New Mexico Geological Society

Downloaded from: https://nmgs.nmt.edu/publications/guidebooks/67



Tectonic evolution of the Lucero Uplift

Jason W. Ricketts, Karl E. Karlstrom, and Matthew T. Heizler
2016, pp. 185-194. https://doi.org/10.56577/FFC-67.185

in:

Guidebook 67 - Geology of the Belen Area, Frey, Bonnie A.; Karlstrom, Karl E. ; Lucas, Spencer G.; Williams, Shannon; Zeigler, Kate; McLemore, Virginia; Ulmer-Scholle, Dana S., New Mexico Geological Society 67th Annual Fall Field Conference Guidebook, 512 p. https://doi.org/10.56577/FFC-67

This is one of many related papers that were included in the 2016 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

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

Free Downloads

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

Copyright Information

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

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

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

New Mexico Geological Society Guidebook, 67th Field Conference, Geology of the Belen Area, 2016, p. 185-194.

TECTONIC EVOLUTION OF THE LUCERO UPLIFT

Jason W. Ricketts[1], Karl E. Karlstrom[2], and Matthew T. Heizler[3]

[1]Department of Geological Sciences, University of Texas at El Paso, 500 W. University Ave., El Paso, TX. 79968, jricketts@utep.edu;
[2]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM, 87131;
[3]New Mexico Geochronology Research Laboratory, New Mexico Bureau of Geology, 801 Leroy Pl., Socorro, NM 87801;

Abstract—The Lucero uplift lies along the western part of the Colorado Plateau and bounds the northwestern edge of the Albuquerque Basin. It preserves a rich geologic history involving a well-exposed upper Paleozoic stratigraphic section and multiple deformational, magmatic, and denudational events. The purpose of this paper is to synthesize EDMAP and STATEMAP mapping and research efforts to highlight developments in our understanding of this region by focusing on two main research locations: Carrizo Arroyo and the Belen travertine quarries owned and operated by New Mexico Travertine, Inc. The Cenozoic deformational history of this part of the western edge of the Rio Grande rift involved the following elements from west to east: (1) Lucero uplift of the eastern Colorado Plateau is a wide region of gently west-dipping (< 10°), undeformed Permian and Triassic rock, (2) the Comanche fault zone is a west-side-up contractional fault zone that developed from approximately east-west compression during the Laramide orogeny, (3) the Comanche deformation domain (~500-m-wide) is made up of steeply-dipping Paleozoic and Mesozoic strata (the steep limb of the Comanche monocline), (4) newly-dated 27.5 Ma igneous intrusions cross-cut steeply dipping beds, (5) low-angle normal faults preserved in the deformation domain are early, rotated rift normal faults, (6) the Santa Fe normal fault forms the eastern side of the Comanche deformation domain and the western boundary of the Rio Grande rift; it cross cuts and down-drops the synclinal hinge of the monocline deep into the rift, (8) the Comanche deformation domain was a zone of fluid flux of deeply-sourced fluids that mixed with meteoric recharge and resulted in travertine mounds and platforms that were deposited by carbonic, saline springs and resulted in world-class travertine deposits in the Belen quarry area, (9) the 3.7 Ma Mesa Carrizo basalt erupted from vents on the Colorado Plateau and flowed southeast across a low relief surface (Ortiz surface) at a time when there was little relief on the western rift flank, (10) the Belen travertine quarries consist of several Quaternary travertine platforms that are cut by multiple sets of rift-parallel and rift-perpendicular extensional calcite veins that show strain rates over the last 2 Ma that are one to two orders of magnitude higher than present-day strain rates measured from GPS, and (11) Carrizo Arroyo, itself, is a spectacular 183-m deep canyon tributary to the Rio Puerco that has been incised at a rate of 50 m/Ma over the last 1 Ma due to river system integration, climate, or base level lowering in the Rio Grande.

HISTORICAL BACKGROUND

As summarized in Duschatko's (1953) Atomic Energy Commission Report, the Lucero Mesa area was first mapped by Darton (1928), who recognized a subvertical fault system that separates undeformed Paleozoic and Mesozoic strata on the west from the Rio Grande rift valley to the east. Kelley and Wood (1946) recognized the deformation zone to include faults of likely different age, the presence of low-angle faults that they interpreted to be Laramide thrust faults, and the likelihood of fault reactivation. Wright (1946) mapped the Carrizo Arroyo area at 1:12,000 but focused on the Tertiary geology and omitted most of the structural complexities. Duschatko (1953) mapped structures in great detail and highlighted the narrow N-S deformation zone of complex faulting and jointing that he interpreted to be due to multiple movements. His description below is similar to our interpretation except that we interpret the Laramide monocline to be the result of west-side-up (not east-side-up) reverse fault displacement. His summary of the evolution of the structures is well worth reproducing here, some five decades later:

> "The writer believes that the most satisfactory explanation of all these phenomena lies in the hypothesis that during an early period of deformation (possibly late Cretaceous or early Tertiary) a very sharp monocline developed along intersecting trends from the south edge of Gray Mesa to the Ladrons. Both the eastern and western limbs of this flexure were very nearly horizontal and the intervening flank was nearly vertical or, locally, slightly overturned towards the west. Possibly the flexure was the expression in the sediments of displacement along major crustal fractures emanating from below with the eastern block moving up. Penecontemporaneous fracturing of the steep flank and subsequent foundering of the east block primarily along the same zone of weakness during a second period of deformation accounts not only for the presence of infaulted pre-Cambrian rocks, but also for the presence of the Permian. These stages in the structural history are illustrated (somewhat diagrammatically) in Plate X" (pg. 28-29).

GEOLOGIC SETTING

The Albuquerque Basin is situated within the heart of the Rio Grande rift in central New Mexico. The modern physiography is controlled by deformation related to the Rio Grande rift that is superimposed upon earlier Laramide deformational events. Structurally, the basin is bounded on almost all sides by normal faults that separate Santa Fe Group basin fill from uplifted rift shoulders. Main uplifts that bound the Albuquerque Basin include the Sandia Mountains, the Manzano Mountains, the Los Pinos Mountains, the Sierra Ladrones, and the Lucero uplift.

The Lucero uplift was described by Darton (1928) as a region of higher summits that create a plateau capped by basalt, where the eastern edge of the plateau is a sharp anticlinal ridge

that is cut by a fault along its eastern side. Subsequent work has refined this description (Kelley and Wood, 1946; Wright, 1946; Duschatco, 1953; Callender and Zilinski, 1976; Ricketts and Karlstrom, 2014), although the basic observations remain relatively unchanged. Its boundary with the western edge of the Albuquerque Basin of the Rio Grande rift is a narrow (~500-m-wide) zone of faulted, steeply dipping Paleozoic and Mesozoic rocks that extends south to north approximately 60 km from Ladron Peak to I-40. This zone of steeply dipping rocks, referred to here as the Carrizo deformation domain, separates flat-lying Permian and Triassic rocks of the relatively undeformed Colorado Plateau to the west from the Santa Fe rift fill of the Rio Grande rift to the east. Like many other uplifts in the region, the Lucero uplift records contractional deformation related to the Laramide orogeny that has been overprinted by extension during development of the Rio Grande rift (Callender and Zilinski, 1976; Ricketts and Karlstrom, 2014).

CARRIZO ARROYO

Carrizo Arroyo is an east-west-trending tributary to the Rio Puerco with an approximately 183-m-deep canyon that has been cut by a (presently ephemeral) small stream that flows southeast across the boundary between the Colorado Plateau and the Albuquerque Basin. It exposes rocks ranging in age from Paleozoic to Quaternary (Fig. 1, see also Color Plates 8, 9), and preserves a remarkable record of tectonic deformation and magmatism affecting the region as well as more recent incision and landscape denudation. The primary structural elements in this region trend north-south and separate Paleozoic and Mesozoic rocks to the west from Cenozoic rocks to the east.

