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CLUES FROM THE SANTA FE GROUP FOR OLIGOCENE-MIOCENE PALEOGEOGRAPHY OF THE SOUTHEASTERN COLORADO PLATEAU NEAR GRANTS, NEW MEXICO

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Abstract—Progressive erosion of the southeastern Colorado Plateau during Miocene deposition shed notable amounts of sediment into the western Albuquerque basin, where it constitutes the Santa Fe Group. We use gravel compositions, clast ages, and paleoflow data from the middle Santa Fe Group to infer the Oligocene-Miocene paleogeography of the southeastern Colorado Plateau. This paper focuses on gravelly strata in the Cerro Conejo Formation (Santa Fe Group) mapped in the central Rio Puerco valley (within 25 km north of I–40), which are assigned to a new informal unit called the Benavidez member (14-8 Ma). These gravelly strata interfinger eastward with the Navajo Draw Member (Arroyo Ojito Formation) and the main, non-gravelly body of the Cerro Conejo Formation. The Benavidez member can be divided into three gravel-based petrosomes: volcanic-dominated, chert-dominated (≤5% volcanics), and mixed volcanic-chert (5-50% volcanics). Minor quartzite, quartz, and Proterozoic metarhyolites are found with the chert gravel. Only the chert-gravel petrosome is present north of latitude 35°9'N. To the south, the volcanic-gravel petrosome lies at the base of the Benavidez member, with stratigraphically higher Benavidez strata consisting of interfingering mixed-gravel and chert-gravel petrosomes. Paleocurrent data from the volcanic-gravel and mixed-gravel petrosomes are slightly more easterly (medians of 112 and116°) than the chert-gravel petrosome (median of 138°), supporting a more northerly source for the latter. $^{40}Ar/^{39}Ar$ radiometric analyses of four ignimbrite clasts in the volcanic-gravel petrosome returned ages and K/Ca values matching the Vicks Peak Tuff (28.77±0.01 Ma) and the La Jencia Tuff (29.00±0.01 Ma)—consistent with lithologic similarities observed in hand samples. Based on the spatial distribution of the Benavidez petrosomes and their associated paleocurrents, we interpret that a volcaniclastic apron sourced from the Mogollon-Datil volcanic field extended northward to ~35°20' N in the Oligocene, coinciding with the northern edge of the younger Mount Taylor volcano (Plio-Pleistocene). This apron interfingered with the Chuska Sandstone and chert-rich gravel derived from the Zuni uplift. During the Pliocene through Pleistocene, exhumation caused a progressive southward retreat of the northward extent of the volcaniclastic sediment, culminating with its complete removal north of the Rio Salado.

INTRODUCTION

One of the fascinating aspects of geology is the reconstruction of past landscapes. This reconstruction is most readily accomplished through recognition of depositional facies in sedimentary rocks where such rocks have been preserved, commonly within a basin. The sedimentary record in a basin, particularly sediment composition and paleoflow indicators, can also offer clues about the nature of the source area(s). This sedimentary record is particularly important for older (typically pre-Quaternary) deposits, where time intervals are significantly long to allow modification of the source area through exhumation or tectonic processes.

In addition to refining our understanding of past landscapes, understanding the original extent of volcaniclastic aprons and ignimbrites is imperative given the recent popularity of using detrital zircon and detrital sanidine methods to understand regional uplift, exhumation, and river history. Intermediate-felsic volcanic complexes can generate particularly large volcaniclastic aprons that have been documented to extend 100 km or more from the source vents. Examples include the volcaniclastic apron on the southwestern flanks of the Latir volcanic field (Abiquiu and Los Pinos formations; Smith, 2004) and the volcaniclastic sediment extending south from the eastern Mogollon Datil field (Thurman Formation, see Seager and Mack, 2003, fig. 13). Likewise, ignimbrites can travel 100-200 km, particularly if "funneled" through paleovalleys (e.g., Chapin and Lowell, 1979). Due to subsequent erosion, the original extent of volcaniclastic aprons can be difficult to establish, and researchers using detrital methods can misinterpret data if these original extents are not recognized.

This paper uses sedimentological and stratigraphic evidence in the Cerro Conejo Formation (Santa Fe Group) to interpret the source of gravel shed into the western Albuquerque basin between ~14 and 8 Ma. The studied gravel is located in the middle Santa Fe Group in the Rio Puerco Valley within 25 km north of I–40 (study area outlined in Fig. 1). Over the past decade, the geology in this part of the Rio Puerco Valley has been mapped at 1:24000 scale by the New Mexico Bureau of Geology and Mineral Resources (Cikoski et al., 2012; Koning and Jochems, 2014; Koning and Rawling, 2017; Rawling and Koning, 2019, in prep), and the data for this paper were collected during this STATEMAP-funded mapping. The generalized geology of the study area is shown in Figure 2. Four tuff-gravel samples were collected for $^{40}Ar/^{39}Ar$ radiometric dating of sanidine to determine if the volcanic gravels were derived from the San Juan or Mogollon-Datil volcanic fields.

Literature on the paleogeography of the southeastern Colorado Plateau includes Cather et al. (2003, 2008, 2012, 2019,

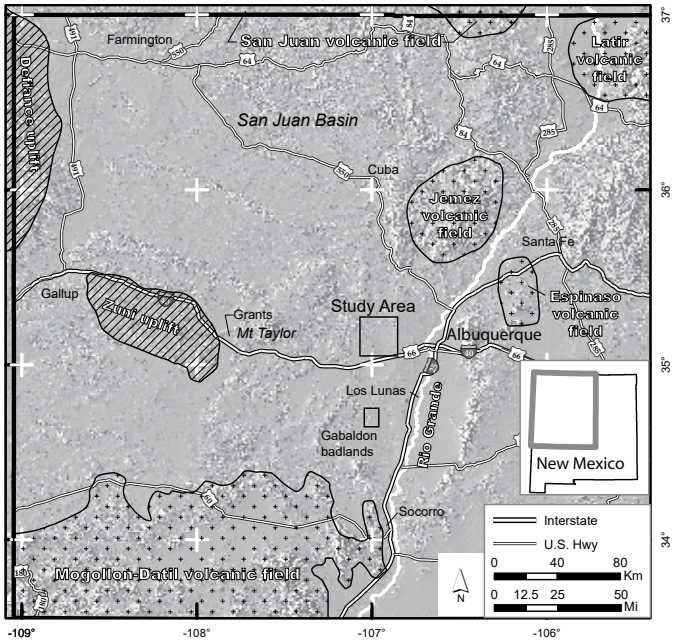


FIGURE 1. Geography of northwest New Mexico depicted on a hillshade DEM. The Rio Puerco Valley study area and Gabaldon Badlands are denoted by black squares. Eighty kilometers to the west lies Mount Taylor and Grants. Beyond 100 km to the south-southwest is the Mogollon-Datil volcanic field. Other volcanic fields are located to the north and northwest of the study area. Laramide uplifts on the southeastern Colorado Plateau are illustrated by diagonal-line patterns.

and references therein). Notable previous stratigraphic work on the Santa Fe Group along the western margin of the Albuquerque basin includes Bryan and McCann (1937, 1938), Wright (1946), Galusha (1966), Gawne (1973, 1981), Kelley (1977), and Lozinsky and Tedford (1991). Richard Tedford spearheaded studies on the paleontology and stratigraphy of the lower to middle Santa Fe Group along the eastern slopes of the Rio Puerco Valley (Tedford, 1981, 1982; Tedford and Barghoorn, 1997, 1999; Tedford et al., 1987). Connell et al. (1999) and Connell (2008a) revised Santa Fe Group stratigraphy and provided related age control. This revised stratigraphy was applied to the east edge of the study area in the geologic map of Connell (2008b). Previous work most applicable to constraining the age of the studied gravelly strata are in the synthesized magnetostratigraphic, paleontological, and radiometric data of Tedford and Barghoorn (1999) together with the focused paleontological work by Morgan and Williamson (2000, 2007) on the Cerro Conejo Formation.

METHODS

Details of mapping methodology are given in the reports for the aforementioned STATEMAP projects. Petrographic analyses were performed on 30-µm thin sections from Middle Miocene Santa Fe Group strata of the Benavidez Ranch quadrangle; those from the Cerro Conejo Formation are presented in this paper. Grain size is predominately medium to coarse grained. Thin sections were analyzed using a polarizing microscope with a 0.1-mm-precision stage caliper. Grid spacings were set larger than the maximum grain size for each thin section. Random point counts of 100-150 grains were conducted. Grains were analyzed in both plane and crossed-polarized light and were subsequently binned into quartz-feldspar-lithic (QFL) classes, with additional notes on texture and the composition of feldspar and lithic grains (Koning and Jochems, 2014).

$^{40}Ar/^{39}Ar$ analysis was conducted on four individual gravel clasts at the New Mexico Geochronology Research Laboratory. Sanidine crystals were concentrated using standard heavy liquid, Franz magnetic, and hand-picking techniques. The separates were irradiated in a machined aluminum tray for 16 hours at the USGS TRIGA facility, using neutron flux monitor Fish Canyon Tuff sanidine (FC-2, assigned age of 28.201 Ma; Kuiper et al., 2008). Following irradiation, sanidine grains were loaded into an ultrahigh vacuum chamber and individual grains were fused with a CO_2 laser to extract the argon. Argon isotopic compositions of the crystals were measured on an Argus VI mass spectrometer. Dates were calculated using a ^{40}K total decay constant of 5.463E-10/a (Min et al., 2000) and ages of clasts are the weighted inverse variance of the crystals deemed to define a population. Uncertainties are reported at 1 sigma and errors are increased by the square root of the MSWD when MSWD is greater than one.

STRATIGRAPHY

Based on observations during the course of geologic mapping, gravelly sand tongues interfinger eastward with the sand-dominated Cerro Conejo Formation in the northeastern study area (Fig. 3). Such gravel tongues are shown in the upper part of the magneostratigraphic section of Tedford and Barghoorn (1999, fig. 3), at stratigraphic heights >250 m above the base of the Cerro Conjeo Formation (column A, Fig. 3). However, to the southwest pebbly sediment occurs lower in the Cerro Conejo Formation (column C, Fig. 3). Sandy strata of the Cerro Conejo Formation near these gravelly intervals are lithologically similar to the sand within the gravelly tongues, including where gravelly strata dominate the section (e.g., cross section E-E' in Fig. 2). Thus, it is reasonable to include these gravelly strata with the Cerro Conejo Formation.

