New Mexico Geological Society

Downloaded from: http://nmgs.nmt.edu/publications/guidebooks/50

Santa Fe Group (Neogene), Ceja del Rio Puerco, northwestern Albuquerque Basin, Sandoval County, New Mexico

Richard H. Tedford and Steven F. Barghoorn, 1999, pp. 327-335

in:

Albuquerque Geology, Pazzaglia, F. J.; Lucas, S. G.; [eds.], New Mexico Geological Society 50th Annual Fall Field Conference Guidebook, 448 p.

This is one of many related papers that were included in the 1999 NMGS Fall Field Conference Guidebook.

Annual NMGS Fall Field Conference Guidebooks

Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual Fall Field Conference that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

Free Downloads

NMGS has decided to make peer-reviewed papers from our Fall Field Conference guidebooks available for free download. Non-members will have access to guidebook papers two years after publication. Members have access to all papers. This is in keeping with our mission of promoting interest, research, and cooperation regarding geology in New Mexico. However, guidebook sales represent a significant proportion of our operating budget. Therefore, only *research papers* are available for download. *Road logs*, *mini-papers*, *maps*, *stratigraphic charts*, and other selected content are available only in the printed guidebooks.

Copyright Information

Publications of the New Mexico Geological Society, printed and electronic, are protected by the copyright laws of the United States. No material from the NMGS website, or printed and electronic publications, may be reprinted or redistributed without NMGS permission. Contact us for permission to reprint portions of any of our publications.

One printed copy of any materials from the NMGS website or our print and electronic publications may be made for individual use without our permission. Teachers and students may make unlimited copies for educational use. Any other use of these materials requires explicit permission.

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

SANTA FE GROUP (NEOGENE), CEJA DEL RIO PUERCO, NORTHWESTERN ALBUQUERQUE BASIN, SANDOVAL COUNTY, NEW MEXICO

RICHARD H. TEDFORD[1] and STEVEN BARGHOORN[2]

[1]Department of Vertebrate Paleontology, American Museum of Natural History, NY 10024; tedford@amnh.org; [2]302 Cross St., Carlisle, MA 0174

Abstract—The badland escarpment of the Puerco River (Ceja del Rio Puerco) in southern Sandoval County, New Mexico exposes 410 m of Miocene sediments at the western edge of the northern Albuquerque basin. Geologic mapping and accompanying lithostratigraphic, biostratigraphic and magnetostratigraphic studies enable the Zia and overlying Arroyo Ojito formations, typified in the Jemez River region to the north, to be recognized in the Ceja outcrops. The Zia Formation (early Miocene) rests unconformably on nonmarine Cretaceous (Menefee Formation) strata. Most of the Zia is volcaniclastic and eolian in origin. It can be subdivided into a lower dune (Piedra Parada Member, 70 m), middle fluvial (Chamisa Mesa Member, 30 m), and an upper playa and dune facies (Cañada Pilares Member, 75 m). These rocks are overlain with apparent conformity by the Arroyo Ojito Formation, of fluvial origin, containing minor lacustrine, and eolian bodies. The Arroyo Ojito is represented primarily by the Cerro Conejo Member (245 m, medial Miocene), which gives way conformably to the gravelly Navajo Draw Member (>30 m thick). Higher units within the Arroyo Ojito Formation are seen only east of the Sand Hill fault, where they include the upper part of the Loma Barbon Member and the locally unconformably overlying Ceja Member. Both are coarse fluviatile bodies with a varied clast composition indicating sources in mountains to the north as well as the Colorado Plateau. A basaltic diatreme (Benevides Hill) that erupted through the Zia and most of the Cerro Conejo strata predates incision of the Puerco River. The youngest deposits, the Pantadeleon Formation of Pliocene and Pleistocene age, fill local fault-angle depressions formed during continuing deformation of the basin-fill.Two prominent down-to-the-east faults of 200–300- m throw break the sedimentary column. The Moquino fault and contiguous Navajo fault have a northeastern trend concordant with the Laramide Puerco fault zone, and show evidence of left-slip as well as syn-rift normal faulting. The Sand Hill fault to the east has a more northerly trend like the major dip-slip faults that break the deeper basin-fill.

INTRODUCTION

During Bryan and McCann's (1937, 1938) pioneering study of the northern Albuquerque basin, New Mexico, they found fragmentary vertebrate fossils in strata exposed in the eastern flank of the Rio Puerco Valley known locally as the Ceja del Rio Puerco ("eyebrow of the dirty river"). By the time Wright reported further occurrences of fossil mammals discovered during his more detailed study of the western Albuquerque basin in 1946, Ted Galusha of the Frick Laboratory of the American Museum of Natural History was sufficiently intrigued to begin a reconnaissance of these outcrops. From that year until 1957, Galusha and his field assistants collected fossils along the Ceja and into the Rincones de Zia at the northern edge of the basin. Galusha carried out an extensive geologic mapping program and stratigraphic studies as the collecting went on, and by 1966 his concepts of the regional stratigraphy had come together with the publication of his principal geological results on an approximate planimetric base. He intended to transfer his data to the 1:24,000 quadrangle base maps that became available in the 1970s, but this effort was cut short by his death in 1979.

The authors of this summary have continued his work based on his archives and the brief field experience one of us (RHT) had with him in the area in 1968. During graduate studies at Columbia University, Constance Gawne (1981) was the first to describe and map part of the Ceja section. Her dissertation (1973) covers the stratigraphy, sedimentology and vertebrate paleontology of the early Miocene rocks. In this contribution we summarize the Neogene geology of the northern Ceja outcrop belt, and deal with its chronology and correlation with the deposits elsewhere in the northern Albuquerque basin.

HISTORY OF INVESTIGATION

Although Hunt (1936) had mapped the western rift-bounding Moquino fault (his San Francisco fault) as a structure dividing the Santa Fe "Formation" from the Mesozoic rocks of the Colorado Plateau, it was Kirk Bryan and Franklin McCann (1937, 1938) who first studied the outcropping edge of the Albuquerque basin and divided the Santa Fe "formation" into three units: the lower gray, middle red and upper buff members. The lower and middle units were "based largely on difference in color" although "lithologically they have much in common and are best treated together" (Bryan and McCann, 1937, p. 811). The "texture [of the upper buff member] is much more variable than that of the lower two members" with basal silts and clays giving way upward to coarse sand and gravel. These authors presented a map (1937, fig. 4) in which the distribution of these units is shown.

Nearly 10 years later, one of Bryan's students, H. E. Wright (1946), had extended this stratigraphy south along the Ceja and into the Apache graben and Gabaldon Badlands west of the Puerco River. He did not map any of the units, but discussed further details of their stratigraphy. Spiegel (1961) studied the stratigraphy near the mouth of the Jemez River and tried to employ the same stratigraphic scheme but was forced to recognize additional informal units to express the relationships as he saw them (see Tedford, 1982, for a review of this and later work).

Galusha's 1966 publication focused on the lower part of the stratigraphic column, essentially the lower gray and part of the middle red members of Bryan and McCann. He proposed a new lithostratigraphic unit, the Zia Sand Formation, on much the same general lithologic character as Bryan and McCann's lower gray member and, indeed, comparing the maps produced, the areal extent is much the same. The type section was along the divide between Cañada Piedra Parada and Cañada de Zia (now Arroyo Ojito,) just west of the Jemez fault. Galusha (1966) subdivided his Zia Sand into two members: the Piedra Parada Member, the lower 130 m of the Zia Sand type section, and the Chamisa Mesa Member from outcrops at the western base of Chamisa Mesa, 17 km northeast of the Zia type section, where 220 m were measured overlying the gray sands of Piedra Parada lithology. The upper 210 m of the type section of the Zia Formation, above an "obscure unconformity," were also referred to the Chamisa Mesa Member (Galusha, 1966, p. 5). Galusha did not characterize these units lithologically, the distinction between members was again based largely on color: the Piedra Parada being dominantly light gray, and the Chamisa Mesa mostly gray, but with yellowish-gray or pinkish-gray sandstones becoming more numerous toward the top of the member.

