**Climate and Landscape Reconstruction of the Arroyo Chijuillita Member of the
Nacimiento Formation, San Juan Basin, New Mexico: Providing Environmental Context to
Early Paleocene Mammal Evolution**

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ABSTRACT

The sedimentologic, stratigraphic, and paleopedologic attributes of a laterally continuous outcrop exposure of the basal portion of the lower Paleocene Arroyo Chijuillita Member of the Nacimiento Formation located in the Bisti/De-Na-Zin Wilderness Area was examined to provide paleoenvironmental context for the Puercan North American Land Mammal Age (NALMA) terrestrial ecosystems of the San Juan Basin, New Mexico. The studied outcrop spans the middle and late Puercan (Pu2-Pu3) NALMA, and thus is an ideal location to assess the potential causes of faunal turnover between Pu2 and Pu3. The stratal succession consists of fluvial channel and laterally continuous sandstone and associated fine-grained floodplain deposits, including paleosols that document variability in drainage and maturity. Quantitative and qualitative reconstructions of paleoclimate from paleosols, supplemented by analyses of fossil floras, indicate no change in climate through the studied interval. Further, there is no evidence that regional tectonics relate to changes in depositional environments. Given the lack of evidence for climate change or regional tectonics, and the characteristics of the fluvial facies and the paleosols across the study locality, we interpret the spatial and temporal variability in paleopedologic and sedimentologic characteristics to be the result of autocyclic channel avulsion and migration. Additionally, the stable climatic conditions and lack of tectonic influence between the Pu2 and Pu3 biozones suggest that mammalian turnover is unlikely to have been caused by extrinsic environmental changes (i.e. climate or tectonics) and is instead probably the result of rapid evolution following the K-Pg boundary and/or competition from the migration of new mammalian species into the basin.

Keywords: Paleocene, Paleoclimate, San Juan Basin, Paleosol, Fluvial Sedimentology, Puercan

INTRODUCTION (1)

Fluvial systems and their associated deposits evolve largely as a result of increases and decreases in accommodation space, which are driven by intrinsic and extrinsic factors that impact local and regional base level. Common intrinsic or autocyclic factors include channel migration, avulsion, and infill of accommodation space (e.g. Kraus, 1987, 1999, 2002; Kraus and Aslan, 1993; Atchley et al., 2004, 2013a, 2013b; Cleveland et al., 2007). Common extrinsic or allocyclic factors include regional tectonism, climate fluctuations, and, in some cases, eustatic sea level change (e.g. Leopold and Bull, 1978; Blair and Bilodeau, 1988; Posamentier and Vail, 1988; Paola et al., 1992; Holbrook et al., 2006; Miall, 2010). Determining the influence of autocyclic and/or allocyclic drivers on ancient fluvial systems can provide important insights on their relative impact on sedimentation, and, as such, their potential role in influencing ecological changes, such as turnover in floral and faunal communities (e.g. Bridge, 1985; Kraus, 1987, 1997, 1999, 2002; Kraus and Aslan, 1993; Demko et al., 2004; Kraus and Hasiotis, 2006; Atchley et al., 2013b).

Rapid changes in climate and regional tectonism affect sedimentation in a predictable way. For example large-scale, rapid shifts in local and/or regional climate are expected to cause abrupt and contemporaneous changes in sedimentation and depositional environments (i.e., grain size, facies, and fluvial style). Modeling of the role of water availability on sedimentation demonstrated that rapid increases in water availability (i.e., shorter than fluvial equilibrium time) results in significant and abrupt progradation and sediment coarsening, whereas changes in water availability over longer time scale (i.e., longer than fluvial equilibrium time) did not influence sedimentation (Paola et al., 1992). Additionally, increases in water availability causes increased stream competency, which in turn may induce channel incision, increased bedload grain size, and

increased sediment load. In basins experiencing continuous tectonism and/or subsidence, sediments document corresponding changes to the fluvial gradient, variations in accommodation, and sediment source (e.g. Paola et al., 1992; Holbrook et al., 2006; Miall, 2010). Modeling of the influence of subsidence on sedimentation indicates that increases in subsidence at all modeled timescales results in the deposition of coarse material proximal to the sediment source whereas decreased subsidence results in the progradation of coarse material across the basin (Paola et al., 1992).

Regardless of the influence of allocyclic factors, autocyclic processes are ongoing as channels aggrade, degrade, migrate, and avulse across the basin at varying spatial and temporal scales (e.g. Kraus, 1987, 1999, 2002; Kraus and Aslan, 1993; Atchley et al., 2004, 2013a, 2013b). These intrinsic processes are highly variable and depend on the geologic and geomorphic context of individual fluvial systems and are also influenced by allocyclic processes. Careful assessment of architectural element and facies changes can help to determine the relative influence of allocyclic vs. autocyclic processes on sedimentation (e.g. Miall, 1978, 1985, 2010). That is, spatial and temporal variability of sediments may be explained by several individual mechanisms or a combination of processes; however, specific evidence for the primary mechanisms driving variability in depositional environments may be identifiable through detailed assessment of sedimentary systems.

In this study we focus on a ~25 m thick and 500 m laterally continuous outcrop exposure through the lower portion of the Arroyo Chijuillita Member of the Nacimiento Formation in the Bisti/De-Na-Zin Wilderness Area located in the San Juan Basin in northwestern New Mexico that spans the Puercan 2-Puercan 3 (Pu2-Pu3) North American Land Mammal Age (NALMA) transition (Figs. 1 and 2). At the study location, referred to as the Photopan Outcrop, we

reconstruct the spatial and temporal variability of paleosols and fluvial facies through the Pu2-Pu3 transition to assess the influence of extrinsic and/or intrinsic controls on depositional environments. We then examine the potential impacts these controls may have had on the faunal turnover between Pu2 and Pu3.

GEOLOGIC SETTING (2)

The San Juan Basin, located in northwestern New Mexico and southwestern Colorado, is a foreland basin that formed during the Laramide orogeny (Fig. 1; e.g., Chapin and Cather, 1983). In the western portion of the San Juan Basin, a series of badlands of upper Cretaceous through lower Eocene sediments are exposed (Figs. 1 and 2). The Paleocene Nacimiento Formation is typically underlain by the earliest Paleocene Ojo Alamo Sandstone and unconformably overlain by the early Eocene San Jose Formation. The Nacimiento Formation is divided into three members: the Arroyo Chiguillita, the Ojo Encino, and the Escavada Members (Williamson and Lucas, 1992; Fig. 1B), which are readily recognized in the field by their lithologic and sedimentologic features (Williamson and Lucas, 1992; Williamson, 1996). In the northern portion of the San Juan Basin, the Arroyo Chiguillita Member, which is the focus of this study, overlies the trough cross-bedded Ojo Alamo Sandstone, and is characterized by drab mudstones, sandy mudstones to muddy sandstones, and sparse brightly colored (red and green) paleosols (Williamson and Lucas, 1992; Williamson, 1996). This is in contrast to the overlying Ojo Encino Member, which is identified by repetitive black-red-green-white banding that is associated with bentonitic mudstones (black), variegated paleosols (red and green), and trough cross-bedded sandstones (white) (Williamson and Lucas, 1992; Williamson, 1996). The

Escavada Member is identified by a predominance of sandstones and increased proportion of silcretes, and is unconformably overlain by the Eocene San Jose Formation (Williamson and Lucas, 1992; Williamson, 1996). The contact between the Ojo Alamo Sandstone and the Nacimiento Formation is complex and variable. In most cases, the first paleosols of the Nacimiento Formation are weathered into the Ojo Alamo Sandstone indicating a conformable contact (Williamson and Lucas, 1992; Williamson, 1996). However, in some areas the contact is less distinct and may be unconformable with relatively little time missing (Williamson and Lucas, 1992; Williamson, 1996). Additionally, the contact is time-transgressive from north to south (Peppe et al., 2013). Therefore, the contact between the Ojo Alamo Sandstone and the Nacimiento Formation is considered to be conformable wherever it is encountered, unless significant incision by the Nacimiento Formation is observed. Paleomagnetic studies indicate that the entire Nacimiento Formation spans as much as ~7 myr during the early and middle Paleocene, with the middle and late Puercan (Pu2-Pu3) interval, which is found in the basal 25 m of the Arroyo Chijuillita Member at the Photopan Outcrop, being constrained to C29n (Fig. 1C) (Lindsay et al., 1978; 1981; Taylor and Butler, 1980; Butler and Lindsay, 1985; Williamson, 1996; Peppe et al., 2013).

