A north-flowing precursor to the Pecos River in the Gatuña formation of southeastern New Mexico and Texas

Steven M. Cather and Matthew T. Heizler

2023, pp. 89-101. https://doi.org/10.56577/FFC-73.89
Supplemental data: https://nmgs.nmt.edu/repository/index.cfml?rid=2023002

in:

Evaporite Karst of the Lower Pecos Region, Land, Lewis; Bou Jaoude, Issam; Hutchinson, Peter; Zeigler, Kate; Jakle, Anne; Van Der Werff, Brittney, New Mexico Geological Society 73 rd Annual Fall Field Conference Guidebook, 152 p. https://doi.org/10.56577/FFC-73

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

New Mexico Geological Society Guidebook, 73rd Fall Field Conference, 2023, p. 89–101, https://doi.org/10.56577/FFC-73.89

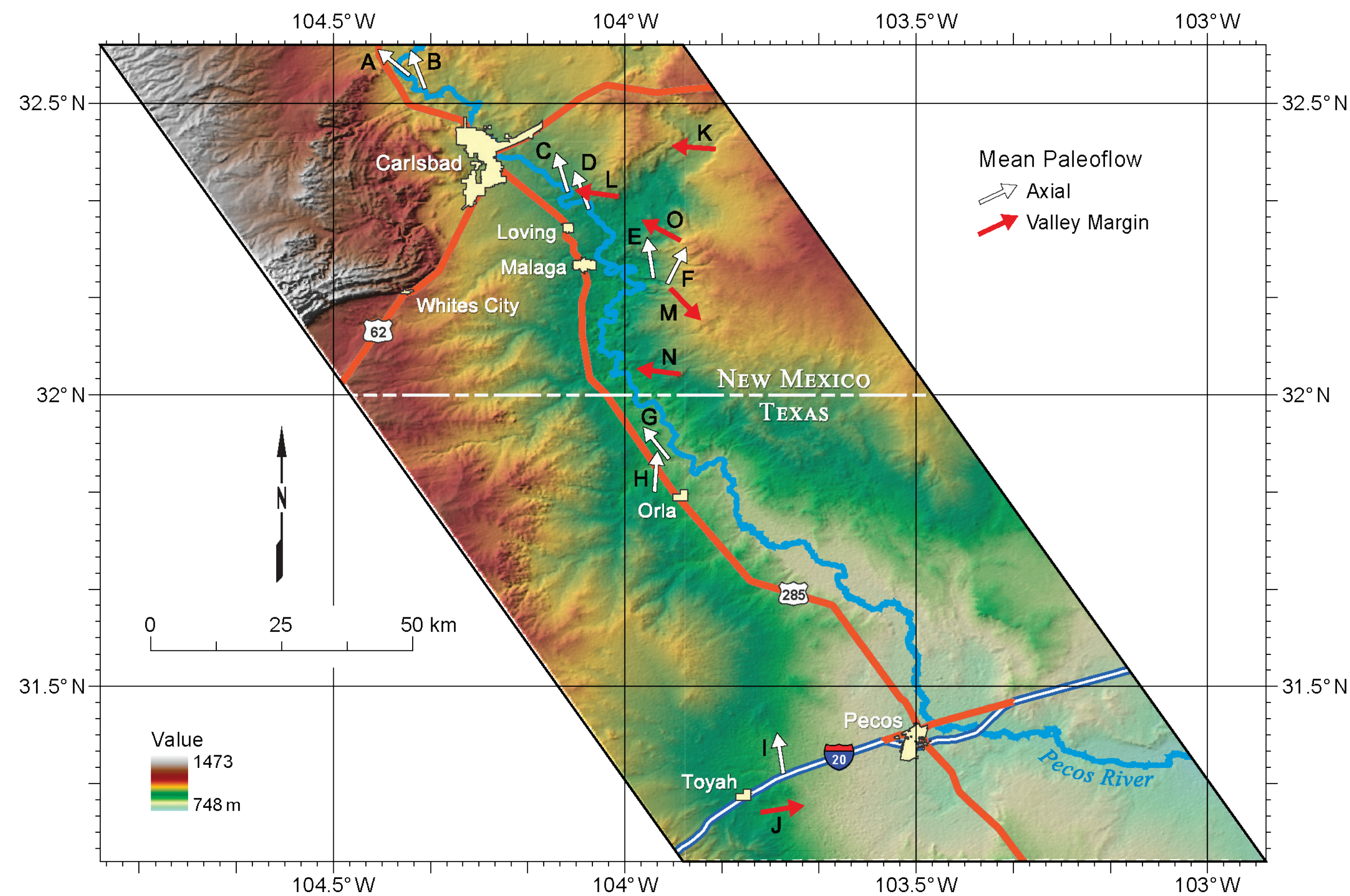

FIGURE 1. Digital-elevation map of the study area showing mean paleoflow at axial-fluvial (white arrows) and valley-margin (red arrows) localities. See Figure 7 for rose diagrams for each locality and Figure 10 for additional geographic and paleogeographic names.

New Mexico Geological Society Guidebook, 73rd Fall Field Conference, 2023, p. 89–101, https://doi.org/10.56577/FFC-73.89

A NORTH-FLOWING PRECURSOR TO THE PECOS RIVER IN THE GATUÑA FORMATION OF SOUTHEASTERN NEW MEXICO AND TEXAS

STEVEN M. CATHER[1] AND MATTHEW T. HEIZLER[1]

[1]New Mexico Bureau of Geology and Mineral Resources, New Mexico Tech, Socorro, NM 87801; steven.cather@nmt.edu

Abstract—Axial-fluvial deposits in the Gatuña Formation of southeastern New Mexico have been recognized for decades. Contrary to existing models, 725 paleocurrent measurements presented here indicate this axial river flowed north, with mean values for individual localities ranging from northwest to north-northeast. Axial sediments were deposited by a regional braided paleoriver within evolving solution-subsidence basins near the modern, south-flowing Pecos River. These dissolution features preserved Gatuña deposits from paleo-landscape positions possibly hundreds of meters above the modern Pecos Valley. Most of the fluvial sedimentary fill within major solution-subsidence features is likely Miocene–Pleistocene, whereas the thin alluvial and eolian Gatuña on the margins of the modern Pecos Valley may be largely Pleistocene. Northward paleoflow (and its subsequent reversal) in southeastern New Mexico resulted largely from epeirogenic warping of the Llano Estacado region since the Oligocene.

INTRODUCTION

The Late Cenozoic paleodrainage history of southeastern New Mexico and adjacent Texas have long been a controversial topic, both in terms of timing and drainage evolution (Bretz and Horberg, 1949; Horberg, 1949; Kelley, 1971, 1980; Reeves, 1972; Bachman, 1980, 1984; Frye et al., 1982; Hawley, 1993a, b; Powers and Holt, 1993; Cather, 2011). For ancient sedimentary strata, there are only two ways to determine paleoflow: (1) the measurement of paleocurrent indicators or (2) the determination of unique detrital source areas. Here we focus on paleocurrent constraints for axial-fluvial beds within the Gatuña Formation. A subsequent paper will describe ongoing $^{40}Ar/^{39}Ar$ characterization of unique volcanic sources to the Gatuña.

In the study area, the Gatuña Formation crops out in and near the Pecos Valley (Fig. 1). Dissolution of Permian evaporites (Lee, 1925) produced numerous Gatuña-filled sinkholes and large solution-subsidence basins. Because regional tectonic tilting is only a few degrees to the east-southeast, steep dips can be attributed to solution subsidence. Intraformational angular unconformities within the Gatuña Formation are common and show that solution subsidence was occurring during sedimentation (Fig. 2).

Strata exposed in southeastern New Mexico and adjacent parts of Texas are of Permian, Late Triassic, Early Cretaceous, and Late Cenozoic age. Permian paleogeographic elements include the Capitan Reef, which passes northeasterly beneath the town of Carlsbad. North of the reef is the Northwest Shelf, which contains relatively thin Guadalupian evaporite beds, mostly gypsum and anhydrite. In contrast, the Delaware Basin to the south hosts great thicknesses of Ochoan halite and anhydrite, primarily in the Castile and Salado formations (Bachman, 1980, 1984). The Salado Formation laps northward across Capitan Reef and the Northwest Shelf, extending north nearly to the latitude of Roswell, where it was beveled out beneath Triassic beds east of the Pecos Valley (Kelley, 1971). Paleocurrent localities A and B (Fig. 1) are on the Northwest Shelf; all others are in the Delaware Basin.

Permian strata in southeastern New Mexico are overlain locally by as much as 50–80 m of Upper Triassic red beds (Bachman, 1984, fig. 6; Lucas and Anderson, 1993; Barnes, 1976). These red beds, termed Dockum Group by most workers (see discussion in Cather et al., 2013), were overlain by an unknown thickness of Lower Cretaceous strata. Rubbly exposures of Lower Cretaceous strata are preserved within a few sinkholes in the study area (Lang, 1947; Bachman, 1984; Kues and Lucas, 1993; Crawford, 1993). Meyer et al. (2012, figs. 6-8 and 6-13) depict as much as ~300 m of "Cretaceous undivided" (probably Lower Cretaceous) in the subsurface west and south of Pecos, Texas. Upper Cretaceous strata may have been present in the study area, but none are preserved. A ~680 m thick section of Upper Cretaceous beds is present in the eastern Sierra Blanca Basin (Rawling, 2004), 150 km northwest of the study area. $^{40}Ar/^{39}Ar$ analysis of detrital sanidine from the

FIGURE 2. Dissolution-induced intraformational angular unconformity exposed at locality I near Toyah, Texas. Geologist W.R. Brewster for scale.