Constance Gawne completed her dissertation study of the Zia Sand in

1973. She undertook a detailed examination of the sedimentology and stratigraphy of the Zia Sand as well as its paleontology. Her geologic results were published in 1981, including additional investigations of the type sections plus an important extension of mapping to Cañada Pilares in the Ceja del Rio Puerco, an area briefly mentioned by Galusha (1966, p. 11). Gawne (1981) was able to show, as Galusha had suspected, that the Piedra Parada Member was dominantly a dune sand that accumulated as transverse dunes driven by a westerly wind. The Chamisa Mesa Member also included dunes and sand sheets stabilized by plants as well as loess, fluviatile and interbedded pond deposits. In Cañada Pilares, the referred Chamisa Mesa Member is succeeded by red claystones and interbedded sandsheets reworked by water in a flood plain or playa environment. Gawne separated these deposits as the Cañada Pilares Member of the Zia Sand. She recognized that the lithic component of the sands in all these units was dominated by intermediate volcanic detritus implying reworking of a pre-existing volcaniclastic alluvium.

In the meanwhile, Kelley (1977) had published his views of the Albuquerque basin, which strongly advocated a return to a three-fold subdivision of the "Santa Fe Formation." He adopted Galusha's Zia as a lower member, equating it with the lower gray member of Bryan and McCann (1937). He introduced a Ceja Member, equating it with the upper buff member of Bryan and McCann (1937), although at its type section at El Rincon along the Ceja just north of I-40, he designated only the coarser gravel at the top of the local section and did not include the underlying finer-grained deposits included in Bryan and McCann's concept of the upper buff. He retained the "middle red member," or "main body" of the Santa Fe, for the remaining facies within this "formation." These units were differentiated on his map and regarded as interdigitating facies of the Santa Fe Formation. Although seemingly a simple system, this view is actually highly hypothetical, arising from notion of facies relationship untested by regional mapping at an appropriate scale. Subsequent work has shown that the outcropping basin stratigraphy can be resolved into mappable units whose mutual relationships are basically sequential and not laterally coextensive on the scale envisioned by Kelley.

Recently, Smith and Lavine (1996) and Smith and Kuhle (1998) have mapped the type area of the Cochiti Formation, a unit rejected by Kelley (1977, p. 13) as simply a volcaniclastic facies of his "middle red member." This unit was regarded by Tedford (1982) as a volcaniclastic facies of the largely epiclastic Ceja Member of Kelley. Present work of Smith and Lavine (1966) clearly shows that the Cochiti is a volcaniclastic apron derived from the upper part of the Keres Group rather than from the whole unit. Ongoing mapping by the University of New Mexico, the U.S. Geological Survey, and the New Mexico Bureau of Mines and Mineral Resources is responsible for a number of geologic quadrangles at a scale of 1:24,000 covering the southern flank of the Jemez Mountains southward into the Rincones de Zia and along the Ceja del Rio Puerco. The present contribution details our work in the northern Ceja del Rio Puerco in southern Sandoval County (Fig. 1).

STRATIGRAPHY

The region under discussion extends from the Sandoval County line northward from T12N into T13N, R1E and R1W of the New Mexico Principal Meridian covering parts of Benavidez Ranch, Volcano Ranch, San Felipe Mesa, and Arroyo de las Calabacillas 1:24,000 quadrangles (Fig. 2). The exposures in Cañadas Benevides, Moquino and Pilares ("Arroyo Benavidez" of the San Felipe Mesa Quadrangle) include 24 mi^2 of nearly continuous outcrop broken only by the remnants of the cover of a pediment developed at an early stage in the Quaternary history of the Puerco River.

Zia Formation

In previous work (Tedford, 1982; Tedford and Barghoorn, 1997) we advocated a broader definition of the Zia Formation than did Galusha (1966) or Gawne (1981), and taking the lead from Manley (1978), extended the unit upward to the base of the Keres Group volcanics of the southern flank of the Jemez volcanic field. However, in the last few years considerable additional knowledge of the distribution and relationships of Santa Fe Group strata have provided a more reliable basis for synthesis of geologic events in the northern Albuquerque basin. These studies include most of the type sections of previously defined lithostratigraphic units leading to a revision (Connell et al., this volume) of the lithostratigraphy based on a particularly complete section in Arroyo Ojito in the Rincones de Zia (Figs. 3, 4). We draw on these data to reassess the subdivision of the lithologic column exposed along the Ceja del Rio Puerco.

Piedra Parada Member

The base of the Zia Formation lies on a low relief (<3 m) surface of unconformity cut on the Cretaceous Menefee Formation. Nearly everywhere along the contact, cobbles of intermediate volcanic rocks fashioned into ventifacts are accompanied by pebbles of siliceous composition that are also commonly wind polished. These clasts lie on a red-tan clay containing a calcic soil developed on the Cretaceous deposits. They indicate the local presence of subcrops of Paleogene rocks (Galisteo Formation, and "unit of Isleta Well") that have been identified in the surface and subsurface of the northern Albuquerque basin (Lozinsky, 1994). This desert pavement is overlain by 70 m of light gray eolian sandstones and thin, scattered interdune deposits including pinkish-orange muddy sandstones, and greenish calcareous mudstone that represent ephemeral ponds. The eolian sandstones occur in planar cross-bedded units in sets up to 2 m thick, separated by subhorizontal accretion surfaces. Observation of cross-bed orientations by Gawne (1981) indicates transport to the east on prevailing westerly wind flow.

Interdune and pond deposits 20–25 m above the base of the Piedra Parada Member contain vertebrate fossils, dominantly those of camels (*Stenomylus, Oxydactylus,* and *Michenia*) and rhinos (*Diceratherium*), species of which indicate a late Arikareean (19–22 Ma: McFadden and Hunt, 1998) or early Miocene age for the dune field. Similar remains were encountered at the same stratigraphic level in the type section of the unit in the Rincones de Zia, and together these represent the oldest Neogene deposits of the Albuquerque basin known in outcrop.

Chamisa Mesa Member

The Piedra Parada dune field grades upward into tabular, thick-bedded yellowish fine sandstones, silty sandstone and siltstones representing a waning eolian contribution and greater fluviatile influence punctuated by weakly developed calcic soils. Depending on the criteria for the contact with the Piedra Parada, there are 30 m of Chamisa Mesa deposits. Only the upper 5 m of the Chamisa Mesa Member is fossiliferous in this area, and the remains are nearly exclusively those of the stenomyline camel *Blickomylus galushai*, the same taxon that characterizes the fossiliferous levels in the member type section on the western flank of Chamisa Mesa. In the type locality at Chamisa Mesa, *Blickomylus* occurs with other camels, rhinos, carnivores, rodents, and rabbits through a 200-m-thick section, the associated fauna indicating a temporal range from early into late Hemingfordian (16–18 Ma) time in the later early Miocene.

