APPENDIX 1. DETAILED DESCRIPTION OF SANTA FE GROUP STRATIGRAPHIC UNITS IN THE STUDY AREA (RIO PUERCO VALLEY WITHIN 25 KM NORTH OF INTERSTATE 25)

STRATIGRAPHY

Santa Fe Group, central Rio Puerco valley

The Santa Fe Group constitutes the basin fill of the Rio Grande rift that overlies the late Eocene-Oligocene intermediate-felsic volcanic rocks that are regionally widespread near the Rio Grande rift (Spiegel and Baldwin, 1963). However, late Eocene-Oligocene volcanic rocks are not present along the exposed margins of the northwestern Albuquerque basin, and the Santa Fe Group overlies the Menefee Formation (Late Cretaceous). The Santa Fe Group in the Rio Puerco valley is divided according to Connell et al. (1999) and Connell (2008a,b). Map units of the Santa Fe Group are listed below in ascending order. The stratigraphic relations of these units are summarized in Figures 3~~4~~-4~~5~~. More detailed treatment of these units are found in the STATEMAP geology maps and reports recently completed for the study area (Cikoski et al., 2012; Koning and Jochems, 2014; Koning and Rawling, 2017; Rawling and Koning, 2019, in prep).

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Zia Formation

The Zia Formation is comprised of sand-dominated, terrestrial strata deposited by ephemeral streams or wind (eolian). It overlies meter-scale paleotopography developed on top of the Menefee Formation. Locally, ventifacted gravel and even paleo-terraces gravel are found at the basal contact. Near the village of Jemez (southwestern Jemez Mountains), a gravel composed predominately of intermediate volcanic clasts lies below the Zia Formation.

The lowest Zia unit, the Piedra Parada Member, typically consists of 15-100 m of medium- to coarse-grained (locally fine-grained) sand that commonly exhibits cross-stratification up to 40 cm thick. The sand fraction is subrounded to rounded and contains 10-30% dark lithic grains composed of chert and volcanic fragments. The relative abundance of these dark lithics and the coarser sand, compared to higher in the Santa Fe Group, serve as diagnostic criteria for recognition. Although minor (<5%), pebbly beds containing chert and intermediate-felsic volcanic gravel types are found to the south in roughly the same areas that volcanic gravel is found higher in the section (in the gravel-bearing Benavidez member).

Commented [s2]: Gilman conglomerate in the Jemez is also below the Zia.

Overlying the Piedra Parada Member are the Chamita Mesa and Cañada Pilares Members (Fig. ~~4~~3). The Chamita Mesa Member is light orangish to tan-colored, tabular-bedded, very fine- to medium-grained sandstone that has local rhizolith concentrations (becoming more common to the north). The ~~Canyada Pilares~~Cañada Pilares Member is a reddish brown playa deposit composed of mudstone interfingering with playa-margin sandstone.

Cerro Conejo Formation

The Cerro Conejo Formation is relatively similar to the Chamisa Mesa Member of the Zia Formation, but its sand fraction is slightly coarser (with local exceptions) and along the central Rio Puerco it exhibits a basin floor lithofacies assemblage (described below). The Cerro Conejo Formation is characterized by relatively tabular, medium to thick beds of sandstone that range from light orange, pastel, tan to red. The lower contact intertongues with the Cañada Pilares Member of the Zia Formation (Koning and Rawling, 2017).

Three lithofacies assemblages have been recognized in the Cerro Conejo Formation along the Rio Puerco valley, whose sand compositions are depicted in Figure ~~7~~6. The first is a distal piedmont facies typified by medium to thick, tabular beds of orangish sand; the sand is moderately to poorly sorted, fine-to very coarse sand, and locally has minor clayey sand intervals; minor cross-stratified sand may represent fluvial facies from a more northerly sourced paleo-river. The second lithofacies represents an inferred basin floor paleo-environment containing channel fill sand and fine-grained floodplain deposits. Strata consist of white to tan to light gray sands interbedded with pastel-colored sands and muddy sands with local greenish mudstone beds; the sand is relatively well sorted, mostly fine- to medium-grained, clean, and in intervals that are typically several meters thick. In these intervals, the sand is either in laminated to very thin, tabular beds or is trough cross-laminated (foresets are a few dm tall). The third lithofacies is characterized by a sandy bedload-dominated, fluvial system. It contains fine- to medium-grained sand in poorly defined, tabular beds that exhibit horizontal-planar laminations to very thin beds. There are trace amounts of very thin to thin beds with very coarse sand and fine pebbles composed mainly of volcanic clasts inferred to be rhyolite to dacite; additional clast lithologies include chert and quartz (each ~10%). In the Benavidez Ranch quadrangle, the sand composition of these lithofacies assemblages is dominated by quartz (40-70%) with lesser feldspar (14-35%) and 11-36% lithic + mafic grains. The lithic grains include volcanic detritus, chert, and subordinate very fine-grained sandstone or siltstone. Volcanic grains are more abundant than chert grains in the older piedmont facies. In addition, the plagioclase vs. potassium feldspar ratio is higher in the ~~older~~ lowest piedmont facies (Fig. 64).