The Nacimiento Formation has long been studied for its diverse mammalian fossil faunas and contains the type faunas for the Puercan and Torrejonian (To) NALMA (e.g., Cope, 1882a, b, c; Marsh, 1889a, b; Marsh, 1894; Wood, H.E. et al., 1941; Archibald et al., 1987; Williamson, 1996; Lofgren et al., 2004). The middle and late Puercan NALMAs in the San Juan Basin are characterized by major, and apparently abrupt, species turnover between Pu2 and Pu3 (Williamson, 1996; Lofgren et al., 2004); however, the driver(s) of the Pu2-Pu3 mammalian turnover is uncertain. Stratigraphic and paleobotanical reconstructions of early Paleocene

terrestrial ecosystems from the Williston, Bighorn, Hanna, and Denver Basins contemporaneous with this mammalian turnover suggest climate was relatively stable during this time (e.g. Hickey, 1980; Barclay et al., 2003; Dunn, 2003; Johnson et al., 2003; Wilf et al., 2003; Peppe, 2010, 2011); however, studies detailing the paleoclimatic and paleoenvironmental conditions in the early Paleocene in the San Juan Basin, which best document the Pu2-Pu3 faunal turnover, are lacking.

METHODS (3)

Measured Sections (3.1)

Six measured section transects along the relatively continuous exposures across the Photopan Outcrop are shown in Fig. 2. Measured sections 2, 3, 4 and 6 intersect five conspicuous channel sandstones, whereas measured sections 1 and 5 do not and thus constrain the sedimentologic and stratigraphic variability across equivalent interchannel areas. Data collected through each section include grain size trends, paleosol distribution and characteristics (i.e., redoximorphic features and slickensides), fluvial aggradational cycle (FAC) boundaries (*sensu* Atchley et al., 2004), and the distribution of sedimentary and biological structures. Classification within fluvial architectural elements and associated facies is after the scheme of Miall (1978; 1985). Outcrop sedimentologic, stratigraphic, and paleopedologic relationships were traced laterally to constrain the stratigraphic framework.

Paleosol Analysis (3.2)

Paleosols are categorized into seven pedotypes based on similar attributes and master and subordinate horizon designations (*sensu* Retallack, 1994; Soil Survey Staff, 1999). Each pedotype was sampled and described for texture, ped structure, color, iron redoximorphic features, and slickensides following the guidelines of Soil Survey Staff (1999). Paleosol horization and macromorphological characteristics are used under a modified version of the USDA modern soil classification for soil order designations for each pedotype (Soil Survey Staff, 1999). A maturity index is assigned to each paleosol based on its pedotype designation and associated composite B horizon thickness (Retallack, 1988; Trendell et al., 2012). Paleosol maturity is considered to be a qualitative indicator of landscape stability as increasing paleosol thickness and horization requires increased weathering time for non-cumulate soils (Retallack, 1988). These index values range from 0 (0cm of B horizon) to 4 (over 150 cm of B horizon). Paleosol color and hydromorphic features are used to evaluate paleosol drainage. Although paleosol colors are commonly considered to be at least somewhat altered as a result of diagenetic changes to iron bearing minerals (Blodgett et al., 1993; Retallack, 2001), all paleosols in the study interval have been subjected to the same diagenetic conditions. The Arroyo Chijuillita Member experienced approximately 1.5 to 2.0 km of cumulative overburden and, based on an average global geothermal gradient, temperatures up to 50 °C (Lucas and Williamson, 1992; Williamson, 1996; Cather et al., 2003). Compaction at these burial depths would have been minimal. For example, using the equation from Sheldon and Retallack (2001), measured section 3 has an uncorrected thickness of 19.6 m and a corrected thickness of 21.2 m (~8% compaction). Thus sedimentary thicknesses were not corrected for compaction. PiPujol and Buurman (1994) discuss three possible origins of red colors in paleosols (a result of Fe (III) bearing minerals)

which include inherited color from parent material, early diagenesis, and late diagenesis. Inherited parent material coloration is not a reasonable explanation, as non-red C horizons are commonly observed below reddened B horizons in paleosols at the Photopan Outcrop. Also, late diagenesis is not preferred as this process would be expected to transform all iron-bearing compounds similarly (PiPujol and Buurman, 1994). However, the variety of red paleosol coloration across the outcrop and within individual paleosols indicate variable oxidation/reduction states caused by variable drainage. As such, homogenization of paleosol coloration is expected if the original ferrous mineralogy were significantly transformed by late diagenesis. Therefore, early diagenesis, or preserved soil coloration, is the best explanation of observed paleosol colors, and paleosol color is, therefore, considered a qualitative proxy for original mineralogy resulting from differing drainage conditions. Drainage index (DI) values are determined as follows: paleosols with predominantly gleyed colors or grey chroma = 1 are considered poorly-drained (DI=1); paleosols that are predominantly gray with chroma ≤ 2 are considered moderately-drained (DI=2); and paleosols that are predominantly red with chroma > 2 are considered to be well-drained (DI=3). Paleosol maturity and drainage index values are plotted against thickness along their respective measured sections to correlate spatial and temporal trends.

Geochemical Analysis (3.3)

Bulk geochemistry data are derived from ICP-MS and ICP-AES analysis performed on A and B horizons at a commercial lab (ALS Minerals, Reno, NV). The bulk geochemistry of the paleosols is used to reconstruct mean annual precipitation (MAP) and mean annual temperature (MAT). Bulk geochemical data are provided in Appendix A.

Mean Annual Precipitation Proxies (3.3.1)

MAP was estimated using the CIA-K (V) and CALMAG geochemical proxies from Nordt and Driese (2010). These relationships rely on the concept that base forming oxides (CaO, MgO, Na₂O, and K₂O) become depleted relative to Al₂O₃ with increased weathering driven by increased rainfall (Sheldon et al., 2002; Nordt and Driese, 2010; Adams et al., 2011; Atchley et al., 2013; Trendell et al., 2013; Beverly et al., 2015). CIA-K (V) and CALMAG use oxide mole percent and are calibrated to modern Vertisol B-horizons and are, therefore, applied only to paleosols interpreted to represent this soil order. CIA-K (V) is related to base forming cations using the equation:

$$CIA - K (V) = [Al_2O_3 / (Al_2O_3 + CaO + Na_2O)] \times 100$$

The resultant index values related to MAP linearly as:

$$MAP (mm) = 18.64 (CIA - K (V)) - 350.4 (r^2 = 0.81; SE = \pm 146 mm/yr)$$

CALMAG is defined by the equation:

$$[Al_2O_3 / (Al_2O_3 + CaO + MgO)] \times 100$$

MAP is estimated using CALMAG linearly as:

$$MAP (mm) = 22.69(CALMAG) - 435.8 (r^2 = 0.90; SE = 108 mm/yr)$$

As a result of their regressions, CALMAG always gives higher MAP estimates than CIA-K (V) (Nordt and Driese, 2010).