Ogallala Formation indicates an unknown thickness of Oligocene tephra, derived mostly from the Mogollon-Datil volcanic field, was present in southeastern New Mexico and was recycled into the Ogallala Formation (Henry, 2017).

Late Cenozoic deposits of southeastern New Mexico and adjacent parts of Texas are assigned largely to two units: the Ogallala and Gatuña formations. The Ogallala Formation is exposed on the southern High Plains (the Llano Estacado) and in erosional remnants west of the Pecos Valley (Kelley, 1971, 1972; Reeves, 1972; Frye et al., 1982; Hawley, 1993a, b; Gustavson and Holliday, 1999). The Ogallala averages ~50 m thick on the Llano Estacado near Lovington, New Mexico, but attains local thicknesses of ~100 m due the effects of pre-Ogallala topography (Ash, 1963). Most of the Ogallala Formation south of the Fort Sumner–Lubbock area is eolian and loessic (e.g., Reeves, 1972; Gustavson and Winkler, 1988; Hawley, 1993a), consisting of very fine sand and silt that have been variably reworked by sheetwash processes, pedogenesis, and bioturbation. Alluvial gravels are minor on the southern Llano Estacado and are restricted to fills of shallow paleovalleys (e.g., Cronin, 1969; Hart and McAda, 1985) beneath the eolian Ogallala.

The biostratigraphy of Ogallala fluvial beds near Lubbock, Texas, indicates an early Clarendonian to Hemphillian age (~13–5 Ma; Winkler, 1985; see also Lucas and Morgan, 2008). A detrital sanidine $^{40}Ar/^{39}Ar$ maximum depositional age of 11.44±0.03 Ma was determined for an eolian sandstone in the upper part of the Ogallala Formation 65 km northeast of Artesia, New Mexico (Henry, 2017). The top of the Ogallala Formation is marked by a major petrocalcic soil, which projects ~500 m above the modern Pecos River at Artesia, New Mexico, based on Google Earth topographic profiling.

Lang (1938) first applied the term Gatuña Formation to reddish alluvial deposits in Gatuña Canyon, 33 km northeast of Carlsbad. The term has since been applied widely to upper Cenozoic deposits in adjacent areas (see discussions in Bachman, 1976; Kelley, 1980; Powers and Holt, 1993; and Hawley, 1993a, b), but not in a consistent manner. Similar to Kelley (1980), we favor broad geographic application of the term Gatuña within the modern Pecos River drainage. As did Hawley (1993a), we regard the “quartzose conglomerates” of Meinzer et al. (1926), Nye (1933), and Bretz and Horberg (1949) as part of the Gatuña Formation (most are axial-river deposits). We also include within the Gatuña Formation the fill of the Toyah solution-subsidence basin (termed the “Pecos Valley Alluvium” by Meyer et al., 2012), but exclude the younger Blackdom, Orchard Park, and Lakewood terrace insets of Nye (1933). The Gatuña Formation encompasses a wide range of lithotypes (sandstone, siltstone, conglomerate, and mudstone, with minor limestone and gypsum) deposited in alluvial, eolian, axial-fluvial, playa, and pedogenic environments.

The volumetrically most important part of the Gatuña consists of Miocene–Pleistocene solution-subsidence fills. Solution-subsidence basins range from shallow sinkholes a few hundred meters wide to the Toyah Basin that is 75 km long and 530 m deep in the area between Toyah and Pecos, Texas (Maley and Huffington, 1953; Meyer et al., 2012). Such dissolution features contain a wide variety of Gatuña sedimentary facies, including axial-fluvial deposits (the emphasis of this study), playa beds, eolianites, and valley-margin alluvium. Depending on their fill lithology, solution-subsidence basins may become topographically inverted, standing as low hills above more easily eroded strata (Fig. 3).

Exposed solution-subsidence fills may represent only the basal part of formerly much-thicker deposits. The cross sections in Meyer et al. (2012, figs. 6-8 through 6-13) show the thickness of Gatuña Formation fills in the Texas part of the Delaware Basin varies inversely with the thickness of the underlying Salado and Castile formations, because dissolution of evaporites in these units controls the overlying fill thickness. The amount of thinning of these Permian units thus may serve as a proxy for the original fill thickness of the overlying solution-subsidence basin. For example, at Pierce Canyon (Fig. 1; near localities E and F) the Gatuña is as much as 100 m thick (Attia and Allen, 2022), despite being underlain by Salado and Castile that combined are ~365 to 670 m thinner than local and regional thickness trends, respectively (Bachman, 1980, figs. 6 and 8). Indeed, the combined Salado and Castile thicknesses near the western part of Pierce Canyon (~670 m in well 30-015-43895; Attia and Allen, 2022) is only ~90 m thicker than that beneath the deepest part of the Toyah Basin, where preserved Gatuña is 530 m thick (Meyer et al., 2012, figs. 6-8 and 6-12). These relationships suggest the Gatuña Formation at Pierce Canyon (and elsewhere in the north-central part of the Delaware Basin) may have been originally much thicker, but only the basal part of the fill has been preserved in the modern landscape.

The axial-fluvial facies of the Gatuña Formation (Reeves, 1972; Bachman, 1984; Hawley, 1993a, Hawley et al., 1993) generally, perhaps exclusively, occurs within solution-subsidence basins or sinkholes near the modern Pecos Valley. Such deposits are characterized by conglomerate and pebbly sandstone with subrounded to well-rounded clasts (Fig. 4). Clasts exhibit a wide range of lithotypes, including (1) carbonate,

FIGURE 3. Interesting juxtaposition of the south-flowing Pecos River with bluffs of north-flowing axial-river deposits of the Gatuña Formation. These deposits developed within sinkholes that became topographically inverted. View to the north from 32.51885°N, 104.33963°W, near locality B. Given this close juxtaposition, it is easy to see why early workers assumed the ancestral river also flowed south.

siltstone, and sandstone from Permian units, (2) chert, quartzite, quartz, and rare basement pebbles (herein termed "resistate clasts") from the Upper Triassic Dockum Group and the Lower Cretaceous Cox Formation, and (3) variable proportions (generally decreasing northward) of intermediate and silicic volcanic rocks. Throughout the study area, maximum clast size (the average of the 10 largest clasts) ranges from 5–15 cm within the axial-river facies, with no obvious regional grain-size trends.

Axial-fluvial deposits are mostly gray and are typically medium- to thick-bedded. Bachman (1984) reported an axial-river lenticular channel conglomerate (deposits of his Ancestral Pecos River) in upper Pierce Canyon that is ~240 m wide and 24 m thick. The stratification style, lack of point-bar deposits, and the scarcity of intercalated floodplain mudstone indicate these deposits pertain to a large, gravelly, braided paleoriver. The best examples of axial-river deposits are in the Pierce Canyon area, near localities E and F (Fig. 1).

Other Gatuña axial-river deposits differ somewhat from the Pierce Canyon examples in clast roundness, clast lithotypes, and/or bedding thickness. We suspect this variation is related to the diachronous development of individual solution-subsidence basins, which tend to preserve axial-river deposits at different times in the development of the paleoriver, or to the varying level of exposure in the modern landscape. In addition, detrital capture by upstream sinkholes will modify input to downstream sinks. This effect was noted by Bachman (1984, p. 17) for the modern Pecos River: "Sediments, except for flocculants, settle into sinks and other dissolution cavities in the river bed and probably are not being transported out of the evaporite karst area."

Gatuña Formation valley-margin deposits include pediment veneers, alluvial deposits, eolianites, paleosols, and sinkhole fills. Gatuña valley-margin deposits are common on the Mescalero Plain, an area of subdued, eolian-mantled topography between the Pecos Valley and the Llano Estacado to the east. The Mescalero Plain slopes west and southwest (Bachman, 1984, fig. 8) and projects 40–80 m above the modern Pecos River. Similar, but less-studied, deposits occur west of the Pecos Valley, on the Diamond A Plain (Nye, 1933).

FIGURE 4. Well-rounded pebble conglomerate of the axial-river facies exposed at locality E in the Pierce Canyon area.

Gatuña deposits on the Mescalero Plain display mostly reddish colors that reflect derivation from Permo-Triassic red beds. Valley-margin deposits commonly contain angular clasts of Dewey Lake, Rustler, and Dockum siltstones and sandstones, as well as rounded resistate pebbles of quartzite, chert, and quartz recycled from the Dockum Group. See Powers and Holt (1993; their Gatuña Canyon, Livingstone Ridge, Quahada Ridge, and Remuda Basin localities) for detailed descriptions of what we consider to be valley-margin deposits. These deposits are probably mostly Pleistocene.

AGE OF THE GATUÑA FORMATION

The age of the Gatuña Formation is poorly understood. Earlier workers have argued for age assignments ranging from middle Miocene to middle Pleistocene. There are no paleontologic constraints on the age of the Gatuña Formation. Other than undiagnostic plant fragments, a threadfin shad is the only fossil recovered from the Gatuña Formation, but its age significance is unknown (Miller, 1982).

