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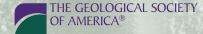
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Laramide fluvial evolution of the San Juan Basin, New Mexico and Colorado: Paleocurrent and detrital-sanidine age constraints from the Paleocene Nacimiento and Animas formations

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ABSTRACT

Understanding the tectonic and landscape evolution of the Colorado Plateau-southern Rocky Mountains area requires knowledge of the Laramide stratigraphic development of the San Juan Basin. Laramide sediment-transport vectors within the San Juan Basin are relatively well understood, except for those of the Nacimiento and Animas formations. Throughout most of the San Juan Basin of northwestern New Mexico and adjacent Colorado, these Paleocene units are mudstone-dominated fluvial successions intercalated between the lowermost Paleocene Kimbeto Member of the Ojo Alamo Sandstone and the basal strata of the lower Eocene San Jose Formation, both sandstone-dominated fluvial deposits. For the Nacimiento and Animas formations, we present a new lithostratigraphy that provides a basis for basinscale interpretation of the Paleocene fluvial architecture using facies analysis, paleocurrent measurements, and 40Ar/39Ar sanidine age data.

In contrast to the dominantly southerly or southeasterly paleoflow exhibited by the underlying Kimbeto Member and the overlying San Jose Formation, the Nacimiento and Animas formations exhibit evidence of diverse paleoflow. In the southern and western part of the basin during the Puercan, the lower part of the Nacimiento Formation was deposited by south- or southeast-flowing streams, similar to those of the underlying Kimbeto Member. This pattern of southeasterly paleoflow continued during the Torrejonian in the western part of the basin, within a southeast-prograding distributive fluvial system. By Torrejonian time, a major east-northeast-flowing fluvial system, herein termed the Tsosie paleoriver, had entered the southwestern part of the basin, and a switch to northerly paleoflow had occurred in the southern San Juan Basin. The reversal of paleoslope in the southern part of the San Juan Basin probably resulted from rapid subsidence in the northeast part of the basin during the early Paleocene. Continued Tiffanian-age southeastward progradation of the distributive fluvial system that headed in the western part of the basin pushed the Tsosie paleoriver beyond the present outcrop extent of the basin.

In the eastern and northern parts of the San Juan Basin, paleoflow was generally toward the south throughout deposition of the Nacimiento and the Animas formations. An important exception is a newly discovered paleodrainage that exited the northeastern part of the basin, ~15 km south of Dulce, New Mexico. There, an ~130-m-thick Paleocene sandstone (herein informally termed the Wirt member of the Animas Formation) records a major east-flowing paleoriver system that aggraded within a broad paleovalley carved deeply into the Upper Cretaceous Lewis Shale. 40Ar/39Ar dating of detrital sanidine documents a maximum depositional age of 65.58 ± 0.10 Ma for the Wirt member. The detrital sanidine grains are indistinguishable in age and K/Ca values from sanidines of the Horseshoe ash (65.49 ± 0.06 Ma), which is exposed 10.5 m above the base of the Nacimiento Formation in the southwestern part of the basin. The Wirt member may represent the deposits of the Tsosie paleoriver where it exited eastward from the basin.

Our study shows that the evolution of Paleocene fluvial systems in the San Juan Basin was complex and primarily responded to variations in subsidence-related sedimentary accommodation within the basin.

INTRODUCTION

The San Juan Basin of New Mexico and Colorado (Fig. 1) is the southernmost major basin in the Rocky Mountain region that contains a relatively complete Laramide sedimentary record (Dickinson et al., 1988). Except for the Paleocene Nacimiento Formation and correlative beds of the Animas Formation, the sediment-dispersal patterns for Laramide fluvial systems are reasonably well known. Here we present the first basin-scale reconnaissance of paleocurrent indicators within these units. We use 40Ar/39Ar sanidine geochronology as a chronostratigraphic tool. We use these new constraints, in concert with previously published paleontologic, geochronologic, magnetostratigraphic, and paleocurrent data, to reconstruct for the first time the entire Laramide sediment-routing history of the basin.

In the San Juan Basin, Laramide stratigraphic units range from Campanian through lower Eocene and include the Lewis Shale, the Pictured Cliffs Sandstone, the Fruitland and Kirtland formations, the Ojo Alamo Sandstone, the Nacimiento, Animas, and San Jose formations (Fig. 2).

In northern New Mexico, there were three peak phases of Laramide subsidence— Campanian, early Paleocene, and early to middle Eocene (Cather, 2004). Campanian subsidence was greatest in the northern and northwestern San Juan Basin; Paleogene episodes of subsidence were greatest in its northeastern part.

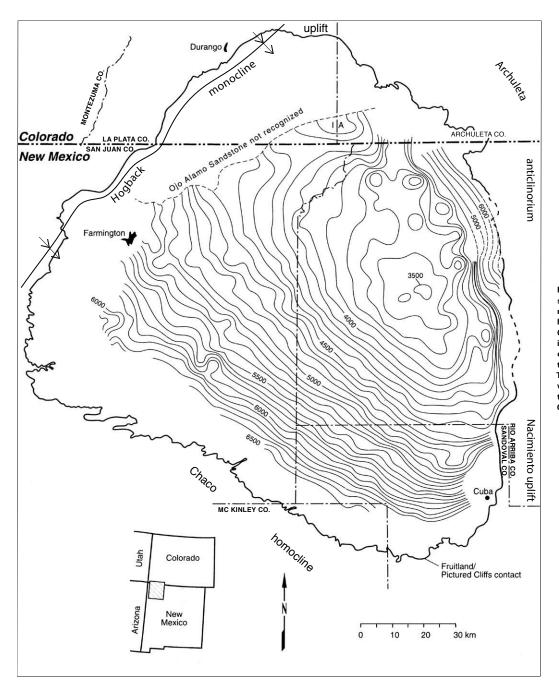


Figure 1. Map of the San Juan Basin with major structural features and structural contours (elevation relative to sea level) on the base of the Cenozoic (the base of the lower Paleocene Kimbeto Member of the Ojo Alamo Sandstone). IA—Ignacio anticline. Contour interval is 100 feet (30.5 m). Basin is outlined by the contact between the Campanian Fruitland Formation and the underlying Pictured Cliffs Sandstone. This contact is dashed along eastern basin margin where Paleocene paleovalleys have eroded the contact. Modified from Ayers and Ambrose (1990) and Cather (2004).

| TABLE | PRAIRCUSERNY DATA FOR PRAIRCUSTS VIRTAL OF THE SAN KAN BANKS | London | Lo

'Supplemental Files. Data and figures. Figure S1. Rose diagrams (north at top) of paleocurrent indicators from individual localities. Numerals on individual roses correspond to numbered localities in text, on Figures 3, 8, and 22, and in Table S1. Please visit https://doi.org/10.1130/GES02072.S1 or access the full-text article on www.gsapubs.org to view the Supplemental Files.

The Hogback monocline defines the northwestern margin of the basin (Fig. 1). The northern and northeastern margins of the basin are the San Juan uplift and Archuleta anticlinorium, respectively. The transpressional Nacimiento uplift defines the southeastern margin of the basin (Baltz, 1967; Pollock et al., 2004). The southern part of basin is the gently northeast-dipping structural ramp of the Chaco homocline (Cather, 2003, 2004).

METHODS

Paleocurrent Analysis

We measured 1486 paleoflow indicators from 51 localities within the Paleocene Nacimiento and Animas formations (see data in Supplemental Files¹). To augment previous studies, 130 paleocurrent measurements were made from three sites in the underlying Kimbeto Member of the Ojo Alamo Sandstone, and 234 measurements were made at nine localities in the overlying San Jose Formation. Paleoflow azimuths were determined primarily by the dip direction of tabular cross beds or the axes of trough cross beds, although pebble imbrications (9% of total) were also measured.

Paleocurrent azimuths in the Nacimiento Formation were measured mostly from well-sorted sandstone and pebbly sandstone deposited within moderate to large fluvial paleochannels. Such sandstones tend to be indurated and form bold outcrops, allowing a three-dimensional perspective of cross bedding. In contrast, sandstone deposited within thin splay deposits and small paleochannels tend to have significant clay content, particularly those low in the Nacimiento Formation in the south and southwest parts of the basin. These sandstones typically form low, rounded outcrops with "popcorn" weathering that obscures cross bedding.

Prior to this report, only three local paleocurrent studies have been published for the Nacimiento Formation. Rains (1981) determined a northeast (040°) mean paleoflow direction based on 22 measurements from a locality in what is now considered the upper part of the Arroyo Chijuillita Member at Torreon Wash. Williamson et al. (1992a, their figure 2.8) published rose diagrams for 19 measurements at two localities in the Escavada Member ~15 km east of Nageezi; their measurements show mostly south-southeast paleoflow, but no mean paleoflow direction was given. Milner (2004, her figure 11) presented rose diagrams (but no mean direction) for 41 paleocurrent measurements from two localities in what we term the upper part of the Kutz Member of the Nacimiento Formation, southwest of Navajo Reservoir. Paleoflow at these localities was fairly random, with a slight tendency toward east-southeast paleoflow.

⁴⁰Ar/ ³⁹Ar Geochronology

Sanidine was dated from a volcanic ash bed, herein informally termed the Horseshoe ash (sample SJ-ASH-2; 65.49 \pm 0.06 Ma), from the lower Kutz

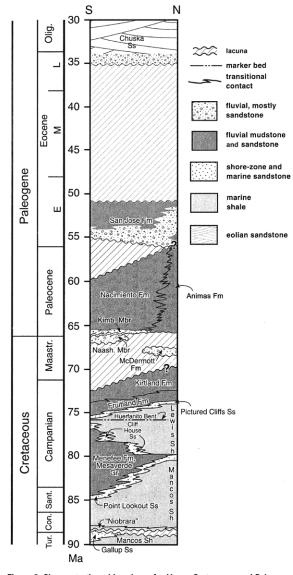


Figure 2. Chronostratigraphic column for Upper Cretaceous and Paleogene strata in the San Juan Basin region of northwestern New Mexico, showing the stratigraphic terminology used in this report. Deposition of Laramide strata occurred ca. 80–50 Ma. Modified from Cather (2004). Naash—Naashoibito Member of the Ojo Alamo Sandstone; Kimb—Kimbeto Member of the Ojo Alamo Sandstone; Fm—Formation; Gr—Group; Mbr—Member; Ss—Sandstone; Sh—Shale; Bent.—Bentonite; Olig.—Oligocene; Tur.—Turonian; Con.—Coniacian; Sant.—Santonian; Maastr.—Maastrichtian; E—early; M—middle; L—late.