Comanche Fault and Monocline System

The Comanche fault is a steeply west-dipping reverse fault that places mainly Pennsylvanian Atrasado and Bursum formations in the hanging wall against Permian Abo and Yeso formations in the footwall (Fig. 1, Callender and Zilinski, 1976; Ricketts and Karlstrom, 2014). This fault cores and cuts an east-facing monocline. Bedding attitudes along minor folds in Permian strata mimic the large-scale fold, and suggest a fold axis that plunges shallowly and trends NNE-SSW (Fig. 2). These orientations suggest an approximate east-west compression direction that can be attributed to deformation during the Laramide orogeny (Callender and Zilinski, 1976). Due to the general northward plunge of the monocline, as the Comanche fault is traced to the north, monoclinal displacement diminishes. Two kilometers north of Carrizo Arroyo the fault dies out within the Permian Yeso Formation in the core of the anticlinal hinge of a monocline, suggesting that the reverse fault-cored monocline is similar to many Colorado Plateau monoclines (e.g., Kelly, 1955; Davis and Bump, 2009).

An alternative interpretation suggested that the apparent contraction associated with the Comanche fault zone was a result of isostatic rebound related to Rio Grande rifting (Lewis and Baldridge, 1994). However, we show here that the contractional features are cross cut by a 27.5 Ma igneous complex and later reactivated by rift-related extensional structures. Other interpretations suggest regionally significant Laramide strike-slip deformation along this zone that accommodated northward translation of the Colorado Plateau microplate relative to the Great Plains (Karlstrom and Daniels, 1993; Chapin and Cather, 1994).

Intrusive Complex

One kilometers south of Carrizo Arroyo, a suite of igneous rocks intrudes and disrupts Paleozoic strata (Fig. 1, Kelley and Wood, 1946; Wright, 1946; Callender and Zilinski, 1976; Ricketts and Karlstrom, 2014). This intrusive stock (Ti in Fig. 1) generally lies along a north-south structural grain for a distance of approximately 3 km with a maximum width of 500 m. Compositionally, these rocks consist of olivine gabbro, norite, quartz monzonite, microdiorite, and biotite-rich diorite (Callender and Zilinski, 1976), representing multiple stages of magmatism in the region. These rocks are in turn cut by a series of felsic dikes and small-offset faults. Where observed, small-offset (0.5- to 1-m offset) normal faults in the intrusion cut the latest stage of felsic dikes. A new biotite $^{40}Ar/^{39}Ar$ age of these intrusive rocks from the New Mexico Geochronology Research Laboratory at the New Mexico Bureau of Geology and Mineral Resources yields a plateau age of 27.5±0.04 Ma (Fig. 3), very similar to a previously reported whole-rock K-Ar age of 27.1±1.0 Ma (Callender and Zilinski, 1976). Numerous basaltic dikes are located surrounding Carrizo Arroyo that are assumed to be temporally related to the intrusion. These dikes are generally ~1-4 m in width and trend approximately north-south or slightly northeast-southwest (Fig. 1). Inferred extension directions from these dikes indicate that by 27.5 Ma the regional stress field was dominated by approximately east-west extension.

Low-Angle Normal Faults

Carrizo Arroyo is a unique locality in the Rio Grande rift because it is one of the few locations that exposes low-angle faults associated with rifting. This fault system was originally interpreted to result from eastward Laramide thrusting, and later modified by relaxational normal faulting (Kelley and Wood, 1946). Alternatively, Duschatco (1953, p. 23) suggested that this area is "one in which a unique series of lithologic, structural and geomorphic relations has combined to form conditions highly conducive to mass gravity ("landslip") movements." Callender and Zilinksi (1976) generally agreed with Duschatco (1953) and suggested that low-angle faults in this region are the result of gravity sliding due to unstable structural relief. One important conclusion of their work, however, is that low-angle faults are cut by the Laramide Comanche fault, making these faults some of the oldest in the region (Callender and Zilinski, 1976).

Excellent exposures of the low-angle fault system can be found approximately 200 m south of Carrizo Arroyo (Fig. 1). At this location fault dips range from approximately 20-40° east, and the fault separates Permian Glorieta Formation in the

footwall from Permian San Andres Formation in the hanging wall, exhibiting a younger-on-older relationship. Recent mapping differs from the interpretation of Callender and Zilinski (1976) and does not show the Comanche fault offsetting the low-angle fault (Ricketts and Karlstrom, 2014). This fault, however, does appear to be truncated to the east by a north-south-trending high-angle normal fault (Fig. 1C). Baldridge et al. (1984) suggested that this fault is a low-angle normal fault as opposed to a reverse fault or a gravity slide, and that it formed through ductility contrasts between stratigraphic units. In this region, the Glorieta Formation is a well-sorted medium-grained sandstone. The overlying San Andres Formation consists of multiple lithologies, including nonfossiliferous limestone, shale, and thick layers of gypsum, argillaceous gypsum, and gypsiferous shale. Thus, these weak gypsum layers could allow for the development of faults that are misaligned with the regional stress field and could explain the anomalously low angle of these structures.

Santa Fe Fault

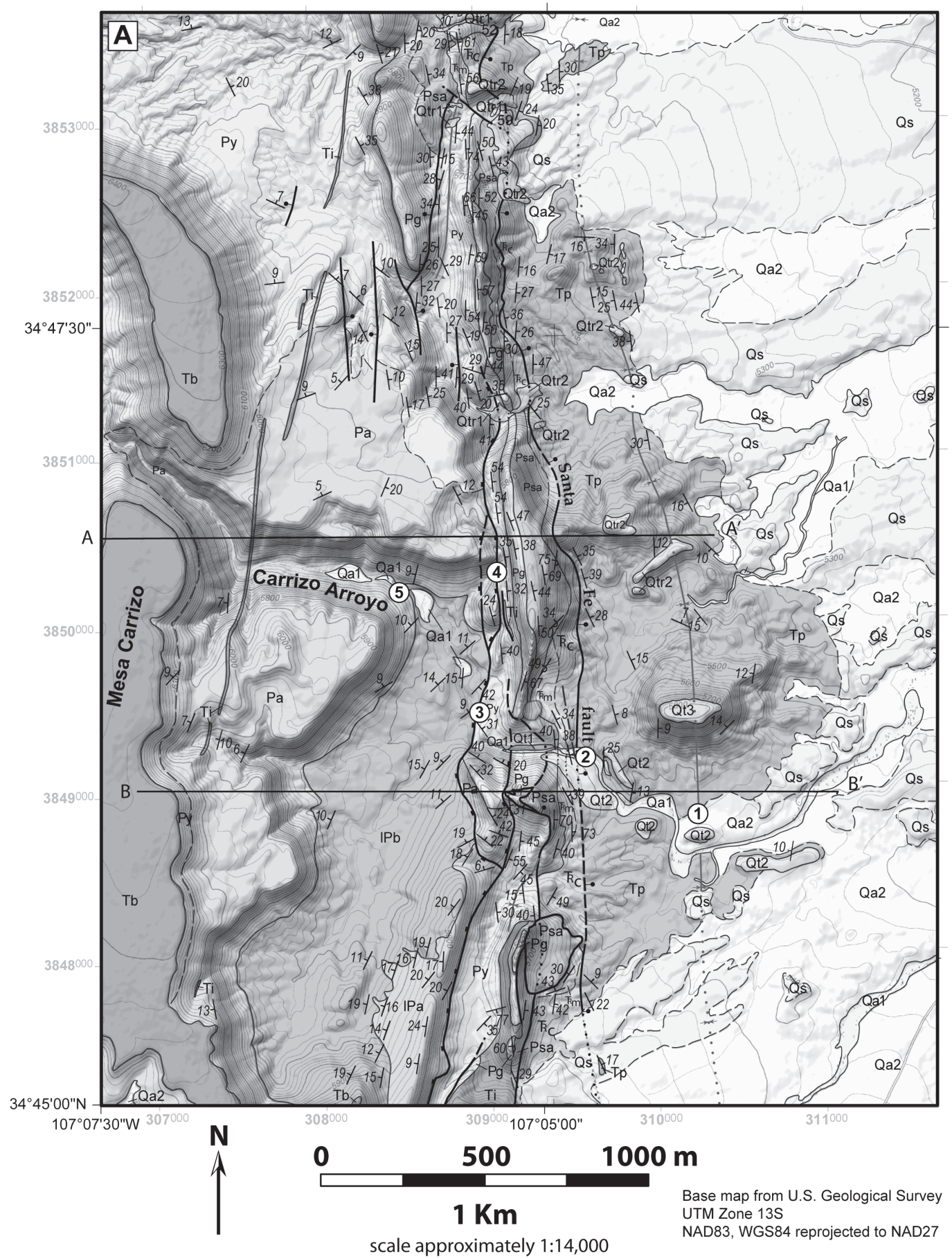
Compressional deformation has since been overprinted by extensional deformation related to development of the Rio Grande rift. The main rift-bounding structure is the east-dipping Santa Fe fault (Fig. 1), which offsets the steep limb of the Laramide monocline. The Santa Fe fault places Paleozoic and Mesozoic rocks in the footwall against the Miocene Popotosa Formation of the Santa Fe Group. Based on seismic data, the Santa Fe fault in deeper parts of the basin displays more than 3050 m of throw (Russell and Snelson, 1994). However, decrease in slip upwards and an overall growth fault geometry for the Santa Fe fault is likely. Bedding attitudes within the Popotosa Formation in the immediate hanging wall of the Santa Fe fault define a fault-parallel syncline with a ~500-m-east-west wavelength that extends at least 10 km from south to north (Ricketts and Karlstrom, 2014). This structure is interpreted to be a drag fold associated with continued post-Popotosa movement along the Santa Fe fault. The syncline can be seen at Bobo Butte immediately north of Carrizo Arroyo. Bobo Butte is a mesa that stands approximately 130 m above the modern Carrizo Arroyo and consists of folded Popotosa Formation that is overlain by horizontal Quaternary travertine deposits (Kolomaznik et al., 2013).