We apply the informal name "Benavidez member" to tabular-bedded, tan to reddish yellow sand that contains ≥1% gravel beds. The Benavidez member is relatively well-exposed near cross section E-E' in Figure 2, but these exposures are on the To'hajiilee Reservation and not publicly accessible. Publicly accessible gravelly strata assigned to the Benavidez member are found in I–40 roadcuts, at a distance 3 km west of the Rio Puerco.

The Cerro Conejo Formation overlies the Zia Formation and underlies the Navajo Draw Member of the Arroyo Ojito Formation (Figs. 4, 5; see Appendix 1 for more detail on these stratigraphic units). Along the Ceja del Rio Puerco, north of the study area depicted in Figure 2, gravelly sands occupy a transitional, 12- to 18-m-thick interval between the Cerro Conejo and Navajo Draw Member of the Arroyo Ojito Formation (Koning and Rawling, 2017). In the northern study area, the lower contact intertongues with the Cañada Pilares Member of

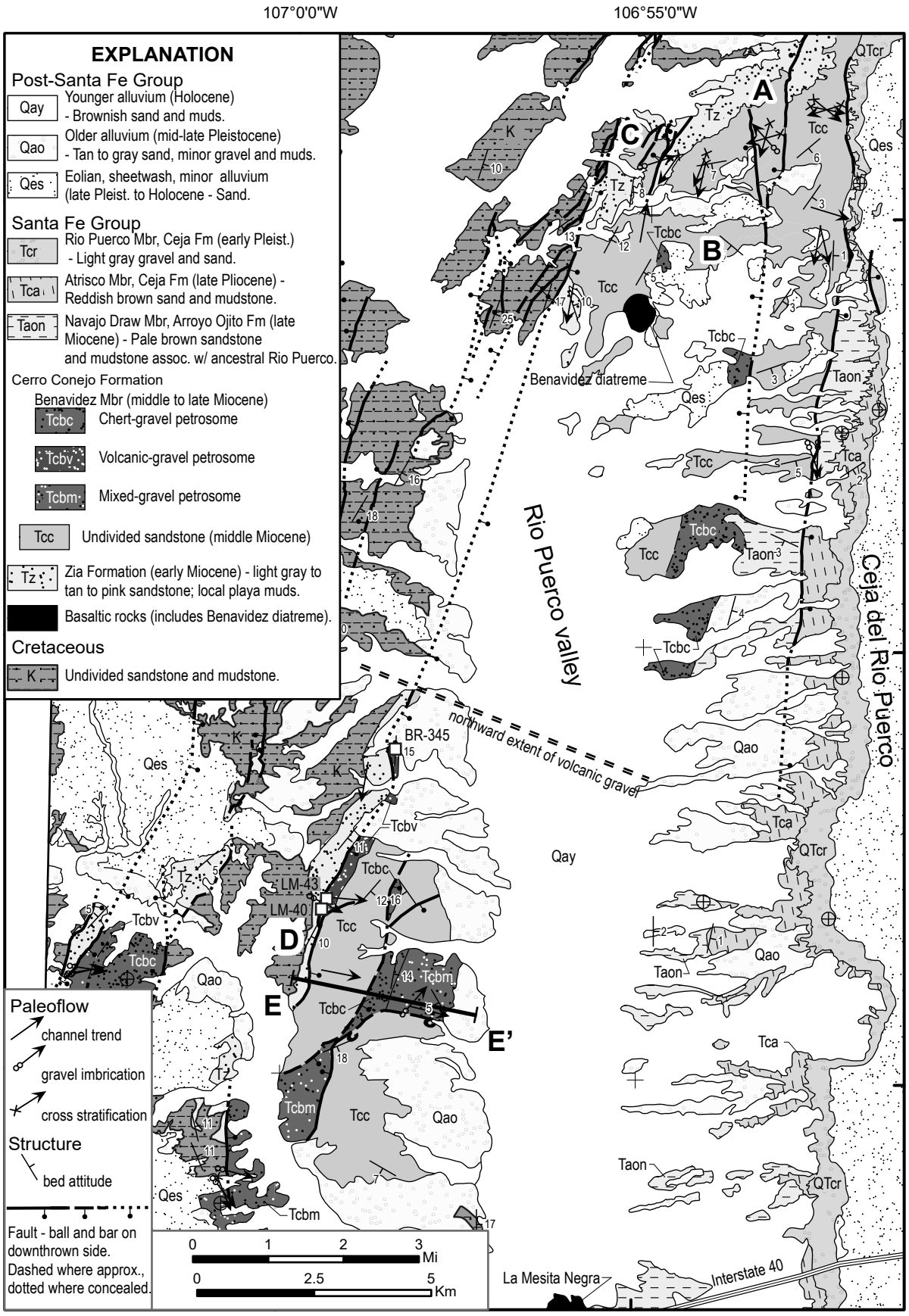


FIGURE 2. Geologic map of the studied Rio Puerco area. Modified from Williams and Cole (2007) according to Connell et al. (2008b) and recent STATEMAP work (Cikoski et al., 2012; Koning and Jochems, 2014; Koning and Rawling, 2017; Rawling and Koning, 2019, in prep). Letters A through D depict the locations of the stratigraphic columns of Figure 3. The white squares are locations of dated graveel samples. Paleocurrent arrows for gravel imbrication is the mean value at a site.

the Zia Formation (Koning and Rawling, 2017). However, this mudstone-rich unit is not present to the south, and there the Cerro Conejo directly overlies tan to pink sands of the upper Zia Formation (Figs. 3, 4, Tzu and Tz respectively). In the southern study area, basal strata of the Cerro Conejo Formation consist of a reddish gravelly sand (Tcblv, Figs. 3, 4), with a gravel fraction that is mostly volcanic in composition. The base of this volcaniclastic tongue is not exposed due to normal faulting. The volcaniclastic gravelly sand is overlain by 70-80 m of sand, locally cross-stratified and inferred to be eolian, interbedded with minor mudstone (Tccu, Figs. 3, 4).

In the northeastern study area, the piedmont lithofacies assemblage has prograded eastward over basin floor assemblages (Tcc4 overlying Tcc2-3, column B in Fig. 3), and lower in the section these basin floor deposits interfinger westward with piedmont deposits (compare columns B and C, Fig. 3). The piedmont lithofacies assemblage throughout the Cerro Conejo Formation is characterized by medium to thick, tabular-bedded, pink to light brown to reddish yellow sandstones. These beds are either massive or laminated (mostly horizontal-planar). There are minor (1-5%) clayey, very fine- to fine-grained sandstone beds and clay-dominated mudstones. The sand is subangular to rounded, and the grain size is mostly fine to medium with minor, scattered coarse to very coarse sand grains composed of quartz, chert, and volcanic lithic grains. The Benavidez member, occupying the gravelly, more medial parts of the aforementioned piedmont lithofacies assemblage, thickens from 100 to 250 m between the northeast and southwest parts of the study area (not including the basal volcaniclastic tongue) along with an increase in the proportion of gravel beds.