Member of the Nacimiento Formation in the southwestern part of the basin, as well as from two siltstone samples (6-2-15-B and 6-2-15-C; maximum depositional age 65.58 ± 0.10 Ma) from the Wirt member of the Animas Formation in the northeastern part of the basin (see description of members below). Analytical data and methods are provided in the Supplemental Files (footnote 1). Processing and mineral separation were done at the New Mexico Geochronology Research Laboratory at New Mexico Tech.

Sample separation included disaggregating the sample in a blender, wet sieving the 80–120 mesh fraction, and then ultrasonically cleaning with H₂O and 5% HF acid. Magnetic and heavy-liquid separation was used to concentrate the K-feldspar grains. Sanidine grains were handpicked from bulk K-feldspar separates using two methods. Early efforts involved handpicking clear K-feldspar grains under a binocular microscope. This method yielded many Paleozoic and Precambrian grains that appear to be clear microcline and orthoclase crystals rather than volcanic sanidine. An improved method was subsequently employed that involved examining K-feldspar grains immersed in wintergreen oil under a polarizing microscope. This method allowed identification of plutonic and/or metamorphic microtextures (perthite, twinning) that were not obvious when viewed with the binocular microscope and thus resulted in better avoidance of non-sanidine grains.

All samples were irradiated at the TRIGA reactor in Denver, Colorado for either 16 or 40 h in multiple packages (see Supplemental Files [footnote 1]) along with Fish Canyon sanidine interlaboratory standard FC-2 with an assigned age of 28.201 Ma (Kuiper et al., 2008). Ages are calculated with a total ⁴⁰K decay constant of 5.463e⁻¹⁰ /a (Min et al., 2000).

After irradiation, at least six crystals of FC-2 were analyzed in irradiation pits closely spaced with unknown samples to determine J-factors, with resulting uncertainties ranging from ~0.01%-0.08%. The larger uncertainty in J is associated with the Horseshoe ash sample where grains were in relatively large irradiation pits, thus individual grains had slightly variable neutron flux leading to variable 40 Ar/39 Ar values. Sample crystals were fused with a CO₂ laser for 30 seconds, and the extracted gas was cleaned with a NP-10 getter operated at 1.6 A for between 30 and 150 seconds. All crystals were dated by single-crystal laser fusion with isotopes measured on an ARGUS VI multi-collector mass spectrometer equipped with five Faraday cups and one ion counting multiplier (compact discrete dynode [CDD]). Variable detector configurations were used and are detailed in the Supplemental Files (footnote 1). All data acquisition was accomplished with New Mexico Tech Pychron software, and data reduction used Mass Spec (v. 7.875) written by Al Deino at the Berkeley Geochronology Center. Extraction line blank plus mass spectrometer background values are provided in the Supplemental Files (footnote 1).

The maximum depositional age of the Wirt member, based on the youngest population of detrital sanidine grains, and the depositional age of the Horseshoe ash were determined by the weighted mean of the selected grains and were weighted based on the inverse variance. The error is the square root of the sum of $1/\sigma^2$ values and is multiplied by the square root of the mean square of weighted deviates (MSWD) for values of MSWD greater than

one. J-error is included for the weighted-mean age error, and all errors are reported at 1σ .

PALEOGENE LITHOSTRATIGRAPHY AND PALEOFLOW OF THE SAN JUAN BASIN

The evolution of stratigraphic nomenclature for uppermost Cretaceous and lowermost Paleocene beds in the San Juan Basin has been quite complex and remains a topic of contention (e.g., Baltz et al., 1966; Powell, 1973; Fassett, 2009, 2010). In this report, we use the nomenclature depicted in Figure 2.

The Paleocene is subdivided into four North American Land Mammal Ages (NALMAs), based on the evolution of fossil mammals. From oldest to youngest, with approximate boundaries following the timescale of Ogg (2012), these are the Puercan (ca. 66–63.5 Ma), the Torrejonian (ca. 63.5–62 Ma), the Tiffanian (ca. 62 Ma–57.5 Ma), and the Clarkforkian (ca. 57.5–56 Ma). The first three NALMAs of the Cenozoic (Puercan, Torrejonian, and Tiffanian) are based on faunas originally described from the San Juan Basin (Wood et al., 1941; Woodburne, 2004).

Kimbeto Member of the Ojo Alamo Sandstone

The base of the Paleogene throughout most of the San Juan Basin is the lowermost Paleocene Kimbeto Member of the Ojo Alamo Sandstone (Table 1). It has been claimed that the underlying Naashoibito Member of the Ojo Alamo Sandstone in the southwestern part of the basin is also Paleocene, although we regard it as upper Maastrichtian (e.g., Peppe et al., 2013; Heizler et al., 2014; Williamson et al., 2014; see the "Paleocene dinosaurs" debate in Fassett, 2009; Lucas et al., 2009; and Fassett, 2013). The Kimbeto Member is not present in the northern fifth of the basin, where it has been eroded or grades laterally into the Animas Formation.

The Kimbeto Member consists of sandstone, pebbly sandstone, pebble to cobble conglomerate, and minor mudstone. The Kimbeto Member ranges from ~12–82 m thick (Powell, 1973). It is thickest and coarsest in its proximal outcrops in the northwestern part of the basin near Farmington. There, it contains clasts of quartz, chert, silicified igneous rocks, and silicified limestone as much as 15 cm across (O'Sullivan et al., 1972). For details concerning the stratigraphy, depositional environments, and petrology of the Kimbeto Member, see Powell (1972, 1973), Lehman (1985), Klute (1986), and Sikkink (1987). Paleoflow during deposition of the Kimbeto Member was generally toward the south or southeast (Fig. 3).

The Kimbeto Member disconformably overlies Upper Cretaceous continental beds throughout the basin (mostly the Campanian Kirtland and Fruitland formations but, locally, the Maastrichtian Naashoibito Member in the southwestern part of the basin). In contrast, there are two areas along the eastern basin margin where thick sandstones fill deep, broad paleovalleys (cf. Fassett and Hinds, 1971) eroded into the underlying marine beds of the Campanian

TABLE 1. SUMMARY OF CHARACTERISTICS OF PALEOCENE STRATIGRAPHIC UNITS IN THE SAN JUAN BASIN

Stratigraphic unit	Age (NALMA)	Location within basin	Thickness (m)	Lithology	Mean paleoflow	Comments
Ojo Alamo Sandstone, Kimbeto Member	Puercan	Central and south	12–82	Sandstone, pebbly sandstone, pebble to cobble conglomerate, and minor mudstone	South to southeast	We use the term Kimbeto Member (Powell, 1973) to refer to all parts of the Ojo Alamo Sandstone exclusive of the Naashoibito Member.
Nacimiento Formation, Arroyo Chijuillita Member ¹	Puercan and Torrejonian	South	30–130	Drab mudstone and fine sandstone, minor coal	South (lower part), north (upper part)	The lower ~30–55 m of the Arroyo Chijuillita Member extends westward to the Kimbeto Wash region (Fig. 4), where it is overlain by beds of the Tsosic Member (Fig. 5). We restrict the upper Arroyo Chijuillita Member to the area from Mesa de Cuba to about ten kilometers west of the continental divide (Fig. 4), where it interfingers with thick channel sandstones of the Tsosie Member (cf. Williamson, 1996; Davis et al., 2016).
Nacimiento Formation, Ojo Encino Member¹	Torrejonian	Southeast	90–122	Strongly variegated mudstone and sandstone	North	We restrict the Ojo Encino Member to the geographic extent of its basal Penistaja Bed, which crops out in the area between Mesa de Cuba and somewhat west of the continental divide. The Ojo Encino Member formerly included thick fluvial channel sandstones farther to the west at Escavada Wash, Betonnie Tsosie Wash, the east flank of Kimbeto Wash, and on the west flank of Kimbeto Wash. We now assign these beds to the Tsosie Member.
Nacimiento Formation, Tsosie Member ²	Late Puercan (?) and Torrejonian	Southwest	Maximum ~200	Thick channel sandstone and drab floodplain mudstone	East-northeast	We designate beds 24–44 of the Betonnie Tsosie Wash measured section of Williamson and Lucas (1992) as the type section of the Tsosie Member. Because of poor exposure, this type section is incomplete in its upper part Within the measured sections of Williamson (1996) at Betonnie Tsosie Wash, the east flank of Kimbeto Wash, and the west flank of Kimbeto Wash, we identify beds 24, 10, and 21, respectively, as the basal beds of the Tsosie Member. All of the beds formerly assigned to the Ojo Encino Member in the Escavada Wash measured section of Williamson (1996) are also tentatively considered to be Tsosie Member.
Nacimiento Formation, Kutz Member²	Puercan and Torrejonian	West	Maximum ~300	Drab to variegated channel sandstone, splay sandstone, and floodplain mudstone	Southeast	Formerly the "main body" of Williamson (1996). In Kutz Canyon, we designate the composite measured sections A through E and beds 1–8 of section F of Williamson (1996) as the type section the Kutz Member. The lower Kutz Member is exposed in measured sections at the West Fork of Gallegos Canyon (locality 57, Fig. 8) and at De-na-zin Wash (locality 59) (note that Williamson, 1996, tentatively correlated these beds with the Arroyo Chijuillita and the Ojo Encino members).
Nacimiento Formation, Angel Peak Member ²	Late Torrejonian to early Tiffanian(?)	West	10–25	Yellowish-gray sandstone and associated thin mudstone	East	Formerly the "unnamed member" of Williamson (1996). We designate the type section of the Angel Peak Member as bed 9 of measured section F in Kutz Canyon (Williamson, 1996). There, it is 16.5 m of yellowish-gray, cross-bedded, medium- to coarse-grained sandstone.
Nacimiento Formation, Escavada Member	Tiffanian	West and South	20–90	Gray fine sandstone, mudstone, and thin silicified ash beds	East-southeast	
Animas Formation, main part	Puercan through Tiffanian	North	Maximum ~700	Grayish-green to brownish-green, partly volcaniclastic sandstone and mudstone	South	Excludes the McDermott Formation (considered by some to be a member of the Animas Formation) and the Wirt member.
Animas Formation, Wirt member ²	Unknown, probably late Puercan and/or Torrejonian	Northeast	Maximum ~130	Buff-colored sandstone, minor greenish-gray mudstone, and rare pebbly sandstone	East	Informal stratigraphic term. Maximum depositional age is 65.58 \pm 0.10 Ma.