Well penetrations show the deep fill of the Toyah Basin consists of Cenozoic volcaniclastic deposits, ash, and bentonitic clay that directly overlie Permian strata (Meyer et al., 2012, p. 26). Missing Mesozoic strata in the Toyah Basin were likely removed during late Oligocene–early Miocene uplift and erosion in the region (i.e., during development of the pre-Ogallala erosion surface; Cather et al., 2012), thus suggesting the base of the Gatuña Formation is no older than late Oligocene.

About 26 km southeast of Orla, Texas, a fine-grained playa(?) facies of the Gatuña Formation contains a 13.0±0.6 Ma volcanic ash ~1 m thick (location 31.68545°N, 103.68702°W). This age is based on K-Ar dating of glass shards and is supported by chemical analysis indicating a relationship to a ~13.5 Ma Yellowstone ash (Powers and Holt, 1993). We resampled this ash but found no crystals suitable for $^{40}Ar/^{39}Ar$ dating. The ~13 Ma ash crops out in the northern part of the Toyah Basin, dips 8°SE, and is underlain by 120–180 m of older Gatuña Formation fill, based on well records (Meyer et al., 2012, fig. 6-15). The Gatuña Formation in the Toyah Basin beneath this ~13 Ma ash may thus predate deposition of the Ogallala Formation (~13–5 Ma) on the Llano Estacado near Lubbock (Winkler, 1985).

Ongoing $^{40}Ar/^{39}Ar$ analysis of <40 Ma detrital sanidines (n=429) from four axial-river sandstones south of Pierce Canyon (near localities E and F; Fig. 1) yielded nine grains from two samples (11-6-13-B and 11-6-13-D; Fig. 5a and data repository) with a maximum depositional age (MDA) of ~8 Ma, while two other samples (11-6-13-A and 11-6-13-C) have MDAs of ~13 and ~23 Ma, respectively. The majority of the detrital sanidine ages in all four samples are 24–40 Ma. Pierce Canyon sample 11-6-13-C had a single 1.4 Ma sanidine grain. However, this date is deemed unreliable because numerous crystals of similar age were irradiated in close proximity and could have contaminated this sample. Moreover, sample 11-6-13-C is ~50 m stratigraphically *below* nearby sample

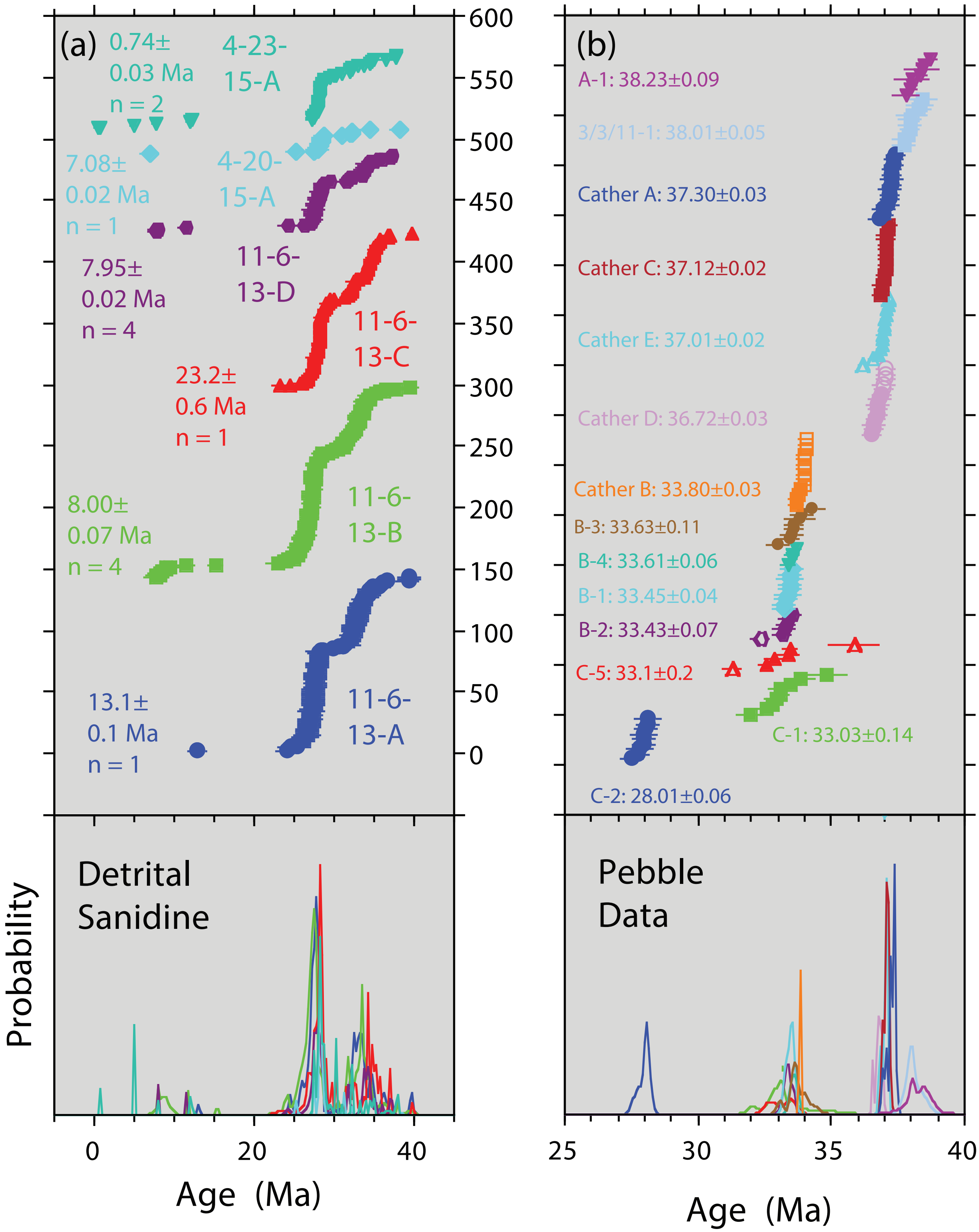

FIGURE 5. (a) $^{40}Ar/^{39}Ar$ dates for detrital sanidine from six sandstones, showing maximum depositional ages for each sample. Maximum depositional ages (MDAs) range between about 23 and 0.7 Ma. Clustering of MDAs between 7 and 8 Ma for three samples may indicate that the Gatuña Formation at these localities is late Miocene. (b) $^{40}Ar/^{39}Ar$ dates for 14 pebbles from the Gatuña Formation in the study area that range between ~38.2 and 28.0 Ma. These pebbles reveal no age correspondence to sanidine-bearing rocks from the Sierra Blanca volcanic field. See text.

11-6-13-D with an MDA of ~8 Ma. Twenty-one Cenozoic detrital sanidines from Gatuña axial-river deposits in sample 4-20-15-A (near locality B; Fig. 1) yielded a single grain with an MDA of ~7 Ma; the remainder are 25–38 Ma. The above five samples are clearly associated with the north-flowing axial river and can be no older than Miocene.

North of the study area, where US-285 crosses Walnut Creek 17 km north of Artesia (32.99255°N, 104.43892°W), Gatuña sample 4-23-15-A yielded two ~0.74 Ma grains, one ~5 Ma grain, two ~8 Ma grains, and two ~12 Ma grains; the remaining 74 grains are 27–44 Ma (Fig. 5). This fluvial exposure yielded no paleocurrent data, so its depositional context is unclear. These Gatuña deposits can be no older than Pleistocene.

The Gatuña Formation on the Mescalero Plain is capped by the Mescalero caliche, a calcic paleosol. Uranium-series dating of the Mescalero caliche has yielded ~0.5 Ma ages (Rosholt and McKinney, 1980). Near Pierce Canyon, an older, pisolitic, stage VI calcrete containing bands of secondary chalcedony locally caps the Gatuña Formation, suggesting a minimum age of several million years for the Gatuña Formation there (Hawley et al., 1993; see also Cikoski, 2019). Attia and Allen (2022), however, considered this caliche to be part of the ~0.5 Ma Mescalero caliche; we concur, although a composite origin is possible. Clasts of pisolitic caliche occur locally within valley-margin deposits of the Gatuña Formation in the Gatuña Canyon reference section of Bachman (1976) and elsewhere on the Mescalero Plain. These clasts were interpreted by Bachman (1976) and Powers and Holt (1993) to have been derived from the calcrete caprock of the Ogallala Formation, thus indicating a post-late Miocene age for the Gatuña Formation. Kelley (1980), who suggested older potential sources for such clasts, questioned this interpretation.

Izett and Wilcox (1982) identified Lava Creek B ash (0.63 Ma; see Jicha et al., 2016) at Livingston Ridge (32.43648°N, 103.83354°W). This ash lies ~2.5 m below the Mescalero caliche, within a shallow paleovalley filled by Gatuña Formation (Bachman, 1980; Attia et al., this guidebook). Microprobe analysis of resampled ash confirms its correlation with the Lava Creek B (N.W. Dunbar, 2011, pers. comm.). Attia et al. (this guidebook) determined that the exposure here is entirely Quaternary, based on a detrital sanidine MDA of ~1.3 Ma obtained from below the Lava Creek B ash.

Kelley (1980) applied the term Gatuña to older alluvium (QTo of Kelley, 1972) of the Pecos Valley of east-central New Mexico. He interpreted the Gatuña there to be older than the Ogallala Formation. The field relationships between the Ogallala and Gatuña formations, however, are ambiguous. The 1.6 Ma Guaje ash (Spell et al., 1996; this is the fallout ash from the lower Bandelier Tuff) lies within Pleistocene pediment deposits that overlie the Gatuña Formation 5 km west of Fort Sumner (34.47256°N, 104.29944°W; Izett et al., 1981). Microprobe analysis of the resampled ash confirms its correlation with the Guaje (N.W. Dunbar, 2011, pers. comm.). The Guaje ash provides a local minimum age for the Gatuña Formation.