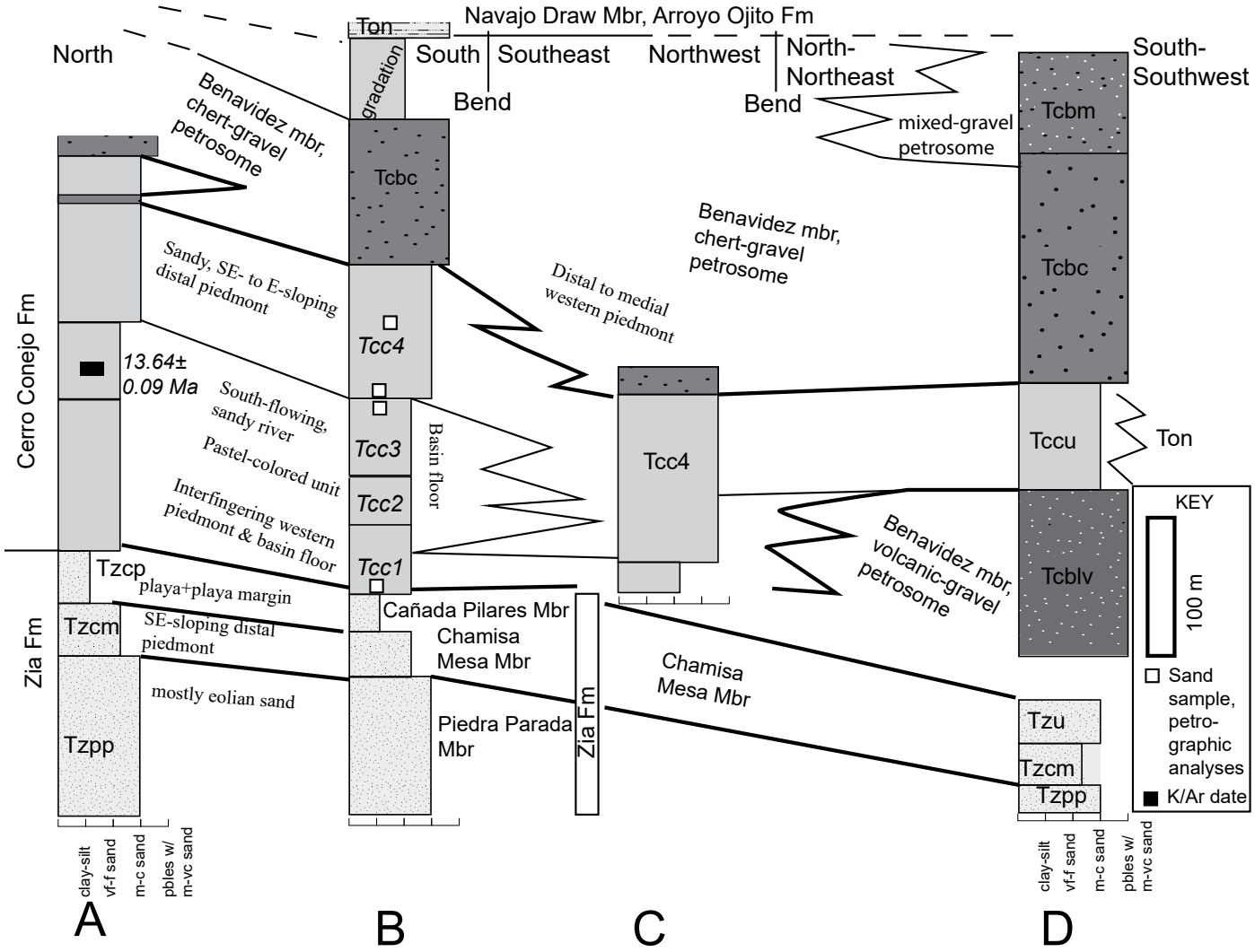


FIGURE 3. Stratigraphic fence diagram illustrating lower to middle Santa Fe Group stratigraphic relations along the studied reach of the Rio Puerco Valley, including the Benavidez member and its associated petrosomes. The locations of Columns A through D are shown in Figure 2. Open squares are the stratigraphic position of petrographic sand samples, taken within 5 km of the Benavidez diatreme. The black rectangle in Column A is the stratigraphic position of the K/Ar sample of Tedford and Barghoorn (1999). Tcc1 through Tcc4 are the subunits of the Cerro Conejo Formation mapped in Koning and Jochems (2014). Abbreviations for members of the Zia Formation: Tzpp = Piedra Parada, Tzcm = Chamisa Mesa, Tzcp = Cañada Pilares. Abbreviations for Benavidez member petrosomes: Tcbc = chert-dominated gravel, Tcbm = mixed gravel, Tcblv = volcanic-dominated gravel. Other abbreviations: Tzu = Upper Zia Formation; Ton = Navajo Draw Member of Arroyo Ojito Formation. Note that we designate the Cerro Conejo Formation base at the top of the playa facies of the Cañada Pilares Member, following Koning and Jochems (2014; cf., Tedford and Barghoorn, 1999).

In the Benavidez member, gravelly intervals occupy 1-25% of the piedmont lithofacies assemblage and are dominated by pebbles with <5% cobbles. Gravel occurs in intervals 1-5 m thick, and the individual gravel beds are mostly very thin to thin and tabular to lenticular; pebbly sand is typically horizontal-planar laminated (Fig. 5). Maximum clast size is commonly 5-7 cm.

Gravel Petrosomes

The Benavidez member can be subdivided into three petrosomes (Figs. 2-4). A petrosome is an informal stratigraphic unit (body of sediment) recognized solely by composition; in our study, we use gravel compositions (Figs. 2-4). The chert-gravel petrosome has ≤5% volcanic clasts and the dominant clast type is chert. The volcanic-gravel petrosome has 50-100% volcanic clasts, with the remainder of the gravel being chert, lesser quartzite and quartz, and trace petrified wood. More variable proportions of chert vs. volcanics (i.e., chert with 5-50% volcanics) are assigned to the mixed-gravel petrosome. The volcanic-gravel petrosome is only found in the lower Benavidez member west of the Rio Puerco (Tcblv, Figs. 2-4).

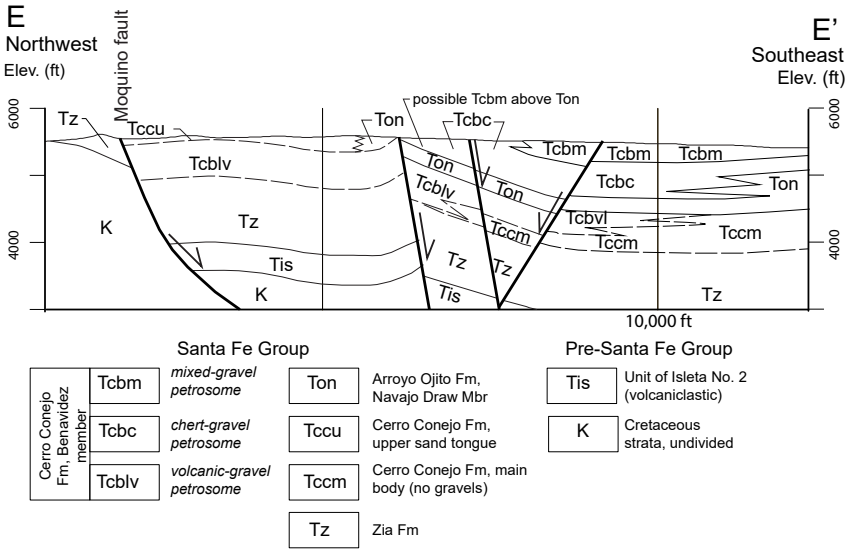


FIGURE 4. Cross section E-E' illustrating stratigraphic and thickness relations in the southwest part of the study area (cross section location given in Figure 2). Slightly modified from Cikoski et al. (2012).

Age

The age of the Benavidez member is ca. 14 to 8 Ma. The minimum age of 8 Ma is based on the age of the interfingering Navajo Draw Member (Arroyo Ojito Formation) in the southwestern study area, which has a lava flow dated at 8.11±0.05 Ma (La Mesita Negra in Fig. 2; Maldonado et al., 2006, table 1). The maximum age is obtained from the following observations in the northeastern study area. Fossils in the Cerro Conejo Formation have primarily been recovered from the basin floor deposits (Tcc2-3, Fig. 3) and are interpreted as being 14-12 Ma (Tedford and Barghoorn, 1999; Morgan and Williamson, 2000, 2007). This age range is consistent with a 13.64±0.09 Ma ash (Tedford and Barghoorn, 1999) found 130 m above the base of the formation (Fig. 3). Comparing the stratigraphic distance of the lowest pebbles to the west (column C, Fig. 3) relative to this dated ash (column A, Fig. 3), the Benavidez member has a maximum age of 13.5 Ma in the northern study area (columns A-C, Fig. 3). However, it is likely older (14-15 Ma?) in the southern study area, considering the stratigraphically low position of the volcanic-gravel petrosome (column D, Fig. 3).

RESULTS
Sedimentological Data

Sand composition in main body of Cerro Conejo Formation

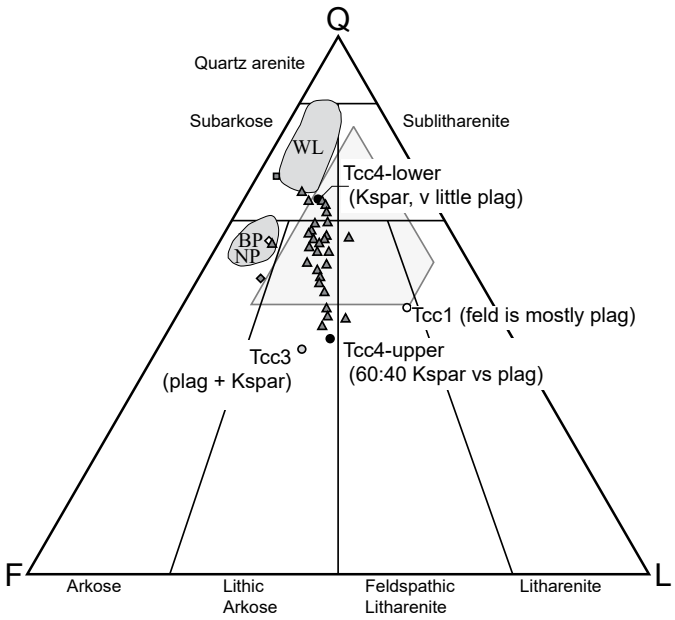
In order to characterize the source area of the Benavidez member, we conducted sand petrographic analyses of the Cerro Conejo Formation. Samples were taken from units Tcc1, Tcc3, and Tcc4 (Fig. 3; Appendix 2). Of particular interest are the two samples from Tcc4, interpreted as a distal piedmont equivalent of the chert-gravel petrosome of the Benavidez Member. In Figure 6, a quartz-feldspar-lithic ternary diagram is used to compare these data with the sand composition of the Arroyo Ojito and Ceja formations (Brandes, 2002) and the Chuska Sandstone (Wright, 1956; Trevena, 1979; Cather et al., 2003; Dickinson et al., 2010).

The sand composition is variable within the Cerro Conejo Formation. For three of the four Cerro Conejo samples, quartz is the most abundant constituent at 42-50%, followed by 14-35% feldspar (plagioclase and potassium feldspar), and 23-36% lithic and mafic grains (Fig. 6). The lithic grains are composed



FIGURE 5. Photograph illustrating gravelly beds associated with the Benavidez member, taken in the southwest part of the study area.

of volcanics, chert, and siltstone to fine-grained sandstone (Appendix 2). One sample that contrasts with this generalization is Tcc4-lower, which has notably higher quartz and lower lithic proportions: 70% quartz, 19% feldspar (dominated by potassium feldspar), and 12% lithic grains consisting of very fine- to fine-grained sandstone and siltstone (Fig. 6, Appendix 2). Sample Tcc4-upper is slightly coarser-grained than the other samples (range of medium to very coarse, with very minor granules up to 7 mm). This coarser texture might account for the higher lithic content of that sample compared to Tcc4-lower—which would be consistent with hand-sample observations elsewhere. The quartz-feldspar-lithic composition of Tcc4-lower compares favorably with the Narbona Member of the Chuska Sandstone and the western piedmont facies of the Arroyo Ojito and Ceja formations (Fig. 6), in addition to its high ratio of potassium feldspar vs. plagioclase (cf. Dickinson et al., 2010, table 2). Higher in the piedmont lithofacies assemblage and closer (stratigraphically) to the gravel tongues, the sand composition (Tcc4-upper) is 44% quartz, 29% feldspar (slightly more potassium feldspar than plagioclase), and 25% lithic grains that contain quartzose sandstone, carbonate, and chert (Appendix 2). This sample, in addition to Tcc1, contains more lithic grains and less quartz than previously reported for the Chuska Sandstone (Fig. 6).



Cerro Conejo Fm, this work
- Upper western piedmont facies (Tcc4)
- Sandy, south-flowing fluvial facies, main body (Tcc3)
- Interfingering, lower western piedmont and basin floor facies (Tcc1)

Arroyo Ojito and Ceja Fm (Brandes, 2002)
- Western piedmont facies

Chuska sandstone
- Wright (1956)
- Deza Mbr -- Trevena (1979)
- Narbona Pass Mbr -- Trevena (1979)

Light-gray shade: values from Cather et al. (2003).
Medium-gray shade: values from Dickinson et al. (2010).
BP & NP = Buffalo and Narbona Pass; WL = Whiskey Lake.
Quartz values adjusted to reflect total quartz.