Benavidez Member of Cerro Conejo Formation

We informally apply the name “Benavidez member” to the piedmont facies of the Cerro Conejo Formation that contains more than trace gravel beds. The dominant lithology is sandstone that is in medium to very thick (mostly thick), tabular beds. These beds are internally massive or else exhibit horizontal-planar laminations. There are minor (1-5%) clayey very fine- to fine-grained sandstone beds and clay-dominated mudstones. Sand colors are mostly orangish to strong brown light brown to tan to pink, with minor brownish yellow to yellowish brown. Locally, there are paleosols characterized by weak to moderate ped development, an illuviated clay (Bt) or cambic (Bw) horizon, and minor calcium carbonate accumulation characterized by slight whitening or nodules. The sand is mostly fine- to medium-grained but ranges from very fine- to very coarse-grained (with very coarse sand associated with pebble beds or beds with scattered pebbles). The majority of the sand is subrounded (minor subangular or rounded), moderately to poorly sorted, and composed of quartz, minor feldspar, and 5-25% lithic grains (variable chert and volcanic grains, but typically chert > volcanics). There are minor (<10%) intervals composed of massive, light yellowish brown, massive, fine- to medium-grained, well-sorted, subrounded to subangular sand that is inferred to be eolian. The Benavidez member is typically weakly to moderately consolidated and non- to weakly cemented.

Gravelly intervals occupy about 5-25% of the unit and are dominated by pebbles with <5% cobbles. Gravels are composed predominantly of chert and volcanic rocks. Minor gravel compositions include quartzite (1-10%), quartz (1-10%), calcium carbonate-cemented sandstones (1-25%), meta-rhyolites (1-15% and likely Proterozoic), trace-1% petrified wood, 0-1% granite, and 0-1% mafic rocks. The clasts are typically well-rounded to subrounded and moderately to poorly sorted. An exception are felsic tuffs, which are relatively angular. Gravel occurs in intervals 1-5 m thick, and the gravel beds are mostly very thin to thin and tabular to lenticular; pebbly sand is typically horizontal-planar laminated.

The Benavidez Member can be subdivided into petrosomes based on gravel compositions. The chert-gravel petrosome has <1% volcanic clasts and the dominant clast type is chert. The volcanic-gravel petrosome has 70-100% volcanic clasts, with the remainder of the gravel being chert, lesser quartzite, and trace petrified wood. More variable proportions of chert vs. volcanics (i.e., abundant chert with 1-70% volcanics) are assigned to the mixed-gravel petrosome. The volcanic-gravel petrosome is only found in the lower Benavidez member west of the Rio Puerco, correlating to the "lower Cerro Conejo Formation" of Cikoski et al. (2012, unit Tccl) and Koning and Jochems (2014, unit Tccw1) . More details of these petrosomes are given below. Figure 2~~3~~ shows the map distribution of these petrosomes in the Benavidez member.