Cañada Pilares Member

Gawne (1981) defined this unit for the laterally persistent 30 m of bright red-brown mudstone and thin-bedded fine sandstone that forms a conspicuous bench above the more indurated Chamisa Mesa Member in upper reaches of Cañada Pilares (Fig. 4). In the Chamisa Mesa, type section, a similar red-brown mudstone occurs at the top of the Chamisa Mesa section (Gawne, 1981, fig. 3). As defined by Gawne (1981), the top of the Cañada Pilares Member in the Ceja outcrops is characterized by a laterally persistent, green claystone and associated limestone deeply cracked by desiccation. Laterally, this limestone marker bed is replaced by cobble-sized, cylindrical oncolites formed around twigs of wood, indicating saline surface water in the Cañada Pilares playa. In the southern part of the outcrop, red mudstones persist upward above the green claystone/limestone marker for 15 m. where they interfinger with

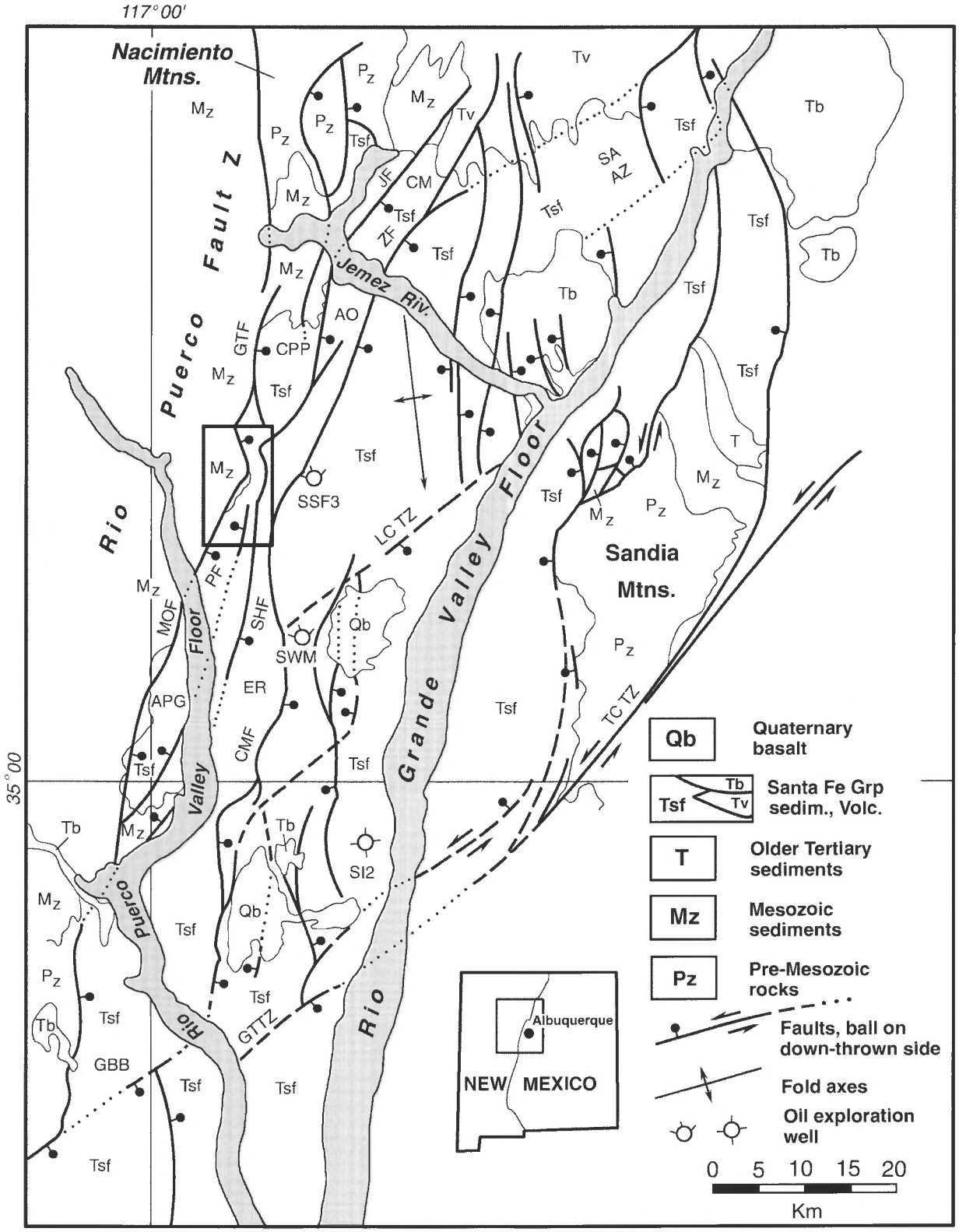

FIGURE 1. Location map and structural synthesis adapted from Kelley (1977) and Hawley (in Hawley and Whitworth 1996, plate 2). Location of Figure 2 indicated, as are the locations of wells used in Figure 7: SI2, Shell Isleta No. 2; SSF3, Shell Santa Fe Pacific No. 3; SWM, Shell West Mesa Federal No. 1. Selected fault and transverse zones abbreviated: CMF, Cat Mesa Fault Zone; GTF, Garcia-Tenorio Fault Zone; GTTZ, Gabaldon-Tijeras transverse zone; JF, Jemez Fault Zone; LCTZ, Loma Colorado Transverse Zone; MOF, Moquino Fault; PF, Pilares Fault Zone; SAAZ, Santa Ana Accommodation Zone; SHF, Sand Hill Fault Zone; TCTZ, Tijeras-Cañoncito Transfer Zone; ZF, Zia Fault Zone. Places mentioned in the text: AO, Arroyo Ojito; APG, Apache Graben; CM, Chamisa Mesa; CPP Cañada Piedra Parada; ER, El Rincon; GBB, Gabaldon Badlands.