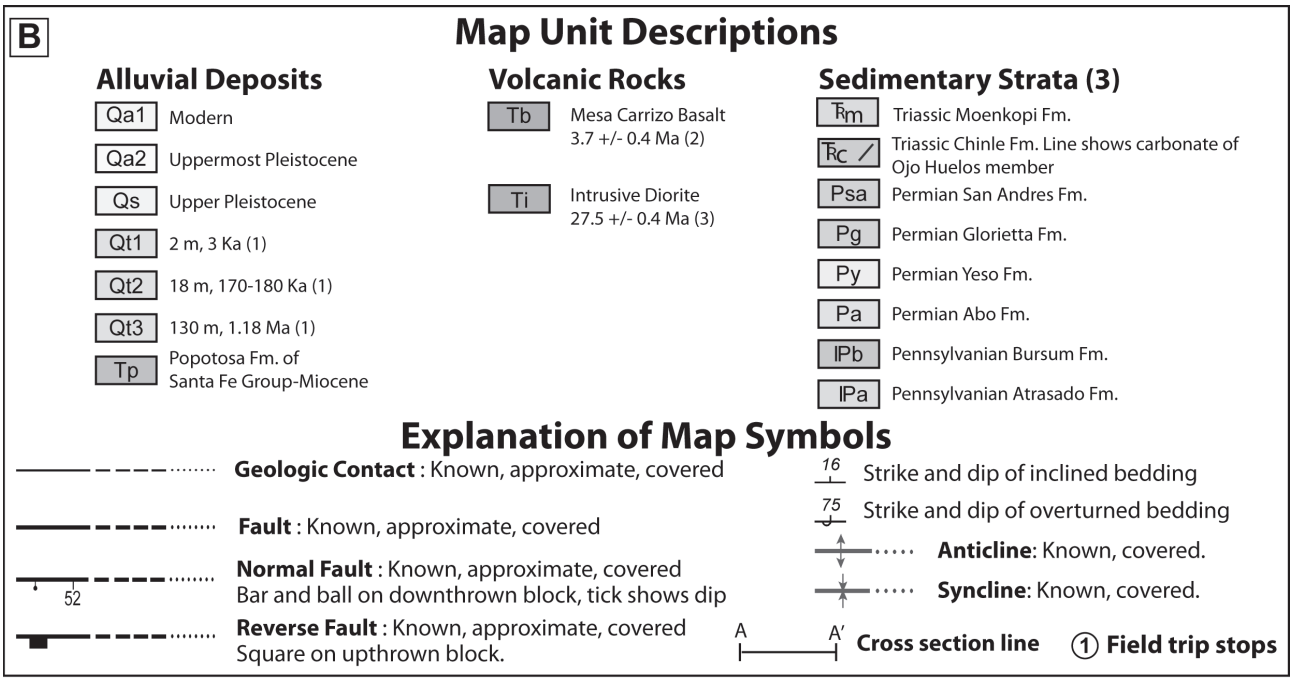
In the footwall of the Santa Fe fault, numerous small-offset normal faults cut Pennsylvanian, Permian, and Triassic strata. North of Carrizo Arroyo, these faults are both antithetic and synthetic to the Santa Fe fault and most can only be traced for several hundred meters. Immediately south of Carrizo Arroyo, the Carrizo fault places Permian Glorieta Formation against Permian San Andres Formation and dips shallower than 40° east (Callender and Zilinksi, 1976). To the south, this fault cuts a late Oligocene intrusive complex. Although total offset along the Carrizo fault is relatively minor and probably not more than several hundred meters at most, this structure is unique because it is only one of several known low-angle normal faults in the Albuquerque Basin.

Exhumation of Lucero Uplift

Both the Laramide orogeny and development of the Rio Grande rift have contributed to exhumation of flanks that bound the Albuquerque Basin. The Albuquerque Basin is bounded on almost all sides by normal faults, and growth of the basin has resulted in the development of multiple sub-basins. The northern Albuquerque sub-basin is an east-tilted half-graben filled with east-dipping Santa Fe Group deposits. These sediments dip towards west-dipping normal faults that bound the western edge of the Sandia uplift (May et al., 1994; Russell and Snelson, 1994; Grauch and Connell, 2013; Ricketts et al., 2015a). In contrast, the southern Belen sub-basin is a more complex region, but Santa Fe Group deposits generally dip towards the western edge of the basin (Grauch and Connell, 2013). In this region, the Ladron uplift is bounded along its eastern edge by the low-angle Jeter fault (Black, 1964; Lewis and Baldridge, 1994; Read et al., 2007; Ricketts et al., 2015a). The accommodation zone separating the two sub-basins has traditionally been interpreted as a narrow fault zone that is a continuation of the NE-trending Tijeras fault exposed along the southern margin of the Sandia uplift. However, a synthesis of diverse geophysical datasets do not directly image such a structure (Grauch, 2001; Grauch and Connell, 2013). Instead, Grauch and Connell (2013) suggest that this accommodation zone consists of a broad zone of north- and northwest-trending anticlinal structures that serve to relay displacement from one rift margin to the other. In this model, the Sandia and Ladron uplifts represent the active margins of the basin where the majority of slip has accumulated.