Mean Annual Temperature Proxies (3.3.2)

Mean annual temperature (MAT) was estimated using the salinization proxy of Sheldon et al. (2002) and the Paleosol Weathering Index (PWI) of Gallagher and Sheldon (2013). The salinization proxy is designed to be applicable to most soil orders (Sheldon et al., 2002), and thus is applied to all of the soil orders represented in the Photopan Outcrop. The salinization proxy uses the relationship between temperature and the molecular ratio of Na₂O and K₂O to Al₂O₃ using the following equation:

$$MAT = -18.516 ((Na_2O + K_2O)/Al_2O_3) + 17.29 (r^2 = 0.37; SE = \pm 4.4 ^\circ C)$$

The PWI proxy is only applicable to paleo-Inceptisols, Alfisols, and Ultisols (Gallagher and Sheldon, 2013), and was only applied to paleo-Inceptisols at the Photopan Outcrop as no paleosols observed at the Photopan Outcrop are interpreted to be paleo-Alfisols or Ultisols. The Paleosol Weathering Index is defined as:

$$PWI = 100 \times [(4.2 \times Na_2O) + (1.66 \times MgO) + (5.54 \times K_2O) + (2.05 \times CaO)]$$

Where the molar ratio of oxide-based elements are used in the calculations; MAT is then calculated as:

$$MAT = -2.74 \times \ln (PWI) + 21.39 (r^2 = 0.57; SE = \pm 2.1 ^\circ C)$$

Grain Size Analysis (3.4)

Several samples from each FAC in measured section 1 (Figs. 2 and 3) were mechanically (shaker table and sonic probe) and chemically (sodium hexametaphosphate) disaggregated. The samples were quantitatively analyzed for grain size using a Malvern Instruments Mastersizer

2000 with a Hydro 2000MU attachment and the associated Mastersizer 2000 software. Measured section 1 is used for grain size analysis because it has no channel sandstone truncating FACs, does not have covered section, and, therefore, has the most continuous sedimentary record.

Point Count Analysis (3.5)

Thin sections from samples collected at the base, middle and top of prominent channel sandstones from measured sections 2, 3, 4, and 6 (Figs. 2, 3, 4, and 5) were point counted to determine major grain constituents. Each sample had a single ~ 400 point count performed using a PELCON Automatic Point Counter and associated software. The analyzed channel sands from measured sections 2, 3, and 4 are from the same stratigraphic interval. The channel sandstone from measured section 6 is from stratigraphically higher in the section, and is thus younger than the other samples (Fig. 2). Normalized proportions of quartz, feldspar, and lithic fragments from the point count data are plotted on ternary diagrams to determine compositional classifications (McBride, 1963) and possible sediment provenance regimes (Dickinson and Suczek, 1979). Total quartz (monocrystalline, polycrystalline, and chert) is used for QFL plots. Additionally, total feldspar modal percentages used in the QFL plots include feldspars interpreted to be replaced by clay where sericitization or intact kaolinite books are observed within or associated with feldspar grains.

RESULTS (4)

Depositional Facies (4.1)

The Photopan Outcrop consists of interbedded mudrocks, siltstones and sandstones that include four depositional facies (*sensu* Miall, 1978 and 1985) identified on the basis of grain size (lithology) and mechanical and biological structures. Facies descriptions are provided in Table 1 and distributions are provided in Figs. 3 and 4 with representative photographs of facies shown in Fig. 5. Thin (≤ 50 cm), silicified horizons, referred to as silcretes, are observed in the section, but the origin of these silica rich, highly indurated, thin sediments is not well understood (Rains, 1981; Williamson et al., 1992). Generally, given the volcanic activity across the Western Interior of North America during the Late Cretaceous and early Paleocene (*sensu* Dickenson et al., 1988), silicified horizons are thought to be devitrified and variably reworked volcanic ashes. Eight to fourteen complete or partial fluvial aggradational cycles (FACs; *sensu* Atchley et al., 2004, 2013a) are observed in measured sections across the Photopan Outcrop (Figs. 3 and 4). Several of these cycles are traceable across the outcrop; however, discontinuous cycles are also common. To simplify nomenclature, only FACs from measured section 1 are numbered (Figs. 3 and 4). Surfaces pertinent to the interpretation of landscape evolution are shown in bold and labeled A-C, and other spatial correlations of FACs are designated by grey lines (Figs. 3 and 4).

Pedogenically altered sediments are divided into proximal and distal floodplain on the basis of associated paleosol order. Paleo-Vertisols are considered to represent a relatively distal floodplain position (Fp) due to increased maturity and complete or near complete destruction of depositional bedforms via pedogenesis (Table 1 and Fig. 5A). These features suggest relatively long periods of non-deposition and landscape stability. Paleo-Inceptisols and Entisols have relatively little pedogenic alteration and abundant depositional bedforms and are considered

characteristic of the proximal floodplain (Fh; Table 1 and Fig. 5B). Sand facies are found in two overall forms, lenticular shaped channel fills (Sl; Table 1 and Fig. 5C) and laterally continuous proximal overbank deposits (Sm; Table 1 and Fig. 5D).

Paleosols (4.2)

Representative examples of pedotype profiles including maturity, drainage and outcrop character are summarized in Fig. 6, and detailed descriptions of pedotypes are provided in Appendix B. Subsurface horizons are restricted to Bss, Bssg, Bw, Bwg, C, and Cg horizons with no observed pedogenic and only minor diagenetic carbonate on ped surfaces. Gleyed horizons are identified by the presence of gleyed colors in the matrix or root traces (halos) (Appendix B). Common hand specimen macroscopic features are shown in Fig. 7. The most common features include ped structure, backfilled burrows, slickensides and redoximorphic features including drab or oxidized root halos (Fig. 7). Ped structure varies widely in degree of development, size, and shape including large wedge-shaped peds and small angular platy peds. Slickensides (Fig. 7B) are common and range from large-scale master surfaces to minor and/or incipient surfaces. Root traces are observed in two dominant forms: (1) fine (mm to sub-mm thick), mat-like roots creating a “brecciated” appearance (Fig. 7G) and (2) thicker (cm), less densely rooted areas with downward bifurcation (Fig. 7C and D). Additional redoximorphic features include Fe-nodules and areas of Fe-depletion and/or concentration (Fig. 7C, G, and F). Burrows are most commonly filled with drab clay or sand in a drab matrix (Fig. 7A). Fig. 7E shows the bedding indicative of a C horizon with variegated overprinting. The paleosols in the Photopan Outcrop tend to have an inverse relationship between maturity and drainage (Figs. 3 and 6).

Paleoclimatic Reconstruction (4.3)

MAP estimates from CALMAG and CIA-K (V) give outcrop averages of 1372 (SE = ± 108) and 1150 (SE = ± 146) mm/yr, respectively, with no significant deviations observed throughout the study interval (Table 2, Fig. 4, and Appendix C). MAT estimates from the salinization and PWI proxies give outcrop averages of 11.5 (SE = ± 4.4) and 12.0 (SE = ± 2.1) °C respectively, with no significant deviations observed (Table 2, Fig. 4, and Appendix C).

Grain Size Analysis (4.4)

Sand/clay ratios from the quantitative grain size analysis of measured section 1 are shown in Fig. 8 along with superimposed facies distributions. Measured section 1 has an average sand/clay ratio of 0.37 with three abrupt positive excursions from the average that are coincident with Sm facies. Overall, higher sand/clay ratios align with facies interpreted to have been deposited proximal to the local channel (Sm, Sl, and Fh) and lower sand/clay ratios tend to align with facies (Fp) interpreted to be deposited distal to the local channel. This suggests an agreement between facies interpretations and grain size analysis, as proximal facies are expected to be coarser grained (Fig. 8).