FIGURE 6. Ternary plot depicting the total quartz-feldspar-lithic (QFL) sand composition of the Cerro Conejo Formation and the Chuska Sandstone. Of particular interest in this study are samples Tcc4-lower and Tcc4-upper from the piedmont lithofacies assemblage. Upslope on this paleopiedmont would be the gravelly sediment associated with the Benavidez member, so the sand composition of these samples would reflect that of the Benavidez member. Shown for comparison is a sandy, south-flowing fluvial facies in the Cerro Conejo Formation (sample Tcc3) and interfingering basin floor-western piedmont lithofacies at the base of the Cerro Conejo Formation (sample Tcc1).

Gravel composition in Benavidez Member

The composition of gravels in the Benavidez member petrosomes was determined by clast counts and visual estimates (Tables 1-2, Appendices 3-4) conducted over the course of mapping. The visual estimates have an estimated error of 3% (for 0-10% ranges), 5% (for 10-15% ranges), and 10% (for 20-50% ranges).

Table 2 presents a detailed list of volcanic gravel compositions at one site in the volcanic-gravel petrosome (LM-43-cc in Table 1); associated photographs are shown in Appendix 3. Of the gravel types, 35% were felsic volcanic and 28% were intermediate-felsic volcanic types; cherts are 21% of the total gravel. The felsic volcanic gravel is mostly a similar, light gray, crystal-poor tuff (20% of total gravel) that has 1-3% phenocrysts dominated by sanidine. Other felsic types include a eutaxitic, reddish brown tuff (2%) and a crystal-rich tuff (5%) with >30% crystals (0.2-1.5 mm in size) composed of quartz, clear feldspar (sanidine + plagioclase), and 1-10% mafics. The intermediate volcanic rocks are mostly a light gray, porphyritic dacite with >15% phenocrysts composed of plagioclase, hornblende, and local biotite. Other intermediate types include relatively fine-grained and darker andesite and basaltic andesite. These same types of volcanic clasts were typically observed in the mixed-gravel petrosome as well.

Stratigraphically above the volcanic petrosome, the Benavidez member consists of the chert-gravel petrosome, which is overlain by (or intertongues with) the mixed-gravel petrosome south of latitude 35°9'N. The chert-gravel petrosome is dominated by chert clasts and has ≤5% volcanic gravel. Locally, intraformational sandstone and reworked calcium carbonate nodules are notable constituents of the gravel (e.g., LM-85, Table 1). Relatively minor gravel components include metarhyolites, quartz, and quartzite—each being ≤15%. Tan to brown sandstone clasts occur locally but are ≤7%. The composition of the mixed-gravel petrosome is relatively similar to that of the chert-gravel petrosome, except that the percentage of volcanic types is as high as 23%. Granite and Pedernal Chert clasts are typically not seen except in the stratigraphically highest parts of the Benavidez member (e.g., upper part of the mixed-gravel unit, eastern part of cross-section E-E', Fig. 4). There, Pedernal Chert is observed in trace amounts, but granite is slightly higher—typically trace to 1% and as much a 15% in LM-85 (Table 1). Pedernal Chert is found in the northern Nacimiento Mountains (Kelley et al., 2013; Vazzana and Ingersoll, 1981; Moore, 2000; Timmer, 1976), and presumably the granite is derived from the western front of the Nacimiento Mountains since this is the closest bedrock source to the Pedernal Chert (NMBGMR, 2003).

Table 1. Gravel composition according to petrosome in the Benavidez member of the Cerro Conejo Formation (values in percent).

	Chert gravel-petrosome (≤5% volcanics)																
	SF-344D	**BR-509**	**BR-136**	**BR-524**	**LM-75**	**LM-79**	**LM-82-cc**	**LM-83**	**LM-85**	**H-578**	**H-581**	**H-583**	**H-585b**	**H-588a**	**H-593**	**H-598**	**H-602**
Int volc	0	0	0	0	0		3	tr	0	0	0	0	0	0	0.5	0	0
Felsic volc$^{\Omega}$	1-3	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0
Volcanic, undivid	1-3	0	0	0	0	1	5	0	0	0	0	0	0	0	0.5	0	0
Chert (approx)	95	85	70	90	85	95	56	90	33	80	80	70-75	80	80	75	70-75	90
Quartz	1-2	1-5	10	5-7	3-5	3	9	5-7	0	5	5-10	5-10	3	5	10	7-10	5
Quartzite	xxx	1-5	10	1-3	3-4	3	8	3	0	10	5-7	10	5	1	5	5	1-3
Metarhyolite	xxx	1-5	xx	xx	5	xx	15	tr-1	0	5	5	10	10	10-15	10	10	xx
Petrified wood	1	1	0	1	0.5	0	tr	0	0	tr	1-2	0	0.5-1	0	0	0	1
Granite	0	0	7-10	0	0	0	0	0	15	0	0	0	0	0	0	0-tr	0
Pedernal Chert	0	0	0	0	0	0	0	0	0.5	0	0	tr	0	0	0	tr	0
Other	0	0	0	0	0	0	1 lm, 7 ss	tr, ss	0	0	tr lm		0	0	0	0	0
IntraFm ss & $CaCO_3$	0	0	0	0	0	0	0	0	50	0	0	0	1	0	0	0	0

	Volcanic gravel		***Mixed gravel-petrosome***												
	BR-345-cc	**LM-43-cc**	**LM-74**	**LM-77**	**LM-87**	**LM-88**	**LM-126**	**LM-133**	**LM-140-cc**	**H-495**	**H-496**	**H-498**	**H-500**	**H-502**	**H-624**
Int volc	33	28	0	1-3	0	3-5	0	3	4						1-2
Felsic volc	43	35	1	5-8	7-10	3	10-20	20	24						3-4
Volcanic, undivid	94	63	5-8	8-10	7-10	6-8	10-20	23	28	15	15	15	15	10	n/a
Chert (approx)		21	75		85-90		40	45	39	65	75	75	70	80	90
Quartz	1	4	7-10	7-10**	3	3-4	5-10	5	1	10	10**	10-15**	15**	10**	5
Quartzite		1	5	**	3	3	5-10	0	3	10	**	**	**	**	1-2
Metarhyolite	1	8	5-7	xx	xx	xx	xx	xx	8	xx	xx	xx	xx	xx	xx
Petrified wood		0.5	0.5	tr	0.5	0	tr	0	1	2-3	0	0	0	0	0
Granite		0	0	1	0	1	0	0	0	0	0	0	0	0	0
Pedernal Chert		0	0	0	0	0	tr	0	0	0	0	0	0	0	0
Other	1 ss	0.5 ss	0	0	0	0	0	0	1 ss	1-5, ss	0	0	0	0	0
IntraFm ss & CaCO3		2.5	1	5	0	1-3	20	20-25	25	0	0	0	0	0	0

Abbreviations:
int = intermediate
volc = volcanic
lm = limestone
ss = sandstone
intrafm = intraformational

Notes: "-cc" indicates that sample underwent a clast count; otherwise, percentages are based on visual estimation. Locations of all samples are in Appendix 4.

** quartzite lumped with quartz; xx = probable metarhyolite that was lumped with cher; and **Ω** = includes extrusives and tuffs.

TABLE 2. Differentiation of volcanic gravel types, Site LM-43.

Gravel type	*Count*	*Percent*	*Comments*
Cenozoic volcanic – intermediate to mafic	**47**	**28%**	
Basaltic andesite	10	6%	Dark gray and commonly vesicular. Mostly fine-grained (crystal size <1 mm) and slightly porphyritic; phenocrysts are pyroxene and plagioclase.
Andesite	8	5%	Medium-gray and fine-grained. Mostly fine-grained and slightly porphyritic; phenocrysts are plagioclase and non-biotite mafics (probably hornblende or pyroxene).
Dacite	29	17%	Light gray and notably porphyritic. >15% phenocrysts (as large as 3 mm) composed of plagioclase, hornblende, ± biotite. Lacks quartz.
Cenozoic volcanic – felsic	**58**	**35%**	
Reddish brown tuff	3	2%	Eutaxitic with 1-10% phenocrysts (vitreous and mafic types) up to 1 mm long.
Light gray, crystal-poor tuff	33	20%	Monolithic; 1-3% phenocrysts (up to 3 mm long) composed of sanidine and very minor quartz. Local fiamme.
Aphanitic rhyolite	12	7%	
Crystal-rich tuff	9	5%	>30% crystals (0.2-1.5 mm) composed of quartz, sanidine + plagioclase, 1-10% mafics; similar to Hells Mesa Tuff.
Miscellaneous tuffs	1	0.5%	
Metamorphic	**15**	**9%**	
Metarhyolite	13	8%	Resinous luster; variable flow foliations; mostly aphanitic.
Quartzite	2	1%	Individual crystals seen, typically ~1 mm in size.
Chert and quartz	**42**	**21**	
Quartz	7	4%	No individual quartz crystals seen.
Chert	35	21%	Range in color from yellow, brown, red, and black.
Sedimentary	**6**	**3.5%**	
Very fine-grained, brown sandstone	1	0.5%	Inferred to be Mesozoic in age.
Reworked Santa Fe Group	3	2%	Sand is fine- to coarse-grained, quartz-rich, and contains chert lithic grains.
$CaCO_3$ nodule	1	0.5%	
Petrified wood	1	0.5%	

Total count: 168. Volcanic rock identification is via hand lens.

Paleocurrent data

We took 471 measurements of paleocurrent indicators for the Benavidez member, which are plotted on a rose diagram per petrosome (Fig. 7) and generalized on the geologic map (Fig. 2). The measurements consist primarily of clast imbrications, with only a few from measurement of channel trends. The average paleocurrent vector is to the southeast, but ranges from northeast to southwest. The mean and median values for the volcanic-gravel and mixed-gravel petrosomes are within 99-116°. However, the mean and median for the chert-gravel petrosome are more southerly at 138-144°, implying a slightly more northern source area.