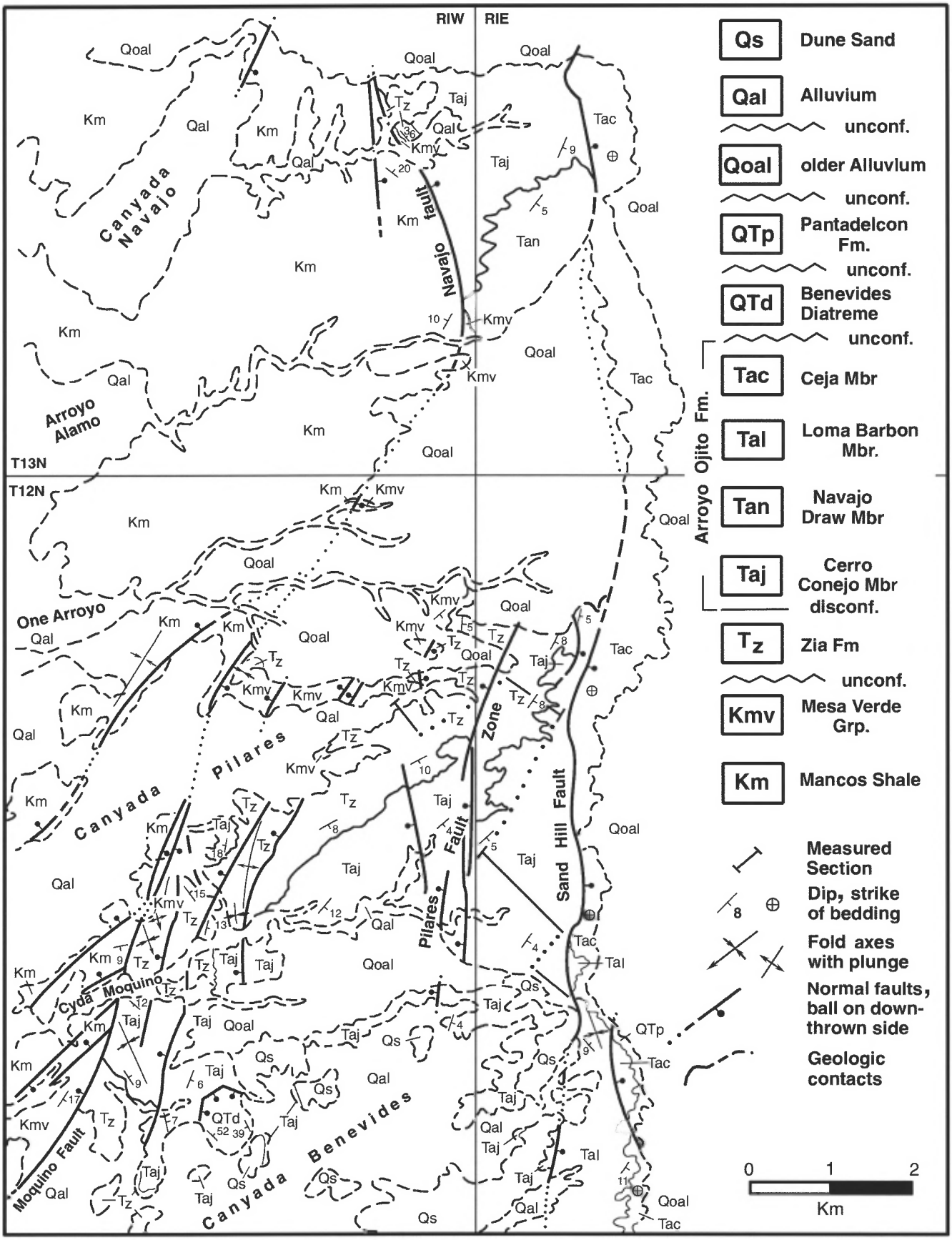

FIGURE 2. Geologic map of a part of the Ceja del Rio Puerco just north of the Sandoval County line (location see Fig. 1). Older alluvium of the Llano de Albuquerque surface bounds the Tertiary outcrops on the east and Cretaceous marine strata of the southeastern Colorado Plateau on the west. Bold lines connected by dots indicate traverse used to establish the data presented in Figure 3.

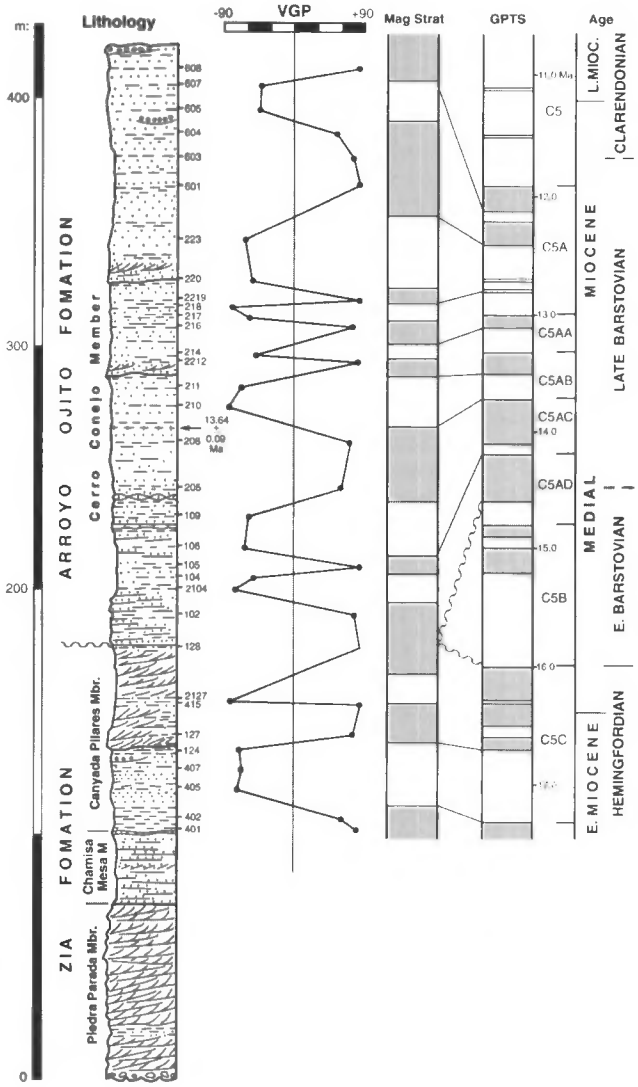

FIGURE 3. Composite stratigraphic column drawn from outcrops in canyadas Pilares and Moquino (see Fig. 2) showing lithology (standard symbols), magnetostratigraphy (sample locations, Virtual Geomagnetic Pole positions, and interpreted magnetostratigraphy, intervals of normal polarity shaded), correlation with the Geomagnetic Polarity Timescale (Cande and Kent, 1995), and age in terms of the standard geological epochs and the North American land mammal "ages" (Tedford et al., 1987).

a 30-m interval of sandstones deposited by eolian processes that caps the Cañada Pilares playa deposits. Local interdune environments break the sequence, and toward the top local planar-bedded, fine sandstone occurs. The top of the Cañada Pilares Member is not marked by conspicuous paleosols or textural changes relative to the overlying Cerro Conejo Member deposits. The upper dune sands are regarded as part of the Cañada Pilares interval from evidence of extensive interdigitation with the red clays of Gawne's type Cañada Pilares, so we have extended the term upward to include these genetically interrelated lithic bodies. In Tedford and Barghoorn (1997), this unit was designated "unnamed member" and shown interdigitating with the Cañada Pilares Member.

Fossil mammal remains occur sporadically in the red mudstones of the Cañada Pilares Member. These are nearly exclusively those of the small camel *Blickomylus galushai*, often preserved as partial skeletons. Sand-filled channels at the stratigraphic position of the limestone marker have local concentrations of bones, largely of single taxa, such as the numerous disarticulated remains of the rhino *Menoceras* cf. *M. marslandense*, that were contained in channel-fill just beneath the green claystone-limestone unit. The most diverse representation of taxa in the Cañada Pilares Member occurs in the upper part of the red mudstone facies, where the composite fauna indicates an early Hemingfordian (17–18 Ma) or late early Miocene age. Rare camel remains at the top of the unit suggest a late Hemingfordian (16 Ma) age for the top of the Zia Formation in the Ceja.

Arroyo Ojito Formation

This recently proposed (Connell et al., this volume) lithostratigraphic unit is here enlarged to include the younger "unnamed member" of our 1997 paper. Many of the newly recognized members of this formation can be traced discontinuously from their type sections to the Ceja del Rio Puerco outcrops. The base of the Arroyo Ojito Formation represents a fundamental change in depositional environment within the northern Albuquerque basin from sediments largely brought together by eolian processes (Zia Formation) to those dominated by fluviatile processes that increase in energy upward, implying more widespread fluvial transport promoted by higher gradients and consistently high water tables (Fig. 5). This natural subdivision relegates the Zia Formation approximately to its original concept and places Galusha's and Gawne's "Santa Fe equivalent" or "Tesuque Formation equivalent" in the newly designated Arroyo Ojito Formation. We differ from Connell et al. (this volume) in including the Cerro Conejo Member, the lowest major fluviatile unit, within the Arroyo Ojito Formation, because it seems lithogenetically continuous with the overlying fluviatile deposits present at its type section.

Cerro Conejo Member

This unit is principally reddish, tabular, thin-bedded, fine sandstone and mudstone, strongly carbonate cemented by groundwater in the basal 30 m to form a persistent cliff-line above the Zia Formation eolian deposits. The Cerro Conejo Member is over 300 m thick in Cañada Moquino, where it is truncated by the Sand Hill fault. It probably includes an additional 30 m in Cañada Navajo (Navajo Draw of the San Felipe Mesa Quadrangle) below the conformably overlying Navajo Draw Member. There is an overall tendency to coarsen upward within the unit, mostly by incorporation of laterally extensive fluviatile units of medium to coarse grain size. In the upper 30 m of the unit, thin lens-

FIGURE 4. Panorama of Santa Fe Group outcrops in Cañada Pilares looking east (right) to north (left). Visible are the correlated Piedra Parada (Tzp) and Chamisa Mesa (Tzc) members and type section of the Cañada Pilares Member (Tzr), Zia Formation, and the lower part of the Cerro Conejo Member (Taj) of the Arroyo Ojito Formation. Contacts between these units are indicated.

