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D. J. Koning, S. D. Connell, F. J. Pazzaglia, and W. C. McIntosh

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D. J. Koning, 14193 Henderson Dr., Rancho Cucamonga, CA 91739; *S. D. Connell*, N.M. Bureau of Geology and Mineral Resources, Albuquerque Office, New Mexico Institute of Mining and Technology, 2808 Central Ave., SE, Albuquerque, NM 87106; *F. J. Pazzaglia*, Lehigh University, Department of Earth and Environmental Sciences, 31 Williams Dr., Bethlehem, PA 18015 ; *W. C. McIntosh*, New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, NM 87801

Abstract

The Ancha Formation contains granite-bearing gravel, sand, and subordinate mud derived from the southwestern flank of the Sangre de Cristo Mountains and deposited on a streamflow-dominated piedmont. These strata compose a locally important, albeit thin (less than 45 m [148 ft] of saturated thickness), aquifer for domestic water wells south of Santa Fe, New Mexico. Spiegel and Baldwin (1963) originally defined a partial type section for the Ancha Formation using a 49-m-thick (16-ft-thick) exposed interval of weakly consolidated, subhorizontal, arkosic strata on the southwest slope of Cañada Ancha. However, new geologic mapping, sedimentologic field studies, and geochronologic data indicate that the Ancha Formation should be restricted to the upper 12 m (39 ft) of Spiegel and Baldwin's type section, with the underlying strata being correlative to the upper Tesuque Formation. Because this 12-m (39-ft) interval is not well exposed at the type section, we designate four new reference sections that illustrate the textural variability of the Ancha Formation and its stratigraphic relationship with other rock units.

New $^{40}Ar/^{39}Ar$ data help constrain the age of the Ancha Formation. A bed of rhyolite lapilli (1.48 ± 0.02 Ma) that is temporally correlative to one of the Cerro Toledo events is recognized near the top of the section south of Santa Fe, New Mexico. A fluvial deposit interpreted to be inset against the Ancha Formation contains lapilli dated at 1.25 ± 0.06 Ma. These dates indicate that deposition of the Ancha Formation generally ended during early Pleistocene time. However, there is evidence suggesting that aggradation continued into the middle or late Pleistocene in mountain-front canyons east of the Santa Fe embayment. The age of the basal Ancha Formation is diachronous and ranges from ~2.7–3.5(?) Ma in the western Santa Fe embayment to ~1.6 Ma in the eastern embayment near the Sangre de Cristo Mountains.

The Pliocene–early Pleistocene aggradation that formed the Ancha Formation in the Santa Fe embayment occurred elsewhere in the Española and Albuquerque Basins, suggesting a regional climatic influence on deposition in the uppermost Santa Fe Group. A rise in base level due to late Pliocene volcanism and tectonism may be responsible for the significant differences of accommodation space, as reflected in deposit thickness, of the Santa Fe embayment compared with the piedmont regions to the south and the generally degraded upland regions to the north.

Introduction

The Ancha Formation underlies the Santa Fe embayment and is a distinct lithostratigraphic unit in the synrift basin fill of the Rio Grande rift. We use the term Santa Fe embayment in the physiographic sense for the southern arm of the Española Basin that extends south of the city of Santa Fe, New Mexico (Fig. 1). There, a west-sloping piedmont along the southwestern flank of the Sangre de Cristo Mountains overlies a north-plunging syncline developed in pre-Pliocene strata (Biehler, 1999; Grant, 1999; Koning and Hallett, 2000). The Santa Fe embayment is bounded by the granite-dominated Sangre de Cristo Mountains to the east, Galisteo Creek to the south, the Cerrillos Hills to the southwest, basalt-capped mesas of the Cerros del Rio volcanic field to the northwest, and the dissected upland underlain by the Tesuque Formation (Miocene) north of the Santa Fe River, called here the Santa Fe uplands (Figs. 1, 2). This piedmont ranges from approximately 1,830 to 2,190 m (6,004–7,185 ft) in elevation and has been incised by drainages associated with the Santa Fe River, Galisteo Creek, and the Rio Grande.

The Ancha Formation was originally proposed by Spiegel and Baldwin (1963, pp. 45–50) for arkosic gravel, sand, and silt, inferred to be from late Pliocene to Pleistocene in age, that lie with angular unconformity upon moderately tilted Tesuque Formation in the regional vicinity of Santa Fe. Spiegel and Baldwin (1963) included the Ancha Formation as the uppermost unit of the Santa Fe Group in the Santa Fe area. The upper boundary of the Ancha Formation in most of the Santa Fe embayment was defined by the Plains surface, a formerly extensive constructional surface preserved on interfluves (Spiegel and Baldwin, 1963; Koning and Hallett, 2000).