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NALMA—North American Land Mammal Age.
¹Stratigraphic term is geographically restricted relative to usage of Williamson and Lucas (1992) and Williamson (1996).

²New term (this study).

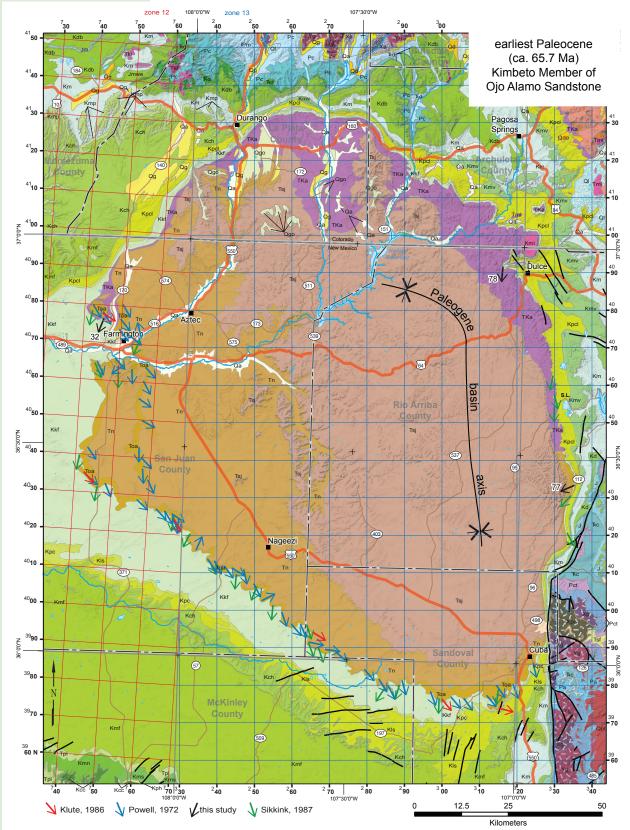


Figure 3. Geologic map of the San Juan Basin showing the mean direction of paleocurrent indicators (arrows) for the early Paleocene Kimbeto Member of the Ojo Alamo Sandstone. The Kimbeto Member is time-equivalent to lower Animas Formation, which was also deposited by generally south-flowing streams (Sikkink, 1987). Paleoflow data for this study (numbered black arrows) correspond to localities in the data in Supplemental Files (see text footnote 1). Stratigraphic units discussed in text include the Lewis Shale (map unit KIs), Pictured Cliffs Sandstone (Kpc), combined Lewis Shale and Pictured Cliffs Sandstone (Kpcl), combined Kirtland and Fruitland formations (Kkf), Ojo Alamo Sandstone (Toa), Nacimiento Formation (Tn), combined Paleocene Animas Formation and Maastrichtian McDermott Formation (TKa; the McDermott Formation occurs only in the northwest part of the basin), and the San Jose Formation (Tsj). For other map-unit abbreviations, see NMBGMR (2003) and Tweto (1979). UTM coordinates are NAD 1927. S.L.—Stinking Lake. Geologic base map from Tweto (1979) and NMBGMR (2003).

Lewis Shale. The southern paleovalley (Fig. 3, locality 77) contains ~75 m of the Kimbeto Member. This paleovalley drained areas to the northeast, and its incision demonstrates that the eastern structural margin of the San Juan Basin (the Archuleta anticlinorium) was extant in the earliest Paleocene. The northern paleovalley (~15 km south of Dulce), however, contains ~130 m of sandstone and minor mudstone deposited by east-flowing paleorivers. We regard these beds as the basal part of the Animas Formation (see discussion of the Wirt member below).

Nacimiento Formation

The paleontology, palynology, and magnetostratigraphy of the Paleocene Nacimiento Formation in the southern and western San Juan Basin have been relatively well studied. The Nacimiento Formation hosts the "type localities" for the Puercan and Torrejonian NALMAs (Wood et al., 1941; see summaries in Williamson, 1996) and contains palynomorphs and fossil leaves of Paleocene age (Anderson, 1960; Fassett and Hinds, 1971; Tschudy, 1973; Newman, 1987; Williamson et al., 2008; Flynn et al., 2015, 2017; Flynn and Peppe, 2018). The Nacimiento Formation hosts magnetic polarity chrons from the near the base of C29n to C25r (Leslie et al., 2018; Williamson, 1996, and references therein), corresponding to a depositional interval of ca. 65.6–60 Ma using the timescales of Ogg (2012) and Sprain et al. (2018).

As much as ~530 m thick (Milner, 2004), the Nacimiento Formation grades northward into, and locally overlies, the Animas Formation. In this report, we revise the member-rank lithostratigraphy of the Nacimiento Formation (see below). The proposed members are laterally gradational but lithologically distinct, with paleocurrent signatures that attest to their differing roles in the fluvial architecture of the basin (Table 1).

Arroyo Chijuillita Member

The Arroyo Chijuillita Member (Williamson and Lucas, 1992), the basal member of the Nacimiento Formation in the southern part of the San Juan Basin (Figs. 4 and 5), conformably overlies the Kimbeto Member of the Ojo Alamo Sandstone and is ~30–130 m thick. We geographically restrict the upper Arroyo Chijuillita Member (Table 1).

The Arroyo Chijuillita Member consists of a poorly exposed, drab succession of gray to black mudstone, light-gray, commonly clay-cemented fine sandstone, and minor coal that was deposited by rivers and in floodplain lakes (Fig. 6). Fluvial channel sandstones are commonly cross bedded and typically thin (~1–3 m thick).

Puercan fossil localities within the "Ectoconus zone" (sensu Sinclair and Granger, 1914; see Williamson, 1996) lie within the lower ~20 m of the Arroyo Chijuillita Member, but the Torrejonian "Pantolambda zone" (sensu Sinclair and Granger, 1914) at Betonnie Tsosie Wash (Williamson, 1996) is within the

Tsosie Member. The upper half of the Arroyo Chijuillita Member at Mesa de Cuba contains Torrejonian fossils (Williamson, 1996).

The paleoflow regime during deposition of the Arroyo Chijuillita Member is incompletely understood. Approximately the lower half of the Arroyo Chijuillita Member shows evidence of southerly paleoflow (mean = 196°; Fig. 7A), similar to paleocurrent indicators within the Kimbeto Member, which it transitionally overlies. Note, however, that we collected paleocurrent measurements at only two localities within the lower Arroyo Chijuillita Member (localities 35 and 79, Fig. 8, and see data in Supplemental Files [footnote 1]). In contrast, five localities in the upper part of the Arroyo Chijuillita Member exhibit evidence of northerly paleoflow (mean = 355°), similar to that of the overlying Ojo Encino Member (Fig. 7B).

These relationships imply that a profound paleoflow reversal occurred in the southern San Juan Basin during deposition of the unfossiliferous strata that lie between the Puercan and Torrejonian fossiliferous beds. Although interpretation is limited by poor exposure, there is no evidence of a significant disconformity marking this reversal within the Arroyo Chijuillita Member. Nor is there evidence that the stratigraphic domains of southerly and northerly paleoflow are divided by the deposits of an axial river, as might be expected if these domains represented oppositely-draining tributary systems. Rather, it seems that the fine-grained deposits of the middle Arroyo Chijuillita Member record a gradual, syndepositional rollover in paleoslope orientation that was related to increased subsidence in the basin axis to the north (see below).

Ojo Encino Member

The Ojo Encino Member (Williamson and Lucas, 1992) occupies the middle part of the Nacimiento Formation in the southeastern San Juan Basin. The Ojo Encino Member is a fluvial succession of mudstone and sandstone, ranging in thickness from 90 to 122 m. Fluvial channel deposits, typically ~2–10 m thick, exhibit cross bedding and horizontal laminations. Variegated Ojo Encino floodplain mudstone displays hues of gray, red, green, and black. Black horizons in the Nacimiento Formation represent poorly drained paleosols (Davis et al., 2016; Hobbs, 2016) and are suggestive of episodes of high water tables. The basal part of the member is the Penistaja Bed (Williamson and Lucas, 1992), a prominent, slightly pebbly sandstone that disconformably overlies the Arroyo Chijuillita Member near, and east of, the continental divide (Fig. 9). The Ojo Encino Member shows evidence of northerly paleoflow (mean = 012°; Fig. 7C). It contains pebbles of indurated fine sandstone and siltstone (Fig. 10) derived from Mesozoic strata exposed to the south on the Chaco homocline.