Stratigraphy

In the main body of the Cerro Conejo Formation east of the Rio Puerco, the vertical succession of the aforementioned lithofacies asemblages tends to be: (1) distal piedmont interbedded with minor, cross-stratified, fluvial sands; (2) pastel-colored, finer-grained basin floor; (3) sandy fluvial system; then back to distal piedmont (4). These correspond to units Tcc1 through Tcc4 of Koning and Jochems (2014), which are labeled as such in the B column of Figure ~~4~~3. The lowest lithofacies assemblage (Tcc1) is 50-55 m thick. The lower 30 m of this lithofacies assemblage contains tongues of cross-stratified, fluvial or eolian sand that lack fossils. It was included in the Canyada Pilares Member (Zia Formation) by Tedford and Barghoorn (1999). Subtle angular unconformities occur only locally in this lower 30 m, and fossil camels near the top suggest a 16 Ma age (Tedford and Barghoorn, 1999). We interpret a compressed section with cryptic unconformities that spans an age of 17-14 Ma. Abundant fossils occur in the overlying, basin floor lithofacies assemblages encompassing the pastel-colored and sandy fluvial system units, corresponding to Tccw2 through Tccw3 of Koning and Jochems (2014). Interpretation of fossil species indicate an age range of 14-12 Ma, consistent with a K-Ar age of 13.64 +/- 0.09 Ma of an ash bed in unit Tccw3. The uppermost unit of the Cerro Conejo

Formation east of the Rio Puerco (Tcc4 of Koning and Jochems, 2014) is composed of reddish sandstone with ~10-20% clayey sandstone and mudstone. The ledge-forming sandstone is mostly in thin to thick, tabular beds that exhibit horizontal-planar lamination, low angle cross-laminations, or are massive. Gravel beds occur in this unit, becoming more abundant up-section and to the south. In the north part of the study area, gravels only occupy a transitional, 12-18 m thick interval between the Cerro Conejo and Arroyo Ojito Formations. The uppermost unit is interpreted to reflect a distal piedmont lithofacies assemblage; and correlating its stratigraphic position to the magnetostratigraphic work of Tedford and Barghoorn (1999) indicate an age of 12.7 to at least 12 Ma—probably to ~11 Ma in areas where higher strata are better preserved compared to the magnetostratigraphic section of Tedford and Barghoorn (1999).

The Benavidez Member interfingers with the main body of the Cerro Conejo Formation as well as the younger Arroyo Ojito Formation (Fig. 3-4~~4~~, 5~~6~~). The >50 m thick volcanic-gravel petrosome lies in the lower or middle Cerro Conejo Formation west of the Rio Puerco (Fig. 4~~6~~), but its base is not exposed. Mapping indicates that the lowest Cerro Conejo Formation strata lacks gravel (i.e., consists of sandstone with very minor mudstone), so the volcanic gravel tongue does not lie at the base of the Cerro Conejo Formation. West of the river, above the volcanic-gravel petrosome (Benavidez Member) lies a 70-80 m (thickness poorly constrained), thick tongue of the main body of the Cerro Conejo Formation. This tongue consists of pink to tan to pastel-colored, fine- to coarse-grained sand that lacks gravels and has 1-3% reddish brown mudstone beds. Sand in this tongue is in thin to thick (mostly thick), tabular beds that are internally horizontal-planar-bedded to very thinly bedded. This sand locally contains cross-stratification with lenticular grain-flow beds and 3 m thick foresets, and thus is inferred to be eolian. West of the Rio Puerco, gravelly strata of the Benavidez member that overlies this sand tongue is roughly 250-300 m thick (Fig. 4~~6~~; unit Towp of Cikoski et al., 2012). This gravely strata contains both the mixed-volcanic and chert-gravel petrosomes. Its lower half is interpreted to correlate with the upper distal piedmont facies east of the Rio Puerco, since tongues composed of chert-dominated gravel occur in that particular unit. The upper half of the 250-300 m thick Benavidez unit interfingers with the Arroyo Ojito Formation, as evident by tongues of the Navajo Draw Member being readily recognized west of the river. East of the Rio Puerco, gravelly strata occur as tongues within the upper ~100 m of the southern extent of the Cerro Conejo Formation. To the north, these gravel tongues are restricted to a 12-18 m thick gradational interval between the Cerro Conejo and Arroyo Ojito Formations (described below).

The Benavidez member of the Cerro Conejo Formation lies in the range of 17 to 8 Ma. The basal volcanic-gravel petrosome of the Benavidez Member is probably 17-14 Ma, since it is thought to correlate to the lowest subunit of the Cerro Conejo Formation east of the river. The Benavidez Member overlying the gravel-lacking, sandy tongue of Cerro Conejo Formation west of the river probably is 13 to 7 Ma. A 13-12 Ma age is interpreted because 14-12 Ma fossils were found in the Benavidez diatreme east of the river (Gary Morgan, personal communication, 2020), and the adjoining country rock of the diatreme are the chert-gravel petrosome of the Benavidez member. The likely minimum age of the Benavidez Member is poorly constrained. Since it interfingers with the Navajo Draw Member (Arroyo Ojito Formation, described below), it is likely 10-8 Ma.