The Ancha Formation constitutes an important hydrogeologic unit in the Santa Fe embayment, where many communities locally rely on ground water. Although only about half of this unit is saturated with ground water, it is as much as ten times more permeable than the more consolidated and cemented Tesuque Formation (Fleming, 1991; Frost et al., 1994). Ground water generally flows west through this saturated zone from the Sangre de Cristo Mountains, but local recharge also occurs (Frost et al., 1994). Aquifer tests from various consultant reports listed in Koning and Hallett (2000) estimate hydraulic conductivity values from 2 to 130 ft/day (7.1 x 10^{-4} to 4.6 x 10^{-2} cm/s) in the Ancha Formation and from 1 to 20 ft/day (3.5 x 10^{-4} to 7.1 x 10^{-3} cm/s) in the underlying Tesuque Formation.

This paper redefines the Ancha Formation type section in light of new mapping, sedimentologic, and geochronologic data. We also designate four reference stratigraphic sections and summarize sedimentologic, surficial, and stratigraphic characteristics. In closing, we discuss the age of the Ancha Formation and possible tectonic and climatic influences on its aggradation.

Regional geology and previous work

The southern Española Basin contains several lithostratigraphic units relevant to the Ancha Formation. The Tesuque Formation underlies most of the Ancha Formation and is a pinkish-tan, arkosic, silty sandstone with minor conglomerate and siltstone that is commonly exposed in the central and eastern parts of the Española Basin north of Santa Fe. Galusha and Blick (1971) proposed the Chamita Formation for Santa Fe Group strata of Miocene age that unconformably lie above the Tesuque Formation north of the Santa Fe embayment. The Chamita Formation is generally brown or gray sand with subordinate gravel of mixed provenance; the gravel contains significant quartzite and other metamorphic clasts mixed together with granite, sedimentary, and volcanic clasts (Galusha and Blick, 1971; Tedford and Barghoorn, 1993). The Puye Formation is a coarse-grained, volcaniclastic, alluvial sequence on the western margin of the Española Basin that was shed primarily from the Tschicoma volcanic center during the Pliocene–early Pleistocene (Manley, 1976b; Waresback, 1986; Turbeville, 1986; Griggs, 1964; Waresback and Turbeville, 1990; Dethier, 1997; and Turbeville et al., 1989). An exposure in Bayo Canyon on the west side of the Rio Grande (Fig. 1) contains a ~5.3 Ma vitric tuff near the base of the Puye Formation; this tuff disconformably overlies Tesuque Formation strata containing an ash dated between 8.5 and 9.0 Ma and provides an age constraint for the base of the Puye Formation (WoldeGabriel et al., 2001). The Pliocene Totavi Lentil of the Puye Formation contains mostly rounded quartzite gravel from an ancestral Rio Grande (Manley, 1976b; Dethier, 1997; Griggs, 1964; and Purtymun, 1995). Waresback and Turbeville (1990) assign these gravels and related lacustrine deposits to the Totavi Formation. The Tuerto formation is a gravel and sand piedmont deposit, approximately 13–27 m (43–89 ft) thick, described by Stearns (1953). The Tuerto formation locally overlies the Ancha Formation south of Galisteo Creek and is locally buried by basalt flows of the Cerros del Rio volcanic field northwest of the Cerrillos Hills. North of and within the Santa Fe uplands, thin, 1–10-m (3–33-ft) thick gravelly terrace deposits occupy many topographic levels from the ridge tops down to the Rio Tesuque (QTg in Fig. 2). The Cerros del Rio volcanic field contains basalt and andesite flows, tephra, and phreatomagmatic sediment deposited during the late Pliocene to the early Pleistocene (Aubele, 1978; Bachman and Mehnert, 1978; Manley, 1976a; David Sawyer, pers. comm. 2001), but basaltic volcanism was primarily active between 2.2 and 2.8 Ma (Sawyer et al., 2001; WoldeGabriel et al., 1996).

Spiegel and Baldwin (1963) mapped the Ancha Formation throughout the Santa Fe embayment, estimated its thickness at 30–90 m (98–295 ft), and extended it northward into the Cañada Ancha drainage, a tributary of the Rio Grande (Fig. 1). At Cañada Ancha, they described and measured a partial type section for the Ancha Formation in a region of notably poor exposures. Subsequent geologic mapping in and near the Santa Fe embayment (Read et al., 1999 and 2000; Koning and Hallett, 2000; Koning and Maldonado, 2001; Bachman, 1975; Johnson, 1975; Booth, 1977; Kelley, 1978) and subsurface investigations (Frost et al., 1994; Grant Enterprises, Inc., 1998; Grant, 1999) indicate that the Ancha Formation of Spiegel and Baldwin (1963) can be mapped in a relatively consistent manner throughout the Santa Fe embayment and are in general agreement with the mapping of Spiegel and Baldwin (1963).

Delineation of Spiegel and Baldwin's (1963) Ancha Formation north of the Santa Fe embayment has been more problematic. Kelley (1978) and Galusha and Blick (1971) assigned Ancha Formation to surficial gravel deposits overlying erosion surfaces in and north of the Santa Fe uplands because of a presumed temporal overlap with the thick Ancha Formation deposits south of the Santa Fe River. Likewise, Miller et al. (1963) correlated ridge-capping gravel deposits in the northeastern Española Basin to the Ancha Formation. However, Manley (1979a) recommended abandoning this term for high-level gravel deposits in the northeastern Española Basin, including the Oso, Entrañas, and Truchas surfaces. Manley (1976a, 1979b) interpreted that the Ancha Formation underlies the Cerros del Rio basalts near Cañada Ancha, although Kelley (1978) did not delineate it there.