The age of Ojo Encino Member is reasonably well constrained, as it hosts several Torrejonian fossil localities (Fig. 5; Williamson, 1996). In the middle of the Nacimiento Formation, in what we consider as lower Ojo Encino Member, a reworked volcanic ash has yielded a sanidine maximum depositional age of 64.4 $\pm\,0.2$ Ma, based on the youngest five of 36 crystals dated (age recalculated from Fassett et al. [2010] using Fish Canyon Tuff sanidine = 28.201 Ma; error is 1σ).

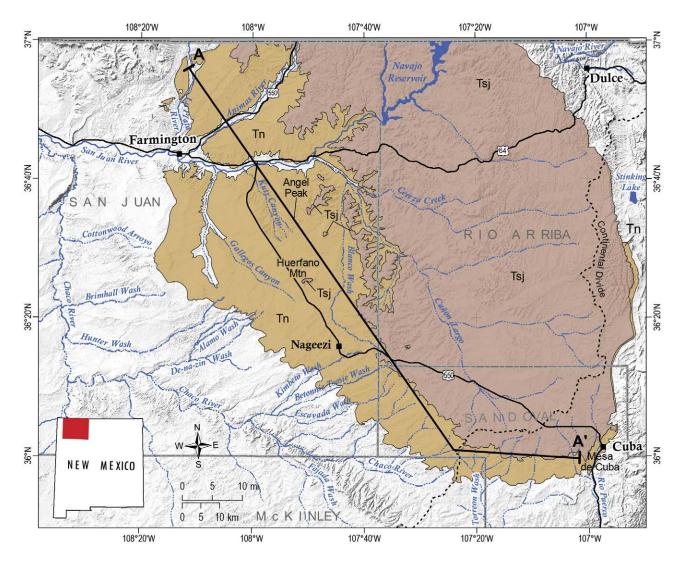


Figure 4. Digital elevation map of northwestern New Mexico showing cross-section line A–A' (Fig. 5) and the geographic distribution of the Paleocene Nacimiento Formation (Tn) and the lower Eocene San Jose Formation (Tsj). Also shown are selected roads, geographic features, and municipalities. Mtn—Mountain.

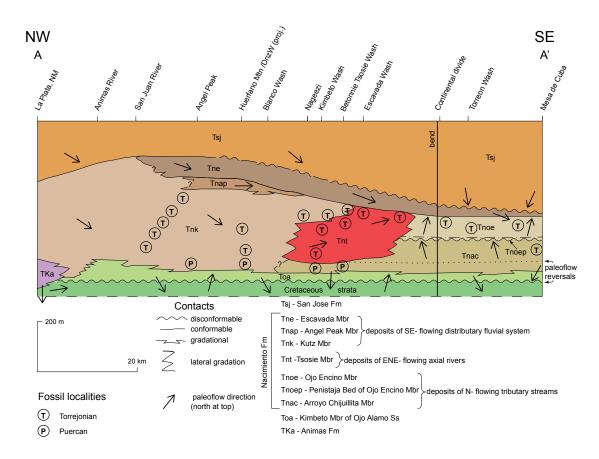


Figure 5. Schematic projected cross section of the western and southern part of the San Juan Basin depicting the spatial arrangement of stratigraphic units, nature of contacts, paleoflow directions, stratigraphic position of major paleoflow reversals, and Puercan and Torrejonian fossil localities (Williamson, 1996). The Horseshoe ash (not shown) occurs 10.5 m above the top of the Kimbeto Member at De-na-zin Wash. Datum is the base of the Kimbeto Member of the Ojo Alamo Sandstone. Line of section and localities are shown in Figure 4. Data are projected onto the line of section from outcrops, petroleum-well data described in Williamson and Lucas (1992) and Williamson (1996), and well data from the area north of the Animas River. Note that only the upper part of the Arrovo Chijuillita Member was deposited by north-flowing streams; the lower part contains southerly paleocurrent indicators (see text). Fm - Formation: Mbr-Member: Ss-Sandstone: DnzW-De-na-zin Wash: Mtn-Mountain: proj.-projected; NM-New Mexico.

Tsosie Member

We propose the new name Tsosie Member for the middle part of the Nacimiento Formation in the southwestern part of the basin (Figs. 4 and 5; Table 1). Tsosie Member strata can be distinguished from the Ojo Encino and the Arroyo Chijuillita members by the presence of thick channel sandstones, the absence of the Penistaja Bed, and the absence of the strongly variegated beds that characterize the Ojo Encino Member.

The Tsosie Member is largely or entirely Torrejonian in age (Fig. 5), although it is possible that its lower part may range into the late Puercan. A detrital-sanidine maximum depositional age of 62.48 ± 0.02 Ma was obtained from a sandstone in the Tsosie Member in Escavada Wash; this age is probably close to the actual depositional age, given its strongly unimodal character (only 20 out of 86 dated sanidines are significantly older than 62.48 Ma; Leslie et al., 2018).

The Tsosie Member is characterized by ~10–35-m-thick, commonly cross-bedded channel-sandstone complexes separated by mostly drab flood-plain mudstone. Sandstone is mostly fine to coarse grained. Conglomerate is absent except for intraformational mudstone clasts. Laterally accreted beds indicative of point-bar migration are locally present, but are not prevalent. In several areas, we have noted preserved channel margins and point-bar deposits that indicate deposition within a deep paleoriver, herein termed the Tsosie paleoriver, with bank-full channel depths of at least 5 m (Fig. 11).

Paleoflow during deposition of the Tsosie Member was east-northeast (mean = 075°; Fig. 7D). Thick fluvial sandstone beds are present in the subsurface within the middle part of the Nacimiento Formation east-northeast (down depositional dip) from the Tsosie Member exposures in the Escavada Wash–Kimbeto Wash area. These sandstones, formerly correlated to the Arroyo Chijuillita and the Ojo Encino members in wells 6–9 of Williamson and Lucas (1992) and wells 11–20 of Williamson (1996), we assign to the Tsosie Member (Fig. 8).



Figure 6. View to the north of light-gray sandstone and medium to dark-gray mudstone of the Arroyo Chijuillita Member of the Nacimiento Formation exposed in the south-ernmost spur of Mesa de Cuba (zone 13, 319687E, 3982679N; all UTM locations are NAD 1927). Channel-form sandstone above dead tree at center of image is ~1.3 m thick.

Kutz Member

The Kutz Member (new term; formerly the "main body" of Williamson, 1996) is a thick succession of cross-bedded fluvial channel sandstone, splay sandstone, and floodplain mudstone best exposed in Kutz Canyon, where it is ~200 m thick (Table 1). Only the middle and upper parts of the unit are exposed in Kutz Canyon. In wells nearby to the east, the total thickness of the Kutz Member is ~300 m (Williamson, 1996). The Kutz Member overlies the Kimbeto Member with apparent conformity.

The lower Kutz Member tends toward drab colors (Fig. 12), whereas reddish or variegated hues prevail in the upper part (Fig. 13), indicating paleosols in the upper part of the member were better drained. Together, upsection increases in coarseness and depth to the paleo—water table are suggestive of progradation.

Paleoflow during deposition of the Kutz Member was southeastward (mean = 125°; Fig. 7E). The proximal facies of the Kutz Member is exposed ~12 km north of Farmington. There, pebbly sandstone (Fig. 14) records where a significant fluvial system entered the basin. This point source and the somewhat radial paleoflow (Fig. 8) suggest the Kutz Member may represent the deposits of a prograding distributive fluvial system (e.g., Weissmann et al., 2010; see also Leslie et al., 2018).

The middle and upper parts of the Kutz Member contain Torrejonian beds (Fig. 5). The lower 30–40 m of the Kutz Member at the measured sections at the West Fork of Gallegos Canyon and at De-na-zin Wash contain Puercan beds

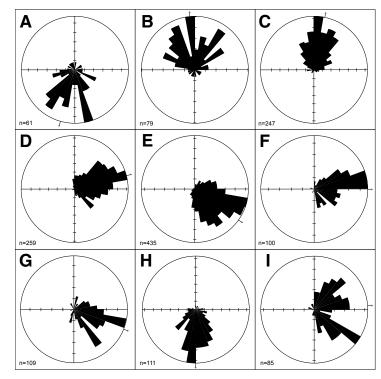


Figure 7. Paleocurrent rose diagrams for the Nacimiento and Animas formations. These are summary plots; for individual localities (numbered arrows on Fig. 8), see data in Supplemental Files (text footnote 1). A—lower part of Arroyo Chijuillita Member; B—upper part of Arroyo Chijuillita Member; C—Ojo Encino Member of the Nacimiento Formation; D—Tsosie Member of the Nacimiento Formation; E—Kutz Member of the Nacimiento Formation; F—Angel Peak Member of the Nacimiento Formation; G—Escavada Member of the Nacimiento Formation; H—combined Animas and Nacimiento formations in the northern and eastern parts of the basin (except Wirt member); I—Wirt member of Animas Formation.

(Williamson, 1996). A recently discovered volcanic ash bed (Fig. 15), 10.5 m above the base of the Kutz Member in De-na-zin Wash, herein informally termed the Horseshoe ash, is the only in situ (i.e., not significantly reworked) ash yet dated from the Paleogene of the San Juan Basin. The Horseshoe ash caps the middle Puercan "Ectoconus zone" at De-na-zin Wash.