In summary, the Gatuña Formation as defined here is no older than late Oligocene, at least locally contains middle Miocene strata, and is no younger than Pleistocene.

PALEOCURRENT ANALYSIS

During 2011–2016, we collected paleocurrent data from axial-fluvial beds (725 measurements) and valley-margin deposits (147 measurements) of the Gatuña Formation from 15 localities in the study area. Pebble imbrications (Fig. 6) account for the majority of the paleoflow data; cross bedding constitutes <10% of the observations. In our experience, some localities exhibit more paleocurrent scatter than is typical for braided-fluvial deposits (Fig. 7), possibly due to the effects of solution subsidence during sedimentation.

Gravel pits near Toyah, Texas, expose conglomeratic Gatuña Formation at localities I and J, within the western part of the Toyah Basin. Locality J (Fig. 1) contains ~90% volcanic clasts, with ~10% Permian and Cretaceous siltstone, sandstone, and carbonate. This braided-stream deposit shows east-northeast paleoflow and is tentatively interpreted as being derived from the western valley margin or the Toyah Basin margin. Maximum clast size is 10 cm.

Locality I exhibits gray, subhorizontal, braided-stream beds overlying reddish, tilted fluvial beds (Fig. 2). Mean paleoflow during deposition of the upper gray beds was northwest, mean for the lower, reddish beds was north-northeast. Figure 1 depicts the average for both. The upper gray bed contains ~30% volcanic clasts, with the remainder (sandstone, carbonate, and chert) derived from Mesozoic and Permian sources. The lower, tilted beds are ~90% volcaniclastic. Maximum clast size is 12 cm, although a few outsized 25 cm volcanic clasts were observed.

Locality H exposes axial-fluvial beds in a gravel pit near a microwave tower, 3 km west of Orla, Texas (optional stop in Austin et al., 1993). Paleoflow was northward. Hawley (1993c, p. 27) described the outcrop as, "Rounded pebbles are mostly carbonates with some cobbles (up to 8 in.) present. Subordinate clast lithologies include "Cox" sandstone, chert, quartzite, quartz, granite, gneiss, and intermediate volcanics. These high-level deposits are here correlated with upper Miocene and

FIGURE 6. Imbricated clasts in the axial-river facies of Gatuña Formation at Pierce Canyon. View toward east from 32.19208°N, 103.94925°W, near locality F.

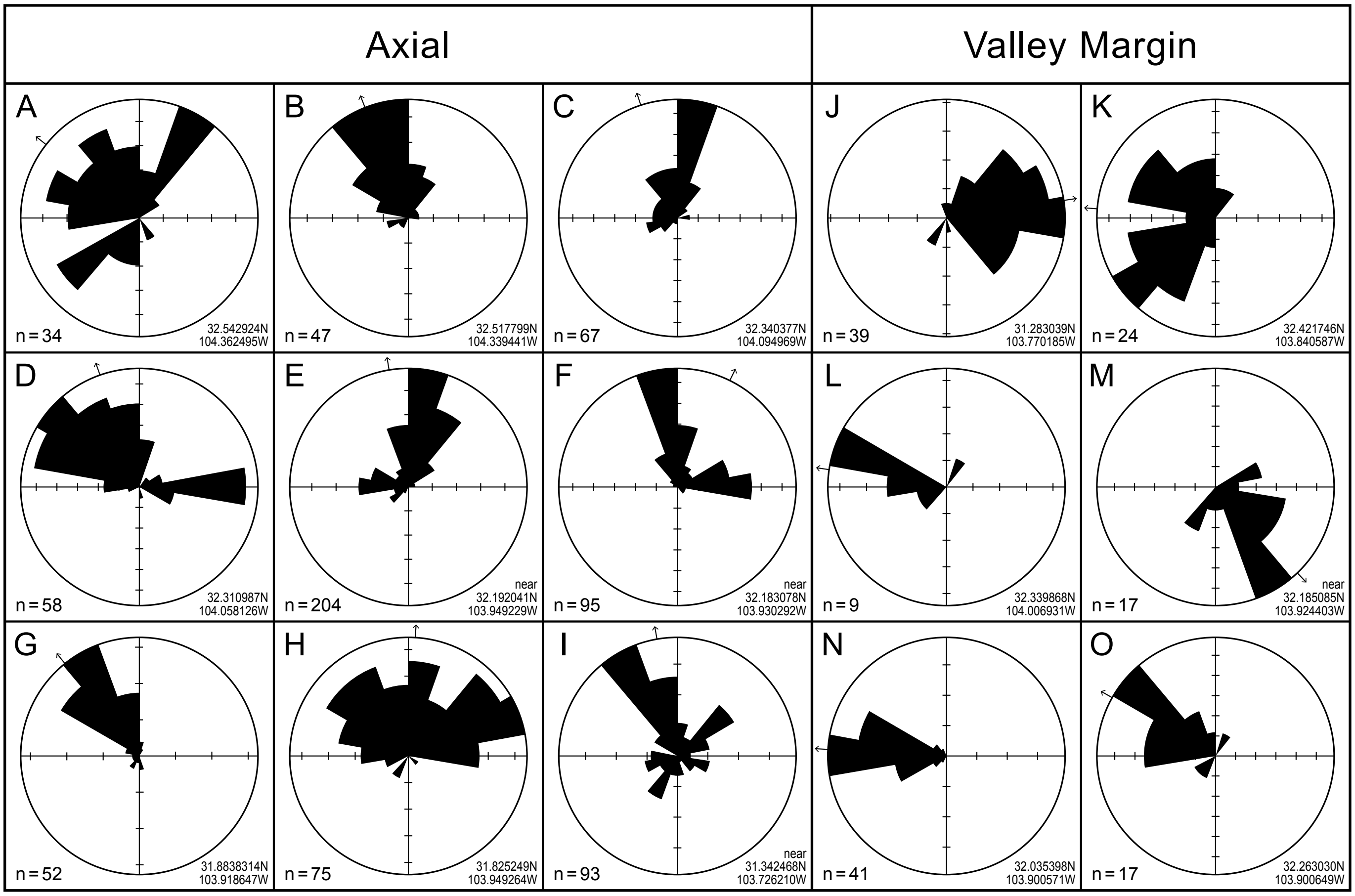

FIGURE 7. Rose diagrams for paleocurrent localities in Figure 1.

Pliocene sediments of the ancestral Pecos system…" Sanidine in a rhyolite pebble (sample 3/3/11-1; Fig. 5b) from this locality was dated by $^{40}Ar/^{39}Ar$ analysis at 38.01±0.05 Ma.

Locality G is axial-river deposits in a roadcut near Red Bluff Lake on Reeves County Road 447 at Screw Bean Arroyo. Clasts are subequal Permian pebbles (carbonate, siltstone, and sandstone) and resistate types. No volcanic pebbles were noted. Maximum clast size is 5 cm. Paleoflow was northwestward.

Locality N is located on the divide between Tucker Draw and Brushy Draw. It consists of reddish valley-margin alluvial deposits 2 m thick, capped by the Mescalero caliche. Clasts are subangular pebbles of Permian carbonate and rounded resistate clasts recycled from the Dockum Group. No volcanic clasts were noted. Maximum clast size is 15 cm; the average is 5 cm. Paleoflow was westward.

Pierce Canyon could be considered the "type area" of the Gatuña axial-river deposits, as it figures prominently in early descriptions of the facies (e.g., Bachman, 1984; Hawley, 1993a). Intercalated with distal valley-margin deposits that contributed reddish sand, silt, and pebbly sand from both eastern and western valley margins, the gray conglomerates and pebbly sandstones of the axial paleoriver (localities E and F) are well exposed, mostly within map unit QTgc of Attia and Allen (2022).

Locality E is south of the central reaches of Pierce Canyon. Strata dip 30°SE. Pebble composition is ~90% Permian carbonate, siltstone, and sandstone. The remainder is resistate clasts and minor volcanic clasts of intermediate to rhyolitic composition. Maximum clast size is 15 cm. Mean paleoflow was toward the north-northwest.

Locality F lies south of the upper reaches of Pierce Canyon. Strata dip 25°SW. Conglomerates consist of rounded Permian pebbles and resistate clasts, and minor volcanic clasts of intermediate and silicic composition. Maximum clast size is 15 cm. Mean paleoflow was north-northeast.

Locality M, also south of upper Pierce Canyon, is an example of a valley-margin braided-stream deposit derived from the northwest. It consists of reddish sandstone and pebbly sandstone. Subangular red clasts of the Dewey Lake and Rustler formations and rounded resistate clasts derived from the Dockum Group dominate the pebble suite. Locality M is an upward-fining deposit ~30 m thick that displays evidence for southeast paleoflow. It is capped by gray axial-river conglomerate (locality F, above) that displays a nearly orthogonal paleoflow toward the north-northeast.

Locality O is in the Remuda Basin (site H of Powers and Holt, 1993). It consists mostly of reddish-brown valley-margin alluvial and eolian sandstones. Conglomerate is minor, with pebbles mostly of recycled Triassic resistate clasts and minor Dewey Lake clasts. Paleoflow was toward the northwest, similar to the results of Powers and Holt (1993).