Methods

Exposures of late Cenozoic strata in or near the Santa Fe embayment (Fig. 1) were examined and described during the summers of 1999 and 2000. In addition, we examined outcrops along five stratigraphic sections. Sections were measured using a Jacob staff and Brunton compass or Abney level. Descriptions of the type and reference sections of the Ancha Formation and other Santa Fe Group deposits are in Connell et al. (in prep.); an abbreviated description of the Ancha Formation type section at Cañada Ancha is in Appendix 1. The base or top of stratigraphic sections was surveyed using a hand-held, non-differentially corrected GPS unit, except in cases where the section could be easily located on a topographic map (within an estimated ± 20 m [66 ft] horizontal distance). Colors were described using Munsell (1992) notation. We described sedimentary structures and textures using methods discussed in Compton (1985), Dutro et al. (1989), and Ehlers and Blatt (1982). Sandstone composition was visually estimated in the field and provisionally classified using the system of Folk (1974). Soil profiles were briefly described using methods and nomenclature of Birkeland (1999). We determined gravel clast composition from sieved pebble concentrates (>9.52-mm diameter clasts) at selected intervals or in situ at well-cemented outcrops. Paleocurrent directions were obtained from clast imbrications along with crossbed and channel orientations.

Radioisotopic dating was performed using the $^{40}Ar/^{39}Ar$ method at the New Mexico Geochronological Research Laboratory in Socorro, New Mexico. The data are discussed and interpreted in Winick (1999) and Peters (2000). Older and less precise K/Ar and fission-track ages are from previously published studies (Bachman and Mehnert, 1978; Manley and Naeser, 1977; Manley, 1976a).

Stratigraphy

Type section at Cañada Ancha

The Ancha Formation partial type section of Spiegel and Baldwin (1963) at Cañada Ancha was re-measured, re-described, and dated (Fig. 3). The lower part of these exposures (units 1–7, Appendix 1) contains more than 37 m (121 ft) of reddish-yellow to strong-brown, sandy pebble conglomerate to pebbly sandstone. Deposits are loose to moderately consolidated with local cementation by calcium carbonate. Beds are subhorizontal. Gravel generally contains 93–99% granite, ≤ 1% quartzite, 5% amphibolite and gneiss, and < 1% volcanic clasts. Only unit 7 contains significant cobbles and has as much as 3% quartzite. A 30-cm-thick (12-inch-thick) pumice bed (unit 5) lies approximately 46 m (151 ft) above the floor of Cañada Ancha. This bed is interpreted to be a primary fallout because it is composed of > 95% white, clast-supported, lapilli-size pumice. In contrast, reworked pumice in overlying beds is subordinate to arkosic sediment and generally coarse ash in size. Pumice clasts in unit 5 were dated at 8.48 ± 0.14 Ma using $^{40}Ar/^{39}Ar$ methods (Table 1).

To the east of Cañada Ancha, deposits assigned to the informal coarse upper unit of the Tesuque Formation are generally reddish-yellow to pink conglomerate and sandstone (Koning and Maldonado, 2001); these strata contain abundant granite with less than 1% quartzite, and paleocurrent data indicate westward paleoflow from the Sangre de Cristo Mountains. We assign units 1–7 of the Cañada Ancha section to the upper Tesuque Formation, principally because these units are lithologically similar to the coarse upper unit of the Tesuque Formation described in Koning and Maldonado (2001). Outcrops and clasts in hillslope colluvium described between these units at the Cañada Ancha section and good exposures of the coarse upper unit of the Tesuque Formation, located 3–4.5 km (2–3 mi) to the northeast, indicate physical continuity between the upper Tesuque Formation and the Cañada Ancha section (Koning and Maldonado, 2001). In addition, pumiceous beds that are similar to units 3, 5, and 6 of the Cañada Ancha section extend northward along strike from the Cañada Ancha section into sandstone and conglomerate strata of the coarse upper unit of the Tesuque Formation, where the average dip of the beds is 3° W (Fig. 2; Koning and Maldonado, 2001). Thus, mapping of these pumiceous beds supports our interpretation that units 1–7 correlate to the upper Tesuque Formation and are Miocene in age rather than correlating to the Ancha Formation. This is consistent with the 8.48 ± 0.14 Ma $^{40}Ar/^{39}Ar$ age for unit 5 at the Cañada Ancha section.