⁴⁰**Ar**/³⁹**Ar geochronology of the Horseshoe ash.** Sample SJ-ASH-2 from the Horseshoe ash at De-na-zin Wash yielded a weighted-mean age of 65.49 ± 0.06 Ma based on 58 of 61 dated crystals (Fig. 16). The Horseshoe ash sample has abundant sanidine grains with few microcline or orthoclase crystals. The MSWD of 5.13 is slightly elevated and indicates scatter above analytical uncertainty. This scatter is likely a combination of both grain-to-grain variation of neutron flux across the irradiation pit as well as some contribution

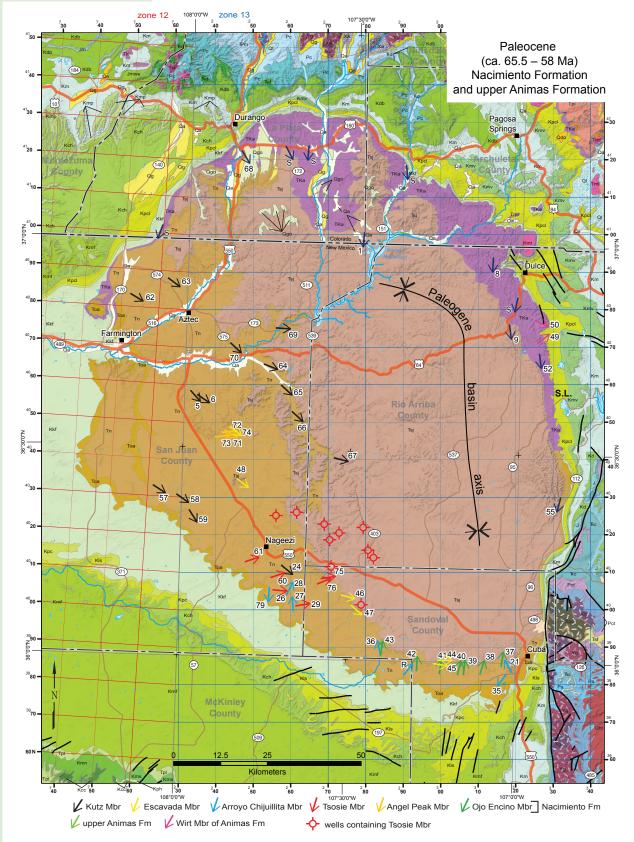


Figure 8. Geologic map of the San Juan Basin showing the mean direction of paleocurrent indicators (arrows) for the Paleocene Nacimiento (Tn) and Animas formations (TKa). See Figure 3 for unit abbreviations. Paleoflow data for this study (numbered localities) are presented in the Supplemental Files (text footnote 1). Note that localities 7 and 42 of the data in Supplemental Files (text footnote 1) are in close proximity and are combined as locality 42 on this map. All data are from this study except for localities marked S (Sikkink, 1987) in the Animas Formation and locality R (Rains, 1981) in the Nacimiento Formation. Well symbols mark petroleum wells that contain thick channel sandstones of the Tsosie Member (well locations from Williamson and Lucas, 1992; Williamson, 1996). UTM coordinates are NAD 1927. S.L. - Stinking Lake; Fm - Formation; Mbr - Member. Geologic base map from Tweto (1979) and NMBGMR (2003).



Figure 9. View to the west of the Penistaja Bed of the Ojo Encino Member of the Nacimiento Formation (Tnoep) disconformably overlying the Arroyo Chijuillita Member (Tnac), ~8 km west-southwest of Mesa de Cuba (zone 13, 310521E, 398277N).



Figure 10. Pebbles within the Penistaja Bed of yellowish-gray, probably Upper Cretaceous sandstone and siltstone, and red, probably Jurassic or Triassic sandstone. Northerly paleoflow during deposition of this bed suggests these pebbles were derived from Mesozoic exposures on the Chaco homocline to the south. These pebbles contrast with the dominantly siliceous, north- to northwest-derived pebbles that characterize the Nacimiento Formation in the western part of the basin and the siliceous pebble suites of the Ojo Alamo Sandstone and San Jose Formation throughout the basin (zone 13, 310596E, 3982667N).



Figure 11. Thick fluvial channel sandstone in the lower part of the Tsosie Member of the Nacimiento Formation (foreground). This sandstone preserves the margin of a ~5-m-deep paleochannel (arrow). Major channel sandstones of the middle part of the Tsosie Member (numbered 1, 2, and 3) are exposed on the north flank of Betonnie Tsosie Wash. All of these fluvial sandstones show evidence of east-northeast paleoflow and are interpreted to represent deposits of a major, extrabasinal paleoriver (the Tsosie paleoriver) that entered the San Juan Basin here. View to the northwest from zone 13, 254873E, 4004909N.



Figure 12. Lower part of the Kutz Member of the Nacimiento Formation showing fine-grained character and dominantly drab coloration. View to the west of the east flank of Black Hill, at the head of the West Fork of Gallegos Canyon (zone 12, ~757100E, 4023200N)



Figure 13. Variegated sandstone and mudstone in upper part of the Kutz Member of the Nacimiento Formation (Tnk), exposed in the upper reaches of Kutz Canyon. Road in canyon at center of image is ~5 m wide. Angel Peak in the distance is capped by the San Jose Formation (Tsj), which is underlain by the Escavada (Tne) and Angel Peak (Tnap) members of the Nacimiento Formation (see Fig. 17). View to the northeast from zone 13, 237365E, 4045820N.



Figure 14. Siliceous pebbles and coarse sandstone in the proximal facies of the lower Kutz Member south of Thompson Arroyo, ~12 km north of Farmington (Fig. 8, locality 62). Zone 12, 752623E, 4083222N.



Figure 15. Exposure of the Horseshoe ash (thin, light-gray bed in excavation) in Dena-zin Wash (zone 12, 769016E, 4024341N) within the lower part of the Kutz Member.

by geological scatter. Geological scatter could be related to several factors, including minor argon loss, excess argon in melt inclusions, or the presence of xenocrysts that are slightly older than the eruption age of the Horseshoe ash. K/Ca values cluster near 100, but have overall high uncertainty due to difficulty measuring small ³⁷Ar signals on a 10e¹² ohm Faraday amplifier. Radiogenic yields were commonly between 99.8% and 100%. See below for comparison between the ⁴⁰Ar/³³Ar sanidine geochronology of the Horseshoe ash and the detrital-sanidine ages from the Wirt member of the Animas Formation.

Angel Peak Member

We use the new term Angel Peak Member (Table 1) for a sandstone-dominated interval above the Kutz Member in the Kutz Canyon–Nageezi region. Williamson (1996) called this interval the "unnamed member." It consists of ~10–25 m of yellowish-gray, commonly cross-bedded fluvial sandstone and associated thin mudstone of floodplain or pond origin (Fig. 17). The Angel Peak Member lies conformably on, and locally intertongues with, the underlying Kutz Member. Paleoflow during deposition of the Angel Peak Member was toward the east (mean = 091°; Fig. 7F). The Angel Peak Member is late Torrejonian to possibly early Tiffanian in age, based on magnetostratigraphy (Williamson, 1996).

Escavada Member

The Escavada Member (Williamson and Lucas, 1992) is a thin (~20–90 m) but widespread unit in the uppermost Nacimiento Formation, extending from

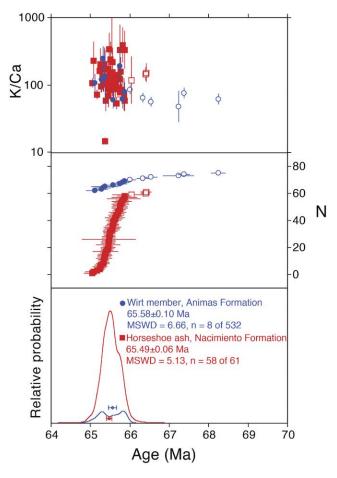


Figure 16. Relative age probability and K/Ca diagrams comparing ⁴⁰Ar/³⁰Ar analytical results of sanidine from the Horseshoe ash (10.5 m above base of the Kutz Member at De-na-zin Wash, 769016E, 4024341N, zone 12) to the post-70 Ma detrital sanidistrom two localities in the upper part of the Wirt member along Jicarilla Apache Road J-15. The eight youngest detrital-sanidine grains are indistinguishable in age and K/Ca from sanidines of the Horseshoe ash. Of these eight sanidine grains in the Wirt member, sample 6-2-15-B yielded one from a green siltstone ~19.5 m below the top of the Wirt member (zone 13, 328256E, 4067042N), and sample 6-2-15-C yielded seven from a greenish-gray siltstone ~10 m below the top of the Wirt member (zone 13, 328221E, 4067058N).

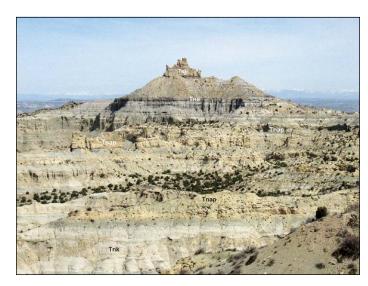


Figure 17. View to the north of the type area of the Angel Peak Member of the Nacimiento Formation from zone 13, 243113E, 4047655N. Stratigraphic units (descending) are the yellowish-gray coarse sandstone of the San Jose Formation (Tsj) capping Angel Peak, the gray fine sandstone and mudstone of the Escavada Member (Tne), the yellowish-gray sandstone of the Angel Peak Member (Tnap), and the gray and buff sandstone and mudstone of the Kutz Member (Tnk) of the Nacimiento Formation. The San Juan Mountains of Colorado are on the distant skyline.

Kutz Canyon to Mesa de Cuba. It consists of a drab (mostly shades of gray) fluvial succession of fine sandstone, mudstone, and thin, laterally extensive, silica-cemented beds that were interpreted by Hobbs (2016) as silicified volcanic ashes, an interpretation with which we concur. Silica-cemented beds in the Nacimiento Formation were termed silcretes by Rains (1981) and Williamson et al. (1992b), who interpreted them as paleosols. Silica-cemented beds are numerous in the Escavada Member (Fig. 18) but also occur more sparsely in the Arroyo Chijuillita Member, the Ojo Encino Member, and the lower part of the Kutz Member.