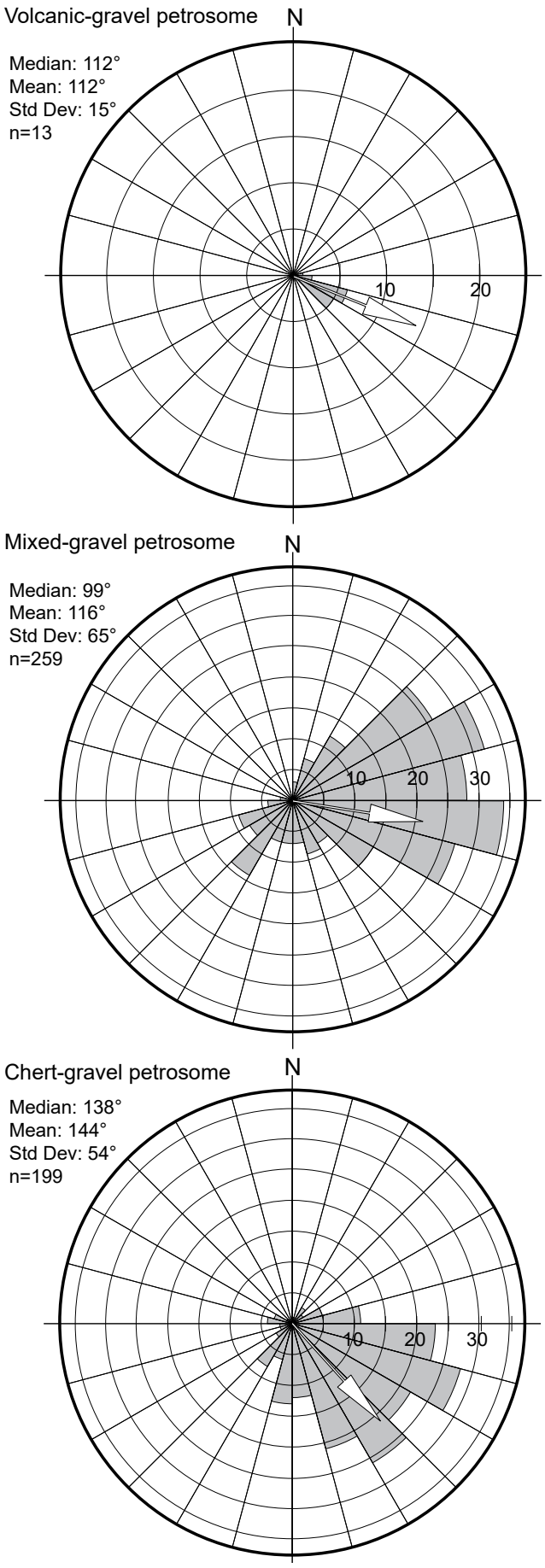
Sampled Gravel

Lithologic description

West of the Rio Puerco, four samples of volcanic clasts from the volcanic-gravel petrosome (plotted as white squares in Fig. 2) were radiometrically dated using the $^{40}Ar/^{39}Ar$ method. The gravel are of two types. The first is a reddish brown (2.5YR 5/3) tuff having 1-10% phenocrysts dominated by sanidine (up to 4 mm) with very minor quartz (samples LM-40, LM-43red, BR-345). The second (LM-43gray) is a light gray, crystal-poor tuff having <3% phenocrysts of sanidine and very minor quartz. These samples correlate to the reddish brown tuff and light gray, crystal-poor tuff identified in the detailed LM-43 clast count (Table 2). Both types of tuff have minor fiamme and the reddish brown tuff is locally eutaxitic, supporting an interpretation that they represent welded tuffs.

Radiometric data

Sanidine was dated from the four clasts described above, and a summary of the results are presented in Figure 8. Details of the analyses are given in Appendix 5. Between 10 and 18 crystals were dated from each clast, and overall the individual dates define age populations with minor scatter. Of the total of 57 grains dated, three were omitted as being anomalously old and are thought to be xenocrysts. One sanidine grain was relatively young and omitted due to suspected argon loss (Appendix 5). The reddish brown tuff clasts returned ages of 28.96±0.02, 29.00±0.03, and 29.06±0.03 Ma (1σ error). The sanidines have associated K/Ca values (derived from the measured $^{37}Ar/^{39}Ar$ ratio) ranging from ~5 to 25, with mean values ~15±5. The light gray, crystal-poor tuff returned a distinctly younger age of



28.76±0.06 Ma; it had much higher K/Ca values, ranging from 50 to 100 and a mean at ~65±20. Thus, the reddish brown clasts (LM-40, LM-43red, BR-345) have sanidines with distinctively different age and K/Ca compared to those of the gray clast (LM-43gray; Fig. 8).

Correlation

The clast eruption ages and their individual sanidine dates and K/Ca results are compared to those of regional ignimbrites of similar age from both the San Juan and Mogollon-Datil volcanic fields (Fig. 8). Age-correlative ignimbrites from the Mogollon-Datil field include the La Jencia and Vicks Peak tuffs. The comparative age data for these two tuffs are taken from Cather et al. (in press). The ages and K/Ca ratios of the reddish brown tuff clasts generally overlap the age range of the La Jencia Tuff sanidines whereas sanidine of the gray clasts results are in good agreement with data of the Vicks Peak Tuff sanidines, both in age and K/Ca.

We also compare our $^{40}Ar/^{39}Ar$ data to ignimbrites from the San Juan volcanic field. Possibly age-correlative tuffs from the southwestern San Juan volcanic field include the Dillian Mesa, Blue Mesa, and Ute Ridge tuffs; the associated sanidine data for these units are taken from Lipman (2007). These units have individual sanidine dates ranging from 28.5-29.3 Ma that overlap the sanidine ages of our sampled clasts (Fig. 8). The San Juan tuff dates are relatively imprecise and, based on age alone, cannot be distinguished from the clast data. However, the K/Ca values of the San Juan volcanic field tuffs are for the most part distinctly different from those of the clast data (Fig. 8). The South Fork and Ra Jadero tuffs from the southeast San Juan Mountains are also possible age-equivalent correlatives to the sampled clasts (Lipman et al., 1996; note these data are not shown in Fig. 8). The sanidines from these tuffs have similar K/Ca composition to the reddish brown sampled-tuff clasts; however, their ages are ~29.2 Ma and distinctly older than the clasts. Thus, based on age there is a poor correlation of the South Fork and Ra Jadero tuffs to the reddish brown tuff clasts. Additionally, the east-southeast paleocurrents in the Benavidez member make a southeast San Juan Mountain source unlikely, considering that the southeastern San Juan Mountains are north-northeast of the study area. Thus, there is no likely correlation between the sampled clasts and the San Juan Mountain tuffs based on age, K/Ca, and paleocurrent data.

Macroscopic features of these gravel samples corroborate the radiometric data in assigning the reddish brown tuff (BR-345, LM-40, LM-43red) to the La Jencia Tuff and the light gray, crystal-poor tuff (LM-43gray) to the Vicks Peak Tuff. The La Jencia Tuff is notably eutaxitic and has 3-7% sanidine phenocrysts and minor amounts of small, rounded quartz phe-

FIGURE 7. Rose diagram showing gravel imbrication data for the Benavidez member, divided according to petrosome (volcanic-, mixed-, and chert-gravel). The associated data primarily represent clast imbrication, with only a few paleochannel trends. The arrow shows the median value of the data. Note that the chert-gravel petrosome has a more southeasterly paleoflow direction than the mixed-gravel petrosome, consistent with a more northerly source area. Total number of measurements is 471.

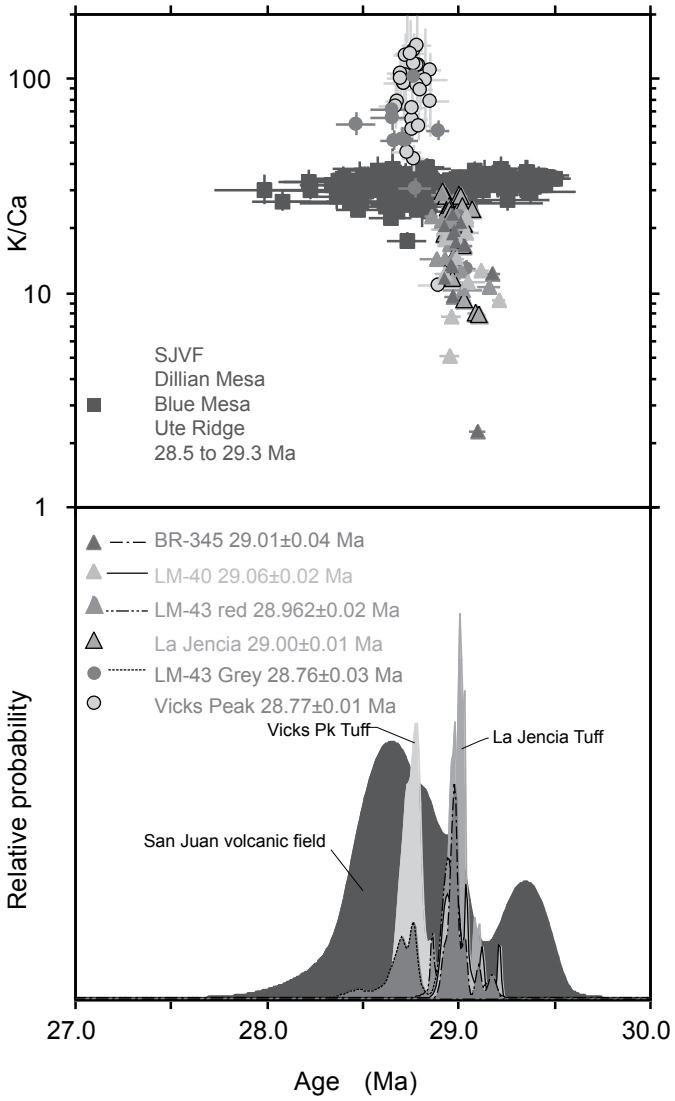


Figure 8. **Top**) K/Ca and age data for clast-derived sanidines, plotted with 1σ error bars. These are compared to ignimbrite data from the Mo-gollon-Datil (i.e., Vicks Peak and La Jencia Tuffs) and southwestern San Juan volcanic fields (Dillian Mesa, Blue Mesa, Ute Ridge tuffs). **Bottom**) Various shades illustrate the age probability distributions for the four Benavidez samples (whose shades are outlined with various line types) and the comparative samples (whose shades are not outlined). The reddish-brown clasts (BR-345, LM-40, LM-43red) show a strong age and composition correlation with sanidine from the La Jencia Tuff, whereas the gray clast (LM-43gray) overlaps with sanidine data from the Vicks Peak Tuff. Although there is age overlap with San Juan sanidines, there is generally poor K/Ca agreement. Therefore, we interpret that the Benavidez clasts were derived from the Mogollon-Datil volcanic field.

nocrysts (Osburn and Chapin, 1983). Where visited by the senior author, outcrops of the La Jencia Tuff near the Datil Mountains are reddish brown and very similar to the reddish brown tuff samples in the Benavidez member. The Vicks Peak Tuff in the Datil and western Gallinas Mountains is light gray, crystal-poor, and contains 1-3% sanidine phenocrysts together with trace amounts of quartz, biotite, clinopyroxene, and plagioclase (Osburn and Chapin, 1983) — very similar to the macroscopic appearance of sample LM-43 and the light gray, crystal-poor tuffs described in Table 2.