Localities L and K are examples of valley-margin braided-stream and eolian deposits that exhibit evidence of westward paleoflow. The Gatuña section at locality K is at least 20 m thick and corresponds to Powers and Holt's (1993) site E at the south end of Quahada Ridge. It consists of reddish, medium-bedded, alluvial sandstone and pebbly sandstone with laterally continuous bedding. Angular clasts of Dewey Lake sandstone and resistate clasts derived from the Dockum Group are common.

Locality L is near site B1 of Powers and Holt (1993), at Livingston Ridge. Deposits consist of 5–15 m of reddish-brown, locally gypsiferous sandstone and pebbly sandstone. Pebble lithotypes are subangular red sandstone, gray sandstone, and gray carbonate mostly derived from Permian sources, and rounded resistate clasts recycled from the Dockum Group. Maximum clast size is 7 cm.

Locality D consist of axial-river deposits exposed where NM-31 crosses the Pecos River. These deposits occupy the east-central part of a 4 km wide sinkhole (see circular trace on USGS Loving, New Mexico, 7.5' topographic quadrangle). Clasts are Permian carbonate and sandstone pebbles with smaller, more rounded resistate clasts. No volcanic pebbles were seen. Maximum clast size is 12 cm. Mean paleoflow was north-northwest.

Locality C is at the north end of Herradura Bend, on the southeast side of the Pecos River. Axial-river conglomerate consists of rounded Permian pebbles and resistate clasts and trace volcanic clasts of intermediate and silicic composition. The lower beds show mean paleoflow toward the north-northwest. The upper conglomerate bed is overprinted by the Mescalero caliche and shows little systematic imbrication, probably due to bioturbation.

Locality B exposes "quartzose conglomerate" east of the Pecos River, 5 km southeast of Brantley Dam. This locality is within topographically inverted sinkholes filled with axial-river conglomerate, consisting of subequal Permian carbonate and resistate pebbles, with trace volcanic clasts. Also exposed near this locality are a stack of ~2 m thick foreset beds (Fig. 8) that prograded to the north-northwest, similar to the paleoflow direction obtained from pebble imbrications in adjacent beds. These deposits are interpreted as Gilbert-type deltas or gravelly linguoid (transverse) bars that prograded into a developing sinkhole.

Locality A is 2 km east of Brantley Dam, on the north side of the Pecos River. Axial-river conglomerate here is 5 m thick and overlies reddish Gatuña sandstone. These "quartzose conglomerate" beds consist of ~50% Permian carbonate and ~50% resistate clasts, with rare volcanic clasts. The dip of Gatuña strata and Permian beds near here is locally chaotic (soft-sediment deformation with clastic dikes) due to the effects of solution subsidence. Mean paleoflow was northwest.

DISCUSSION

Early studies (e.g., Bachman, 1976, 1987) envisioned a south-flowing ancestral Pecos River that was initially localized by solution subsidence. The river eroded headward, eventually capturing the headwaters of the Brazos River (including what is now the northern Pecos River) near Fort Sumner and causing abandonment of the Portales Valley. No paleocurrent data have been presented to support this hypothesis. To explain the volcanic clasts in the Gatuña, early workers invoked the Sierra Blanca volcanic field as a source. Ongoing $^{40}Ar/^{39}Ar$ dating of sanidine in rhyolite pebbles from the axial Gatuña deposits, however, has encountered no clasts that can be attributed to the Sierra Blanca area. Of the 14 pebbles analyzed, 6 range in age from 36.72–38.23 Ma (Fig. 5b), significantly predating the oldest known sanidine-bearing unit in the Sierra Blanca area (the 34.28 Ma Buck Pasture Tuff; Kelley et al., 2014, table 1).

FIGURE 8. Stacked sets of gravelly foreset beds in the Gatuña Formation, produced by north-northwest progradation of Gilbert-type deltas or linguoid (transverse) bars. More such features are exposed directly to the south. Telephoto view across the Pecos River toward the east from 32.51806°N, 104.34081°W, near locality B.

Contrary to earlier interpretations, paleocurrent data presented here argue for northerly paleoflow during deposition of axial-river deposits of the Gatuña Formation. We show that northerly axial paleoflow, and its subsequent reversal, are compatible with the effects of known epeirogenic episodes on regional paleoslopes. A tectonic reversal of paleoflow direction is not without precedent in the southwestern USA. The best-documented example is the Salt River of southcentral Arizona. The Salt River today drains southwestward, but prior to middle Miocene it flowed northeast, toward the Colorado Plateau, as shown by remnants of older fluvial deposits preserved within its modern canyon (Potochnik and Faulds, 1998; Potochnik, 2001; Anderson et al., 2021).

Mantle density changes and flow related to volcanism (e.g., Nereson et al., 2013; Stephenson et al., 2014) and warming of the lithosphere (e.g., Roy et al., 2009) are commonly invoked drivers of epeirogenesis. During the Oligocene to early Miocene, epeirogenic uplift and erosion began in southeastern New Mexico associated with major magmatism in the Sierra Madre Occidental and Trans-Pecos Texas volcanic fields (Cather et al., 2012, fig. 5). The base of the Ogallala Formation overlaps progressively older strata to the south on the High Plains, indicating greater uplift and erosion to the south (Fig. 9).

This episode was followed by the uplift of Alvarado Ridge,

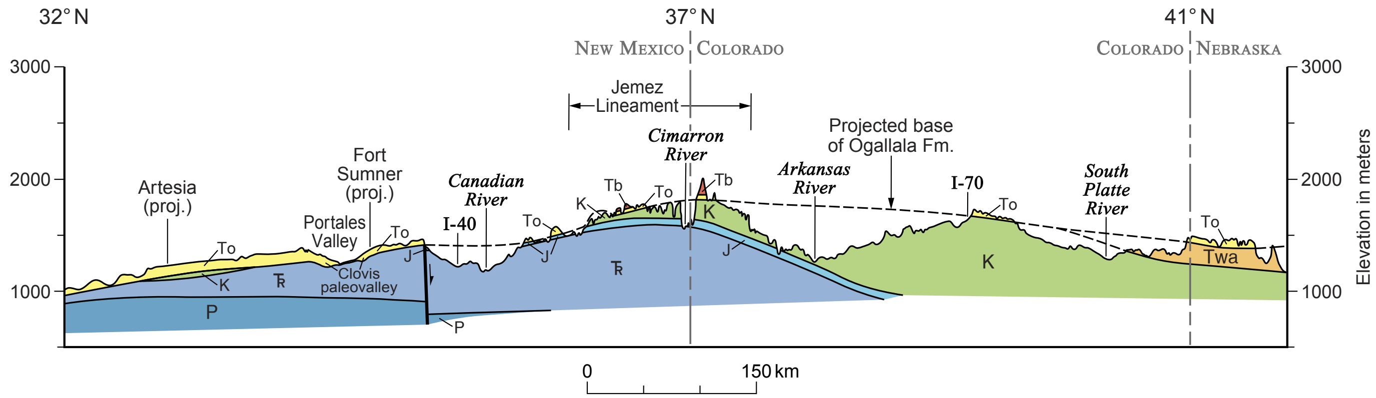

FIGURE 9. North–south cross section along longitude 103.5°W, showing projected elevation difference between the latitude of Fort Sumner and that of Artesia (see text). Vertical exaggeration is 100x. Stratigraphic units are: P–Permian; Tr–Triassic; J–Jurassic; K–Cretaceous; Twa–White River Group and Arikaree Formation (upper Eocene to lower Miocene); To–Ogallala Group (middle to upper Miocene); Tb–basalt flows (upper Miocene). Note the Ogallala Group bevels across progressively older strata to the south, and that the Ogallala Group was subsequently broadly arched by the Jemez volcanic lineament. Modified from Cather et al. (2012).

a broad epeirogen encompassing the Rio Grande Rift and its flanks, including the High Plains (Eaton, 1987; Ricketts et al., 2016). As Alvarado Ridge developed, the pre-Ogallala surface was tilted eastward, beveling more deeply toward the west. The Miocene depth of erosion was at least 2 km near the Capitan stock (Cather et al., 2012), as shown by the reconstructed land-surface paleoelevation above the 28 Ma stock and the Ogallala remnants around its base (Kelley, 1971).

As erosion proceeded, the pre-Ogallala surface cut down through Mesozoic strata and groundwater came into contact with underlying Permian evaporites, beginning a prolonged episode of solution subsidence that continues today. Similar to Kelley (1972, figs. 6 and 7), we envision a north-south alignment of sinkholes on the Northwest Shelf, controlled primarily by the Triassic subcrop geometry of the evaporite-bearing Seven Rivers Formation. These sinkholes initially formed west of the modern Pecos River (Kelley, 1972) and eventually localized the north-flowing axial river. As it incised, the axial river beveled eastward, following the dip slope of the Guadalupian Seven Rivers Formation, as the modern Pecos River does today in most places. Lateral incision caused erosion in areas to the west, resulting in only local preservation of axial Gatuña deposits on the Northwest Shelf. Episodes of post-Gatuña aggradation resulted in deposition of the inset Blackdom, Orchard Park, and Lakewood terraces.