Significant lithologic and provenance differences are recognized between units 1–7 of the Cañada Ancha section and the Miocene Chamita Formation described by Galusha and Blick (1971) to the north. In the Cañada Ancha section, the preponderance of pink granitic clasts and paleocurrent data indicate westward paleoflow from the Sangre de Cristo Mountains. In

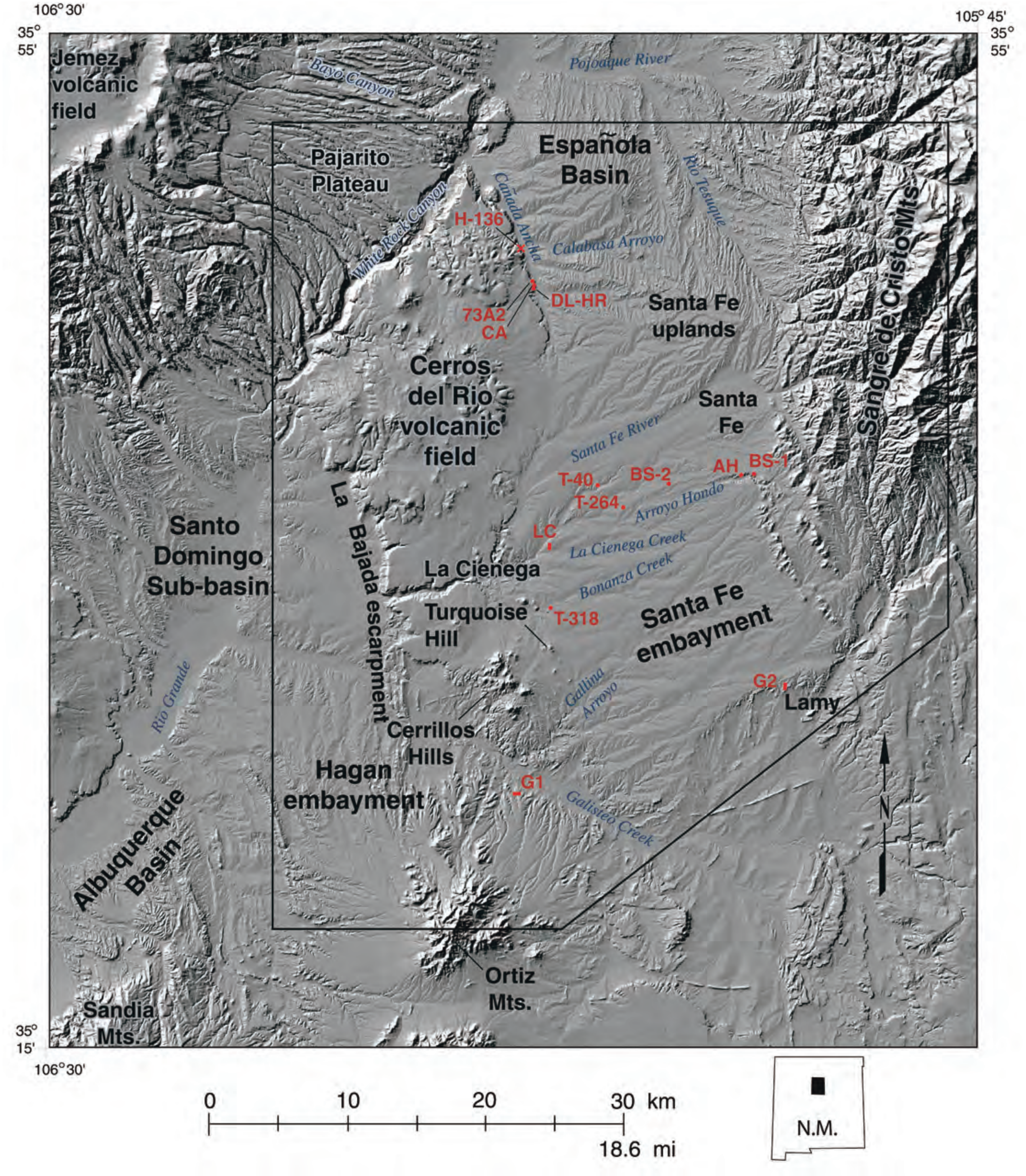

FIGURE 1—Shaded-relief map of the Santa Fe embayment, Hagan embayment, and Santo Domingo sub-basin of the Albuquerque Basin. Major geographic and physiographic features include the Cerros del Rio volcanic field, Santa Fe uplands, Sangre de Cristo Mountains, Ortiz Mountains, and Cerrillos Hills. Abbreviations of stratigraphic sections (shown by short red dash) include: Cañada Ancha (**CA**), La Cienega (**LC**), Arroyo Hondo (**AH**), and Galisteo #1 and #2 (**G1** and **G2**, respectively). Red x and label denotes field exposure H-136. Red circles denote tephra sample localities (Table 1). Black line encloses area shown in Figure 2. Base created from 30-m DEM data from the U.S. Geological Survey National Elevation Database (NED). Black outline shows the map area for Figure 2.