The Escavada Member is Tiffanian, based on its magnetostratigraphy (Williamson, 1996). It conformably overlies the Angel Peak Member, the Tsosie Member, and the Ojo Encino Member (Fig. 5) and shows evidence of east-southeasterly paleoflow (mean = 112°; Fig. 7G). The Escavada Member was deposited more slowly than underlying strata (Williamson, 1996), probably a reflection of decreased accommodation in the Tiffanian.

Animas Formation

The Paleocene Animas Formation crops out in the northern part of the San Juan Basin and consists of fluviatile, partly volcaniclastic beds. It is as much as ~700 m thick in the northeastern San Juan Basin (Stone et al., 1983) and thins southward. The Animas Formation disconformably overlies the Campanian Kirtland Formation in most places in the northeastern San Juan Basin. In the northwestern San Juan Basin, the Animas Formation overlies the McDermott Formation. The McDermott Formation is Maastrichtian, as shown by the presence of dinosaur fossils (Reeside, 1924), palynomorphs (Newman, 1987), and detrital zircon that indicates a maximum depositional age of ca. 69–68 Ma (Donahue, 2016; Pecha et al., 2018).

The basal Animas Formation near Durango is Puercan, based on palynomorphs (Newman, 1987). South of Dulce, the lower Animas Formation contains detrital-sanidine grains that indicate a maximum depositional age of 65.58 $\pm\,0.10$ Ma (see below). Detrital zircons from the Animas Formation ~8 km east of Durango yield a maximum depositional age of 63.6 $\pm\,0.6$ Ma (Donahue, 2016; her sample WP44). In southern Colorado, the upper Animas Formation hosts the "type" Tiffanian beds. These were deposited during magnetic polarity chron C25r (Lofgren et al., 2004), ca. 58 Ma (Ogg, 2012). The upper Animas Formation near Dulce contains turtle bones of probable Torrejonian age (Dane, 1946).

The Animas Formation can be distinguished by its color (grayish green to brownish green; Fig. 19) and its partly volcaniclastic nature from the dominantly siliciclastic Nacimiento and San Jose formations. In the eastern San Juan Basin, the Paleocene outcrop belt is subparallel to depositional dip, giving rise to a broad lateral gradation between the Nacimiento Formation and the Animas Formation. We place the lateral contact at the north boundary of T. 26 N., similar to Manley et al. (1987) and NMBGMR (2003). We emphasize, however, that this contact placement is arbitrary (cf. Anderson, 1960; Fassett and Hinds, 1971), and we note that no worker has yet identified a mappable lateral contact within the broad transition between the Nacimiento and Animas formations in the eastern basin.

In the northwestern part of San Juan Basin, our observations suggest the Kutz Member of the Nacimiento Formation was deposited by a major southeast-flowing paleoriver system that entered the basin north of Farmington, whereas the Animas Formation was deposited by tributary streams that drained volcanic terranes farther north (Fig. 8). Paleocurrent measurements obtained during this study within the Animas Formation are southerly (mean = 180°; Fig. 7H), similar to those of Sikkink (1987; see localities labeled "S" in Fig. 8).

Wirt Member

An exception to the southerly mean-paleoflow indicators of the Animas Formation is a thick succession of buff-colored sandstone, minor greenish-gray mudstone, and rare pebbly sandstone at the base of the Animas that fills a broad paleovalley incised into the Lewis Shale ~15 km south of Dulce. These deposits (Fig. 20), herein informally termed the Wirt member of the Animas Formation, are named for the abandoned Wirt lookout tower in SW1/4 s. 15, T. 30 N., R.1 W. The Wirt member displays evidence of easterly paleoflow (mean = 085°; Fig. 7I), and grades upsection into the greenish-gray mudstone



Figure 18. View to the east of the Escavada Member of the Nacimiento Formation (Tne) disconformably overlain by the San Jose Formation (Tsj) at the head of Escavada Wash (zone 13, 268374E, 4008494N). Arrows denote thin, silica-cemented beds (silicified volcanic ash beds; Hobbs, 2016) in the Escavada Member.



Figure 19. Channel-filling, greenish-gray fluvial sandstone and gray floodplain mudstone and fine sandstone of the Animas Formation in road cut along U.S. Highway 64 at Dulce Lake (zone 13, 321463E, 4082875N).

and sandstone of the Animas Formation. Wirt member sandstones are mostly medium to coarse grained and occur in beds ~1–4 m thick that exhibit horizontal stratification, low-angle bedding, and cross bedding. Sandstone beds are interpreted to have been deposited by braided, bedload-dominated streams. Rare pebbles consist of granite, chert, quartz, quartzite, altered feldspar, and intermediate-composition volcanic rocks. Maximum clast size is ~0.5 cm.

Sandstone of the Wirt member has previously been included in the lower part of the Animas Formation by Dane (1946, 1948), Dane and Bachman (1957, 1965), and NMBGMR (2003) but was mapped as Ojo Alamo Sandstone by Fassett and Hinds (1971). We disfavor correlation of this sandstone to the Ojo Alamo for the following reasons. (1) The Wirt sandstone is as much as ~130 m thick, thicker than the Ojo Alamo Sandstone in nearby exposures (~20-40 m thick) and in nearby well penetrations (~20-50 m thick; Stone et al., 1983). Indeed, the Wirt member is thicker than even the proximal Ojo Alamo Sandstone near Farmington in the western basin (~82 m, Powell, 1973; ~67 m, O'Sullivan et al., 1972). (2) Paleoflow during deposition of the Wirt Member was easterly, orthogonal to the southerly paleoflow evidenced by nearby Ojo Alamo Sandstone outcrops along the Navajo River (Fig. 3, locality 78) and near Stinking Lake (Sikkink, 1987). (3) The youngest mode of sanidines of the Wirt member is statistically indistinguishable in age and K/Ca value from sanidines of the Horseshoe ash, exposed 10.5 m above the Ojo Alamo Sandstone in the lower part of the Kutz Member at De-na-zin Wash (Fig. 16; see below). Figure 21 is our interpretation of the stratigraphic relationships south of Dulce.

40Ar/39Ar geochronology of the Wirt member. To establish a maximum depositional age for the Wirt member, detrital K-feldspar from three siltstone samples of the Wirt member were analyzed. These samples yielded grains that range in age from ca. 65 Ma to the Mesoproterozoic (Fig. 16; Supplemental Files [footnote 1]). In the initial detrital-sanidine dating attempt of the



Figure 20. View to the northeast of the Wirt member of the Animas Formation from zone 13. 3227331E. 4073852N. Arrow marks the ~30 m Wirt lookout tower.

Wirt member, crystals were irradiated in package NM-277. The three samples, 6-2-15-A, 6-2-15-B, and 6-2-15-C, yielded similar results, with most grains being older than 100 Ma (see Supplemental Files [footnote 1]). These samples contained many plutonic and metamorphic K-feldspar grains with Precambrian apparent ages. However, two crystals (one from 6-2-15-B, one from 6-2-15-C) gave Paleocene ages (Fig. 16). These results led to a second dating attempt (irradiation NM-284) of sample 6-2-15-C where 247 grains were dated. In this

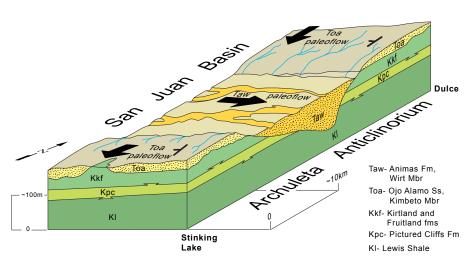


Figure 21. Schematic block diagram showing proposed stratigraphic relationships in the Dulce-Stinking Lake area during deposition of the Wirt member of the Animas Formation. Note that prior to paleovalley development, paleoflow was southward during deposition of the Kimbeto Member of the Ojo Alamo Sandstone, but became eastward during cutting of the paleovalley and subsequent aggradation of the Wirt member. Following filling of the Wirt paleovalley, southward progradation of the younger part of the Animas Formation saw restablishment of southward paleoflow in the area.

case, 83 of the 247 grains yielded ages less than 300 Ma. This dating effort recovered two additional Paleocene crystals. A final attempt of detrital-sanidine dating on 6-2-15-C (irradiation NM-289) was made, and 54 of 99 grains yielded ages less than 300 Ma. This attempt yielded four grains with Paleocene ages and constitutes our most successful attempt at finding a young population of detrital grains.

A maximum depositional age for the Wirt member of 65.58 ± 0.10 is given by the weighted-mean age of the eight youngest grains. As with the Horse-shoe ash crystals, the MSWD of 6.66 is slightly elevated and thus may indicate the presence of multiple age populations. The youngest normally distributed group of ages (n = 5) in the Wirt samples yields a weighted-mean age of 65.38 ± 0.08 Ma, which also could be used to define the maximum depositional age. Both of the above ages, however, are statistically indistinguishable from the 65.49 ± 0.06 Ma Horseshoe ash, as are K/Ca values (Fig. 16). Since the range of the eight youngest sanidine grains from the Wirt member coincides closely with the range of sanidine ages in the Horseshoe ash sample, we think it best to include all eight grains to calculate the maximum deposition age.

In summary, detrital-sanidine grains from the Wirt member have ages and K/Ca ranges essentially identical to those of sanidines from the Horseshoe ash, a result that strongly suggests reworking of the Horseshoe ash into the Wirt member. Moreover, the low abundance of young detrital-sanidine grains in the Wirt member (eight of 532 grains analyzed) and the fact that these grains occur in two beds separated stratigraphically by ~10 m suggest the maximum depositional age of the Wirt member may be significantly older than its actual depositional age. Based on additional geologic considerations described below, we infer the Wirt member may record the same axial fluvial system (the mostly Torrejonian Tsosie paleoriver) that deposited the Tsosie Member of the Nacimiento Formation.