DISCUSSION

Source Area for Benavidez Member

Our initial hypothesis for the source area of the Benavidez member was reworking of a volcaniclastic apron shed from the southwestern San Juan volcanic field; such a large, southwest- to south-sloping fan had been previously interpreted by Cather et al. (2003, 2008). This initial inference was based on the southeast average paleoflow trend, the Late Miocene age (younger than the late Eocene-early Oligocene age of the San Juan volcanic field), and the mixed intermediate-felsic composition of the gravel in the Benavidez member. Although the Mogollon-Datil contains intermediate and felsic volcanic rocks, including many ignimbrites, this field is to the south, contrary to the paleoflow directions. The Latir volcanic field (Fig. 1) is a possible candidate, given that its volcaniclastic apron may have extended to the northern part of the Nacimiento Mountains (Smith, 2004, fig. 7), but that extent is still east of the northwest projection of the streams depositing the Benavidez member and no Amalia Tuff clasts were observed. The Mount Taylor volcanic field did not exist until the middle Pliocene (3.74 Ma; Goff et al., 2019), so it can be ruled out as a volcanic source area. Other than Oligocene mafic intrusions and diatremes associated with the Navajo volcanic field (Semken, 2001), there are no other volcanic centers upstream (northwest) of the Rio Puerco valley study area. The western San Juan volcanic field is the right age and more directly upstream from the study site than these other potential sites and would be expected to have both intermediate volcanic rocks and ignimbrites.

However, the ages and K/Ca ratios of the four volcanic gravel clasts correlate better to the La Jencia and Vicks Peak Tuffs of the Mogollon-Datil field rather than to tuffs from the San Juan volcanic field. Furthermore, sedimentologic and stratigraphic work to the south of our study area supports a source area ultimately derived from the Mogollon-Datil volcanic field. In the Late Miocene Popotosa Formation in the Gabaldon badlands, located 25 m southwest of Los Lunas (Fig. 1), gravelly sediment is interpreted as being deposited on a piedmont-slope that graded downstream into alluvial flats (Lozinsky and Tedford, 1991). The gravel composition of the conglomerates is predominately composed of volcanic types, where rhyolites and ash flow tuffs greatly outnumber basalts, and no andesite was recognized (Lozinsky and Tedford, 1991, p. 22, table 2). Moreover, G.R. Osburn, an expert on the volcanic stratigraphy of the northern Mogollon-Datil field, identified some of these felsic clasts as being La Jencia Tuff or Vicks Peak Tuff (based on hand-sample identification; Lozinsky and Tedford, 1991, p. 12). Sand petrographic analyses indicated a source area dominated by intermediate volcanic rock types with lesser amounts from a sedimentary terrane, probably Cretaceous strata. Similar to our study area, paleoflow in the Gabaldon badlands also averaged southeast. The upstream projection of these streams, then, would have been near Grants. This is significantly farther north than what is typically recognized as the northern extent of the Mogollon-Datil field (e.g., Chapin et al., 2004). In the southwestern corner of the Albuquerque basin, western-sourced

alluvial fan deposits of Miocene age also are commonly composed of volcaniclastic fanglomerate (Machette, 1978).

Given the southeasterly paleoflow data in our study area and the Gabaldon badlands (Lozinsky and Tedford, 1991), a Mogollon-Datil source for the volcanic gravel in the Benavidez member (and correlative Popotosa strata in the Gabaldon badlands) would involve three possibilities: (1) fluvial reworking of an older (Eocene-Early Miocene), gravelly volcaniclastic apron shed northward from the Mogollon-Datil volcanic field, (2) erosion of in-situ Vicks Peak and La Jencia Tuffs that were emplaced as far north as Grants, or (3) a Middle to Late Miocene paleoriver that flowed north (west of the Rio Grande rift) for 120-130 km and then doglegged back into the rift. We favor the first option for four reasons. One, although the La Jencia and Vicks Peak Tuffs could have been emplaced as ignimbrite flows far north of the Mogollon-Datil field, the diverse mixture of other felsic and intermediate volcanic gravel types with clasts of the La Jencia and Vicks Peaks Tuff indicate that such flows would have been interbedded within heterolithic sands and gravels of volcanic origin. Two, the long north-south extent of the Middle-Late Miocene, piedmont-slope depositional environments along the western margin of the Albuquerque basin (>100 km) is more consistent with exhumation of an older volcaniclastic apron than a paleo-river dog-legging back into the rift at a relatively fixed point. In addition, such a northward paleoflow immediately west of the rift margin would be opposite that of the southerly paleoflow within most of the northwestern Albuquerque basin (Connell et al., 1999). Three, the older volcaniclastic apron correlates lithologically and chronologically with the unit of Isleta No. 2 (Lozinsky, 1994), which in the southern Albuquerque basin is inferred to be sourced from the Mogollon-Datil volcanic field (Cather et al., 2008). Lastly, rift-flank exhumation would be expected during active tectonism of the Rio Grande rift in the Miocene (House et al., 2003).

We interpret that the volcaniclastic apron interfingered with the age-equivalent Chuska Formation and chert-rich gravels shed from the Zuni uplift. The Chuska Sandstone consists of sand that blanketed the southeastern Colorado Plateau in the Early Oligocene (Cather et al., 2003, 2008). The pre-rift, volcaniclastic apron was likely shed during or shortly after the 40-24 Ma volcanic activity of the Mogollon-Datil field (age from Chapin et al., 2004), and thus its middle-upper parts are time-correlative to the Chuska Sandstone.

We infer that the chert-rich gravel was eroded from the Zuni uplift (Laramide age), probably from gravel-bearing Mesozoic units (e.g., basal Dakota Formation, Jackpile Sandstone, and the Shinarump Member of the Chinle Formation). The general lack of Pedernal Chert negates a source from the Nacimiento Mountains, and the gravel deposited in south-flowing paleo-rivers of the San Jose Formation is purported to contain more quartzite and quartz clasts compared to chert clasts, with other minor lithologies including granite, sandstone, mudrock rip-ups, and volcanic rock (Baltz, 1967, p. 48, 51; Smith and Lucas, 1991, p. 19). The Zuni uplift-derived gravels are inferred to have been transported northward into the San Juan Basin in Paleogene time, where they may have partly interfingered with the San Jose Formation south of the preserved extent of the latter (note that Nacimiento stratigraphic units with northward paleoflow into the San Juan Basin only contain sandstone and siltstone gravel; Cather et al., 2019). Continued gravelly deposition into the Early Oligocene would have resulted in interfingering of the chert-dominated gravels with the Chuska Formation and the Mogollon-Datil volcaniclastic apron.

Sand petrographic results from our Cerro Conejo Formation samples are consistent with sand derived from a Chuska Sandstone source area mixed with chert- and volcanic-detritus from the Zuni uplift and Mogollon-Datil volcanic fields. In the QFL plot of Figure 6, one of our samples (Tcc4-lower) is compositionally similar with the Chuska Sandstone. The other three samples (Tcc1, Tcc3, and Tcc4-upper) have more lithic grains and plagioclase than the Chuska Sandstone. These samples may define a mixing relation between the Chuska Sandstone and a more plagioclase- and lithic-rich source; this mixing may also be reflected in the linear compositional trend of stratigraphically higher data of Brandes (2002; Fig. 6). The lithics in Cerro Conejo Formation sand are predominately chert and volcanic (hand lens inspection in Koning and Jochems, 2014; Koning and Rawling, 2017). Thus, one could explain the QFL composition of samples Tcc1, Tcc3, and Tcc4-upper by mixing of a Chuska Sandstone source with chert detritus from the Zuni uplift and volcanic- and plagioclase-rich detritus from the Mogollon-Datil field.

Given our interpretation of reworking of a volcaniclastic apron shed northward from the Mogollon-Datil field, stratigraphic relations coupled with paleoflow data indicates that the apron extended approximately as far north as what is now the north flank of Mount Taylor (35°20'N latitude). There is no volcanic gravel within any stratigraphic level of the Benavidez member north of about 35°9'N latitude. But volcanic gravel is found in the Benavidez member south of that latitude, and the proportion of volcanic gravel increases further south in the Gabaldon badlands (Lozinsky and Tedford, 1991). A straight-line projection from the northern boundary of the volcanic-bearing petrosomes (35°9'N latitude), using a representative paleoflow of 115° (from the volcanic- and mixed-gravel petrosomes, Fig. 7), extends to 35°20'N latitude (Fig. 9).

In summary, we propose an Oligocene paleogeographic model of a Datil-Mogollon volcaniclastic apron interfingering with the Chuska Sandstone eolianite and a chert-dominated sandy gravel up to about 35°20'N latitude (Fig. 9). The chert-dominated gravel unit extended perhaps 60-80 km further north (from 35°20'N) into the San Juan Basin, where it interfingered with the Chuska eolianite (Fig. 9). Since chert is less abundant in the Gabaldon Badlands compared to our study area, presumably the chert-dominated gravel was located north of where the majority of that volcaniclastic sediment was derived—consistent with the slightly more southerly paleocurrent direction associated with the chert-gravel petrosome of the Benavidez member.