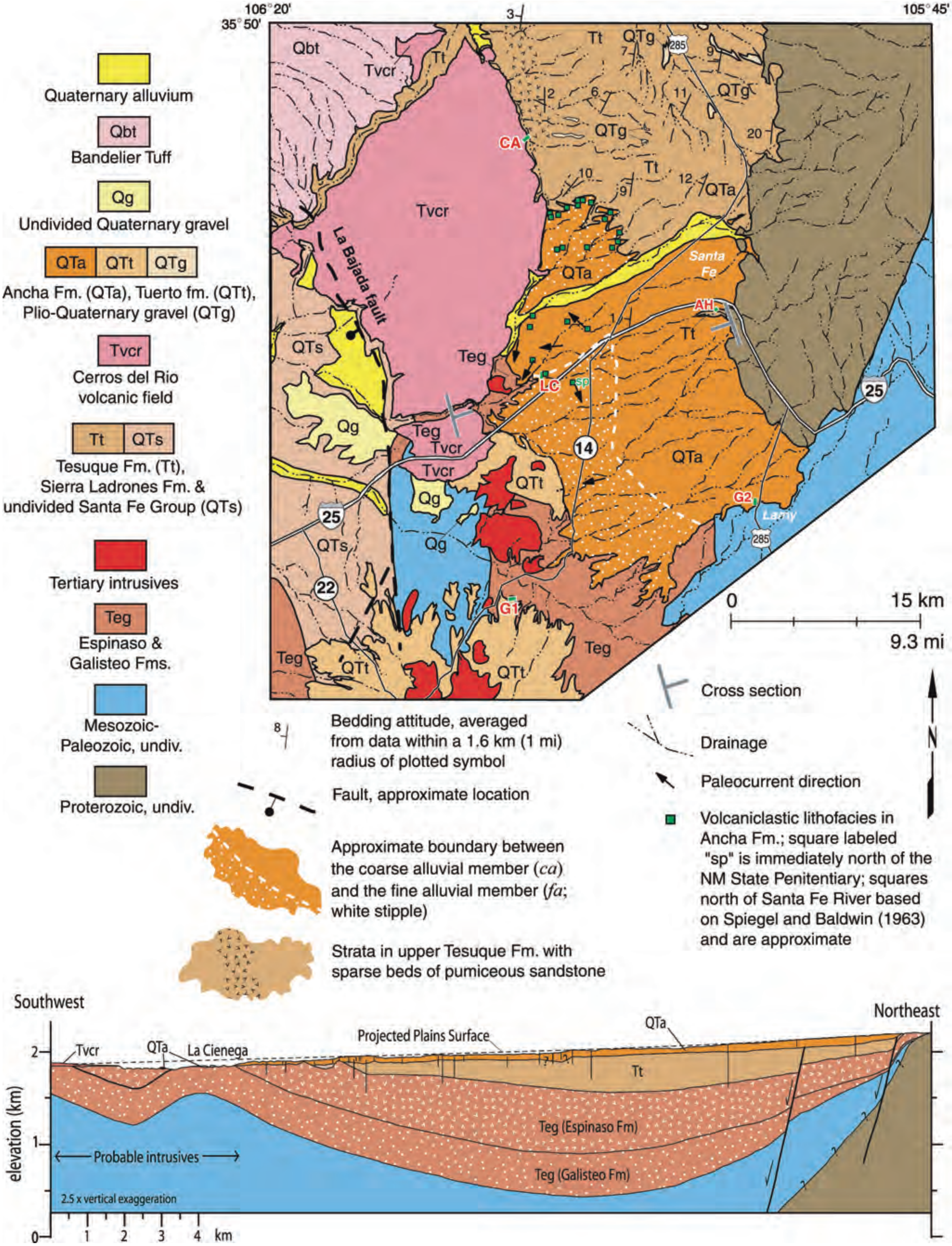

FIGURE 2—Simplified geologic map and northeast-southwest cross-section of the Santa Fe embayment and vicinity (modified from Koning and Maldonado, 2001; Read et al., 1999 and 2000; Koning and Hallett, 2000; Borchert and Read, 2002; Dethier, 1997; Kelley, 1978; Johnson, 1975; Bachman, 1975; Spiegel and Baldwin, 1963; Sawyer et al., 2001). Drainages and major highways shown for reference. Short vertical lines on the cross-section denote drill-holes (refer to Koning and Hallett, 2000; Read et al., 1999). On map, v-patterns denote strata in upper Tesuque Formation that contain sparse beds of poorly sorted, brownish to grayish, pumiceous sandstone and pebble conglomerate. Abbreviations of stratigraphic sections (shown by short green dash) include: Cañada Ancha (**CA**), La Cienega (**LC**), Arroyo Hondo (**AH**), and Galisteo #1 and #2 (**G1** and **G2**, respectively).

contrast, the Chamita Formation contains a diverse assemblage of clasts, including abundant quartzite, which indicates derivation of sediment from the north and northeast (Galusha and Blick, 1971; Tedford and Barghoorn, 1993). These observations, in addition to map data (i.e. Galusha and Blick, 1971, and Koning and Maldonado, 2001), do not support correlation of units 1–7 of the Cañada Ancha section with the Chamita Formation of Galusha and Blick (1971).

Overlying units 1–7 at the Cañada Ancha section is 6 m (20 ft) of loose and very poorly exposed, light yellowish-brown, gravelly arkosic sand containing 3–5% rounded quartzite cobbles and pebbles (unit 8, Appendix 1). A 2-m-thick (7-ft-thick) pumice bed underlying similar sediment at the same stratigraphic position as unit 8, exposed 200–250 m (656–820 ft) downstream of the Cañada Ancha section (Manley, 1976b, p. 22; K. Manley, pers. comm. 2002), returned a zircon fission-track age of 2.7 ± 0.4 Ma (Table 1; Manley and Naeser, 1977). This pumice is stratigraphically higher than unit 5 and provides a lower age constraint for the Pliocene sediment exposed near the type section.

