper Cenozoic normal faults.

14. Epeirogenic uplift of the southern Rio Grande rift commenced after the late Eocene in concert with the initiation and evolution of the Rio Grande rift; at least 800 m of uplift has accumulated.

Figure 32. Flat-topped San Diego Mountain in distance with northern part of West Selden Hills at upper right and the Rio Grande in foreground. The bluffs at the water's edge below San Diego Mountain and rising to the upper right of the photo are formed by Hayner Ranch fanglomerate that onlaps Palm Park Formation (see Fig. 15). View looks north.

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