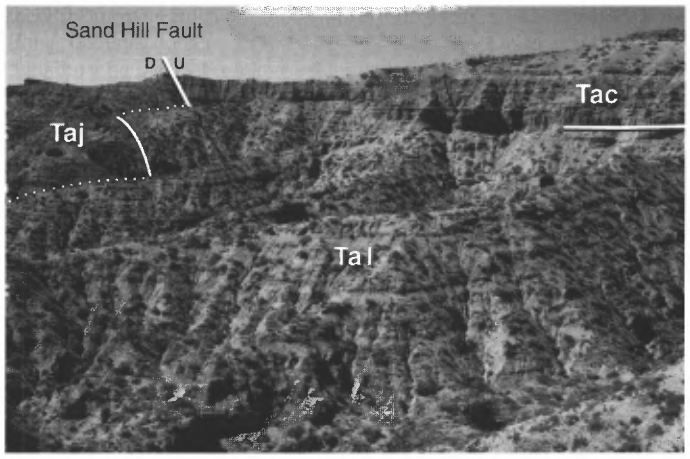

FIGURE 5. View northward along the wall of the Ceja del Rio Puerco at the head of Cañada Benevides showing the deposits that crop out east of the Sand Hill fault (indicated). Gently folded Loma Barbon (Tal) and nearly horizontal overlying Ceja (Tac) members are indicated.

es of pebble conglomerate (siliceous and rare intermediate volcanic clasts) occur as a prelude to a lithology characteristic of the overlying Navajo Draw Member. Thin volcanic ash beds occur throughout the Cerro Conejo but are more frequent in a 70-m interval near the middle of the unit in the Cañada Pilares and Moquino outcrops. Two, 1–2-m-thick green mudstone and associated limestone units occur within 10 m of one another 50 m above the base of the member. Both are persistent across the outcrop belt from Cañadas Pilares to Benevides. The upper unit is characterized by the presence of large stromatolites that encrusted erosional irregularities in the substrate and large driftwood fragments. Such algal carbonate structures are lacking in the lower green claystone, but this unit bears many remains of the muskrat-like beaver *Eucastor*, suggesting a fresher-water environment for the lower bed.

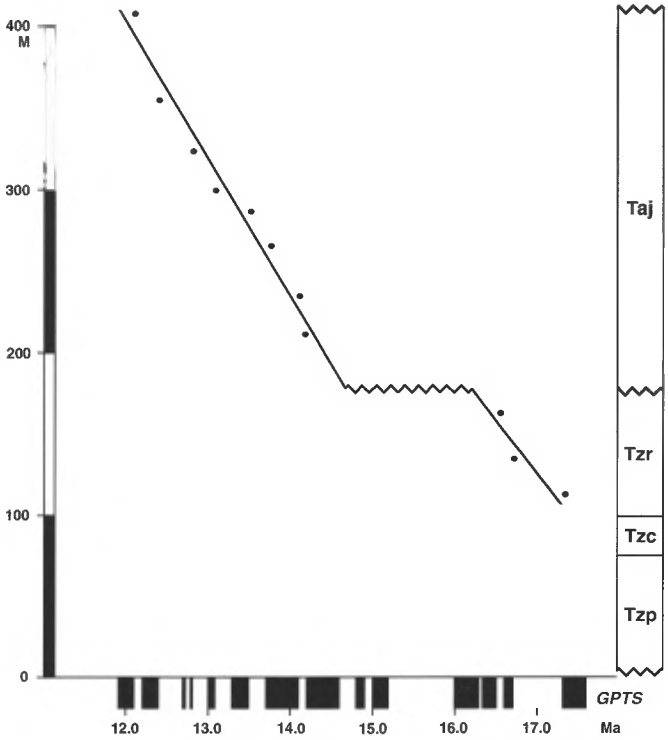

FIGURE 6. Plot of rate of accumulation of parts of the Santa Fe Group, Ceja del Rio Puerco. Cerro Conejo (above) and Cañada Pilares members from data of Figure 3, and correlation with the Geomagnetic Polarity Time Scale (GPTS) of Cande and Kent (1995), intervals of normal polarity shaded.

Fossil mammal remains are most abundant in the middle part of the Cerro Conejo Member along the Ceja del Rio Puerco. The fauna represents a decided change in composition over the Zia assemblages. It is characterized by the presence of the mastodont *Gomphotherium productum*, the pronghorn *Ramoceras*, the camels *Protolabis, Michenia, Aepycamelus*, and *Procamelus*, rare equine horses and large borophagine carnivores (Tedford and Barghoorn, 1997). These mammals are also present in the unit's type section in the Rincones de Zia. Such assemblages are regarded as typical of the late Barstovian interval (12–14 Ma) of early medial Miocene time.

An airfall ash 27 m above the upper green claystone yielded a K-Ar (biotite) date of 13.64 ± 0.09 Ma (C. Swisher, Berkeley Geological Center) compatible with the biochronological data and with the magnetostratigraphy for the Cerro Conejo in the Ceja outcrops. This ash date helps correlate the composite magnetostratigraphic column with the Geomagnetic Polarity Timescale (Fig. 3, calibration follows Cande and Kent, 1995). The interval represented extends from Chron 5ADn through 5An.1n, approximately 14.6 through 12.0 Ma, of late medial Miocene time. The additional section exposed in Cañada Navajo probably extends the Cerro Conejo Member to 11.9 Ma, if the sedimentation rate of the uppermost strata is similar along the Ceja outcrop belt (Fig. 6). This temporal span seems to also apply to the type section of the Cerro Conejo, although faunal evidence from the base of the Cerro Conejo in the western Rincones de Zia suggests it may descend into the late early Barstovian at about 15 Ma.

The magnetostratigraphy of the Ceja del Rio Puerco outcrops (Fig. 3) lacks the long reversed interval of Chron 5B, and thus seems to juxtapose Chron 5ADn on Chron 5Cn.1n (a minimal temporal reconstruction) based on paleontologic assessment of the age of the upper part of the Cañada Pilares Member of the Zia Formation. In this synthesis, the hiatus between the Zia and Arroyo Ojito formations would be about 1.6 m.y. and perhaps closer to 1 m.y. in the Rincones de Zia.

Navajo Draw Member

This unit is proposed by Connell et al. (this volume) and is represented in Cañada Navajo by more than 30 m of medium to coarse, cross-bedded brown sandstone and interbedded pebble to cobble conglomerate lenses that rest with shallow scour and apparent conformity on the top of the Cerro Conejo red beds. The clast composition of the gravel is dominated by siliceous rocks (quartz, quartzite, chert, jasper, and fossil wood) recycled from pre-Neogene deposits with rare pebbles of intermediate volcanic rocks, and coarse grains and granules of red granite. The clast composition is the same as that seen in scattered gravel lenses within the upper part of the underlying Cerro Conejo in Cañada Moquino and Cañada Navajo. A similar coarsening-upward succession is present in Arroyo Ojito, where the first such coarse deposits are interbedded with red and yellow muddy sediments in a color and textural transition to the yellow-buff conglomeratic sandstones of the Navajo Draw deposits. Higher in that unit in the Rincones de Zia, the volcanic component in the gravel becomes more conspicuous, as do bright red claystone clasts probably derived from the late Paleozoic rocks in the Nacimiento Mountains to the northwest.

No fossils are known from this unit, but its base must lie near 12 Ma from evidence cited above for the Cerro Conejo Member. Water-laid tuff is locally preserved about 15 m above the base in Cañada Navajo.