Units 9–11 do not contain quartzite clasts but have scattered pebbles and cobbles of granite and basalt within silty sand and sandy silt (Appendix 1). These strata possess very thin, tabular, even-bedded basaltic lapilli from the Cerros del Rio volcanic field that are interpreted to represent fallout phreatomagmatic tephra (Koning and Maldonado, 2001). A 14-m-thick (46-ft-thick) basalt flow caps the sediment at the Cañada Ancha section (unit 12). Although this has not been dated, mesa-capping basalt and basaltic andesite(?) flows near this site have yielded K/Ar and $^{40}Ar/^{39}Ar$ ages of 2.0–2.5 Ma (WoldeGabriel et al., 1996; Manley, 1976a).

Units 8–9 are similar to deposits mapped to the north (Ta on the maps of Koning and Maldonado, 2001, and Dethier, 1997). These deposits are generally loose to weakly consolidated, brownish to yellowish, granitic sand and pebbles with 5–20% cobbles. Approximately half of the cobbles and 1–5% of the pebbles in these deposits are quartzite. Although the difference is subtle and not ubiquitous, these deposits may be distinguished locally from the underlying Tesuque Formation by their slightly more brownish color, looser overall consistence, relatively higher cobble content, and their relatively higher (by at least a factor of 2) quartzite clast content. The contact between these units and subhorizontal beds of the Tesuque Formation is a planar disconformity that is not obvious in the coarse strata. These deposits underlie the flows and phreatomagmatic deposits of the Cerros del Rio volcanic field and in places are interbedded with Cerros del Rio phreatomagmatic deposits. Extensive basaltic talus and colluvium generally cover these sediment units, but one good exposure demonstrating this interbedded relationship is observed 3.1 km (2 mi) downstream along Cañada Ancha, across from the mouth of Calabasa Arroyo (H-136 in Fig. 1). Along the western edge of the Santa Fe embayment to the south, the Ancha Formation is interbedded with fluvially reworked volcaniclastic deposits, probably phreatomagmatic in origin, of the Cerros del Rio volcanic field (see below). Thus, units 8 and 9 and the nearby correlative deposits of unit Ta (Koning and Maldonado, 2001; Dethier, 1997) occur in the same stratigraphic position and are of similar age to the Ancha Formation. We therefore interpret that units 8 and 9 and Ta represent a northern tongue of the Ancha Formation. Perhaps these units could correlate to one of the discontinuous, high-level, gravel-bearing terrace deposits mapped to the east in the Santa Fe uplands (QTg in Fig. 2).

Ancha Formation

The Ancha Formation is predominantly silty sand to pebbly sand with varying amounts of gravel derived from the Sangre de Cristo Mountains. Common colors range from brownish yellow, yellowish brown, and light yellowish brown to very pale brown (7.5–10YR hues). Strong-brown (7.5–10YR) clayey sand is subordinate and mostly found to the southwest. The sand is subangular to subrounded, poorly to well sorted, and arkosic. The sand is predominately fine grained in the southwest part of the embayment but is mostly medium to very coarse grained to the north and east near the front of the Sangre de Cristo Mountains. Gravel is generally clast supported, subrounded, and commonly contains 85–97% granite with sparse amphibolite, quartzite, and gneiss. Around the Cerrillos Hills, sparse Oligocene intrusive clasts derived from these hills are scattered in the Ancha Formation within 2 km (1.2 mi) from its contact with the Tuerto formation. Bedding is tabular (particularly for sand and mud) or lenticular (particularly for gravels), and very thin to thick. Sedimentary structures are sparse and only locally recognized. Buried soils in the Ancha Formation are generally not common. Where exposed, these buried intraformational soils generally contain calcic horizon(s) with stage II to III pedogenic carbonate morphology that are overlain by clayey Bt horizon(s). A veneer of sheetwash or colluvium commonly covers the Ancha Formation; good exposures tend to be limited to roadcuts and a few arroyo walls.

Muddy volcaniclastic deposits containing altered and multicolored tephra and basalt clasts are present as discontinuous or channel-shaped bodies as much as 4 m (13 ft) thick. These are locally recognized in the western Santa Fe embayment along the lower reaches of the Santa Fe River, Arroyo Hondo, and La Cienega Creek (Figs. 2, 3). These volcaniclastic lithofacies probably represent fluvially reworked phreatomagmatic deposits derived from the Cerros del Rio volcanic field.

The Ancha Formation is weakly to nondeformed, and its lower contact is an angular unconformity with tilted Miocene and Paleogene strata. The basal unconformity is locally well exposed in the bluffs north of Galisteo Creek and at the Arroyo Hondo reference section. Subsurface relief of the basal Ancha contact where it overlies distinctive Espinaso Formation near the western margin of the embayment (Fig. 2; Koning and Hallett, 2000) indicates that the unconformity is not everywhere a planar, beveled surface. Bedding is subhorizontal or dips less than 2° west-southwest. Where exposed, the Ancha Formation is not obviously cut by faults except for a locality 900–950 m (2,953–3,117 ft) northeast of the town of Lamy (Lisenbee, 1999).