Point Count Analysis (4.5)

All sandstones include feldspar grains (ranging from unweathered to heavily weathered or completely replaced), volcanic rock fragments, quartz with abraded overgrowths, and hexagonal quartz (Fig. 9). All sandstone compositions and interpreted provenance, except one, classify as lithic arkose originating from a dissected arc (Fig. 10). The one exception in composition and origin is from the top of the channel sandstone in measured section 6 (sample 06C6-3), which is classified as a lithic subarkose derived from a recycled orogen (Fig. 10). The

difference in this single sample is either a result of an actual increase in quartz percentage or misidentification of untwinned feldspar as monocrystalline quartz. In addition to the different composition, the sample is the most fine grained and has the highest matrix proportion. Due to the considerable differences between 06C6-3 and the 11 other samples, sample 06C6-3 is treated as a trend outlier and was not considered when making interpretations about possible changes in sandstone composition.

DISCUSSION (5)

Paleoclimate (5.1)

The preponderance of paleo-Vertisols in the Photopan Outcrop with conspicuous slickensides indicates that precipitation was seasonal such that during the dry season precipitation was low enough to allow desiccation of the soil profile. MAP estimates from CALMAG and CIA-K (V) are relatively consistent and neither proxy show temporal variability; however, the CIA-K (V) estimates are consistently lower than the CALMAG estimates (Figs. 4 and 11; Table 2). The CALMAG MAP estimates are in general agreement with a MAP of 1813 mm/yr (+1524/-828 mm/yr) estimated using fossil leaves from the underlying Ojo Alamo Sandstone (Fig. 11; Flynn et al., 2014). Although they are not from the same deposits as the Photopan Outcrop, the Ojo Alamo floras are at most a few hundred thousand years older (Flynn et al., 2014). Paleoclimate estimates for the earliest Paleocene across North America indicate that climate was relatively stable (e.g., Hickey, 1980; Barclay, 2003; Dunn, 2003; Johnson et al., 2003; Wilf et al., 2003; Peppe, 2010, 2011). This suggests that the paleoclimate estimates from the Ojo Alamo floras (Flynn et al., 2014) are likely representative of climate in the San Juan

Basin during the earliest Paleocene, and thus are useful for comparison with the paleosol estimates from the Photopan Outcrop. Given the similarities between the CALMAG and paleobotanical MAP estimates, the abundance of paleo-Vertisols across the Photopan Outcrop, and a higher r^2 and lower standard error of the CALMAG proxy, we interpret the CIA-K (V) estimates to be underestimates of MAP and the CALMAG MAP estimates to be the most reasonable paleosol-derived values. Interestingly, the CALMAG MAP estimates from the Photopan Outcrop are very similar to paleobotanical MAP estimates from fossil floras found in C29r in the nearby Denver Basin (avg. 1550 mm/yr; Barclay et al., 2003), suggesting that precipitation may have also have been similar regionally.

MAT estimates from both salinization (avg. 11.5 ± 4.4 °C) and PWI (avg. 12.0 ± 2.1 °C) show no change through time (Figs. 4; Table 2). These temperatures are similar to paleobotanical estimates (10.25 ± 2.97 °C) from the Williston Basin, located 1600 km north of the San Juan Basin (Peppe, 2010), and to high latitude, deep ocean temperatures (Zachos et al., 2001). Additionally, the occurrence of crocodiles (Williamson, 1996) and fossil palms (Flynn et al., 2014; Peppe et al., 2015) in the Arroyo Chijuillita Member indicate a minimum MAT of >14 °C (Marwick, 1998) and winter temperatures above freezing (Larcher and Winter, 1981; Sakai and Larcher, 1987; Wing and Greenwood, 1993), respectively. Thus, we consider the paleosol MAT estimates to be significant underestimations of actual MAT. Temperature estimates from floras found in the underlying Ojo Alamo Sandstone of $19.0 (\pm 3.0)$ °C (Flynn et al., 2014) are similar to paleobotanical estimates of $18.6 (\pm 2.6)$ °C from the Denver Basin (550 km north) (Barclay et al., 2003). Given that these MAT estimates from the Ojo Alamo Sandstone are in better agreement with the fossil vertebrate and floral evidence from the Arroyo Chijuillita Member, we consider the MAT estimates from the Ojo Alamo floras to be reasonable approximations of

MAT. Although the paleosol MAT estimates are considerable underestimates (~7-8 °C too low), the trend, which shows no change in MAT through the Photopan Outcrop, is likely accurate. The consistency of MAT and MAP estimates through the Puercan in the San Juan Basin is in agreement with other studies of contemporaneous sediments (e.g., Hickey, 1980; Barclay et al., 2003; Johnson et al., 2003; Dunn, 2003; Wilf et al., 2003; Peppe et al., 2010, 2011), and indicates that there is little evidence for climate change through the Puercan across the Western Interior of North America.

Landscape Evolution (5.2)

Climate is stable through the Pu2-Pu3 transition, thus climate change cannot explain the facies and paleosol variability observed at the Photopan Outcrop. Alternative explanations for facies and pedotype distributions are regional tectonism and/or local autocyclic channel migration (e.g. Kraus, 1987, 1999, 2002; Paola et al., 1992; Kraus and Aslan, 1993; Atchley et al., 2004, 2013a, 2013b; Cleveland et al., 2007; Miall, 2010). If tectonism was a significant mechanism for depositional cyclicity, then the system likely experienced two episodes of subsidence: one before surface A and one before surface C (Figs. 3, 4 and 8). In this model, the coarsening observed following surface A would have been caused by a decrease in subsidence and the subsequent progradation and infill of the accommodation space between surfaces A and B (e.g. Paola et al., 1992). The deposition of fine-grained (silt and clay) material above surface B would indicate renewed subsidence, as coarser sediment would have been deposited proximal to the uplift (e.g. Paola et al., 1992). The trend of sediment coarsening above surface C, would have been the result of a second period of progradation and infill of accommodation space. In this interpretation, assuming relatively continuous sedimentation, the trends of coarsening and fining

would be expected to be relatively gradational. Based on our observations at the Photopan Outcrop and interpretations of regional geology, we do not favor this interpretation for four main reasons. (1) It is not supported by interpretations of the subsidence and depositional history of the Nacimiento Formation. Cather (2004) documented a three-phase subsidence history of the San Juan Basin through the Cretaceous-Eocene. The second subsidence phase (~74-67 Ma) is the period responsible for the subsequent deposition of the Nacimiento Formation. However, this period of accommodation gain ended over 1 myr before the onset of the deposition of the Nacimiento Formation. Therefore, latent tectonic pulsing influencing deposition at this time is unlikely to have influenced the sedimentologic variability observed at the Photopan Outcrop. (2) Sedimentation rates (Williamson, 1996) indicate that the Photopan Outcrop exposures only represents ~200-400 kyr. As such, if the changes in depositional environments were tectonically driven, any tectonic influence of sedimentation would have to be have been very rapid and recurring, which is unlikely. (3) There is no sedimentological or mineralogical evidence for tectonism during deposition of the Photopan Outcrop. The sediments show abrupt rather than gradual changes in grain size between major surfaces (A, B, and C). (4) The results of point count analyses on channel sandstones do not indicate changes in sediment sources through the section (Figs. 9 and 10), which would be expected if the second tectonic pulse activated a new, or reactivated an old, sediment source.