Moreover, we interpret the following paleogeographic scenario for the southeastern Colorado Plateau near the town of Grants. First, Paleocene-Eocene (Laramide) erosion of the Zuni Uplift produced a northeast-sloping piedmont containing chert-dominated gravel that extended into the southern

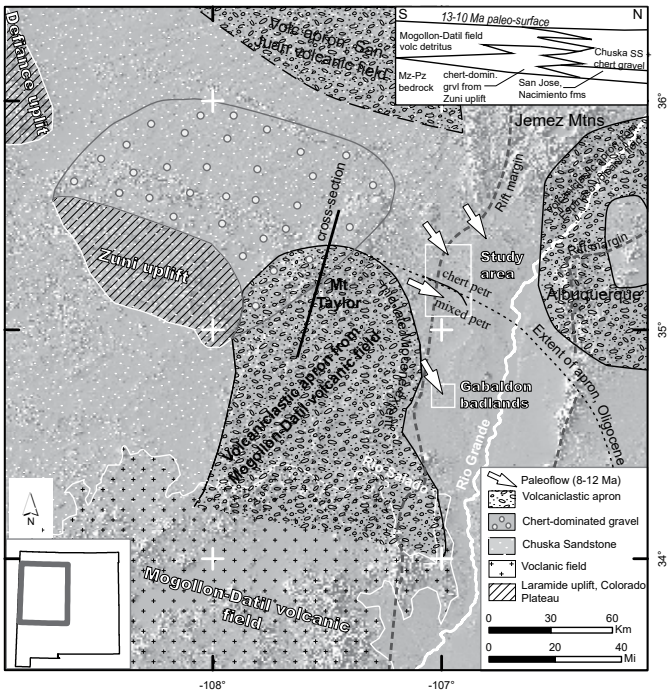


FIGURE 9. Paleogeographic map showing the northward extent of the volcaniclastic apron derived from the Mogollon-Datil volcanic field. To the northwest was chert-dominated gravel inferred to be eroded from the Zuni uplift. Tongues of the Chuska Sandstone interfingered with the chert gravel and the northern Mogollon-Datil volcaniclastic apron. To the north, the Chuska Sandstone also interfingered with the distal part of the volcaniclastic apron of the San Juan volcanic field (Cather et al., 2008). In the upper-right of the figure, a schematic north-south cross-section across the Mount Taylor region depicts the inferred geology ca. 13-10 Ma. Note that the Zuni uplift may possibly have been completely buried by the Chuska Sandstone ca. 27 Ma (Cather et al., 2008), although Dickinson et al. (2010) thought the Zunis persisted as a paleotopographic high. Post-Chuska exhumation may have caused deposition of thin chert gravels overlying various erosional surfaces (not shown in the cross-section).

San Juan Basin. Second, during Late Eocene-Early Oligocene time, a volcaniclastic apron sourced from the Mogollon-Datil volcanic field extended northward to about ~35°20'N, following a northward paleotopographic gradient created by uplift of the Mogollon-Datil volcanic field (Cather et al., 2012). This volcaniclastic apron interfingered northward with a mixture of chert-dominated gravel (from the Zuni uplift) and arkosic to subarkosic sand of the Chuska Formation. The Vicks Peak and La Jencia Tuffs were either in the source area of this volcaniclastic apron, consistent with their stratigraphically high position in the northern Datil and Gallinas Mountains (e.g., Osburn and Chapin, 1983), and/or emplaced as ignimbrite flows on the volcaniclastic apron. Eolian sand tongues of the Chuska Sandstone may have extended far across the volcaniclastic fan. During the Middle to Late Miocene (and probably the Early Miocene), exhumation of the aforementioned sedimentary package occurred. Assuming a wedge-shaped geometry of the volcaniclastic apron (thinning to the north), spatially constant rates of exhumation would have caused a progressive southward retreat of the preserved northward extent of the volcaniclastic sediment with time. By the early Pleistocene, this erosion and southward recession of the Oligocene-age volcaniclastic fan remnants culminated in complete removal of the volcaniclastic sediment north of the Rio Salado (see Fig. 9 with NMBGMR, 2003). Thin, chert- and quartz-rich gravels and sands locally lie beneath the Pliocene lava flows of the Mount Taylor volcanic field (Shari Kelley, written communication, March 30, 2020). These likely are late to middle Pliocene in age, but if they are late Eocene-early Oligocene then it would indicate that the volcaniclastic apron existed immediately east of Mount Taylor.

Implications for regional uplift and detrital studies

Previous studies, particularly Cather et al. (2012), have interpreted pulses of uplift and exhumation of the southeastern Colorado Plateau during the Oligocene-Early Miocene (25-15 Ma) and again after 6 Ma. The pause in the Middle Miocene and early Late Miocene is largely inferred based on the presence of the ~250 m thick Bidahochi Formation (Cather et al., 2008) near the border of Arizona and New Mexico (extending southeast into New Mexico as the Fence Lake Formation). However, our study shows that the Bidohochi Formation did not extend further east than about Gallup. Rather, the Colorado Plateau was being exhumed in the Grants and Mount Taylor area during 14 Ma through 8 Ma (age of Benavidez member) and likely as early as 20 Ma (age of basal Zia Formation; Tedford and Barghoorn, 1999), consistent with thermochronologic interpretations of the Lucero uplift (40 km west of Los Lunas) by Ricketts et al. (2016). This exhumation along the rift margin may be driven, in part, by rift shoulder or mantle-driven uplift associated with the Rio Grande rift. In other words, the "Alvarado Ridge" seen in modern topography (Eaton, 1987) may have been occurring as early as ca. 14 Ma. One cannot rule out uplift along the Jemez lineament as a possible driver (McCann, 1938), although previous studies infer that this uplift occurred after ca. 8 Ma (Wisniewski and Pazzaglia, 2002; Nereson et al., 2013; Channer et al., 2015).

Lastly, our study should be useful for future detrital zircon and detrital sanidine studies. The source area for zircons and sanidines associated with the Mogollon-Datil field can be found as far north as latitude 35°20'N. Furthermore, these grains were recycled into the northwestern Albuquerque basin. Therefore, the presence of these grains in Neogene-Quaternary sediment does not necessarily imply a source area coinciding with what is strictly the Mogollon-Datil volcanic field.

CONCLUSIONS

Gravelly strata composed mainly of chert and volcanic rock types interfinger with the sand-dominated Cerro Conejo Formation as well as the Navajo Draw Member of the Arroyo Ojito Formation. We informally refer to these gravelly strata as the Benavidez member of the Cerro Conejo Formation. Three gravel-based petrosomes can be recognized in the Benavidez member: chert-gravel, volcanic-gravel, and mixed-gravel. Volcanic gravel is not present north of 35°9'N, and south of this latitude volcanic gravel is most abundant in the lowest parts

of the Benavidez member. $^{40}Ar/^{39}Ar$ analyses of four volcanic clasts from the volcanic-gravel petrosome indicate correlation with the La Jencia and Vicks Peak Tuffs of the Mogollon Datil field. We thus infer that the volcanic gravel was derived from erosion of a volcaniclastic apron that extended north of the Mogollon-Datil field. Using a representative paleoflow of 115° measured in the mixed- and volcanic-gravel petrosomes of the Benavidez member, and considering the northern extent of the volcanic gravel in the Benavidez member, we conclude that the northern extent of the Oligocene-age volcaniclastic apron was about 35°20'N — coinciding approximately with what is now the northern flank of Mount Taylor.

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REFERENCES

Baltz, E.H., 1967, Stratigraphy and regional tectonic implications of part of upper Cretaceous and Tertiary rocks, east-central San Juan basin, New Mexico: U.S. Geological Survey, Professional Paper 552, 101 p.

Brandes, N.N., 2002, Lithostratigraphy and petrography of Upper Santa Fe Group deposits in the northern Albuquerque Basin, New Mexico [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 208 p.

Bryan, K., and McCann, F.T., 1937, The Ceja del Rio Puerco: A border feature of the Basin and Range Province in New Mexico. I. Stratigraphy and structure: Journal of Geology, v. 45, p. 801-828.

Bryan, K., and McCann, F.T., 1938, The Ceja del Rio Puerco: A border feature of the Basin and Range Province in New Mexico. II. Geomorphology: Journal of Geology, v. 46, p. 1-16.

Cather, S.M., Heizler, M.T., and McIntosh, W.C., in press, Middle Eocene to Pliocene volcanic, volcaniclastic, and intrusive rocks of the Quebradas Region: New Mexico Bureau of Geology and Mineral Resources, Memoir 51.

Cather, S.M., Peters, L., Dunbar, N.W., and McIntosh, W.C., 2003, Genetic stratigraphy, provenance, and new age constraints for the Chuska Sandstone (upper Eocene-lower Oligocene), New Mexico-Arizona: New Mexico Geological Society, Guidebook 54, p. 397-412.

Cather, S.M., Connell, S.D., Chamberlin, R.M., McIntosh, W.C., Jones, G.E., Potochnik, A.R., Lucas, S.G., and Johnson, P.S., 2008, The Chuska erg: Paleogeomorphic and paleoclimatic implications of an Oligocene sand sea on the Colorado Plateau: Geological Society of America Bulletin, v. 120, no. 1/2, p. 13-33; doi: 10.1130/B26081.1.

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, no. 6, p. 1177-1206; doi: 10.1130/GES00801.1.

Cather, S.M., Heizler, M.T., and Williamson, T.E., 2019, Laramide fluvial evolution of the San Juan Basin, New Mexico and Colorado: Paleocurrent and detrital –sanidine age constraints from the Paleocene Nacimeinto and Animas formations: Geosphere, v. 15, no. 5, p. 1641-1665, https://doi.org/10.1130/GESO2072.1.

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, no. 5, p. 1384-1400.

Chapin, C.E., and Lowell, C.E., 1979, Primary and secondary flow structures in ash-flow tuffs of the Gribbles Run paleovalley, central Colorado, *in* Chapin, C.E., and Elston, W.E., eds., Ash-flow tuffs: Geological Society of America, Special Paper 180, p. 137-154.

Chapin, C.E., McIntosh, W.C., and Chamberlin, R.M., 2004, The Late Eocene-Oligocene peak of Cenozoic volcanism in southwestern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society, Special Publication 11, p. 271-293.