Apatite fission-track and apatite (U-Th)/He thermochronologic data have been combined for most rift flanks surrounding the Albuquerque Basin (Kelley et al., 1992; House et al., 2003; Ricketts et al., 2015b). Thermal history models derived from these data suggest that the Sandia and Ladron uplifts were exhumed at ca. 22-13 Ma and ca. 18-10 Ma, respectively, whereas the Manzano uplift preserves more complex cooling reflecting Laramide contraction followed by extensional exhumation during development of the Rio Grande rift (House et al., 2003; Ricketts et al., 2015b). No apatite fission-track data exist for the Lucero uplift, but 11 single-grain apatite (U-Th)/He ages were obtained from three samples in this region to document its low-temperature cooling history and compare it to surrounding rift flank uplifts (Ricketts et al., 2015b). These ages cluster within a narrow range from 9.0±0.3 Ma to 22.5±1.0 Ma, and thermal history models of these data, although not very well constrained due to the lack of accompanying apatite fission-track data, suggest exhumation of the Lucero uplift from ca. 25-15 Ma (Ricketts et al., 2015b). The times of exhumation are very similar to the times of exhumation documented in the Sandia and Ladron uplifts, and suggest that the entire western flank of the Albuquerque Basin was exhumed during growth of the Rio Grande rift, rather than during the Laramide orogeny. These observations also support the interpretation by Grauch and Connell (2013) that the Tijeras accommodation does not extend across the entire Albuquerque Basin. Rather, exhumation of the Lucero uplift was apparently primarily accomplished through slip along the east-dipping Santa Fe fault.


A
A'
B
B'
Mesa Carrizo
Carrizo Arroyo
Santa Fe fault
1
2
3
4
5
Qa2
Qa1
Qt3
Qt2
Qtr2
Qtr1
Qs
Tp
Tc
Tm
Psa
Pg
Py
Ti
Pa
Tb
lPb
lPa
3853000
3852000
3851000
3850000
3849000
3848000
34°47'30"
34°45'00"N
307000
308000
309000
310000
311000
107°07'30"W
107°05'00"
N
0
500
1000 m
1 Km
scale approximately 1:14,000
Base map from U.S. Geological Survey
UTM Zone 13S
NAD83, WGS84 reprojected to NAD27



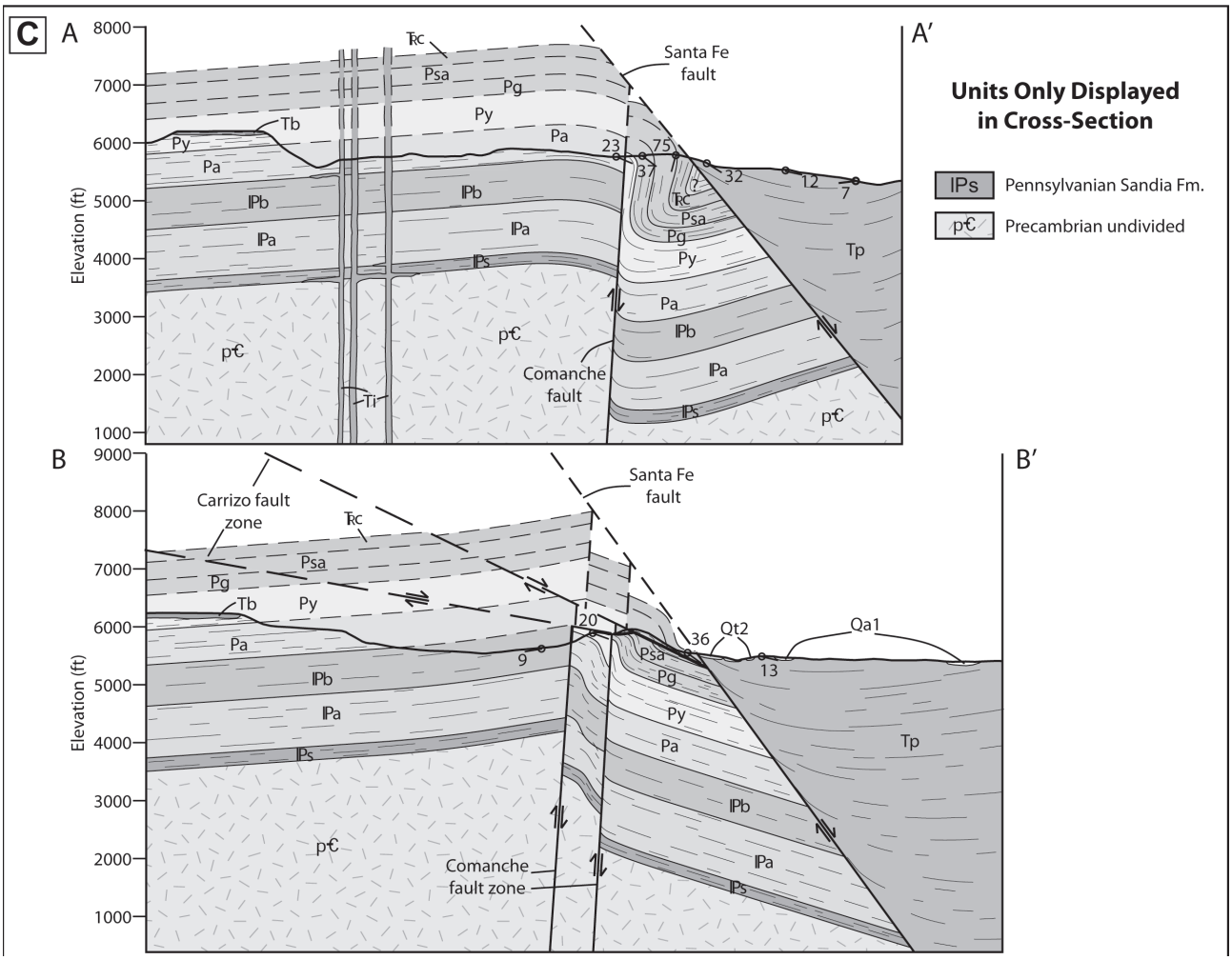


FIGURE 1. **A**) Geologic map of the western edge of the Lucero uplift at Carrizo Arroyo. Modified from Ricketts and Karlstrom (2014), including **B**) Explanation of map units and symbols and **C**) Cross-sections. The color versions of these figures are in Color Plates 8 and 9.