While abrupt sedimentologic transitions (i.e. shorter timescales than fluvial equilibrium time) and consistent sandstone composition argue against tectonism as the driver for the cyclic sedimentation observed at the Photopan Outcrop, these observations are consistent with autocyclic fluvial processes (Kraus, 1987, 1999; Bown and Kraus, 1987; Wright and Marriot, 1993). In this interpretation, surfaces A-C demarcate significant avulsion events, and the

differences in pedotypes are a function of channel proximity (Figs. 3 and 8). This autocyclically driven evolution of the sediments at the Photopan Outcrop is summarized in Fig. 8, with interpreted channel positions plotted along the measured section 1 transect. Under this model, significant avulsion events at surfaces A, B, and C each resulted in the repositioning of the local channel to relatively proximal or distal positions. Positive excursions of sand/clay ratios, indicating a short-lived increase in grain size, generally coincide with surfaces A, B, and C, supporting our interpretation that these surfaces mark avulsion events.

Paleosols associated with distal channel positions (base-A, and between B-C surfaces) are relatively fine-grained, poorly-drained, and well-developed (Fig. 8). They are interpreted to have been deposited in topographic lows relative to the channel levee, and therefore closer to the water table. Additionally, being distal to the local channel, these relatively poorly-drained soils are interpreted to have formed in association with lower sedimentation rates allowing them to become relatively well-developed as pedogenesis would have rarely been interrupted. Although the soils forming distal to the channel are poorly-drained, they typically have pervasive slickensides indicating regular desiccation. So, while these paleosols are relatively poorly-drained, they could not have formed under continually saturated and hydromorphic conditions (Retallack, 1988; Soil Survey Staff, 1999).

Paleosols forming proximal to the local channel (between surfaces A-B and above C) are relatively coarse-grained, well-drained, and poorly-developed. Sedimentologic evidence indicating a proximal channel position include the lenticular channels, scours, and lateral accretion deposits between surfaces A and B (Figs. 2, 3, 4, and 8). As a result, these paleosols are interpreted to have developed atop channel levees in topographically high positions. In this environment the soil profile is raised above the water table aiding in soil drainage; however,

regular sedimentation interrupts pedogenesis resulting in a coarser grain size and poor soil development.

Interestingly, in addition to the relatively abrupt increases in grain size that occur at surfaces A, B, and C, there is also a general upward coarsening trend in the Photopan Outcrop deposits (Fig. 8). This coarsening trend may indicate long-term progradation of the main fluvial system into the San Juan Basin as it infilled the accommodation gained from the late Cretaceous phase of tectonism described in Cather (2004). More broadly, there is a general coarsening upward trend through the Nacimiento demonstrated by an increase in sandstone (~20-58%) and decreases in mudstone proportions (~49-31%) up section (Williamson, 1996). This suggests that there was probably little, if any, renewed subsidence in the San Juan Basin during the early Paleocene and that, to at least some extent, deposition of the Nacimiento Formation is the result of sediment infill via progradation into the basin.

Implications for mammalian turnover (5.3)

Throughout Pu2 and across the Pu2-Pu3 transition, our data indicates that climate was stable and the basin was likely in an interval of relative tectonic quiescence. As such, neither climate nor regional tectonism are plausible drivers for turnover documented across the Pu2-Pu3 transition. Autocyclic processes that affected deposition of the Photopan Outcrop succession were ongoing throughout the entire Pu2-Pu3 interval and were likely only locally significant. Autocyclicity, therefore, is also unlikely to have influenced mammalian evolution and turnover. Therefore, we suggest that the Pu2-Pu3 transition in the mammalian faunas was most likely driven by intrinsic processes related to the mammalian communities, such as rapid evolution and

speciation following the K-Pg boundary, or competition related to the migration of mammalian taxa into and out of the San Juan Basin (see Williamson, 1996; Lofgren et al., 2004).

SUMMARY (6)

MAP and MAT estimates indicate that climate was warm and relatively wet (Fig. 11), and vertic features in the paleosols throughout the section indicate that precipitation was seasonal. MAP and MAT estimates from geochemical proxies (this study) and paleobotanical analyses (Flynn et al., 20014) indicate that climate was relatively stable in the San Juan Basin during the middle Puercan (Figs. 4 and 11). These results are consistent with paleobotanical and stratigraphic studies in roughly contemporaneous sediments from the Denver, Williston, Bighorn and Hanna Basins, which also document climate stability through the same interval (Hickey, 1980; Barclay et al., 2003; Johnson et al., 2003, Dunn, 2003; Wilf et al., 2003; Peppe, 2010, Peppe et al., 2011). As such, we conclude that climate was relatively stable during the early Paleocene, and is therefore unlikely to have significantly impacted biologic turnover in the San Juan Basin during this time.

Although there is some evidence to suggest that long term trends in deposition of the Nacimiento Formation may be driven by sediment infilling accommodation space gained by subsidence in the early Cretaceous, the sedimentologic changes observed at the Photopan Outcrop are unlikely to have been caused by regional tectonics. Instead, changes in depositional environments at the Photopan Outcrop were driven by autocyclic fluvial channel migration across the landscape. In particular, the Photopan Outcrop documents three major channel avulsion events coinciding with conspicuous facies and paleosol changes as a result of channel

proximity. Because climate was relatively stable and the Photopan Outcrop samples an interval of tectonic quiescence, the Pu2-Pu3 faunal turnover is unlikely to have been driven by climate and tectonic change. Instead, the mammalian turnover is most likely related to intrinsic biologic factors, such as rapid evolution following the K-Pg boundary or competition from new mammalian species dispersing into the basin.

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Appendix A (6.1)

Geochemical data used in the calculation of estimates provided in Appendix C. All oxide % are calculated with standard conversion factors.

SAMPLE	Soil Order	Al	Al	Ca	Ca	K	K	Mg	Mg	Na	Na
DESCRIPTION	paleo-	oxide %	oxide mol ratio	oxide %	oxide mol ratio	oxide %	oxide mol ratio	oxide %	oxide mol ratio	oxide %	oxide mol ratio
AD14_1_1	Vertisol	16.06	0.16	0.80	0.01	1.35	0.01	0.93	0.02	1.29	0.02
AD14_1_3	Vertisol	14.72	0.14	0.62	0.01	0.61	0.01	0.71	0.02	0.97	0.02
AD14_1_5	Inceptisol	17.35	0.17	0.49	0.01	2.51	0.03	0.85	0.02	1.36	0.02
AD14_1_7	Vertisol	17.46	0.17	0.64	0.01	0.78	0.01	0.66	0.02	1.23	0.02
AD14_1_8	Vertisol	15.68	0.15	0.77	0.01	2.17	0.02	1.21	0.03	1.66	0.03
AD14_1_10	Vertisol	14.62	0.14	0.76	0.01	1.95	0.02	1.16	0.03	1.71	0.03
AD14_1_11	Inceptisol	15.25	0.15	0.64	0.01	1.64	0.02	1.04	0.03	1.68	0.03
AD14_1_12	Vertisol	14.78	0.14	0.73	0.01	1.66	0.02	1.13	0.03	1.75	0.03
AD14_1_14	Vertisol	11.81	0.12	0.53	0.01	1.89	0.02	0.60	0.01	1.60	0.03
AD14_1_15	Entisol	14.36	0.14	0.77	0.01	2.22	0.02	1.28	0.03	1.97	0.03
AD14_2_1	Vertisol	14.85	0.15	0.73	0.01	1.75	0.02	0.99	0.02	1.60	0.03
AD14_2_3	Vertisol	13.98	0.14	0.63	0.01	0.94	0.01	0.56	0.01	1.29	0.02
AD14_2_6	Vertisol	14.78	0.14	0.84	0.01	2.16	0.02	1.04	0.03	1.97	0.03
AD14_2_8	Vertisol	15.49	0.15	0.77	0.01	1.99	0.02	1.31	0.03	1.75	0.03
AD14_2_9	Vertisol	15.46	0.15	0.74	0.01	1.31	0.01	0.86	0.02	1.77	0.03
AD14_2/4_1	Vertisol	19.37	0.19	0.77	0.01	0.31	0.00	0.75	0.02	1.19	0.02
AD14_2/4_3	Vertisol	17.19	0.17	0.81	0.01	1.34	0.01	0.91	0.02	1.28	0.02
AD14_2/4_7	Vertisol	17.44	0.17	0.69	0.01	0.80	0.01	0.81	0.02	1.20	0.02
AD14_2/4_9	Inceptisol	16.93	0.17	0.45	0.01	2.65	0.03	0.85	0.02	1.50	0.02
AD14_2/4_10	Inceptisol	17.50	0.17	0.52	0.01	2.47	0.03	0.90	0.02	1.29	0.02