Arroyo Ojito Formation

Gravel-bearing strata to the northeast of the study that underlie the Rincones paleosurface are designated as the Arroyo Ojito Formation (Connell et al., 1999; Connell, 2008a; Connell et al., 2013). The Arroyo Ojito Formation is comprised of three members deposited by southerly to southeasterly flowing fluvial systems. Near the type section, the stratigraphically higher members are the Loma Barbon and Picuda Peak members, which are described in Koning et al. (1998), Connell et al. (1999), Koning and Personius (2002), and Connell (2008a). However, recent inspection of exposures 20 km northeast of the Rio Puerco valley, in the western part of the upper Arroyo Ojito drainage, establish that the Navajo Draw and Loma Barbon Members interfinger with each other.

The Navajo Draw Member is the only member of the Arroyo Ojito Formation exposed in the Rio Puerco valley. It consists of very pale brown to pale brown sand interbedded with minor mudstone and gravel beds. The sand is in very thin to thick, tabular beds that commonly exhibit internal laminations (or very thin beds) that are horizontal-planar, wavy, or cross-laminated (up to 20 cm thick foresets). Distinctive channel fills may have tangential foresets up to 30 cm thick. There are 0-50% gravelly intervals, decreasing to the south, that are typically 30-100 cm thick and tabular to lenticular; individual beds within these intervals are 1-30 cm thick and tabular to lenticular. The gravel are poorly to moderately sorted, subrounded to rounded, and clast- to matrix-supported. The gravel consists of pebbles with 0.5-2% cobbles; clast composition is: chert, sandstone (mostly older Santa Fe Group or intraformational, with only minor possible Cretaceous sources), 0-50% intraformational calcium carbonate nodules, variable iron-oxide fragments (siderite?), trace to 5% hornblende-plagioclase-phyric dacite, 1-7% quartzite, 5-7% quartz, and 1% petrified wood. Spatial trends in clast compositions is noted below. The sand is fine- to very coarse-grained, becoming mostly fine- to medium-grained to the south, subrounded to rounded, poory to well sorted, and composed of quartz, minor feldspar, and 7-20% lithic grains (volcanic, chert, siderite?). The member is weakly to moderately consolidated and has 1-3% variable cementation by calcium carbonate. Exposed thickness is about 50-100 m.

The Loma Barbon overlies the Navajo Draw Member (Connell et al., 1999, 2008a), but recent field visits establishes that the two members also interfinger with each other towards the west. This interfingering explains why the Loma Barbon Member is not present in the Rio Puerco valley. Compared to the Navajo Draw Member, the Loma Barbon is redder-browner in color, and its gravel is composed of granite, sandstone, quartzite, and volcanic rocks together with minor (~4%) Pedernal Chert. It was derived by relatively sinuous streams (Connell et al., 1999) that were sourced in the easternmost San Juan basin and Nacimiento Mountains, the latter being the source of the granite gravel and Pedernal Chert.

Ceja Formation

The Late Miocene Arroyo Ojito Formation is unconformably overlain by the Ceja Formation, whose lower 50 m consists of reddish to light brown, very fine- to medium-grained sand. The upper 35-45 m of the Ceja Formation is a relatively coarse sand and pebbly to cobbly sand.

Santa Fe Group, Gabaldon badlands

As reported by Lozinsky and Tedford (1991), the exposed Santa Fe Group in the Gabaldon badlands is >1,138 m thick. The Santa Fe Group there consists of alternating beds of sand, silty sand, clayey sand, and conglomerate assigned to the Popotosa Formation. Relatively thin and tabular, interbedded fine sand and clayey beds were assigned to an alluvial flat found between the distal ends of alluvial fans (or piedmont slopes) and a playa. A lithofacies assemblage of poorly sorted, fine- to very coarse-grained sand and lenticular beds of conglomeratic sand were assigned to a distal piedmont-slope depositional environment. Gravel are predominately composed of rhyolite or ash flow tuff (50-88%) followed by 2-5% light-colored sandstone (inferred to be Cretaceous), 4-21% chert, 0-23% quartz, 0-6% mafic volcanic rocks, 0-2% petrified wood, and 0-3% limestone. Fossil identification indicates a 9-7 Ma age.