Northerly paleoflow in the early axial drainage probably developed in response to the regional tilting by the Sierra Madre epeirogen. The axial river captured drainages to the west, beheaded drainages to the east, and caused onset of dominantly eolian sedimentation on the southern Llano Estacado. This interpretation supports Bretz and Horberg's (1949, p. 478) contention, "...the 'quartzose conglomerate' in the bottom of the Pecos Valley is probably basal Ogallala instead of an early Pleistocene valley deposit." We also agree with Horberg's suggestion (1949, p. 470), "...the depression in which the fill is now preserved is due largely to solution-subsidence rather than to erosion by the Pecos River."

The nearest plausible eastward turning point for a north-flowing paleoriver is near Fort Sumner (Fig. 10). The Fort Sumner–Lubbock area was a major fluvial axis during ~13–5 Ma deposition of the Ogallala Formation, which was deposited as a series of nested fluvial valley fills and associated eolian strata (Reeves, 1972; Gustavson and Finley, 1985; Gustavson and Winkler, 1988; Winkler, 1990). Two deep, east-southeast-draining, pre-Ogallala paleovalleys lie beneath this axis (the Clovis and Slaton paleovalleys; Gustavson and Winkler, 1988), and the incised Portales Valley trends east-southeast above it. The Ogallala paleoriver deposits are oversteepened to the east-southeast, primarily due to tilting related to increased mantle buoyancy to the north and west (Pattat, 2017). The eastward-shallowing Portales Valley has long been regarded as having been cut by a tributary of the Brazos River (Baker, 1915; Reeves, 1972; Hawley, 2005). We suggest here that the Portales Valley also may have accommodated the north-flowing axial river described in this report (Fig. 10). If the Gatuña axial paleoriver is indeed Miocene, then the Ogallala Formation fluvial deposits in the Fort Sumner–Lubbock area likely host sediment from the north-flowing river as well.

The elevation of the modern Pecos River at Fort Sumner is 1225 m. The floor of the Portales Valley projects ~150 m above this point, to an elevation of 1375 m. Because it is steeper than the Portales Valley, the pre-Ogallala Clovis paleovalley projects to approximately the same 1375 m elevation (data from Cronin, 1969). The modern Pecos River at Artesia lies at 1010 m. Assuming a typical Ogallala thickness of 50 m, the erosion surface at the base of the Ogallala Formation projects ~450 m above the river at Artesia to 1460 m elevation, only slightly higher than the elevation projections (1375 m) at Fort Sumner. This elevation difference, however, cannot account for the northward paleoriver gradient over the 180 km between the two towns. Estimation of gradients for ancient rivers is difficult because of numerous unknown hydrologic parameters. If the gradient were similar to the Rio Grande in central New Mexico (~1 m/km), the elevation difference between the projected surface at Artesia and Fort Sumner (85 m) accounts for only about half of the calculated 180 m elevation difference. We suggest epeirogenesis along the Jemez lineament and thermal relaxation of the Sierra Madre epeirogen may readily account for the remaining 95 m.

Figure 9 is a cross section through the High Plains along

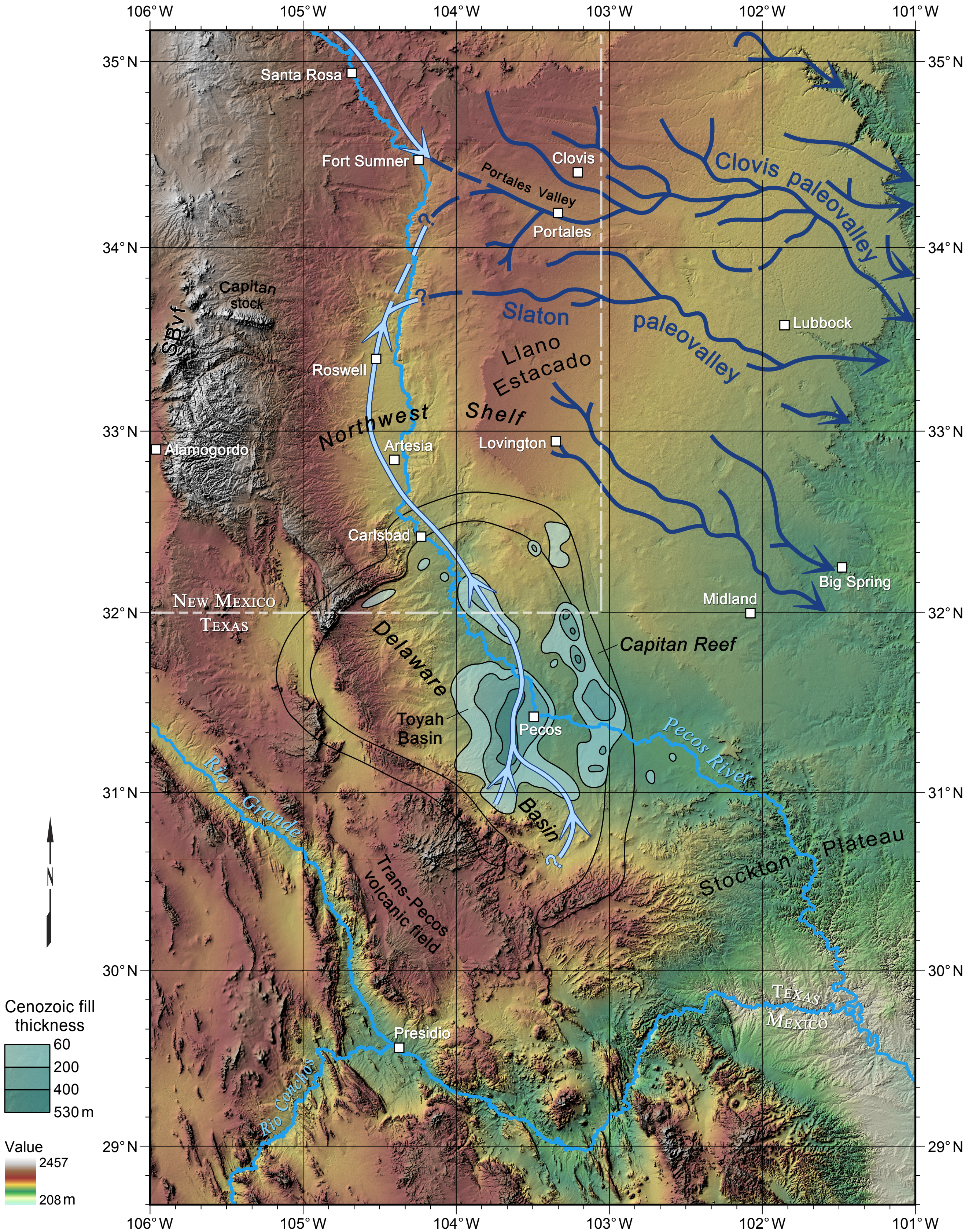

FIGURE 10. Digital elevation map of southeastern New Mexico and adjacent Texas showing Permian features (Delaware Basin, Capitan Reef, and Northwest Shelf) in relation to the proposed Miocene(?) axial Gatuña paleodrainage and Paleogene volcanic fields. Pre-Ogallala paleovalley trends are from Cronin (1969) and Hart and McAda (1985). Note that only the Clovis and Slaton paleovalleys extend beyond the western Llano Estacado escarpment. Cenozoic fill thicknesses modified from Meyer et al. (2012) and Bachman (1987, fig. 29). The line of cross section (unmarked) for Figure 9 extends northward along 103.5°W from the Texas–New Mexico line to southern Nebraska. SBvf—Sierra Blanca volcanic field.

103.5°W longitude. It shows broad arching of the Ogallala Formation centered on the Jemez volcanic lineament (Cather et al., 2012; Nereson et al., 2013) and the underlying Jemez low-velocity mantle anomaly (Schmandt and Humphreys, 2010). Similar uplift has been demonstrated elsewhere along the lineament (Wisniewski and Pazzaglia, 2002; Channer et al., 2015). Uplift of the High Plains along the lineament probably began in the late Miocene and was related to magmatism in the Raton volcanic field (9.0 Ma to 34 ka; Stroud, 1997; Nereson et al., 2013) and the Ocate volcanic field (8.2–0.8 Ma; Olmsted and McIntosh, 2004). Late Miocene southward tilting of the flank of the Jemez epeirogen was probably enhanced by lithospheric cooling and subsidence associated with middle Miocene cessation of volcanism in the Sierra Madre Occidental and Trans-Pecos Texas (Cather et al., 2009, and references therein). These effects probably both contributed to the 850 m difference in elevation of the Ogallala Formation across New Mexico (Fig. 9).

The elevation difference of the base of the Ogallala at the latitude of Fort Sumner to that of Artesia is ~170 m (Fig. 9). Thus, retrodeformation of the southward tilting on the flank of the Jemez epeirogen alone is probably enough to account for the former northward river gradient. In addition, because the pre-Ogallala erosion surface bevels down-section southward on the flank of the Sierra Madre epeirogen, this area may have stood an unknown amount *higher* than regions to the north prior to the middle Miocene.

In summary, northerly components of epeirogenic tilting by the Oligocene–early Miocene Sierra Madre epeirogen may explain the early northward axial paleoflow in the southeast New Mexico region. Beginning in the late Miocene, southward tilting by the Jemez epeirogen and similar-aged thermal subsidence of the Sierra Madre epeirogen eventually caused reversal of the former northerly paleoslope. Prior to, or during, Pleistocene integration of the Rio Grande through the Big Bend region (~2.06–0.8 Ma; Repasch et al., 2017), we suggest a fluvial system eroded headward across the Stockton Plateau (Fig. 10). Headward erosion eventually intersected the valley of the former north-flowing river within the Delaware Basin and rapidly captured it (flow reversal is relatively efficient within preexisting paleovalleys; Harel et al., 2019). When headward erosion reached the Fort Sumner area, the Portales Valley was abandoned.