AD14_3_1	Vertisol	15.91	0.16	0.57	0.01	0.64	0.01	0.71	0.02	1.02	0.02
AD14_3_2	Inceptisol	16.42	0.16	0.48	0.01	2.51	0.03	0.83	0.02	1.44	0.02
AD14_3_4	Vertisol	15.19	0.15	0.76	0.01	1.72	0.02	1.14	0.03	1.66	0.03
AD14_3_6	Vertisol	14.93	0.15	0.78	0.01	1.99	0.02	1.26	0.03	1.60	0.03
AD14_3_8	Vertisol	15.49	0.15	0.71	0.01	1.57	0.02	1.11	0.03	1.73	0.03
AD14_3_9	Vertisol	14.42	0.14	0.66	0.01	1.05	0.01	0.90	0.02	1.23	0.02
AD14_4_1	Vertisol	15.34	0.15	0.78	0.01	2.28	0.02	1.21	0.03	1.71	0.03
AD14_4_4	Vertisol	15.78	0.15	0.85	0.02	2.16	0.02	1.23	0.03	1.95	0.03
AD14_4_6	Inceptisol	14.17	0.14	0.66	0.01	2.37	0.03	1.18	0.03	1.77	0.03
AD14_4_8	Entisol	14.87	0.15	0.88	0.02	2.13	0.02	1.06	0.03	2.25	0.04
AD14_5_1	Vertisol	15.00	0.15	0.74	0.01	0.65	0.01	0.60	0.01	1.43	0.02
AD14_5_3	Vertisol	15.12	0.15	0.83	0.01	2.12	0.02	1.26	0.03	1.71	0.03
AD14_5_4	Vertisol	14.66	0.14	0.92	0.02	2.23	0.02	1.13	0.03	2.16	0.03
AD14_5_5	Vertisol	15.74	0.15	0.81	0.01	2.07	0.02	0.88	0.02	2.37	0.04
AD14_5_5.1	Inceptisol	14.51	0.14	0.73	0.01	1.51	0.02	1.26	0.03	1.58	0.03
AD14_5_6	Vertisol	15.81	0.16	0.60	0.01	0.58	0.01	0.66	0.02	1.44	0.02
AD14_5_7	Vertisol	14.51	0.14	0.70	0.01	2.07	0.02	1.41	0.03	1.75	0.03
AD14_6_1	Entisol	15.85	0.16	0.52	0.01	2.83	0.03	0.90	0.02	2.18	0.04
AD14_6_2.1	Inceptisol	15.42	0.15	0.52	0.01	2.72	0.03	0.85	0.02	2.04	0.03
AD14_6_2.6	Inceptisol	14.96	0.15	0.62	0.01	2.54	0.03	0.80	0.02	2.26	0.04
AD14_6_3	Vertisol	15.46	0.15	0.81	0.01	2.14	0.02	1.58	0.04	1.86	0.03
AD14_6_4.1	Vertisol	15.76	0.15	0.77	0.01	1.98	0.02	1.43	0.04	1.79	0.03
AD14_6_5	Entisol	14.53	0.14	0.77	0.01	2.29	0.02	1.31	0.03	1.78	0.03
AD14_6_6	Vertisol	14.40	0.14	0.87	0.02	2.20	0.02	1.08	0.03	2.28	0.04
AD14_6_7	Vertisol	15.51	0.15	1.04	0.02	2.13	0.02	1.08	0.03	2.41	0.04
AD14_6_8	Vertisol	15.51	0.15	0.85	0.02	1.82	0.02	1.18	0.03	2.01	0.03
AD14_6_2.3	Inceptisol	16.74	0.16	0.59	0.01	2.78	0.03	1.01	0.03	2.12	0.03

Appendix B (6.2)

Description of pedotypes found in Photopan Outcrop. Abbreviations M and D in Pedotype # column refer to pedotype maturity and drainage respectively.

Pedotype 1 (M=0; D=3)	Horizon	Depth (cm)	Colors	Structure*	Texture	Slicks†	Fe-features	Biologic	Sed-Structures
	A/Bg	0-45	7.5R 4/3 (75%; matrix); Gley1 8/10GY (25%; root halos)	1m	sandy siltstone	-	-	Clay infilled drab root halos	-
	C	45-70	5Y 8/1	0	sandy siltstone	-	-	-	Laminations
Pedotype 2 (M=2; D=3)	Horizon	Depth (cm)	Colors	Structure*	Texture	Slicks†	Fe-features	Biologic	Sed-Structures
	Bssg1	0-40	10R 4/3 (60%; matrix); Gley1 7/5GY (40%; root halos)	3mabk	silty mudstone	mp	-	-	-
	Bssg2	40-75	5R 4/3 (60%; matrix); Gley1 6/10Y (40%; root halos)	3m-cabk	mudstone	mp	-	-	-
	Cg	75-95	5R 5/2 (50%); Gley1 7/10Y (50%)	0	siltstone	-	-	-	Conspicuous red and green laminations (stratigraphic datum)
Pedotype 3 (M=1; D=3)	Horizon	Depth (cm)	Colors	Structure*	Texture	Slicks†	Fe-features	Biologic	Sed-Structures
	A/Bg	0-40	5YR 4/6 (60%; matrix); Gley1 7/5GY (40%; root halos)	1csbk	mudstone	-	Fe-oxide concentrations	Fine drab root halos	-
	B/Cg	40-60	Gley1 7/5GY (75%; matrix); 5YR 5/6 (25%; redoximorphic features)	1msabk	silty sandstone	-	Fe-oxide nodules	-	-
Pedotype 4 (M=4; D=1)	Horizon	Depth (cm)	Colors	Structure*	Texture	Slicks†	Fe-features	Biologic	Sed-Structures
	Bss1	0-25	2.5Y 5/1	3mabk	siltstone	ff	-	-	-