Reference sections. We designate four reference sections (Fig. 3) to supplement the poorly exposed type section at Cañada Ancha. These sections also illustrate the textural variability of the Ancha Formation and its relationship with other rock units. Complete descriptive data is forthcoming (Connell et al., in prep.).

The Arroyo Hondo section (AH) is located on the north slope of Arroyo Hondo, 1.1 km (0.7 mi) west of the exposed bedrock of the Sangre de Cristo Mountains (Figs. 1–3). The sediment is loose and composed primarily of lenticular-bedded, locally cross-stratified sand and gravel channel deposits that unconformably overlie redder, tilted sandstone beds of the Tesuque Formation. The gravel includes poorly sorted pebbles, cobbles, and boulders and is composed of granite with 1–3% amphibolite and gneiss. Fluvially recycled pumice is dispersed in the sand and gravel in the lower 9.5 m (31 ft) of the Ancha Formation. We correlate this pumice to an outcrop of pumice lapilli located 120 m (394 ft) to the southwest that was mapped by Read et al. (1999 and 2000) as the Guaje Pumice Bed (lower Bandelier Tuff). Near the top of the section is a well-developed soil possessing a calcic horizon with stage III calcium carbonate morphology; this is overlain by 1.7 m (6 ft) of sandy gravel (unit 6) whose top has likely been eroded.

The La Cienega (LC) section includes 28 m (92 ft) of Ancha Formation (Fig. 3). The lower 16 m (52 ft; units 2–6) is composed of sand, silt, and clay. One 3.7-m-thick (12-ft-thick) interval (unit 4) contains local thin to medium, wavy, well-cemented beds. This horizontally bedded sediment is not correlated to the Tesuque Formation because a nearby outcrop of Tesuque Formation, located 0.6 km (0.37 mi) to the northwest, has indurated gravel beds dipping 26° southeast. The upper 13 m (43 ft) of the Ancha Formation contains sandy pebbles and cobbles composed of granite with 5–7% rounded quartzite and 1–2% amphibolite and gneiss. Locally within the upper Ancha Formation are 2–4-m-thick (7–13-ft-thick), non-laterally extensive, channel(?) deposits of reworked volcaniclastic sediment composed of massive muddy sand with 10–50% altered tephra and volcanic pebbles. Above the Ancha Formation, across a covered contact, lies approximately 3 m (10 ft) of Quaternary sand and gravel terrace deposits (Qao1 of Koning and Hallett, 2000).

Two sections, Galisteo #1 and #2, were described along Galisteo Creek, where the Ancha Formation clearly overlies tilted Paleogene and Cretaceous strata with distinct angular unconformity (Fig. 3, G1 and G2). The basal 10–13 m (33–43 ft) is a well-cemented pebbly sandstone and subordinate pebble to cobble conglomerate. Clasts are composed primarily of granite with minor limestone, schist, fine-grained to porphyritic volcanic and intrusive rocks, sandstone, siltstone, and quartz. The porphyritic intrusive and volcanic rocks are probably derived from the Ortiz Mountains and related Oligocene igneous centers. At Galisteo #2, the upper 7 m (23 ft) of strata is weakly cemented and poorly exposed. At section Galisteo #1, granite-bearing conglomerate and sandstone of the Ancha Formation is overlain by 5 m (16 ft) of Tuerto formation containing sand with porphyritic andesite- and monzonite-bearing gravel. Paleocurrent directions measured from trough cross-stratification in the lower Ancha Formation range from 270° to 280°.

Members. The texture of the Ancha Formation varies across the Santa Fe embayment, and this allows the differentiation of two informal members. The fine alluvial member (*fa*) is located south of I–25 in the western part of the Santa Fe embayment (Fig. 2). There, the Ancha Formation is generally composed of clayey to silty sand, with minor pebble lenses and coarse- to very coarse grained sand beds. This member is represented by units 2 through 6 of the lower La Cienega reference section (Fig. 3). Sediment coarsens to gravelly sand in the eastern part of the Santa Fe embayment and is informally called the coarse alluvial member (*ca*; Fig. 2), represented by the Arroyo Hondo reference section and unit 7 of the La Cienega reference section (Fig. 3).

Between the Santa Fe River and Arroyo Hondo drainages, the coarse alluvial member extends to the western margin of the Santa Fe embayment and consists mostly of sandy gravel with subequal proportions of pebbles to cobbles. Boulders compose approximately 2–5% of the total sediment volume in the west and as much as 20% in the east. The westward extension of the coarse alluvial member north of the fine alluvial member (Fig. 2) may represent deposition by an ancestral Santa Fe River. Quartzite clasts compose 1–15% of the gravel in this alluvium but are significantly sparser to the south.