CONCLUSIONS

1) Paleocurrent measurements show axial-fluvial deposits of the Gatuña Formation were deposited by a north-flowing river. This axial paleoriver headed at least as far south as the Trans-Pecos volcanic field. Speculatively, it may represent an ancestral Rio Conchos (Fig. 10), which drained part of the Sierra Madre Occidental prior to its capture by the Rio Grande during the Pleistocene.
2) The age of the Gatuña Formation is poorly understood but may range from Miocene to Pleistocene. Alluvial and eolian veneers marginal to the Pecos Valley are likely mostly Pleistocene. Axial-fluvial parts of the Gatuña that lie within solution-subsidence basins are likely Miocene–Pleistocene.
3) Cenozoic dissolution of Permian evaporites was triggered by regional downcutting of the pre-Ogallala erosion surface through Mesozoic strata. The erosion surface projects ~450 m above the modern Pecos River at Artesia, suggesting initial Gatuña-filled sinks may have originated hundreds of meters above the present land surface. Fluvial dissolution and erosion on the Northwest Shelf generally migrated eastward down the dip slope of the Seven Rivers Formation. Dissolution and erosion within the Delaware Basin were subvertical and did not migrate laterally in a systematic fashion.
4) The present disparities in elevation of Gatuña axial-fluvial deposits between the Delaware Basin and the probable eastward exit point for the north-flowing paleodrainage near Fort Sumner can be reconciled by the effects of deep solution subsidence and known episodes of epeirogenesis.

ACKNOWLEDGMENTS

Field support for this project was from the New Mexico Bureau of Geology and Mineral Resources. We benefitted from discussions with many people during the course of this investigation, including Bruce Allen, Snir Attia, Nelia Dunbar, John Hawley, and Tom Lehman. Robin Brewster and Dave McCraw assisted in the field. Bill McIntosh contributed greatly to the ongoing project. Lisa Peters facilitated much of the dating of the pebble samples, and her efforts are much appreciated. Mark Mansell and Becky Titus prepared the figures. The paper was improved by suggestions from NMGS reviewers John Hawley and Dennis Powers and by informal reviews by Karl Karlstrom and Fred Phillips. This paper is dedicated to John Hawley, one of the most knowledgeable scientists we've met.

REFERENCES

Anderson, J.C., Karlstrom, K.E., and Heizler, M.T., 2021, Neogene drainage reversal and Colorado Plateau uplift in the Salt River area, Arizona, USA: Geomorphology, v. 395, 107964, https://doi.org/10.1016/j.geomorph.2021.107964.

Ash, S.R., 1963, Ground-water conditions in northern Lea County, New Mexico: U.S. Geological Survey, Hydrologic Investigations Atlas HA-62, 2 sheets, scale 1:250,000.

Attia, S., and Allen, B.D., 2022, Geologic map of the Pierce Canyon quadrangle, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map 299, scale 1:24,000.

Attia, S., Allen, B.D., Ricci, J., and Heizler, M.T., 2023, Quaternary age of the Gatuña Formation at Livingston Ridge: New Mexico Geological Society, this guidebook.

Austin, G.S., Barker, J.M., Crawford, J.E., Hawley, J.W., Love, D., Lucas, S.G., and Adams, J.W., 1993, First-day road log from Carlsbad to White City, Orla, Loving, potash enclave and return to Carlsbad: New Mexico Geological Society, Guidebook 44, p. 1–42, https://doi.org/10.56577/FFC-44.1.

Bachman, G.O., 1976, Cenozoic deposits of southeastern New Mexico and an outline of the history of evaporite dissolution: U.S. Geological Survey Journal of Research, v. 4, p. 135–149.

Bachman, G.O., 1980, Regional geology and Cenozoic history of Pecos region, southeastern New Mexico: U.S. Geological Survey, Open-File Report 80-1099, 116 p., https://doi.org/10.3133/ofr801099.

Bachman, G.O., 1984, Regional geology of Ochoan evaporites, northern part of Delaware Basin: New Mexico Bureau of Mines and Mineral Resources, Circular 184, 22 p.

Bachman, G.O., 1987, Karst in evaporates in southeastern New Mexico: Albuquerque, Sandia National Laboratories, SAND86-7078, 82 p.

Baker, C.L., 1915, Geology and underground waters of the northern Llano Estacado, Texas: University of Texas Bulletin 57, 224 p.

Barnes, V.E., 1976, Geologic atlas of Texas, Pecos sheet: The University of Texas at Austin, Bureau of Economic Geology, scale 1:250,000.

Bretz, J.H., and Horberg, C.L., 1949, The Ogallala Formation west of the Llano Estacado: The Journal of Geology, v. 57, p. 477–490, https://doi.org/10.1086/625662.

Cather, S.M., 2011, A north-flowing ancestral Pecos River in southeastern New Mexico: A record of late Paleogene-early Neogene epeirogeny: New Mexico Geology, v. 33, p. 45, https://doi.org/10.56577/SM-2011.556.

Cather, S.M., Dunbar, N.W., McDowell, F.W., McIntosh, W.C., and Scholle, P.A., 2009, Climate forcing by iron fertilization from repeated ignimbrite eruptions: The icehouse-silicic large igneous province (SLIP) hypothesis: Geosphere, v. 5, p. 315–324, https://doi.org/10.1130/GES00188.1.

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

Cather, S.M., Zeigler, K.E., Mack, G.H., and Kelley, S.A., 2013, Toward standardization of Phanerozoic stratigraphic nomenclature in New Mexico: Rocky Mountain Geology, v. 48, p. 101–124, https://doi.org/10.2113/gsrocky.48.2.101.

Channer, M.A., Ricketts, J.W., Zimmerer, M., Heizler, M., and Karlstrom, K.E., 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, p. 1384–1400, https://doi.org/10.1130/GES01145.1.

Cikoski, C.T., 2019, Geologic map of the Malaga 7.5-minute quadrangle, Eddy County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Digital Geologic Map 285, scale 1:24,000.

Crawford, J.E., 1993, K Hill and Yeso Hills selenite occurrence: New Mexico Geological Society, Guidebook 44, p. 8–10.

Cronin, J.G., 1969, Ground water in the Ogallala Formation in the Southern High Plains of Texas and New Mexico: U.S. Geological Survey, Hydrologic Investigations Atlas, HA-330, 4 sheets, scale 1:500,000, 9 p.

Eaton, G.P., 1987, Topography and origin of the southern Rocky Mountains and Alvarado ridge, *in* Coward, M.P. et al., eds., Continental extensional tectonics: Geological Society of London, Special Publication 28, p. 353–369, https://doi.org/10.1144/GSL.SP.1987.028.01.22.

Frye, J.C., Leonard, A.B., and Glass, H.D., 1982, Western extent of Ogallala Formation in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 175, 41 p.

Gustavson, T.C., and Finley, R.J., 1985, Late Cenozoic geomorphic evolution of the Texas panhandle and northeastern New Mexico: Austin, Bureau of Economic Geology Report of Investigations no. 148, 42 p., https://doi.org/10.23867/RI0148D.

Gustavson, T.C., and Holliday, V.T., 1999, Eolian sedimentation and soil development on a semiarid to subhumid grassland, Tertiary Ogallala and Quaternary Blackwater Draw Formations, Texas and New Mexico High Plains: Journal of Sedimentary Research, v. 69, p. 622–634, https://doi.org/10.2110/jsr.69.622.

Gustavson, T.C., and Winkler, D.A., 1988, Depositional facies of the Miocene–Pliocene Ogallala Formation, northwestern Texas and eastern New Mexico: Geology, v. 16, p. 203–206, https://doi.org/10.1130/0091-7613(1988)016<0203:DFOTMP>2.3.CO;2.

Harel, E., Goren, L., Shelef, E., and Ginat, H., 2019, Drainage reversal toward cliffs induced by lateral lithologic differences: Geology, v. 47, p. 928–932, https://doi.org/10.1130/G46353.1.

Hart, D.L., Jr., and McAda, D.P., 1985, Geohydrology of the High Plains aquifer in southeastern New Mexico: U.S. Geological Survey Hydrologic Investigations Atlas HA-679, 1 sheet.

Hawley, J.W., 1993a, The Ogallala and Gatuña Formations in the southeastern New Mexico region: A progress report: New Mexico Geological Society, Guidebook 44, p. 261–269, https://doi.org/10.56577/FFC-44.261.

Hawley, J.W., 1993b, Overview of the geologic history of the Carlsbad area: New Mexico Geological Society, Guidebook 44, p. 2–3.

Hawley, J.W., 1993c, Upper Neogene valley and depression fills of the Orla, Texas area: New Mexico Geological Society, Guidebook 44, p. 27.

Hawley, J.W., 2005, Five million years of landscape evolution in New Mexico: An overview based on two centuries of geomorphic conceptual-model development, *in* Lucas, S.G., et al., eds., New Mexico's Ice Ages: New Mexico Museum of Natural History and Science, Bulletin 28, p. 9–93.

Hawley, J.W., Love, D.W., and Lucas, S.G., 1993, Cenozoic confusion, controversy and collapse at Pierce Canyon: New Mexico Geological Society, Guidebook 44, p. 33–34.