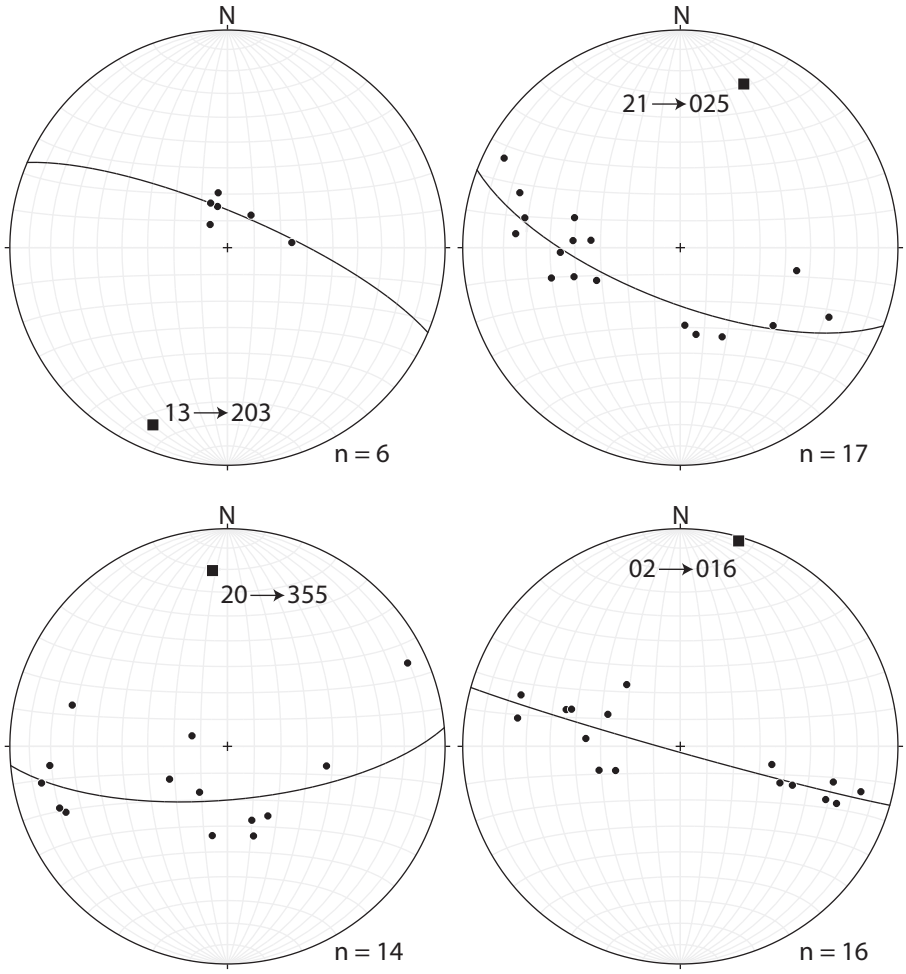


FIGURE 2. Lower-hemisphere equal-area stereographic projections displaying poles to bedding planes within the Permian Yeso Formation. These bedding measurements are from four small-scale (several meter) folds near the Comanche fault. The calculated best-fit great circle girdle to the data is plotted as a solid black line, and the inferred fold axis is shown by the square. Plots are from Stereonet 9 software.

Pliocene and Younger Incision of Carrizo Arroyo

Recent and ongoing incision of the Lucero uplift is best preserved by multiple basalt flows as well as remarkable large-volume travertine deposits and travertine-cemented gravels (Callender and Zilinski, 1976; Lozinski and Tedford, 1991; Kolomaznik et al., 2013; Priewisch et al., 2014; Ricketts and Karlstrom, 2014). At the highest elevations, the Mesa Carrizo basalt flow caps Permian Abo and Yeso formations (Fig. 1). This basalt flow has a K-Ar age of 3.7±0.4 Ma (Bachman and Mehnert, 1978) and is deeply incised by Carrizo Arroyo. At lower elevations, inactive and perched travertine deposits and travertine-cemented gravels are preferentially located along the Comanche and Santa Fe fault systems, and extend the entire north-south length of the Lucero uplift (Ricketts and Karlstrom, 2014). In many locations active springs are currently precipitating travertine in arroyo bottoms, forming coatings on vegetation and sometimes resulting in spring mounds and travertine platforms. The more vigorous springs are also currently precipitating travertine that mantles the modern topography. Ricketts and Karlstrom (2014) map at least four terraces at different elevations above arroyo bottoms, including actively-precipitating travertine.

At Carrizo Arroyo, a total of three abandoned terraces have been identified, together with the higher-elevation Mesa Carrizo basalt flow (Kolomaznik et al., 2013; Ricketts and Karlstrom, 2014). Using the age and height of the Mesa Carrizo basalt flow, Carrizo Arroyo incised at an average long-term rate of 50 m/my since 3.7 Ma (Kolomaznik et al., 2013; Channer et al., 2015). Perched terrace deposits offer an opportunity to investigate the more recent incision rates through time at Carrizo Arroyo because they are situated at lower elevations and are younger than the Mesa Carrizo basalt flow. Abandoned terraces consist of Carrizo Arroyo river gravels that are made up of pebble- to cobble-sized clasts of sandstone and limestone that are locally derived from the adjacent Pennsylvanian and Permian bedrock units. Terraces also contain travertine as both flowstone and gravel-coating cement.

Travertine was collected from each of the three perched terraces and dated using U-series methods and model ages (Bourdon et al., 2003; Kolomaznik et al., 2013). Qt1 at the lowest elevation yields a U-series age of 3±0.02 ka. Two U-series ages from Qt2 at intermediate elevations range from 169±0.9 ka to 179±1.2 ka. At the highest elevation, Qt3 is outside of the upper limit of U-series geochronology, but model ages suggest it was deposited at 930±440 ka (Kolomaznik et al., 2013). These data, combined with the terrace heights above the modern Carrizo Arroyo, suggest that incision rates dramatically increased from 19 m/my to 150 m/my at about 1 Ma (Kolomaznik et al., 2013). This change mimics increased incision rates in the nearby Rio Puerco (Love and Connell, 2005), suggesting that it likely resulted from a regional process. Possible processes to explain this trend vary widely, but include climatic changes (Molnar, 2004; Connell et al., 2005), surface uplift due to Quaternary volcanism and mantle-driven uplift (Fialko and Simons, 2001; Dunbar, 2005; Nereson et al., 2013; Channer et al., 2015), and integration of the Rio Grande system through the Albuquerque Basin (Connell et al., 2005).

TRAVERTINE QUARRIES

Some of the largest travertine mounds exposed within the Lucero uplift are currently being quarried by New Mexico Travertine, Inc., providing a spectacular display of their in-

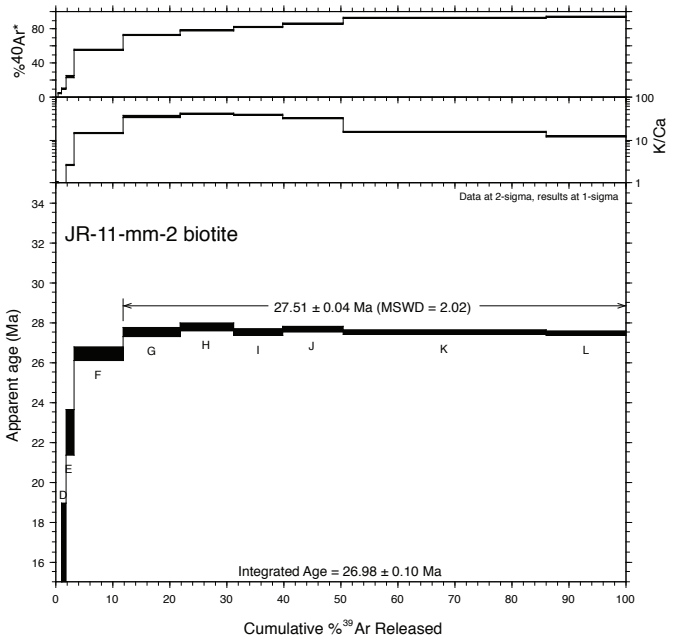


FIGURE 3. Biotite age spectra from the intrusion south of Carrizo Arroyo. Also included is K/Ca and radiogenic yield (%^{40}Ar*). Errors are reported at 2σ.

ternal structure (Fig. 4). These quarry sites are located within the southern region of the Lucero uplift, approximately 10 km south of Carrizo Arroyo. Tectonically, this area is analogous to Carrizo Arroyo and the northern portions of the Lucero uplift. Contractional deformation is expressed by a series of approximately north-south-trending reverse faults and folds in Pennsylvanian and Permian rocks (Fig. 4). The most prominent contractional structure is the west-dipping Comanche fault, which places Pennsylvanian rocks in the hanging wall against Permian rocks in the footwall. This region, too, has been further modified by extensional stresses during development of the Rio Grande rift, which is best expressed through the east-dipping Santa Fe fault, which separates Rio Grande rift fill to the east from Permian rocks to the west (Callender and Zilinski, 1976; Ricketts et al., 2014). Travertine deposits are preferentially located within the narrow zone of deformation defined by the Comanche-Santa Fe fault systems. In contrast to the northern Lucero uplift, the travertine quarries offer a rare opportunity to investigate young deformation in the Rio Grande rift because they expose numerous sets of extensional calcite-filled veins that cross-cut the horizontal bedding of the travertine.