	Bss2	25-80	2.5Y 2.5/1	2m-csbk	silty mudstone	cd	-	-	-
	Bss3	80-125	2.5Y 3/1	3mabk	mudstone	cp	-	-	-
	Bss4	125-230	2.5Y 6/1	2m-cabk	mudstone	cp	-	-	-
	Bss5	230-270	2.5Y 5/1	3cwe	silty mudstone	cp	-	-	-
	Bw	270-290	2.5Y 6/1	2cabk	silty mudstone	-	-	-	-
Pedotype 5 (M=3; D=2)	Horizon	Depth (cm)	Colors	Structure*	Texture	Slicks†	Fe-features	Biologic	Sed-Structures
	Bss1	0-25	5Y 6/2	1mabk-pl	sandy siltstone	ff	-	-	-
	Bw	25-45	5Y 7/2 (~3% 5R 4/2 oxidized root/burrows)	1cabk	sandy siltstone to vf sandstone	-	Oxidized root and/or burrows	-	-
	Bss2	45-65	2.5Y 5/1	2mabk	sandy mudstone	cp	-	-	-
	Bssg	65-100	5R 7/1 (50%); Gley1 7/10Y (50%)	2mbk	sandy mudstone	cd	-	Mottling of colors	-
	C	100-220		0	f-vf sandstone	-	-	-	Upward fining, sheet like
Pedotype 6 (M=3; D=1)	Horizon	Depth (cm)	Colors	Structure*	Texture	Slicks†	Fe-features	Biologic	Sed-Structures
	Bssg	0-30	Gley1 6/10Y (90%; matrix); 5R 4/4 (10%)	2cabk	mudstone	cd	Fe-oxide concentrations	-	-
	Bw	30-65	5YR 6/1	2c-vcsbk	sandy siltstone	-	-	-	-
	Bss	65-145	10YR 4/1	3m-cabk	sandy siltstone	cd	-	-	-
Pedotype 7 (M=0; D=2)	Horizon	Depth (cm)	Colors	Structure*	Texture	Slicks†	Fe-features	Biologic	Sed-Structures

A/Cg	0-50	Verigated red (7.5R 3/4) to purple (5R 5/1) with drab root halo overprinting (Gley1 7/10Y to Gley1 7/5GY)	0	vf sandstone to sandy siltstone	-	Fe-oxide concentrations	Drab root halos increasing up profile	Thin bedding
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* 0-structureless, 1-weak, 2-moderate, 3-strong grade; m-medium, c-coarse, vc-very coarse; sbk-subangular blocky, abk-angular blocky, we-wedge, pl-platy, m-massive type

† f-few, c-common, m-many abundance; f-faint, d-distinct, p-prominent

Appendix C (6.3)

All paleoclimate estimates from paleosols in Photopan Outcrop.

SAMPLE	Soil Order	MAP-CALMAG	CIA-K (V)	Salinization	PWI
DESCRIPTION	paleo-	MAP	MAP	MAT	MAT
AD14_1_1	Vertisol	1399	1174	13.2	-
AD14_1_3	Vertisol	1457	1223	14.4	-
AD14_1_5	Inceptisol	-	-	12.0	12.1
AD14_1_7	Vertisol	1515	1226	14.3	-
AD14_1_8	Vertisol	1331	1125	11.3	-
AD14_1_10	Vertisol	1317	1098	11.0	-
AD14_1_11	Inceptisol	-	-	11.8	12.3
AD14_1_12	Vertisol	1333	1101	11.4	-
AD14_1_14	Vertisol	1440	1078	9.9	-
AD14_1_15	Entisol	-	-	10.0	-
AD14_2_1	Vertisol	1367	1232	11.6	-
AD14_2_3	Vertisol	1481	1267	13.1	-
AD14_2_6	Vertisol	1334	1179	10.3	-
AD14_2_8	Vertisol	1304	1221	11.3	-
AD14_2_9	Vertisol	1411	1219	12.1	-
AD14_2/4_1	Vertisol	1504	1343	15.1	-
AD14_2/4_3	Vertisol	1424	1310	13.5	-
AD14_2/4_7	Vertisol	1472	1324	14.3	-
AD14_2/4_9	Inceptisol	-	-	11.5	12.0
AD14_2/4_10	Inceptisol	-	-	12.2	12.2
AD14_3_1	Vertisol	1489	1241	14.5	-
AD14_3_2	Inceptisol	-	-	11.6	12.1
AD14_3_4	Vertisol	1336	1117	11.7	-
AD14_3_6	Vertisol	1298	1115	11.3	-
AD14_3_8	Vertisol	1358	1121	11.9	-
AD14_3_9	Vertisol	1394	1174	13.2	-
AD14_4_1	Vertisol	1320	1110	10.9	-
AD14_4_4	Vertisol	1316	1081	10.8	-
AD14_4_6	Inceptisol	-	-	10.1	11.8
AD14_4_8	Entisol	-	-	9.8	-
AD14_5_1	Vertisol	1470	1145	13.5	-
AD14_5_3	Vertisol	1296	1099	11.0	-
AD14_5_4	Vertisol	1297	1024	9.8	-

AD14_5_5	Vertisol	1401	1039	10.1	-
AD14_5_5.1	Inceptisol	-	-	11.9	12.3
AD14_5_6	Vertisol	1495	1178	13.8	-
AD14_5_7	Vertisol	1266	1099	10.7	-
AD14_6_1	Entisol	-	-	9.5	-
AD14_6_2.1	Inceptisol	-	-	9.7	11.6
AD14_6_2.6	Inceptisol	-	-	9.3	11.6
AD14_6_3	Vertisol	1241	1091	10.8	-
AD14_6_4.1	Vertisol	1286	1110	11.3	-
AD14_6_5	Entisol	-	-	10.4	-
AD14_6_6	Vertisol	1311	1010	9.4	-
AD14_6_7	Vertisol	1313	1003	9.8	-
AD14_6_8	Vertisol	1320	1069	11.0	-
AD14_6_2.3	Inceptisol	-	-	10.1	11.5
Average		1373	1150	11.5	12.0

Figure 1: A) Geologic map of the San Juan Basin showing Cretaceous-Eocene sediments (modified from Williamson et al., 2008). Bisti/De-Na-Zin Wilderness Area is shown outlined in red and the Photopan Outcrop is designated by a yellow circle. B) Late Cretaceous and early Paleocene stratigraphy (Williamson, 1996) and chronologic constraint in the San Juan Basin (Butler and Lindsay, 1985; Ogg, 2012; Peppe et al., 2013, 2015). Geomagnetic Polar Time Scales (GPTS) after Ogg (2012). North American Land Mammal Ages (NALMA) from Lofgren et al. (2004). Mammal biozones specific to the San Juan basin after Williamson (1996). Interval of study is bracketed in red.

Figure 2: A) Panoramic photograph of Photopan Outcrop (Arroyo Chijuillita Member) from north to west. B) Northern portion of Photopan Outcrop (Z to Z'). Red lines indicate measured section transects. Yellow inset box shows outcrop placement of (D) and (E). C) Western portion of Photopan Outcrop (Z' to Z''). Red lines indicate measured section transects. D) Unannotated photograph of yellow inset box from (B). E) Annotated photograph of yellow inset box from (B). Yellow lines show scour surfaces and lateral accretion deposits.

Figure 3: Stratigraphic and paleopedologic information from northern measured sections at Photopan Outcrop (Figure 2). Western measured sections are shown in Figure 3, con't below. Stratigraphic framework is constructed by correlating fluvial aggradational cycles (FAC) between measured sections (grey lines). A conspicuous red and green laminated bed found in each measured section is used as the datum. Facies and associated architectural elements are determined by sediment character and structures following Miall (1978; 1985). Complete facies descriptions are provided in Table 1. Pedotype maturity (MI) is based on composite B horizon thickness and paleosol drainage (DI) and is related to paleosol color. Bold horizons labeled A-C are interpreted to be surfaces (FAC boundaries or correlative surface) showing distal-proximal shifts in channel position. These are also shown in Figure 4 and are related to quantitative grain size data in Figure 8. Second panel of Figure 3 with measured sections 1, 5, and 6 follows the same layout and uses the same acronyms.

Figure 3 con't: Western portion of Photopan Outcrop (Figure 2) showing stratigraphic and paleopedologic data continued from Figure 3 above. Fluvial aggradational cycles (FAC) are numbered in measured section 1 for reference in discussion and in Figure 8 below.