San Jose Formation

The Nacimiento Formation and the Animas Formation are overlain by the lower Eocene San Jose Formation, a dominantly fluvial succession as much as ~700 m thick (Fassett, 1974; Milner, 2004). Paleoflow during deposition of the San Jose Formation was generally southerly (Fig. 22). The San Jose Formation has been divided into several members (Baltz, 1967; Smith and Lucas, 1991; Smith, 1992), including a basal sandstone-dominated unit (the Cuba Mesa Member). The erosional top of the San Jose Formation is modern topography. Regional stratigraphic relationships indicate 1.0–1.5 km of middle Eocene through Oligocene strata have been removed by Neogene erosion in the San Juan Basin (Cather et al., 2008, 2012).

The lower contact of the Cuba Mesa Member with the underlying Nacimiento Formation is an unconformity with slight (1°–3°) angularity at Mesa de Cuba in the southeastern part of the basin. This unconformity may represent a lacuna of ~3–6 m.y., but estimation of its duration is imprecise because of the poorly constrained age of the Cuba Mesa Member (Williamson, 1996; Cather, 2004).

Throughout the remainder of the southern and central basin, the contact at the base of the Cuba Mesa Member is sharp and disconformable (Fig. 18). Early studies (Smith and Lucas, 1991; Smith, 1992) inferred that this disconformity gives way to an area of conformity and uninterrupted sedimentation near the basin center. Examination of well logs near the synclinal basin axis by one of us (SMC) and B.S. Brister, however, suggested continuation of the basal disconformity into this area, which was attributed to an episode of diminished basin subsidence and low accommodation (Cather, 2004). A subsequent detailed analysis of numerous well logs indicates a persistent disconformity at the base of the Cuba Mesa Member throughout the central and southern San Juan Basin, with greater erosion (~75 m deep) of the Nacimiento Formation along the basin axis than elsewhere (Milner, 2004; Milner et al., 2005). In northernmost New Mexico and southern Colorado, the upper parts of the mudstone-dominated Nacimiento and Animas formations appear to intertongue with basal sand-stone of the San Jose Formation, suggesting a conformable contact.

■ LARAMIDE DEPOSITIONAL SUMMARY

Our analysis of fluvial paleoflow during deposition of the Nacimiento and Animas formations fills the final major gap in the knowledge of the Laramide sedimentary evolution of the San Juan Basin. What follows is a synopsis of that evolution, which began in the Campanian and continued through the early Eocene.

If the beginning of the Laramide orogeny is considered to be marked by initiation of local intraforeland basins and uplifts within the former Western Interior Seaway, then the Laramide orogeny in northwestern New Mexico began ca. 80–75 Ma, as shown by local thickening of the marine Lewis Shale within the San Juan Basin and the thinness or absence of regressive shoreline deposits of the overlying Pictured Cliffs Sandstone along its southeastern margin (Cather, 2004, and references therein). The onset of Laramide deformation coincided temporally with the passage of the subducted conjugate Shatsky Rise beneath the region (Liu et al., 2010).

Regression of the Lewis seaway during the late Campanian was driven by northeastward progradation of the Fruitland and Kirtland formations (Fassett and Hinds, 1971; Fassett, 2000). The direction of Pictured Cliffs shoreline regression was ~030°, as shown by the trend of coastal-plain fluvial channels on sandstone isolith maps of the Fruitland Formation (Ambrose and Ayers, 1990). Northwestward thickening of the Fruitland and Kirtland formations was, in part, the result of increased subsidence along the Hogback monocline, which forms the northwestern margin of the basin. The Hogback monocline shed sediment eastward into the basin, resulting in deposition of the eastward-thinning Farmington Sandstone Member of the Kirtland Formation (Fig. 23A; Cather, 2003). Campanian subsidence was the first of three Laramide subsidence events in northern New Mexico (Cather, 2004).

Detrital zircon in the Pictured Cliffs Sandstone and Fruitland Formation was derived largely from the Mogollon Highland of southern Arizona (Pecha et al.,

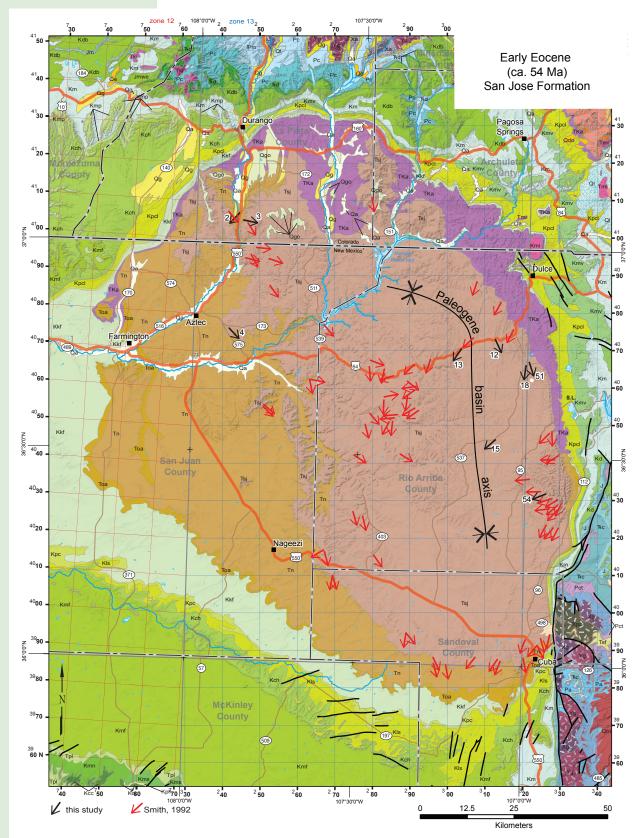
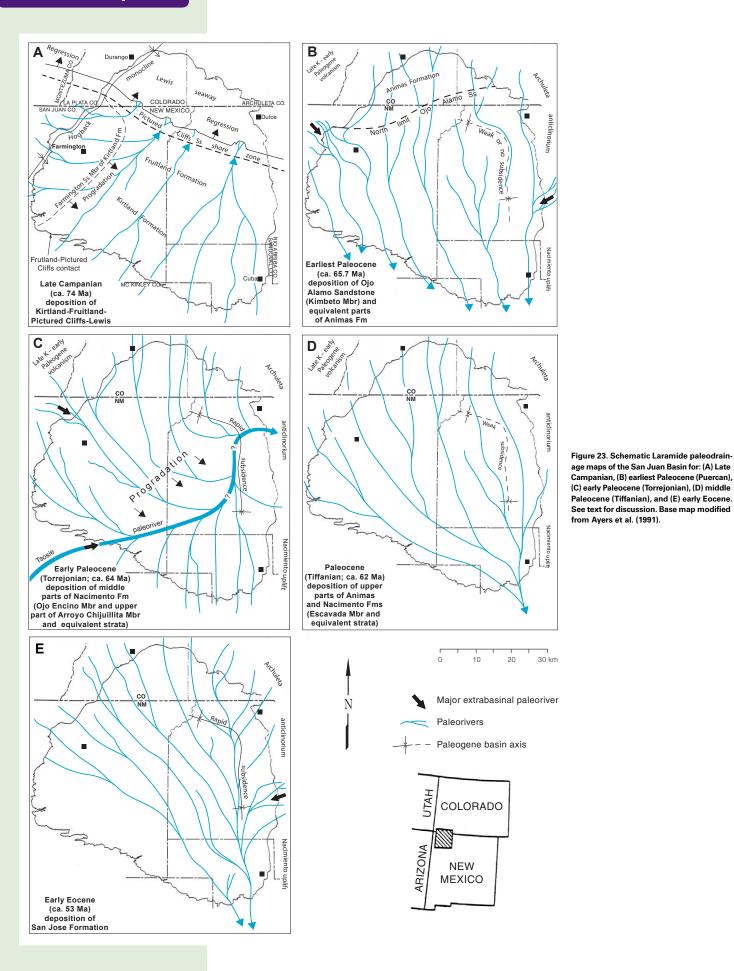


Figure 22. Geologic map of the San Juan Basin showing the mean direction of paleocurrent indicators (arrows) during deposition of the lower Eocene San Jose Formation (Tsj). See Figure 3 for other unit labels. Paleoflow data for this study (numbered black arrows) correspond to numbered localities in the data in Supplemental Files (see text footnote 1). UTM coordinates are NAD 1927. S.L. - Stinking Lake. Geologic base map from Tweto (1979) and NMBGMR (2003).



2018). In contrast, zircon in the overlying Kirtland Formation, the Ojo Alamo Sandstone, and the Nacimiento, Animas, and San Jose formations reflects derivation mostly from nearby Laramide basement uplifts (Pecha et al., 2018).

During the Maastrichtian, a major basin-wide unconformity developed atop the Kirtland Formation, which contains a 73.34 ± 0.12 Ma ash in its upper part (Fassett and Heizler, 2017). The unconformity probably developed in response to a decreased basin subsidence and accommodation (Cather, 2004). The unconformity is overlain locally by Maastrichtian beds (the McDermott Formation and the Naashoibito Member of the Ojo Alamo Sandstone) but is more widely overlain by the lower Paleocene Kimbeto Member of the Ojo Alamo Sandstone. The associated lacuna has a duration of ~5–7.5 m.y.

The paleoflow regime during deposition of the Naashoibito Member of the Ojo Alamo Sandstone in the Hunter Wash–De-na-zin Wash region (Fig. 4) is uncertain. Similarities in pebble composition of the Naashoibito Member and overlying Kimbeto Member (Baltz et al., 1966) suggest that both share similar northerly sources. Powell (1972) reported an average paleoflow direction for the Naashoibito Member of ~210°, but he did not present the paleocurrent data or state where his measurements were collected. Moreover, he correlated beds along the entire eastern basin margin to the Naashoibito Member, a correlation no worker before or since has supported.