Henry, K.D., 2017, ^{40}Ar/^{39}Ar detrital sanidine dating of the Ogallala Formation, Llano Estacado, southeastern New Mexico and west Texas [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 103 p.

Horberg, L., 1949, Geomorphic history of the Carlsbad Caverns area, New Mexico: Journal of Geology, v. 57, p. 464–476, https://doi.org/10.1086/625661.

Izett, G.A., and Wilcox, R.E., 1982, Map showing localities and inferred distributions of the Huckleberry Ridge, Mesa Falls and Lava Creek Ash Beds (Pearlette family ash beds) of Pliocene and Pleistocene age in the western United States and southern Canada: U.S. Geological Survey, Miscellaneous Investigations Map 1-1325, scale 1:4,000,000.

Izett, G.A., Obradovich, J.D., Naeser, C.W., and Cebula, G.T., 1981, Potassium-argon and fission-track zircon ages of Cerro Toledo Rhyolite tephra in the Jemez Mountains, north-central New Mexico: U.S. Geological Survey, Professional Paper 1199D, p. 37–43.

Jicha, B.R., Singer, B.S., and Sobol, P., 2016, Re-evaluation of the ^{40}Ar/^{39}Ar sanidine standards and supereruptions in the western U.S. using Noblesse multi-collector mass spectrometer: Chemical Geology, v. 431, p. 54–66, https://doi.org/10.1016/j.chemgeo.2016.03.024.

Kelley, S.A., Koning, D.J., Goff, F., Cikoski, C., Peters, L., and McIntosh, W.C., 2014, Stratigraphy of the northwestern Sierra Blanca volcanic field: New Mexico Geological Society, Guidebook 65, p. 197–208, https://doi.org/10.56577/FFC-65.197.

Kelley, V.C., 1971, Geology of the Pecos Country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 27, 75 p., https://doi.org/10.58799/M-24.

Kelley, V.C., 1972, Geology of the Fort Sumner sheet, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 98, 55 p., https://doi.org/10.58799/B-98.

Kelley, V.C., 1980, Gatuña Formation (Late Cenozoic), Pecos Valley, New Mexico, and Trans-Pecos Texas: New Mexico Geological Society, Guidebook 31, p. 213–217, https://doi.org/10.56577/FFC-31.213.

Kues, B.S., and Lucas, S.G., 1993, Stratigraphy, paleontology and correlation of lower Cretaceous exposures in southeastern New Mexico: New Mexico Geological Society, Guidebook 31, p. 245–260, https://doi.org/10.56577/FFC-44.245.

Lang, W.B., 1938, Geology of the Pecos River between Laguna Grande de la Sal and Pierce Canyon, *in* Robinson, T.W., and Lang, W.B., Geology and ground-water conditions of the Pecos River Valley in the vicinity of Laguna Grande de la Sal, New Mexico, with special reference to the salt content of the river water: New Mexico State Engineer 12th and 13th Biennial Reports, p. 80–86.

Lang, W.B., 1947, Occurrence of Comanche rocks in Black River Valley, New Mexico: American Association of Petroleum Geologists Bulletin, v. 31, p. 1472–1478, https://doi.org/10.1306/3D933A19-16B1-11D7-8645000102C1865D.

Lee, W.T., 1925, Erosion by solution and fill, *in* Campbell M.R., Contributions to the Geology of the United Sates, 1923–24: U.S. Geological Survey, Bulletin 760-C, p. 107–121.

Lucas, S.G., and Anderson, O.J., 1993, Triassic stratigraphy in southeastern New Mexico and southwestern Texas: New Mexico Geological Society, Guidebook 44, p. 231–235, https://doi.org/10.56577/FFC-44.231.

Lucas, S.G., and Morgan, G.S., 2008, The Proboscidean *Amebelodon* from east-central New Mexico and its biochronological significance: New Mexico Museum of Natural History and Science, Bulletin 44, p. 89–91.

Maley, V.C., and Huffington, R.M., 1953, Cenozoic fill and evaporate solution in the Delaware Basin, Texas and New Mexico: Geological Society of America Bulletin, v. 64, p. 539–546, https://doi.org/10.1130/0016-7606(1953)64[539:CFAESI]2.0.CO;2.

Meinzer, O.E., Renich, B.C., and Bryan, K., 1926, Geology of No. 3 reservoir site of the Carlsbad irrigation project, New Mexico with respect to water tightness: U.S. Geological Survey, Water-Supply Paper 580, p. 12–13.

Meyer, J.E., Wise, M.R., and Kalaswad, S., 2012, Pecos Valley aquifer, west Texas: Structure and brackish groundwater: Texas Water Development Board, Report 382, 86 p.

Miller, R.R., 1982, First fossil record (Plio-Pleistocene) of threadfin shad, *Dorosomo petenense*, from the Gatuña Formation of southeastern New Mexico: Journal of Paleontology, v. 56, p. 423–425.

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

Nye, S.S., 1933, Physiography, *in* Fiedler, A.G., and Nye, S.S., Geology and ground-water resources of the Roswell artesian basin, New Mexico: U.S. Geological Survey, Water Supply Paper 639, p. 7–18.

Olmsted, B.W., and McIntosh, W.C., 2004, $^{40}Ar/^{39}Ar$ geochronology of the Ocate volcanic field, north-central New Mexico, *in* Cather, S.M., et al., eds., Tectonics, geochronology, and volcanism in the southern Rocky Mountains and Rio Grande rift: New Mexico Bureau of Geology and Mineral Resources, Bulletin 160, p. 297–308.

Pattat, A., 2017, Assessing post-Miocene tilting of the Southern High Plains through paleoslope reconstructions of the Ogallala Formation [M.S. thesis]: Lubbock, Texas Tech University, 56 p.

Potochnik, A.R., 2001, Paleogeomorphic evolution of the Salt River region: Implications for Cretaceous–Laramide inheritance for ancestral Colorado River drainage, *in* Young, R.A., and Spamer, E.E., eds., Colorado River: Origin and evolution: Grand Canyon, Arizona, Grand Canyon Association, p. 17–22.

Potochnik, A.R., and Faulds, J.E., 1998, A tale of two rivers; mid-Tertiary structural inversion and drainage reversal across the southern boundary of the Colorado Plateau, *in* Duebendorfer, E.M., ed., Geologic excursions in northern and central Arizona: Flagstaff, Northern Arizona University, p. 149–173.

Powers, D.W., and Holt, R.M., 1993, The upper Cenozoic Gatuña Formation of southeastern New Mexico: New Mexico Geological Society, Guidebook 44, p. 271–282, https://doi.org/10.56577/FFC-44.271.

Rawling, J., 2004, Geologic map of the Angus quadrangle, Lincoln County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map 94, scale 1:24,000.

Reeves, C.C., Jr., 1972, Tertiary-Quaternary stratigraphy and geomorphology of west Texas and southeastern New Mexico: New Mexico Geological Society, Guidebook 23, p. 108–117, https://doi.org/10.56577/FFC-23.108.

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

Ricketts, J.W., Kelley, S.A., Karlstrom, K.E., Schmandt, B., Donahue, M.S., and van Wijk, J., 2016, Synchronous opening of the Rio Grande rift 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. 397–324, https://doi.org/10.1130/B31223.1.

Rosholt, J.N., and McKinney, C.R., 1980, Uranium series disequilibrium investigations related to the WIPP site, New Mexico, Part II, Uranium trend dating of surficial deposits and gypsum spring deposit near WIPP site, New Mexico: U.S. Geological Survey, Open-File Report, no. 80-879, p. 7–16.

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

Schmandt, B., and Humphreys, E., 2010, Complex subduction and small-scale convection revealed by body-wave tomography of the western United States upper mantle: Earth and Planetary Science Letters, v. 297, p. 435–445, https://doi.org/10.1016/j.epsl.2010.06.047.

Spell, T.L., Kyle, P.R., and Baker, J., 1996. Geochronology and geochemistry of the Cerro Toledo rhyolite: New Mexico Geological Society, Guidebook 47, p. 263–268, https://doi.org/10.56577/FFC-47.263.

Stephenson, S.N., Roberts, G.G., Hoggard, M.J., and Whittaker, A.C., 2014, A Cenozoic uplift history of Mexico and its surroundings from longitudinal river profiles: Geochemistry, Geophysics, Geosystems, v. 15, p. 4734–4758, https://doi.org/10.1002/2014GC005425.

Stroud, J.R., 1997, The geochronology of the Raton-Clayton volcanic field, with implications for the volcanic history and landscape evolution [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 116 p.

Winkler, D.A., 1985, Stratigraphy, vertebrate paleontology and depositional history of the Ogallala Group in Blanco and Yellowhouse Canyons, northwestern Texas [Ph.D. dissertation]: Austin, The University of Texas at Austin, 243 p.

Winkler, D.A., 1990, Stop 3: Ogallala Formation (Group) exposed at Janes Quarry, *in* Gustavson, T.C., ed., Tertiary and Quaternary stratigraphy and vertebrate paleontology of parts of northwestern Texas and eastern New Mexico: Austin, Bureau of Economic Geology, Guidebook 24, p. 38–40.

Wisniewski, P.A., and Pazzaglia, F.J., 2002, Epeirogenic controls on Canadian River incision and landscape evolution, Great Plains of northeastern New Mexico: Journal of Geology, v. 110, p. 437–456, https://doi.org/10.1086/340441.

Appendices can be found at
https://nmgs.nmt.edu/repository/index.cfml?rid=2023002