At the quarry sites Temple Cream, Scheherazade, and Vista Grande, exposed quarry faces reveal abundant extensional veins that cross-cut the horizontal bedding of the travertine. The majority of these veins range from ~1 mm to 10-20 cm in width (Ricketts et al., 2014). To the north, Permian Yeso Formation is capped by travertine deposits at Red Hill. At this location, Yeso Formation is cut by calcite-filled extensional veins as well as small-offset normal faults that contain minor amounts of calcite along the slip plane. A final location, Comanche, preserves calcite-filled extensional veins, although these veins cut pebble-to-cobble conglomerate rather than travertine deposits. Together, these five sites offer an opportunity to investigate young deformation in the central Rio Grande rift that is not preserved elsewhere.

Vein and Fault Orientations

At each of the three quarry sites (Temple Cream, Scheherazade, and Vista Grande), veins can be grouped into three orthogonal, mutually cross-cutting sets (Fig. 4), indicating that all vein sets essentially formed contemporaneously. Veins are useful as extension direction indicators because extension is perpendicular to the vein walls. While the three vein sets at each of these locations suggest three orthogonal extension directions, the majority of veins belong to a single set, indicating predominant extension directions of 091° at Temple Cream, 101° at Scheherazade, and 136° at Vista Grande (Ricketts et al., 2014).

In contrast, veins cutting Permian Yeso Formation and overlying travertine deposits at Red Hill are very consistent, indicating a single extension direction of 116°. Red Hill is also unique because it is the only study site that is also cut by small-offset conjugate normal faults. These faults together suggest an extension direction of 120°, essentially identical to the results from extensional veins (Fig. 4, Ricketts et al., 2014).

At Comanche, Santa Fe Group rift-fill deposits are cut by a single set of calcite-filled extensional veins. This location is unique because the veins, and sedimentary deposits that enclose them, have been tilted from their original orientation. This tilting is most likely due to recent slip along the Santa Fe fault because mapped synclines and anticlines in the Santa Fe Group are parallel to the trace of the fault. When Santa Fe Group deposits are restored back to horizontal, calcite-filled extensional veins indicate a single extension direction of 116°, consistent with extension directions obtained from extensional veins and normal faults at Red Hill (Fig. 4).

Vein Ages

Along the western margin of the Albuquerque Basin, several authors have noted that travertine platforms are likely Pleistocene and younger (Kelley, 1977) and waters have been moving through fault zones in this region for the past 2 Ma (Callender and Zilinski, 1976). The abundance of travertine and calcite in faults and fractures provides a unique and powerful method for further constraining the times of extensional activity at each of the study sites because times of calcite precipitation can be accurately calculated using U-series dating and model ages. U-series dating has an upper age limit of ~500,000-700,000 years. For samples that are older than this, geochemical analysis of each sample can be used to calculate model ages, with an upper limit of~1.5 Ma (Bourdon et al., 2003; Ricketts et al., 2014). Therefore, if Callender and Zilinksi (1976) are correct, most of the travertine and calcite in the study region should be dateable using U-series methods and model ages.

Out of 12 samples of calcite that were collected from extensional veins for U-series dating, four yielded robust U-series ages, six samples were outside of U-series range but yielded model ages, and two samples were older than the upper limit of U-series model ages (older than ~1.5 Ma, Ricketts et al.,

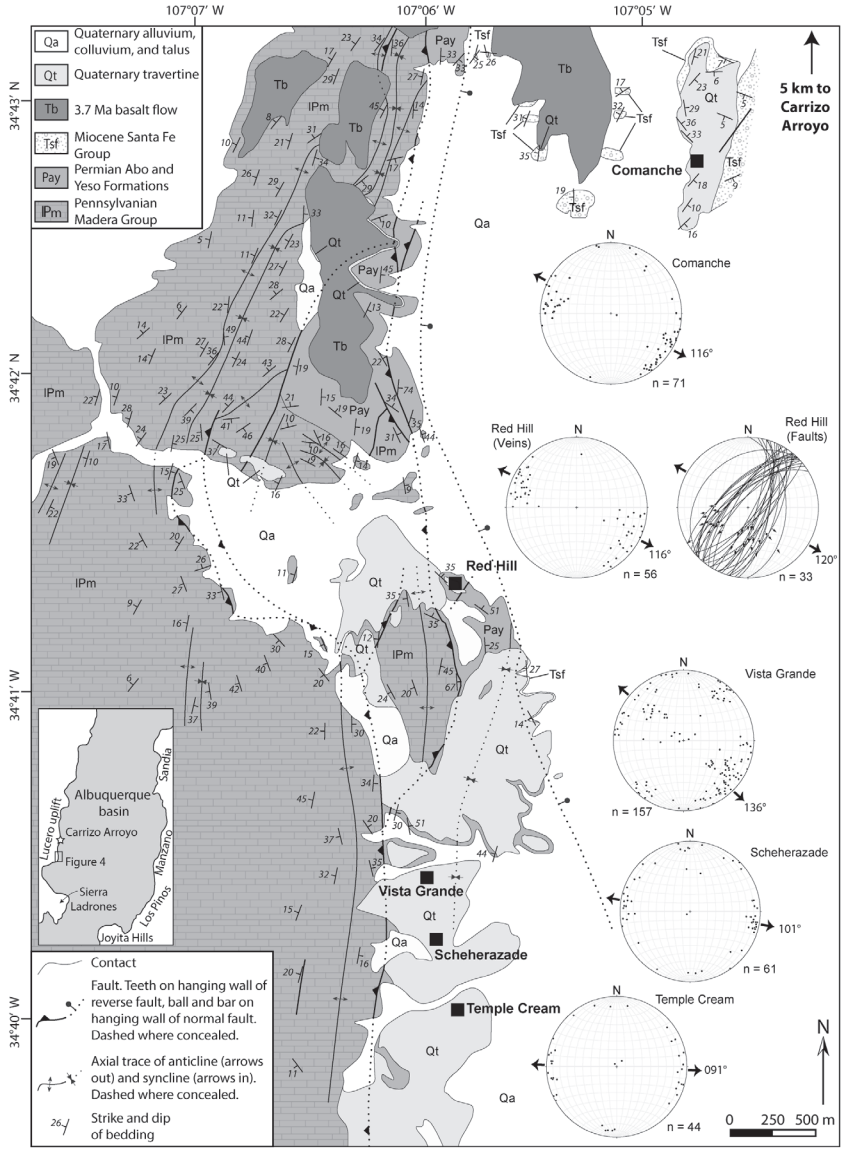


FIGURE 4. Geologic map of the travertine quarries along the western edge of the Albuquerque Basin. Stereographic projections show poles to extensional veins and fault planes (at Red Hill). Arrows show inferred extension direction from stereonet data. Modified from Ricketts et al. (2014).

2014), consistent with the observations of Kelley (1977) and Callender and Zilinski (1976). U-series dating and model ages of 12 samples suggest that calcite precipitation at these study sites occurred episodically from ca. 250 ka to 2 Ma.

Strain Rates

The relatively consistent extension directions indicated by veins and faults at five separate locations along the western margin of the Albuquerque Basin suggest that vein and fault formation are responses to the regional tectonic stress field controlling development of the Rio Grande rift. Further, the timing constraints on calcite precipitation from U-series dating and model ages reveal that much of the preserved fluid flow and tectonism is Quaternary in age (Ricketts et al., 2014). These deposits, therefore, offer rare insight into the young deformational history of the Rio Grande rift and the complex interaction between tectonism and fluid flow in the upper and lower crust.