Loma Barbon Member

Along the Ceja del Rio Puerco, correlatives of this unit (Connell et al., this volume) are exposed only in the hanging wall of the Sand Hill fault in the head of Cañada Benevides (Fig. 5) and to the south along the Ceja del Rio Puerco. Near the fault, these rocks are folded into a syncline and unconformably overlain by the flat-lying Ceja Member. In this area, the Loma Barbon Member is a tan, thin-bedded, fine sandstone interbedded with yellow-tan mudstone and gray, pebble-to-cobble gravel lenses with a clast assemblage composed of Mesa Verde sandstone (clasts up to boulder size), recycled siliceous rocks, red granite, Pedernal Chert, and varied volcanics. The clast assemblage is similar to

that of the overlying part of the Arroyo Ojito Formation. Locally conspicuous are white tuff and tuffaceous sandstone clasts, but no in situ occurrences of ash were seen. The unit is more than 10 m thick and is capped by a white calcic soil. No fossils have been discovered in this unit.

Ceja Member

Outcrops of the Ceja Member mainly lie east of the projected trace of the Sand Hill Fault, although the uppermost part extends west across the footwall. They represent the top of a coarsening-upward cycle that grades downward through interbedded gravel lenses and red-brown muddy sands to thin-bedded, red-brown, and yellow-tan fine sandstones and siltstones at the base of the outcrop. This unit can be traced virtually continuously north from its type section in The Rincon near I-40 (Kelley, 1977, p. 20) to Cañada Benevides (Fig. 5) and farther to Cañada Navajo in the northern Ceja. No fossils are known from this unit in the area under discussion, but Blancan fossils have been reported to the south (Tedford, 1981; Morgan and Lucas, this volume). It is capped by a persistent calcic soil.

Benevides Diatreme

Bryan and McCann (1937) and Wright (1946) mapped volcanics of Benevides Hill on the northwall of Cañada Benevides as "pre-Santa Fe andesitic tuff" and "Miocene(?) non-basaltic volcanoes," respectively. That these outcrops represented a diatreme was later recognized and briefly described by Kelley and Kudo (1978). The northern perimeter of this phreatomagmatic explosion structure is outlined by ring faults, but structures of the southern margin are obscured by eolian sand and alluvium. The explosion pit is filled with a complex mixture of basaltic tuff breccia, and various sized blocks of Cerro Conejo Member wall rocks that slid into the pit after eruption. The volcanic structure now stands 30 m above the surrounding region and is capped by 15 m of laminated, locally deformed, and radially inwardly dipping calcareous shale and fine-grained sandstone. These sediments accumulated in a maar lake confined by a tuff ring that is now completely eroded away. Bedded pebbly sands containing the siliceous assemblage and rare volcanic clasts, identified as the Cerro Conejo or Navajo Draw members, are involved in the drag folds of the ring faults of the northern perimeter and occur as clasts in the diatreme-fill, indicating a maximum late Miocene age for the explosion.

Pantadeleon Formation

This name is applied to the deposits of the youngest extensional basins of the Llano de Albuquerque (Connell et al., this volume). They represent the filling of local half-grabens by fluviatile and eolian sediments, often punctuated by calcic paleosols, reflecting the episodic activity on the hanging walls of major down-to-the-east faults. Several such basins are exposed near the western rim of the Llano de Albuquerque, and one is particularly well exposed along the East Sand Hill fault of Wright (1946) at the head of Cañada Benevides. Wright (1946, table 4) measured 20 m of intercalated brown sand and calcic soils (20 cycles in all) overlying the down-faulted Ceja Member in this local basin.

No fossils have been recovered from these local basin fills, but an air-fall tuff of distant source (Nomlaki Tuff, 3.3 ± 0.4 Ma, of the northern San Joaquin Valley, California: Sarna-Wojcicki et al., 1979) occurs in the type section of the unit deposited against the Zia Fault at the head of Arroyo Ojito (Connell et al., this volume). This date also gives a minimum late Pliocene age for the upper Arroyo Ojito Formation strata. Deposits contained in a similar structural setting adjacent to the County Dump fault near Albuquerque are of Pleistocene age (0.4 Ma minimum age: Machette, 1978).

STRUCTURE

The northern Ceja del Rio Puerco is cut by two large down-to-the-east faults that displace and locally fold the Neogene basin-fill. The westernmost faults are the northeast-trending Moquino fault and the related Navajo fault recognized by Bryan and McCann (1937) that juxtapose Cretaceous rocks of the Puerco fault zone against the Santa Fe Group deposits. To the east, trending in a northerly direction, the Sand Hill fault brings the youngest part of the Arroyo Ojito Formation on the east against the lower part of the same unit to the west. The vertical throw on the Moquino fault is at least 300 m, and that on the Sand Hill fault is also approximately 200 m (similar estimates were made by Bryan and McCann, 1937, table 1).

The Moquino fault has a complex history. Its northeast trend is parallel to down- to-the-west faults of the adjacent Laramide Puerco fault zone (Hunt, 1934, who labeled it the Fernando fault; Slack, 1975; Slack and Campbell 1976). Indeed, faults subparallel with the Moquino and Puerco fault zone exhibiting <30-m displacement extend into Cañada Pilares east of the Moquino fault, where they break only the Cretaceous Menefee Formation, are thus related to the Puerco fault zone province. In Cañada Moquino, the Moquino fault bends to the west and gives rise to a number of down-to-the-west faults of small throw (<30 m) that repeat the Mancos Shale–Crevasse Canyon Cretaceous sequence. At this same point, the Zia and Arroyo Ojito formations east of the fault are folded along axes approximately 45° to the Moquino fault and broken repeatedly by nearly parallel down-to-the-west faults that outline an anticlinal axis (Fig. 2). These structural relationships imply some left slip on this segment of the Moquino fault in post-Zia Formation time. Farther to the south, the Moquino fault appears to extend across the Puerco River (Fig. 1) where it continues to bring Zia and Arroyo Ojito Formation equivalents down against the Cretaceous strata along the western margin of the Apache graben.

To the north, the Moquino fault is truncated by the down-to-the-east Navajo fault of similar throw, but of north-northwesterly trend. The Navajo fault juxtaposes the Menefee and overlying Zia formations with Mancos Shale and Mesa Verde strata just as the Moquino fault does to the south. North of Cañada Navajo, the Navajo fault appears to turn northward to merge with the Garcia fault and its extension, the Tenorio fault, as suggested by Kelley (1977). An angular unconformity between the Arroyo Ojito and Zia Formation is strikingly exposed just east of the Navajo fault in Cañada Navajo. At this site, moderately northeasterly-dipping strata of the Piedra Parada Member (identified lithologically and paleontologically) are overlain by gently southeasterly-dipping upper Cerro Conejo Member rocks. Most of the Zia Formation and the lower part of the Cerro Conejo Member are missing at the exposed contact. Such intense local deformation on the Navajo fault segment of this rift-bounding fault system may have occurred at a time when accelerated subsidence of the basin as a whole was underway (May and Russell, 1994).

Thus, the Moquino fault and its related northwest-striking faults form the western structural margin of the northern Albuquerque basin. The northeast to northerly trend probably involved transformation of Laramide and younger faults into a sinuous boundary for the basin margin. Evidence of abrupt thinning of the Neogene section against the Moquino fault suggests that such a structure may have localized the pinch-out of the Santa Fe Group on the western side of the basin. For the most part, the Moquino fault is a high-angle, east-dipping, normal fault, but we have cited evidence above of transverse motion at some time in its Neogene history.

The Sand Hill fault (West Sand Hill fault of Wright, 1946) emerges from alluvial cover just south of the Sandoval County line to become an important high-angle (70–80°), east-dipping, down-to-the-east fault that brings the Ceja Member of the Arroyo Ojito Formation down against the upper part of the Cerro Conejo Member of the same formation. The throw is estimated to be approximately 200 m based on the stratigraphic separation of these units in their type area in Arroyo Ojito. The Sand Hill fault maintains a broadly sinuous northerly course into the head of Cañada Navajo, where it appears to turn to the northeast toward the Jemez fault. The same stratigraphic units are juxtaposed on this fault, demonstrating that the throw is maintained along this segment of the Ceja del Rio Puerco.