Cikoski, C.T., Koning, D.J., and Connell, S.D., 2012, Geologic map of the La Mesita Negra quadrangle: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 223, scale 1:24,000.

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

Connell, S.D., 2008b, Geologic map of the Albuquerque-Rio Rancho metropolitan area, Bernalillo and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Geologic Map GM-78, scale 1:50,000, 2 plates.

Connell, S.D., Koning, D.J., and Cather, S.M, 1999, Revisions to the stratigraphic nomenclature of the Santa Fe Group, northwestern Albuquerque Basin, New Mexico: New Mexico Geological Society, Guidebook 50, p. 337-353.

Dickinson, W.R., Cather, S.M., and Gehrels, G.E., 2010, Detrital zircon evidence for derivation of arkosic sand in the eolian Narbona Pass Member of the Eocene-Oligocene Chuska Sandstone from Precambrian basement rocks in central Arizona: New Mexico Geological Society, Guidebook 61, p. 125-134.

Eaton, G.P., 1987, Topography and origin of the southern Rocky Mountains and Alvarado Ridge: Geological Society of London, Special Publications, v. 28, p. 355-369.

Galusha, T., 1966, The Zia Sand Formation, new early to medial Miocene beds in New Mexico: American Museum Novitates, no. 2271, 12 p.

Gawne, C.E., 1973, Faunas and sediments of the Zia Sand, medial Miocene of New Mexico [Ph.D. dissertation]: New York, Columbia University, 354 p.

Gawne, C.E., 1981, Sedimentology and stratigraphy of the Miocene Zia Sand of New Mexico: Summary: Geological Society of America Bulletin, v. 92, p. 999-1007.

Goff, F., Kelley, S.A., Goff, C.J., McCraw, D.J., Osburn, G.R., Lawrence, J.R., Drakos, P.G., and Skotnicki, S.J., 2019, Geologic map of the Mount Taylor area, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Geologic Map 80, scale 1:36,000.

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, no. 5, p. 14-1–14-18.

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

Kelley, S.A., Kempter, K.A., McIntosh, W.C., Maldonado, F., Smith, G.A., Connell, S.D., Koning, D.J., and Whiteis, J., 2013, Syndepositional deformation and provenance of Oligocene to Lower Miocene sedimentary rocks along the western margin of the Rio Grande rift, Jemez Mountains, New Mexico, *in* Hudson, M.R., and Grauch, V.J.S., eds., New Perspectives on Rio Grande Rift Basins: From Tectonics to Groundwater: Geological Society of America Special Paper 494, p. 101-123, doi: 10.1130/2013.2494(05).

Koning, D.J., and Jochems, A.P., 2014, Geologic Map of the Benavidez Ranch 7.5-Minute Quadrangle, Bernalillo and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 234, scale 1:24,000.

Koning, D.J., and Rawling, G., 2017, Geologic map of the San Felipe Mesa 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 266, scale 1:24,000.

Kuiper, K.F., Deino, A., Hilgen, F.J., Krijgsman, W., Renne, P.R., and Wijbrans, J.R., 2008, Synchronizing rock clocks in Earth history: Science, v. 320, p. 500-504.

Lipman, P.W., 2007, Incremental assembly and prolonged consolidation of Cordilleran magma chambers: Evidence from the Southern Rocky Mountain volcanic field: Geosphere, v. 3, no. 1, p. 42-70; doi: 10.1130/GES00061.1.

Lipman, P.W., Dungan, M.A., Brown, L.L., and Deino, A.L., 1996, Recurrent eruption and subsidence at the Platoro Caldera complex, southeastern San Juan volcanic field, Colorado; new tales from old tuffs: Geological

Society of America Bulletin, v. 108, issue 8, p. 1039-1055.
Lozinsky, R.P., 1994, Cenozoic stratigraphy, sandstone petrology, and depositional history of the Albuquerque Basin, central New Mexico: Geological Society of America Special Paper 291, p. 73-82.
Lozinsky, 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 Geology and Mineral Resources, Bulletin 132, 35 p. and 3 sheets.
Machette, M.N., 1978, Geologic map of the San Acacia quadrangle, Socorro County, New Mexico: U.S. Geological Survey, Map GQ-1415, scale 1:24,000.
Maldonado, F., Budahn, J.R., Peters, L., and Unruh, D.M., 2006, Geology, geochronology, and geochemistry of basaltic flows of the Cat Hills, Cat Mesa, Wind Mesa, Cerro Verde, and Mesita Negra, central New Mexico: Canadian Journal of Earth Sciences, v. 43, no. 9, p. 1251-1268.
McCann, F.T., 1938, Ancient erosion surface in the Gallup-Zuni area, New Mexico: American Journal of Science, v. 36, p. 260-278.
Min, K., Mundil, R., Renne, P. R. and Ludwig, K. R., 2000, A test for systematic errors in $^{40}Ar/^{39}Ar$ geochronology through comparison with U–Pb analysis of a 1.1 Ga rhyolite: Geochimica et Cosmochimica Acta, v. 64, p. 73–98.
Moore, J.D., 2000, Tectonics and volcanism during deposition of the Oligocene-Lower Miocene Abiquiu Formation in northern New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 144 p.
Morgan, G.S., and Williamson, T.E., 2000, Middle Miocene (late Barstovian) vertebrates from the Benavidez Ranch local fauna, Albuquerque Basin, New Mexico: New Mexico Museum of Natural History and Science Bulletin No. 16, p. 195-207.
Morgan, G.S., and Williamson, T.E., 2007, Middle Miocene (late Barstovian) mammal and bird tracks from the Benavidez Ranch local fauna, Zia Formation, Albuquerque Basin, Sandoval County, New Mexico: New Mexico Museum of Natural History and Science Bulletin 42, p. 319-330.
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, no. 3, p. 521-545, https://doi.org/10.1130/GES00837.1.
New Mexico Bureau of Geology and Mineral Resources, 2003, Geologic Map of New Mexico: New Mexico Bureau of Geology and Mineral Resources, scale 1:500,000.
Rawling, G.C., and Koning, D.J., 2019, Geologic map of the Herrera 7.5-minute quadrangle, Sandoval and Bernalillo Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map 273, scale 1:24,000.
Rawling, G.C., and Koning, D.J., in preparation, Geologic map of the Canoncito School 7.5-minute quadrangle, Bernalillo County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map XX, scale 1:24,000.
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 evalution of possible driving mechanisms: Geological Society of America Bulletin, v. 128, no 3/4, p. 397-424; doi:10.1130/B31223.1.
Osburn, G.R., and Chapin, C.E., 1983, Nomenclature for Cenozoic rocks of northeast Mogollon-Datil volcanic field, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Stratigraphic Chart 1.
Seager, W.R., and Mack, G.H., 2003, Geology of the Caballo Mountains, New Mexico: New Mexico Bureau of Geology and Mineral Resources Memoir 49, 136 p.
Semken, S.C., 2001, The Navajo volcanic field, *in* Crumpler, L.S., and Lucas, S.G., eds., Volcanology of New Mexico: New Mexico Museum of Natural History and Science Bulletin, p. 79-83.
Smith, G.A., 2004, Middle to late Cenozoic development of the Rio Grande rift and adjacent regions in northern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico, A Geologic History: New Mexico Geological Society, Special Publication 11, p. 331-358.
Smith, L.N., and Lucas, S.G., 1991, Stratigraphy, sedimentology, and paleontology of the lower Eocene San Jose Formation in the central portion of the San Juan Basin, northwestern New Mexico: New Mexico Bureau of Geology and Mineral Resources, Bulletin 126, 44 p.
Tedford, R.H., 1981, Mammalian biochronology of the late Cenozoic basins of New Mexico: Geological Society of America Bulletin, Part 1, v. 92, p. 1008-1022.
Tedford, R.H., 1982, Neogene stratigraphy of the northwestern Albuquerque basin: New Mexico Geological Society, Guidebook 33, p. 273-278.
Tedford, R.H., and Barghoorn, S., 1997, Miocene mammals of the Española and Albuquerque basins, north-central New Mexico: New Mexico Museum of Natural History and Science Bulletin No. 11, p. 77-95.
Tedford, R.H., and Barghoorn, S., 1999, Santa Fe Group (Neogene), Ceja del Puerco, northwestern Albuquerque basin, Sandoval County, New Mexico: New Mexico Geological Society, Guidebook 50, p. 327-335.
Tedford, R.H., Skinner, M.F., Fields, R.W., Rensberger, J.M., Whistler, D.P., Galusha, T., Taylor, B.E., Macdonald, J.R., and Webb, S.D., 1987, Faunal succession and biochronology of the Arikareean through Hemphillian interval (late Oligocene through earliest Pliocene epochs) in North America, *in* Woodburne, M.D., eds., Cenozoic mammals of North America, geochronology and biostratigraphy: Berkeley, University of California Press, p. 153-210.
Timmer, R.W., 1976, Geology and sedimentary copper deposits in the western part of the Jarosa and Seven Springs quadrangles, Rio Arriba and Sandoval Counties, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 151 p.
Trevena, A.S., 1979, Studies in sandstone petrology: Origin of the Precambrian Mazatzal Quartzite and provenance of detrital feldspar [Ph.D. dissertation]: Salt Lake City, University of Utah, 316 p.
Vazzana, M.E., and Ingersoll, R.V., 1981, Stratigraphy, sedimentology, petrology, and basin evolution of the Abiquiu Formation (Oligo-Miocene), north-central New Mexico: Summary: Geological Society of America Bulletin, v. 92, Part I, p. 990-992, Part II, p. 2401-2483.
Williams, P.L., and Cole, J.C., 2007, Geologic map of the Albuquerque 30' X 60' Quadrangle, north-central New Mexico: United States Geologic Survey, Scientific Investigations Map 2946, scale 1:100,000.
Wisniewski, P., 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, doi: 10.1086/340441.
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.
Wright, H.E., Jr., 1956, Origin of the Chuska Sandstone, Arizona-New Mexico: A structural and petrographic study of a Tertiary eolian sediment: Geological Society of America Bulletin, v. 67, p. 413-434, doi: 10.1130/0016-7606(1956)67[413:OOTCSA]2.0CO;2.

Supplemental data can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2020005