Strain rates were calculated at each quarry site in an effort to compare them to regional strain rates in the Rio Grande rift. Strain was calculated by measuring the total lengths of quarry faces and comparing them to the original lengths by subtracting the combined widths of extensional veins. To convert these strain values to strain rates, a maximum travertine mound age of 2 Ma was assumed. Ricketts et al. (2014) found that calculated strain rates at each of the quarry sites during the last 2 Ma are one to two orders of magnitude larger than the present-day strain rates as measured by GPS (Berglund et al., 2012). The anomalously high strain rates at this location coupled with the high volumes of fluid in the upper crust to precipitate the travertine deposits suggests a genetic link. Elevated fluid pressures alter the regional tectonic stress field by reducing the normal stress (Hubbert and Rubey, 1959). At the travertine quarries, fluid flow associated with spring deposits reduced the normal stress during the Quaternary and amplified the development of fractures. In this model, the orientation of the fractures is due to the orientation of the regional stress field, but the quantity of fractures is due to elevated fluid pressures in the upper crust during the last 2 Ma along the western edge of the Albuquerque Basin.

Nature of Fluids

Geochemical tracers of spring waters in the Rio Grande rift indicate that they are a mix of predominantly meteoric and river water with minor amounts of deeply derived endogenic fluids (Newell et al., 2005; Williams et al., 2013). In the Lucero uplift, main faults such as the Comanche and Santa Fe faults penetrate into Precambrian rocks, and can thus potentially provide pathways for endogenic fluids to reach the surface. These endogenic fluids are preserved in active springs in Arroyo Salado, for example, which contain ^{3}He values that indicate ~7.6% mantle-derived helium (Williams et al., 2013). Therefore, these deeply-derived fluids offer insight into possible connections between rifting and fluid migration through the upper crust from deep levels.

One intriguing possible source of deeply derived fluids is from underlying magma bodies. The Socorro magma body is a thin midcrustal magma body located 19 km deep beneath central New Mexico (Sanford et al., 1973; Reinhart and Sanford, 1981; Balch et al., 1997). Observed heat-flow data at the surface above the Socorro magma body suggest that melts heating the crust have been present in the region for the past 1 Ma, and

possibly longer (Reiter et al., 2010), overlapping with the time deposition of large-volume travertine deposits and the development of extensional veins. These observations suggest that fluids derived from midcrustal magma bodies may have been transported to the surface through high-porosity fault zones, where they mixed with shallow waters and were ejected in natural springs, where they precipitated travertine deposits and developed the cross-cutting vein networks displayed within the quarry sites.

CONCLUSIONS

The Lucero uplift offers an exceptional opportunity to examine the various tectonic and magmatic processes that have affected central New Mexico throughout the Cenozoic. This paper by no means represents a complete understanding of the complex interactions between various processes, nor is it meant to be an exhaustive overview of previous work in the region. Instead, this paper highlights recent work on the main tectonic and magmatic events in the region in an effort to encourage future research. The main conclusions of this summary paper are: (1) The Lucero uplift records deformation related to multiple tectonic events, including the Laramide orogeny and development of the Rio Grande rift, (2) a suite of dikes and sill-like intrusions cross-cut Paleozoic strata at 27.5 Ma, and may represent magmatism related to the ignimbrite flare-up emplaced within an overall extensional environment, (3) exhumation of the Lucero uplift was primarily accomplished from 25-15 Ma based on apatite (U-Th)/ thermochronology, (4) extensional veins in travertine deposits record a period of rapid extension in the central Rio Grande rift from 2 Ma to Recent that is possibly attributed to high pore fluid pressures and involving a mixture of shallow fluids combined with minor amounts of deeply-derived fluids from underlying magma bodies, and (5) incision rates of the Lucero uplift dramatically increased at approximately 1 Ma from 19 m/Ma to 150 m/Ma.

ACKNOWLEDGMENTS

Mapping as part of this research comes from EDMAP award number G11AC20152 awarded to Karl Karlstrom and New Mexico STATEMAP funding awarded to Karl Karlstrom and Jason Ricketts. U-series analyses of travertine samples was supported by National Science Foundation grant 0838575 to Laura Crossey and Karl Karlstrom and was completed at the Radiogenic Isotope Laboratory at the University of New Mexico. Ar^{40}/Ar^{39} analysis was supported by EDMAP funds, and was completed at the New Mexico Geochronology Research Laboratory at the New Mexico Bureau of Geology and Mineral Resources. Jason Ricketts was supported by the Geological Society of America, the New Mexico Geological Society, and the University of New Mexico. This manuscript benefited from reviews by Spencer G. Lucas and Adam Read.

REFERENCES

Bachman, G.O., and Mehnert, H.H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, p. 283-292, doi: 10.1130/0016-7606(1978)89<283:NKDATL>2.0CO;2.

Balch, R.S., Hartse, H.E., Sanford, A.R., and Lin, K.W., 1997, A new map of the geographic extent of the Socorro mid-crustal magma body: Bulletin of the Seismological Society of America, v. 87, p. 174-182.

Baldridge, W.S., Olsen, K.H., and Callender, J.F., 1984, Rio Grande rift: Problems and Perspectives: New Mexico Geological Society, Guidebook 35, p. 1-12.

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

Black, B.A., 1964, The geology of the northern and north- eastern parts of the Ladron Mountains, Socorro County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 117 p.

Bourdon, B., Turner, S., Henderson, G.M., and Lundstrom, C.C., 2003, Introduction to U-series geochemistry: Reviews in Mineralogy and Geochemistry, v. 52, p. 1-21, doi: 10.2113/0520001.

Callender, J.F., and Zilinski, R.E., 1976, Kinematics of Tertiary and Quaternary deformation along the eastern edge of the Lucero uplift, central New Mexico, *in* Woodward, L.A., and Northrop, S.A., eds., Tectonics and Mineral Resources of Southwestern North America: New Mexico Geological Society, Special Publication 6, p. 53-61.

Channer, M.A., Ricketts, J.W., Zimmerer, M., Heizler, M., and Karlstrom, K., 2015, Surface uplift above the Jemez mantle anomaly in the past 4 Ma based on $^{40}Ar/^{39}Ar$ dated paleoprofiles of the Rio San Jose, New Mexico, USA: Geosphere, v. 11, doi: 10.1130/GES01145.1.

Chapin, C.E., and Cather, S.M., 1994, Tectonic setting of axial basins of the northern and central Rio Grande rift, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Geological Society of America, Special Paper 291, p. 5-25.

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

Darton, N.H., 1928, "Red beds" and associated formations in New Mexico: U.S. Geological Survey, Bulletin 794, 356 p.

Davis, G.H., and Bump, A.P., 2009, Structural geologic evolution of the Colorado Plateau, *in* Kay, S.M., Ramos, V.A., and Dickinson, W.R., eds., Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision: Geological Society of America, Memoir 204, p. 99-124, doi: 10.1130/2009.1204(05).

Dunbar, N., 2005, Quaternary volcanism in New Mexico; *in* S.G. Lucas, G.S. Morgan, and K.E. Zeigler, eds., New Mexico's Ice Ages: New Mexico Museum of Natural History and Science, Bulletin 28, p. 95-106.

Duschatco, R.W., 1953, Fracture studies in the Lucero uplift, New Mexico: United States Atomic Energy Commission, RME-3072, 49 p.

Fialko, Y., and Simons, M., 2001, Evidence for on-going inflation of the Socorro magma body, New Mexico, from interferometric synthetic aperture radar imaging: Geophysical Research Letters, v. 28, p. 3549–3552, doi:10.1029/2001GL013318.

Grauch, V.J.S., 2001, High-resolution aeromagnetic data, a new tool for mapping intrabasinal faults: Example from the Albuquerque basin, New Mexico: Geology, v. 29, p. 367–370, doi: 10.1130/0091-7613(2001)029<0367:HRADAN>2.0.CO;2.