The Pilares fault zone is made up of short en-echelon segments of a

down-to- the-west system that lies between the Moquino and Sand Hill fault. This zone was misinterpreted by Kelley (1977) as having opposite throw, and he traced it much farther north and south of Cañada Pilares than we were able to do because of cover. Geologic mapping reveals that motion on the Pilares fault has been taken up by the associated strands that effectively dissipate the throw to the north, suggesting that this is a localized feature. The maximum throw is on the order of 200 m at the southernmost outcrop of the fault in the north wall of Cañada Benevides.

DISCUSSION

A comparison of the thicknesses of the total Santa Fe Group exposed in the Ceja del Rio Puerco (420 m) with correlative units to the north in Arroyo Ojito (1060 m) indicates that in all cases individual members are present but thinner in the Ceja del Rio Puerco, implying westward attenuation of the total section. No large hiatuses were detected between these units except for that between the Zia and Arroyo Ojito formations. A simple age-thickness plot (Fig. 6) indicates, within the limits of the data, that the rate of deposition of the Cerro Conejo Member remained relatively constant over 2.6 my (83 m/Ma), the data points indicating a high correlation ($r^2 = 0.971$). At the level of analysis (sample internal of 10–50 m), there were no significant hiatuses during deposition of this unit. Only three data points are available for the upper Zia Formation. Its rate of deposition is slightly lower (64 m/Ma), but comparable to that of the Arroyo Ojito.

Subsurface reconstructions (Russell and Snelson, 1994, and in more detail by Hawley and Whitworth, 1996) suggest that the basin-fill does not markedly increase in thickness eastward until it crosses the Sand Hill fault, the southward projection of the Jemez fault (approximately the "West Mesa fault" of Russell and Snelson, 1994). As depicted by data from the Shell Santa Fe Pacific No. 3 well, 5 km east of Cañada Navajo, the Santa Fe Group thickens to 1218 m, nearly three-times the total thickness of the outcrop along the Ceja. Lozinsky's (1988, 1994) petrographic analysis of deep wells penetrating the Santa Fe Group in the northern Albuquerque basin indicates that the major lithologic facies are discernable in the deep basin (Fig. 7). In particular, a well-sorted volcaniclastic sand unit with minor mudstones at the base is overlain by a heterogeneous suite of sands, clays, and silts corresponding, in a broad sense, with the Zia and Arroyo Ojito formations as defined in this study. Deeper in the basin, in the Shell West Mesa Federal No. 1 well, 18 km south-southeast of Shell Santa Fe No. 3, the thickness of the Arroyo Ojito Formation has more than tripled to 1646 m. Near the basin depocenter (Shell Isleta No. 2), the Zia correlative is replaced by red mudstone suggesting the presence of a persistent playa that may represent a significant facies of the Arroyo Ojito Formation as well as the Zia Formation.

May and Russell (1994) have cited the striking increase in thickness of the "unnamed member" of the Santa Fe Group (largely Arroyo Ojito Formation in the sense used here) as part of their evidence for a basin-wide acceleration of extension during the "late Miocene." Initiation of this subsidence is not well constrained temporally in the deep basin, but it could be expressed on the western margin as the regional hiatus and the change in sedimentary regime between the Zia and Arroyo Ojito formations noted on this paper. Systematic eastward thickening of units of the Arroyo Ojito Formation, and their coarsening upward character, observed along the Jemez River, also suggests acceleration of subsidence in the northern Albuquerque basin in late Miocene time.

SUMMARY

In this paper, we present a summary of our geological mapping, lithostratigraphic and magnetostratigraphic studies and the results of our analysis of the available paleontological collections with reference to the geologic ages for components of the Neogene geologic section exposed in the northern part of the Ceja del Rio Puerco, in southern Sandoval County, New Mexico. Contrasting sedimentary environments separate the two Miocene and Pliocene formations recognized in this area: the older, Zia Formation (175 m), whose type section lies 20 km north of the Ceja outcrops in the Rincones de Zia, is dominated by eolian deposits that represent a persistent transverse dune field and associated interdune, low energy fluviatile deposits, and red mudstone playas that existed in this part of the northern Albuquerque basin from early into early medial Miocene time (16–22 Ma). These deposits are disconformably overlain by the Arroyo Ojito Formation, a thicker (>245 m) sequence of fluviatile sandstone; mudstone and siltstones with rare (but laterally persistent) thin green mudstone and lacustrine carbonate units. This formation gradually coarsens upward to include prominent gravel units at the top of the exposed sequence. In the Rincones de Zia, the type section of the Arroyo Ojito Formation continues to coarsen and to incorporate a wide range of volcaniclastic and epiclastic debris derived from the Sierra Nacimiento and southern Jemez volcanic field immediately to the north of the Albuquerque basin and the Colorado Plateau to the west. In the Ceja del Rio Puerco, the basal Arroyo Ojito Member, the Cerro Conejo, is well exposed, and fossil mammal, magnetostratigraphic, and radiometric age data indicate that it nearly spans the medial Miocene (12–14 Ma).

The Santa Fe Group units exposed along the Ceja del Rio Puerco are less than half the thickness of correlatives in the Rincones de Zia to the northeast. Nevertheless, it is possible to recognize correlative units between these outcrops and to establish their age relationships, thus giving evidence that the Ceja outcrops are attenuated western equivalents of the deeper basin correlates in the northern Albuquerque basin. This flanking section thickens to nearly 5 km as it passes into the depocenter to the southeast.

A hiatus between the Zia and Arroyo Ojito formations in the Ceja was determined magnetostratigraphically and supported paleontologically as the loss of about 1.6 m.y. on the disconformity between these units. Paleontological evidence from the western Rincones de Zia, where those units are also seen in contact, shows a break in a similar position and of similar magnitude. A marked differential increase in thickness of the Arroyo Ojito over the Zia formation in the northern Albuquerque basin seems to reflect accelerated subsidence in the medial Miocene.

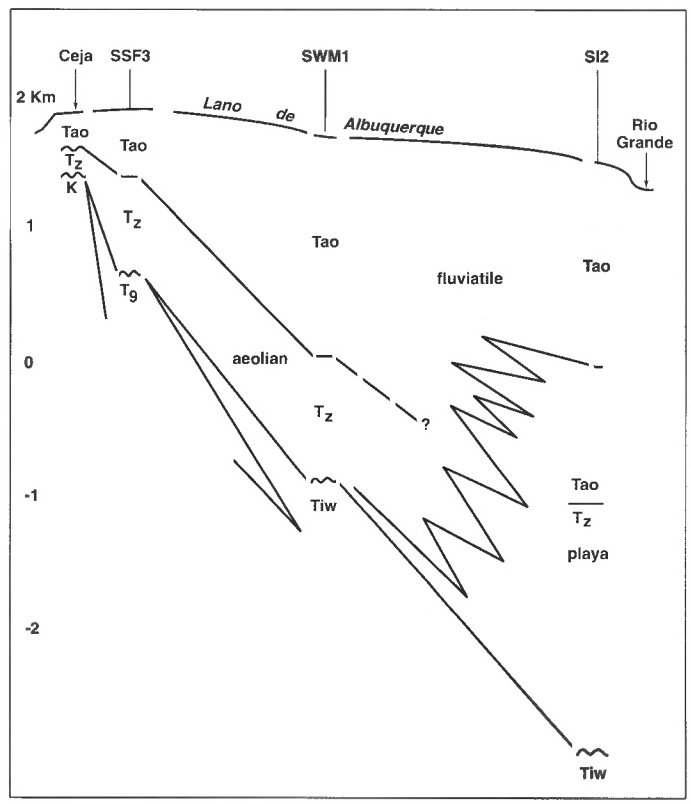

FIGURE 7. Thickness and facies changes of major stratigraphic units (Tao, Arroyo Ojito Formation; Tz, Zia Formation) and nature of underlying rocks (K, Cretaceous rocks; Tg, Galisteo Formation; Tiw, Unit of Isleta Well). Data from Lozinsky (1988). Wells abbreviated as in Figure 1.