Figure 4: Mean annual temperature (MAT) and mean annual precipitation (MAP) estimates from geochemical proxies shown alongside stratigraphic and paleopedologic information and facies distributions from Figure 3. CALMAG (Nordt and Driese, 2010) is applied only to paleo-Vertisols, PWI (Gallagher and Sheldon, 2013) is only applied to paleo-Inceptisols, and the salinization (Sheldon et al., 2002) is applied to all paleosols (paleo-Vertisols, Inceptisols, and Entisols). Ranges of paleosol geochemical proxy estimates are given in Table 2. As in Figure 3, bold horizons labeled A-C are interpreted to be surfaces showing distal-proximal shifts in channel position. Second panel of Figure 4 with measured sections 1, 5, and 6 follows the same layout and uses the same acronyms.

Figure 4 con't: Western portion of Photopan Outcrop (Figure 2) showing MAT and MAP estimates continued from Figure 4 above. As in Figure 3 panel 2, fluvial aggradational cycles (FAC) are numbered in measured section 1 for reference in discussion and in Figure 8 below.

Figure 5: Outcrop examples of each facies from Table 1 and Figure 3. A) Pedotype 1 (Fp facies) from measured section 4. B) Fh facies in measured section 6. C) SI facies from measured sections 3 and 2. D) Laterally continuous Sm facies from top of measured section 3. Example of massive sand is provided in inset image.

Figure 6: Diagrammatic profiles of pedotypes identified in Photopan Outcrop. Maturity index values 0-4 are based on composite thickness of B horizons (Retallack, 1988; Trendell et al., 2012) with higher values indicating more mature profiles. Drainage index values 1-3 are based on paleosol color with more red and higher chroma colors indicating better drainage (Retallack, 2001). Horizon designations are given to the right of each profile. Detailed pedotype descriptions are provided in Appendix B.

Figure 7: Photographs of paleosol hand samples showing prominent pedologic features. A) Clay infilled burrow from pedotype 5 outlined in black. B) Well-developed slickensides from pedotype 2. C) Oxidized halo around drab root trace from pedotype 2. D) Downward bifurcating clay filled root trace from pedotype 1. E) Laminations in C horizon of pedotype 2. F) View of top of bedding plane from pedotype 7 showing variegated coloring including drab root traces (green outline) and purple Fe-concentrations (three outlined by black circle). G) Fine mat-like drab root traces and soft Fe-concretions/concentrations (outlined in black) from pedotype 3.

Figure 8: Sand/clay ratios from measured section 1 shown alongside stratigraphic data and paleosol indexes (maturity index- MI and drainage index- DI) from Figure 3 to interpret channel position. Shifts in distal-proximal channel position are also highlighted by bold lines labeled A, B, and C. These surfaces correspond across the landscape and are also shown in Figures 3 and 4. Fluvial aggradational cycles (FAC) numbering is from base to top and corresponds to numbering in first panel of Figures 3 and 4.

Figure 9: XPL photomicrographs of representative grain constituents from thin sections of samples collected from channel sandstones at Photopan Outcrop. First number in sample name indicates the measured section from which the sample was collected. A) Photomicrograph showing representative appearance of channel sandstones. Highly birefringent material is likely a concentration of aligned clay matrix within what is possibly a pore infill or a recycled grain from a paleosol. Scale bar = 1.0 mm. B) Several feldspar species including partially sericitized, fresh plagioclase, and zoned (sanidine?) feldspars. Scale bar = 0.4 mm. C) Completely sericitized feldspar grain. Scale bar = 1.0 mm. D) Volcanic rock fragment with lath shaped crystals. Scale bar 0.1 mm. E) Quartz grain with abraded overgrowth cement. Scale bar = 0.4 mm. F) Hexagonal quartz grain. Scale bar = 0.4 mm.

Figure 10: QFL classification (left; modified from McBride, 1963) and provenance (right; modified from Dickinson and Suczek, 1979) plots of described samples using normalized estimations of quartz, feldspar, and lithic fragments. Quartz is plotted as total quartz (monocrystalline + polycrystalline + chert) and feldspar includes those interpreted to be replaced by sericite or kaolinite.

Figure 11: Geochemical (this study) and paleobotanical (Flynn et al., 2014) climate estimates related to biomes after Whittaker (1975). Leaf Margin Analysis (LMA) and Leaf Area Analysis (LAA) estimates are from the Ojo Alamo Sandstone and CALMAG estimates are from the overlying Arroyo Chijuillita Member of the Nacimiento Formation. TF = temperate forest; TSF = temperate seasonal forest.

Figure 1

Figure 2

Figure 3 panel 1

Legend			
↑ FAC	∩ Burrows	∧ Rooting	∪ Trough Cross Bedding
	× Slickensides	mm to cm Laminations	≡ Planar-Tabular Cross Bedding
Facies		Sand - lenticular (Sl)	Sand - massive (Sm)
Silcrete		Floodplain fines - horizontally bedded (Fh)	Floodplain fines - unstratified (Fp)

Figure 1 is a geological cross-section diagram showing three stratigraphic columns (MS 1, MS 5, MS 6) with depth markers (0 to 25 m) and various geological features like faults, folds, and units (Mud, Vc, FAC, MI, DI). The diagram is divided into three horizontal sections labeled A, B, and C. A 'Covered Section' is indicated between MS 1 and MS 5. The diagram shows complex geological structures with various colored layers and fault lines.

Figure 4 panel 1

Legend			Proxy Symbols
Burrows	Rooting	Trough Cross Bedding	PWI with standard error
Slickensides	mm to cm Laminations	Planar-Tabular Cross Bedding	CALMAG
Facies	Sand - lenticular (SI)	Sand - massive (Sm)	Salinization
Silcrete	Floodplain fines - horizontally bedded (Fh)	Floodplain fines - unstratified (Fp)	Margin of error for associated proxy

Figure 4 panel 2

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Table Captions

- 1 Table 1: Fluvial facies and architectural elements (Miall, 1985) observed within the study interval.
- 2
- 3 Table 2: Summary of MAP and MAT estimate ranges and averages from geochemically derived proxies.
- 4

1 Table 1: Fluvial facies and architectural elements (Miall, 1985) observed within the study interval.

Facies	Lithology	Description	Architectural Element
Fp	Mudrock	Unstratified clays to very fine sand; evidence of pedogenic alteration	Distal Floodplain (Vertisol)
Fh	Mudrock-Vf Sandstone	Laminated and horizontally bedded; clay-Vf sandstone; has minor to abundant drab root halos overprinting sedimentary structure	Proximal Floodplain (Inceptisol/Entisol)
Sl	Sandstone	Isolated, lenticular, fining upward fine to medium grained sandstone with scour base. Massive or with minor trough crossbedding and planar-tabular cross bedding	Lateral Accretion (point-bar channel fill from channel migration)
Sm	Sandstone	Relatively laterally continuous massive sandstones	Lateral Accretion/Proximal Overbank (non-pedogenically altered overbank)

2

3 Table 2: Summary of MAP and MAT estimate ranges and averages from geochemically derived proxies.

Proxy [n]	Min	Max	Range	Average	Standard Error
CALMAG [33]	1241 mm/yr	1514 mm/yr	273 mm/yr	1372 mm/yr	± 108 mm/yr
CIA-K (V) [33]	1003 mm/yr	1342 mm/yr	339 mm/yr	1150 mm/yr	± 146 mm/yr
Salinization [47]	9.3 °C	15.1 °C	5.9 °C	11.5 °C	± 4.4 °C
PWI [10]	11.5 °C	12.3 °C	0.8 °C	12.0 °C	± 2.1 °C

4