Grauch, V.J.S., and Connell, S.D., 2013, New perspectives on the geometry of the Albuquerque Basin, Rio Grande rift, New Mexico: Insights from geophysical models of rift-fill thickness, *in* Hudson, M.R., and Grauch, V.J.S., eds., New Perspectives on Rio Grande Rift Basins: From Tectonics to Groundwater: Geological Society of America, Special Paper 494, p. 427–462, doi: 10.1130/2012.2494(16).

House, M.A., Kelley, S.A., and Roy, M., 2003, Refining the footwall cooling history of a rift flank uplift, Rio Grande rift, New Mexico: Tectonics, v. 22, doi: 10.1029/2002TC001418.

Hubbert, M.K., and Rubey, W.W., 1959, Role of pore fluid pressure in mechanics of overthrust faulting. Part I: Geological Society of America Bulletin,

v. 70, p. 115-166, doi: 10.1130/0016-7606(1959)70[115:ROFPIM]2.0.CO;2.

Karlstrom, K.E., and Daniels, C.G., 1993, Restoration of Laramide right-lateral strike slip in northern New Mexico by using Proterozoic piercing points: Tectonic implications from the Proterozoic to the Cenozoic: Geology, v. 21, p. 1139-1142, doi: 10.1130/0091-7613(1993)021<1139:ROLRLS>2.3.CO;2.

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

Kelley, V.C., 1955, Monoclines of the Colorado Plateau: Geological Society of America Bulletin, v. 66, p. 789-804, doi: 10.1130/0016-7606(1955)66[789:MOTCP]2.0.CO;2.

Kelley, V.C., 1977, Geology of the Albuquerque Basin, New Mexico: New Mexico Bureau of Mineral and Mineral Resources, Memoir 33, 60 p.

Kelley, V.C., and Wood, G.H., 1946, Lucero uplift, Valencia, Socorro and Bernalillo Counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigations, Preliminary Map 47.

Kolomaznik, M., Ricketts, J.W., Priewisch, A., Crossey, L.J., Karlstrom, K.E., Asmerom, Y., and Polyak, V., 2013, U-series dating and stable isotope analysis of Quaternary travertines with implications for incision rates in western Rio Grande rift, Carrizo Arroyo, New Mexico: N. M. Geological Society, Guidebook 64, p. 199-204.

Lewis, C.J., and Baldridge, W.S., 1994, Crustal extension in the Rio Grande rift, New Mexico: Half-grabens, accommodation zones, and shoulder uplifts in the Ladron Peak–Sierra Lucero area, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Geological Society of America, Special Paper 291, p. 135–155.

Love, D.W., and Connell, S.D., 2005, Late Neogene drainage developments on the southeastern Colorado Plateau, New Mexico, *in* S.G. Lucas, G.S. Morgan, and K.E. Zeigler, eds., New Mexico's Ice Ages: New Mexico Museum of Natural History and Science, Bulletin 28, p. 151-170.

Lozinski, R. P., and Tedford, R. H., 1991, Geology and paleontology of the Santa Fe Group, southwestern Albuquerque Basin, Valencia County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 132, 34 p.

May, S.J., Kelley, S.A., and Russell, L.R., 1994, Footwall unloading and rift shoulder uplifts in the Albuquerque Basin: Their relation to syn-rift fanglomerates and apatite fission-track ages, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Geological Society of America, Special Paper 291, p. 125–134.

Molnar, P., 2004, Late Cenozoic increase in accumulation rates of terrestrial sediment: How might climate change have affected erosion rates?: Annual Review of Earth and Planetary Sciences, v. 32, p. 67–89, doi:10.1146/annurev.earth.32.091003.143456.

Nereson, A., Stroud, J., Karlstrom, K.E., Heizler, M., and McIntosh, W., 2013, Dynamic topography of the western Great Plains: Geomorphic and 40Ar/39Ar evidence for mantle-driven uplift associated with the Jemez lineament of NE New Mexico and SE Colorado: Geosphere, v. 9, p. 521-545, doi: 10.1130/GES00837.1.

Newell, D.L., Crossey, L.J., Karlstrom, K.E., and Fischer, T.P., 2005, Continental-scale links between the mantle and groundwater systems of the western United States: Evidence from travertine springs and regional He isotope data: GSA Today, v. 15, p. 4-10, doi: 10.1130/1052-5173(2005)015[4:CSLBTM]2.0CO;2.

Priewisch, A., Crossey, L.J., Karlstrom, K.E., Polyak, V., Asmerom, Y., Nereson, A., and Ricketts, J.W., 2014, U-series geochronology of large-volume Quaternary travertine deposits of the southeastern Colorado Plateau: Evaluating episodicity and tectonic and paleohydrologic controls: Geosphere, v. 10, doi: 10.1130/GES00946.1.

Read, A.S., Cather, S.M., Chamberlain, R.M., Connel, S.D., and Karlstrom, K.E., 2007, Geologic map of the Ladron Peak Quadrangle, Socorro County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map 142, scale 1:24,000.

Reinhart, E.J., and Sanford, A.R., 1981, Upper crustal structure of the Rio Grande rift near Socorro, New Mexico, from inversion of micro-earthquake S-wave reflections: Seismological Society of America Bulletin, v. 71, p. 437-450.

Reiter, M.R., Chamberlain, R.M., and Love, D.L., 2010, New data reflect on the thermal antiquity of the Socorro magma body locale, Rio Grande rift, New Mexico: Lithosphere, v. 2, p. 447-453, doi: 10.1130/L115.1.

Ricketts, J.W., and Karlstrom, K.E., 2014, Geologic map of the South Garcia SE 7.5-minute quadrangle, Valencia County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 246, scale 1:24,000.

Ricketts, J.W., Karlstrom, K.E., Priewisch, A., Crossey, L.J., Polyak, V.J., and Asmerom, Y., 2014, Quaternary extension in the Rio Grande rift at elevated strain rates recorded in travertine deposits, central New Mexico: Lithosphere, v. 6, p. 3-16, doi: 10.1130/L278.1.

Ricketts, J.W., Karlstrom, K.E., and Kelley, S.A., 2015a, Embryonic core complexes in narrow continental rifts: The importance of low-angle normal faults in the Rio Grande rift of central New Mexico: Geosphere, v. 11, p. 425-444, doi: 10.1130/GES01109.1.

Ricketts, J.W., Kelley, S.A., Karlstrom, K.E., Schmandt, B., Donahue, M.S., and van Wijk, J., 2015b, Synchronous opening of the Rio Grande rift along its entire length at 25-10 Ma supported by apatite (U-Th)/He and fission-track thermochronology, and evaluation of possible driving mechanisms: Geological Society of America Bulletin, v. 128, p. 397-424, doi: 10.1130/B31223.1.

Russell, L.R., and Snelson, S., 1994, Structure and tectonics of the Albuquerque Basin segment of the Rio Grande rift: Insights from reflection seismic data, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Geological Society of America Special Paper 291, p. 83–112.

Sanford, A.R., Alptekin, O.S., and Toppozada, T.R., 1973, Use of reflection phases on micro-earthquake seismograms to map an unusual discontinuity beneath the Rio Grande rift: Bulletin of the Seismological Society of America: v. 63, p. 2021-2034.

Williams, A.J., Crossey, L.J., Karlstrom, K.E., Newell, D., Person, M., and Woolsey, E., 2013, Hydrogeochemistry of the Middle Rio Grande aquifer system – Fluid mixing and salinization of the Rio Grande due to fault inputs: Chemical Geology, v. 351, p. 281-298, doi: 10.1016/j.chemgeo.2013.05.029.

Wright, H.E. Jr., 1946, Tertiary and Quaternary geology of the lower Rio Puerco area, New Mexico: Geological Society of America Bulletin, v. 57, p. 383-456.