A major change in paleoslope occurred during development of the Maastrichtian unconformity, from a northeastward slope during Kirtland Formation sedimentation to a southerly or southeasterly paleoslope during deposition of the Kimbeto Member. The sandstone-dominated Kimbeto Member of the Ojo Alamo Sandstone was deposited during the earliest Paleocene (Fig. 23B), a time of low sedimentary accommodation in the San Juan Basin (Cather, 2004). Heller et al. (2013) related deposition of the Ojo Alamo Sandstone to the effects of the subducted conjugate of the Shatsky Rise. We note, however, that during the early Paleocene, the Shatsky conjugate was far to the northeast, centered beneath eastern Wyoming (Liu et al., 2010), so any connection between the conjugate and sedimentation in northwestern New Mexico seems tenuous. We think it is more likely that mantle-buoyancy-related epeirogenic uplift associated with ca. 74-68 Ma onset of magmatism in the southwestern part of the Colorado Mineral Belt (Mutschler et al., 1987; Cunningham et al., 1994; Semken and McIntosh, 1997; Gonzales, 2017) was responsible for widespread post-Kirtland erosion and subsequent shift to southerly and southeasterly paleoflow.

Southerly to southeasterly paleoflow continued throughout Puercan, Torrejonian, and early Tiffanian time in the northern and western parts of the basin during deposition of the Nacimiento Formation (the Kutz and Angel Peak members) and the Animas Formation. In the southern part of the basin, however, southerly paleoflow persisted only during deposition of the lower Arroyo Chijuillita Member during the Puercan (Figs. 5 and 8).

Beginning during deposition of the unfossiliferous interval between Puercan and Torrejonian fossil localities (Williamson, 1996), paleoflow reversed in the southern basin. As the upper Arroyo Chijuillita Member and the Ojo Encino Member were being deposited, mostly during the Torrejonian, paleoflow was northerly. Situated between these north-flowing paleorivers and the southeast-to east-flowing paleorivers that deposited the Kutz and Angel Peak members was a major east-northeast-flowing paleoriver that deposited the mostly Torrejonian Tsosie Member. We interpret these relations to represent an axial Tsosie paleoriver flanked by opposing tributary systems (Fig. 23C) during deposition of the middle part of the Nacimiento Formation.

The Torrejonian, a time of subsidence and lake development in the Powder River and Wind River basins to the north (Yuretich, 1989), was also marked by renewed rapid subsidence and sedimentary accommodation in the San Juan Basin (i.e., the middle episode of rapid Laramide subsidence of Cather, 2004). During this time, there was no southward fluvial exit from the basin. The entire paleodrainage at this time was either endorheic or exited somewhere along the east side of the basin. We have examined numerous well logs near the basin axis (e.g., Stone et al., 1983) and see no evidence for thick mudstone deposits representing a long-lived paleolake beneath the San Jose Formation. After extensive reconnaissance, we have seen no candidate for a major fluvial exit point along the eastern basin margin other than the Wirt member exposures. We therefore postulate that the Wirt member represents the deposits of the Tsosie paleoriver as it exited the basin toward the east.

If we are correct, the Wirt member is likely Torrejonian, with possible late Puercan or early Tiffanian beds in its lower and upper parts, respectively (i.e., ca. 65–61 Ma). However, because the depositional age of the Wirt member is poorly constrained, its correlation to a time-transgressive Kimbeto Member cannot be ruled out. Such a correlation would suggest the exit point for Torrejonian paleodrainage of the San Juan Basin is undiscovered or was eroded.

Figure 24 is our interpretation of the architecture of Torrejonian fluvial systems in the Four Corners region. We suggest that the position of the Tsosie paleoriver on the rather featureless Chaco homocline was determined by the gap between the rising Zuni and Defiance uplifts to the southwest. Given the large scale of this paleoriver, we infer its headwaters were in the Mogollon Highland, although it is possible it headed more locally in the Zuni-Defiance area. We note that the late Laramide Baca Basin, south of the Zuni uplift, did not begin to accumulate sediment until the middle Eocene (Cather and Johnson, 1984, 1986; Cather, 2004). We also note that the old, non-sanidine, K-feldspars dated from the Wirt member represent cooling ages, and not crystallization ages, and thus are not as useful as detrital-zircon data for differentiating basement source regions. This is because most Proterozoic basement terranes in the region share similar K-feldspar 40Ar/39Ar cooling ages, commonly between ca. 800 and 1200 Ma (e.g., Sanders et al., 2006; Karlstrom et al., 2010), irrespective of their age of crystallization or metamorphism.

We suggest that the Tsosie paleoriver crossed the San Juan Basin near its synclinal axis. It then probably exited the basin ~15 km south of Dulce, where it is recorded by the Wirt member of the Animas Formation. The paleoriver crossed the Archuleta anticlinorium through a structurally low area east of the Wirt exposures. Beyond this point, there are two main possibilities for the path of the paleoriver. It may have turned south and acted as a sedimentary bypass system through the area of the Galisteo–El Rito Basin, which, prior

to the latest Paleocene to early Eocene, had not yet begun to accumulate sediment (Lucas et al., 1997). Alternatively, the Tsosie paleoriver may have turned to the northeast and contributed sediment to the Poison Canyon and Raton formations in the Raton Basin. This latter possibility may be testable with petrographic, detrital-sanidine, and detrital-zircon studies.

During Tiffanian deposition of the Escavada Member and equivalent strata, continued southeastward progradation of the distributive fluvial system sourced in the western part of the basin pushed the axial Tsosie paleoriver beyond the present extent of Paleocene outcrops in the San Juan Basin (Fig. 23D). In the central and southern part of the basin, following a 3–6 m.y. lacuna that encompassed at least the latest Paleocene, the sandstone-dominated Cuba Mesa Member of the San Jose Formation was deposited by generally south-flowing paleorivers (Fig. 23E). The Cuba Mesa Member, its underlying disconformity, and the subjacent Escavada Member correspond to a second Laramide episode of weak basin subsidence, diminished accommodation, and basin overfilling (Cather, 2004; Milner, 2004, Milner et al., 2005, Leslie et al., 2018). The disconformity represents erosion both along the basin margins (except in the north) as well as in the basin axis, where the Nacimiento Formation has been erosionally thinned (Milner et al., 2005).

It is interesting to speculate whether the final phase of rapid Laramide basin subsidence, which culminated ca. 50 Ma in central and northern New Mexico (Cather, 2004), produced a third episode of paleoflow reversal in the southern San Juan Basin. Although beds of this age are not preserved in the San Juan Basin, ca. 50 Ma saw the culmination of basin closure and centripetal paleoflow in the Green River lake systems to the north (e.g., Smith et al., 2003).

CONCLUSIONS

Our study demonstrates that the evolution of Paleocene fluvial systems in the Laramide San Juan Basin was complex and primarily reflected the role of varying intrabasin subsidence and sedimentary accommodation. The Puercan began with deposition of the Kimbeto Member of the Ojo Alamo Sandstone during a time of weak subsidence. It overlies an unconformity throughout most of the basin, and its extensive, thin, and relatively sheet-like geometry suggests deposition during a time of basin overfilling. Puercan paleorivers flowed southward or southeastward and exited the basin toward the south, during deposition of the Kimbeto Member, the lower parts of the Kutz and Arroyo Chijuillita members of the Nacimiento Formation, and the lower part of the Animas Formation.

During the Torrejonian, a new fluvial architecture was established during a regime of rapid subsidence in the northeast part of the basin. At this time, a major regional paleodrainage (the Tsosie paleoriver) entered the southwestern part of the basin and may have exited to the northeast near Dulce. All Torrejonian paleodrainages within the basin appear to have been tributaries to the Tsosie paleoriver. Strata deposited by tributaries to the Tsosie paleoriver include the upper part of the Arroyo Chijuillita Member and the Ojo Encino

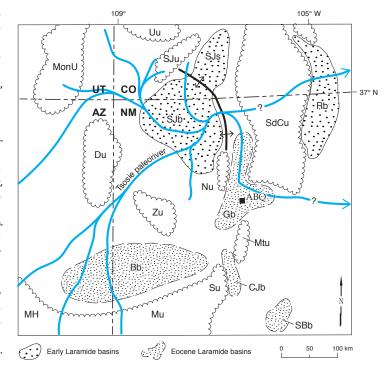


Figure 24. Proposed paleodrainage system in the Four Corners region during the early Paleocene (Torrejonian). The San Juan (SJb) and Raton (Rb) basins contain Laramide deposits of Campanian through Eocene age, but Laramide basins to the south contain only Eocene sediments and thus postdate the Tsosie paleoriver. Note two possible paleodrainage pathways (see text) east of the Archuleta anticlinorium (anticline symbol). Other basins and uplifts are: Monument upwarp (MonU), Uncompahgre uplift (Uu), San Juan uplift (SJu), San Juan sag (SJs), Sangre de Cristo uplift (SdCu), Defiance uplift (Du), Zuni uplift (Zu), Nacimiento uplift (Nu), Galisteo–El Rito Basin (Gb), Baca Basin (Bb), Sierra uplift (Su), Carthage–La Joya Basin (CJb), Montosa uplift (Mtu), Mogollon Highland (MH), Morenci uplift (Mu), and the Sierra Blanca Basin (SBb). ABQ—Albuquerque; UT—Utah; CO—Colorado; AZ—Arizona; NM—New Mexico.

Member (both deposited by north-flowing paleostreams), the middle and upper part of the Kutz Member, the Angel Peak Member, and the middle part of the Animas Formation (all deposited by south- or southeast-flowing paleostreams).

During the Tiffanian, southeastward progradation of the Escavada Member of the Nacimiento Formation and southward progradation of the upper part of the Animas Formation pushed the axial Tsosie paleoriver out of the basin. The Tiffanian succession in the central and southern part of the basin records a second episode of weak subsidence, low accommodation, and basin overfill marked by two probable condensed sections (the Escavada Member of the Nacimiento Formation and the lower Eocene Cuba Mesa Member of the San Jose Formation) and the unconformity that divides them.

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