This acceleration of subsidence would have been expressed by increased activity on the syn-rift faults, particularly those master breaks bounding the eastern side of the basin. Some western faults may have been activated by these events, for there is a step in the thickness of basin-fill across the Jemez fault and associated Sand Hill fault, that isolate the thin Santa Fe sections of the Ceja from the dramatically thickened basin-fill to the east. Movement on the Navajo fault has given rise to a striking local angular unconformity of the Arroyo Ojito on lower Zia strata.

The exposed syn-rift faults, the Moquino and Sand Hill faults, have only modest throws of a few hundred meters down to the east, nevertheless they form the structural boundary of the northern Albuquerque basin. The trend of the Moquino fault suggests reactivation of Laramide precursors, including evidence for continued lateral slip on segments of this structure. The Sand Hill fault strikes more northerly and may represent a structure originating with the development of the Santa Fe rift.

ACKNOWLEDGEMENTS

We again acknowledge our indebtedness to Ted Galusha and his field parties who for 10 years worked in the northern Albuquerque basin acquiring and documenting the fossil collections that now provide insight into the chronological and environmental significance of the basin-fill outcrops. The personal recollections and indefatigable archival work of his wife, Marian Galusha, have been essential to the project. From an early stage in our work Frank Kottlowski and John Hawley, now retired members of the New Mexico Bureau of Mines and Mineral Resources, have provided encouragement and financial aid. We are also indebted to the Don King family for access to their ranch lands, and to the help and kindness of their managers, Frank and Arbutus Parker. We have benefited in discussions of the geology of the basin with many workers. Sean Connell and John Hawley have helped us by reviewing this contribution.

REFERENCES

Barghoorn, S. F., 1981, Magnetic-polarity stratigraphy of the Miocene type Tesuque Formation, Santa Fe Group, in the Española Valley, New Mexico: Geological Society of America Bulletin, v. 92, p. 1027–1041.

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

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

Cande, S. C. and Kent, D. V., 1995, Revised calibration of the geomagnetic polarity time scale for the late Cretaceous and Cenozoic: Journal of Geophysical Research, v. 100, p. 6093–6095.

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

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

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

Hawley, J. W. and Whitworth, T. M., 1996, Hydrogeology of potential recharge areas for the basin- and valley-fill aquifer systems, and hydrogeochemical modeling of proposed artificial recharge of the upper Santa Fe aquifer, northern Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 402-D, 575 p.

Hunt, C. B., 1936, Geology and fuel resources of the southern part of the San Juan Basin, New Mexico. Part 2. The Mount Taylor Coal Field: U.S. Geological Survey, Bulletin 860-B, 80 p.

Kelley, V. C., 1977, Geology of the Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 33, 59 p.

Kelley, V. C. and Kudo, A. M., 1978, Volcanoes and related basalts of Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 156, 30 p.

Lozinsky, R. P., 1988, Stratigraphy, sedimentology and sand petrology of the Santa Fe Group and pre-Santa Fe Tertiary deposits in the Albuquerque basin, central New Mexico [Ph.D. dissertation]: Socorro, New Mexico Institute of Mining and Technology, 298 p.

Lozinsky, R. P., 1994, Cenozoic stratigraphy, sandstone petrology, and depositional history of the Albuquerque basin, central New Mexico; *in* Keller, G. R. and Cather, S. M., eds., Basins of the Rio Grande rift: Structure, stratigraphy, and tectonic setting: Geological Society of America, Special Paper 291, p. 73–81.

MacFadden, B. J. and Hunt, R. M., Jr., 1998, Magnetic polarity stratigraphy and correlation of the Arikaree Group, Arikareean (late Oligocene–early Miocene) of northwestern Nebraska; *in* Terry, D. O., Jr., LaGerry, H. E. and Hunt, R. M., Jr., eds., Depositional environments, lithostratigraphy and biostratigraphy of the White River and Arikaree Groups (late Eocene to early Miocene, North America): Geological Society of America, Special Paper 325, p. 143–165.

Machette, M. N., 1978, Bernalillo County Dump fault; *in* Hawley, J. H., ed., Guidebook to the Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources, Circular 163, p. 153–154.

Manley, K., 1978, Geologic map of the Bernalillo NW Quadrangle, Sandoval County, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ-1446, scale 1:24,000.

May, S. J. and Russell, L. R., 1994, Thickness of the syn-rift Santa Fe Group in the Albuquerque basin and its relation to structural style: Geological Society of America, Special Paper 291, p. 113–123.

Russell, R. R. and Snelson, S., 1994, Structure and tectonics of the Albuquerque basin segment of the Rio Grande rift: Insights from reflection seismic data; *in* Keller, G. R. and Cather, S. M., eds., Basins of the Rio Grande rift: Structure, stratigraphy and tectonic setting: Geological Society of America, Special Paper 291, p. 83–112.

Sarna-Wojcicki, A., Bowman, H. W. and Russell, P. C., 1979, Chemical correlation of some late Cenozoic tuffs of northern and central California by neutron activation analysis of glass and comparison with x-ray fluorescence analysis: U.S. Geological Survey, Professional Paper 1147, 15 p.

Slack, P. B., 1975, Tectonic development of the northeast part of the Rio Puerco fault zone, New Mexico: Geology: v. 11, p. 665–668.

Slack, P. B. and Campbell, J. A.,1976, Structural geology of the Rio Puerco fault zone and its relationship to central New Mexico tectonics; *in* Woodward, L. A. and Northrop, S. A., eds, Tectonics and mineral resources of southwestern North America: New Mexico Geological Society, Special Publication 6, p. 46–52.

Smith, G. A. and Kuhle, A. J., 1998, Hydrostratigraphic implications of new geological mapping in the Santo Domingo basin, New Mexico: New Mexico Geology, v. 20, p. 21–27.

Smith, G. A. and Lavine, A., 1996, What is the Cochiti Formation? New Mexico Geological Society, Guidebook 47, p. 219–224.

Spiegel, Z., 1961, Late Cenozoic sediments of the lower Jemez River region: New Mexico Geological Society, Guidebook 12, p. 132–138.

Tedford, R. H., 1981, Mammalian biochronology of the late Cenozoic basins of New Mexico: Geological Society of America Bulletin, Part 1, v. 92, p. 1008–1022.

Tedford, R. H., 1982, Neogene stratigraphy of the northwestern Albuquerque basin: New Mexico Geological Society, Guidebook 33, p. 273–278.

Tedford, R. H. and Barghoorn, S., 1997, Miocene mammals of the Española and Albuquerque basins, north-central New Mexico; *in* Lucas, S. G., Estep, J. W., Williamson, T. E. and Morgan, G. S., eds., New Mexico's fossil record 1: New Mexico Museum of Natural History and Science, Bulletin No. 11, p. 77–95.

Tedford, R.H., Skinner, M. F., Fields, R. W., Rensberger, J. M., Whistler, D. P., Galusha, T., Taylor, B. E., Macdonald, J. R. and Webb, S. D., 1987, Faunal succession and biochronology of the Arikareean through Hemphillian interval (late Oligocene through earliest Pliocene epochs) in North America; *in* Woodburne, M. D., ed., Cenozoic mammals of North America, geochronology and biostratigraphy: University of California Press, Berkeley, p. 153–210.

Wright, H. E., Jr., 1946, Tertiary and Quaternary geology of the lower Rio Puerco area, New Mexico: Geological Society of America Bulletin v. 57, p. 383–456.

Russ Clemons (on right side with campaign hat) explaining the intricate geology of southwestern New Mexico to participants on the 1988 NMGS trip. When you sit down to listen in New Mexico, you must to be very careful as was obvious to those seated and standing on the left (photograph courtesy of George Austin).