Cementation zones. In the southern Santa Fe embayment, the Ancha Formation is divided into two zones based on cementation. Here, the lower Ancha Formation is called the well-cemented zone because it is well-cemented with sparry calcite and typically forms ledges or cliffs (Fig. 3, G1 and G2). The upper unit is called the weakly cemented zone; it typically forms poorly exposed slopes and is mostly covered by colluvium. These zones are generally not mappable at a scale of 1:24,000 but are distinctive in outcrop. The well-cemented zone is commonly recognized in the southern Santa Fe embayment near Galisteo Creek, where the Ancha Formation rests upon the Espinaso Formation, Galisteo Formation, and older strata. The weakly cemented zone is more laterally extensive than the well-cemented zone, particularly in the north where it lies upon deposits of the Tesuque Formation.

Plains surface. The top of the Ancha Formation is typically modified by erosion and is best preserved locally on broad interfluves between entrenched drainages in the Santa Fe embayment. The relatively flat surface preserved on these broad interfluves has been called the Plains surface by Spiegel and Baldwin (1963). Soils developed on the Plains surface locally exhibit < 25 cm (< 9.75 inches) thick, clayey Bt or Btk horizons underlain by 50 cm (20 inches) to over 100 cm (39 inches) thick calcic and siliceous Bk or Bkq horizons with stage II to III+ pedogenic carbonate morphology. Soil development is weaker where the Plains surface has been eroded or affected by younger deposition.

Near major drainages, such as Arroyo Hondo, erosion and subsequent deposition of younger inset stream deposits have locally modified the Plains surface. For example, exposures in railroad cuts near upper Arroyo Hondo show loose granitic sand and gravel disconformably overlying the Ancha Formation. The upper 1.7 m (7 ft) of sandy gravel at the Arroyo Hondo reference section (unit 6), overlying a well-developed soil with a stage III calcic horizon, may also represent a younger inset stream deposit (Fig. 3, AH). These thin (< 4-m-thick [< 13-ft-thick]) deposits are lithologically identical to the underlying Ancha Formation, locally strip the Plains surface and associated soils, and can be differentiated from the Ancha Formation only locally because of the lack of exposure. Radioisotopic age control is not available for these younger inset deposits.

Thickness. The Ancha Formation ranges from 10 to 90 m (33–295 ft) in thickness based on geologic map, drill-hole, and seismic data. Surface exposures of the Ancha Formation are commonly 10–40 m (33–131 ft) thick. Using drill cuttings and well logs to differentiate the Ancha and Tesuque Formations is difficult because of lithologic similarities between the two units. However, analysis of drill-hole data and surface geologic observations suggest that differentiating these formations may be possible locally based on slight textural changes, with the Tesuque Formation being slightly finer, and on pronounced local color changes, such as observed in the Arroyo Hondo reference section. In the upper reach of Gallina Arroyo, seismic refraction studies suggest that the Ancha Formation is approximately 30–90 m (98–295 ft) thick (S. Biehler, pers. comm. 1999). Ten to 11 km (6–7 mi) to the south, however, exposures along the bluffs north of Galisteo Creek near Lamy, New Mexico, are approximately 25–45 m (82–148 ft) thick (map data from Johnson, 1975, and Lisenbee, 1999). The difference between these two thickness estimates suggests a northward thickening of the Ancha Formation or may reflect the uncertainty in the geophysical modeling. Between the Cerrillos Hills and the Sangre de Cristo Mountains, the thickness of the Ancha Formation is relatively easy to constrain using well data because it overlies light- to dark-gray, lithic-rich sandstone and conglomerate of the Espinaso Formation; reddish-brown, clay-rich sandstone and mudstone of the Galisteo Formation; or limestone of the Madera Formation (Koning and Hallett, 2000; Grant Enterprises, Inc., 1998). In the southwestern Santa Fe embayment, east of the Cerrillos Hills, interpretation of well data indicates a thickness of 40–70 m (131–230 ft) for the Ancha Formation and approximately 30 m (98 ft) of relief on its lower contact with the Espinaso Formation (Koning and Hallett, 2000; American Groundwater Consultants, 1985). Similar subsurface relief is also interpreted for the western embayment east of La Cienega based on drill-hole data (Fig. 2). In the southeastern Santa Fe embayment near the Sangre de Cristo Mountains, well data suggest as much as 90 m (295 ft) of Ancha Formation (Grant Enterprises, Inc., 1998). The Tesuque Formation generally underlies the Ancha Formation in the northern Santa Fe embayment, and here it is difficult to confidently determine the thickness of the Ancha Formation and the underlying paleotopography.

Stratigraphic position. South of Galisteo Creek, the Tuerto formation overlies approximately 13 m (43 ft) of granite-bearing gravel and sand of the Ancha Formation (Fig. 3, G1). Measurements of cross-stratification and channel margins indicate a westerly paleoflow, suggesting an ancestral Galisteo Creek deposited the Ancha Formation at the Galisteo #1 section. Southern tributaries of Galisteo Creek near Cerrillos, New Mexico, drain the Ortiz Mountains, and this was probably true during the time of Ancha Formation aggradation. The composition of the sediment delivered by these tributary drainages

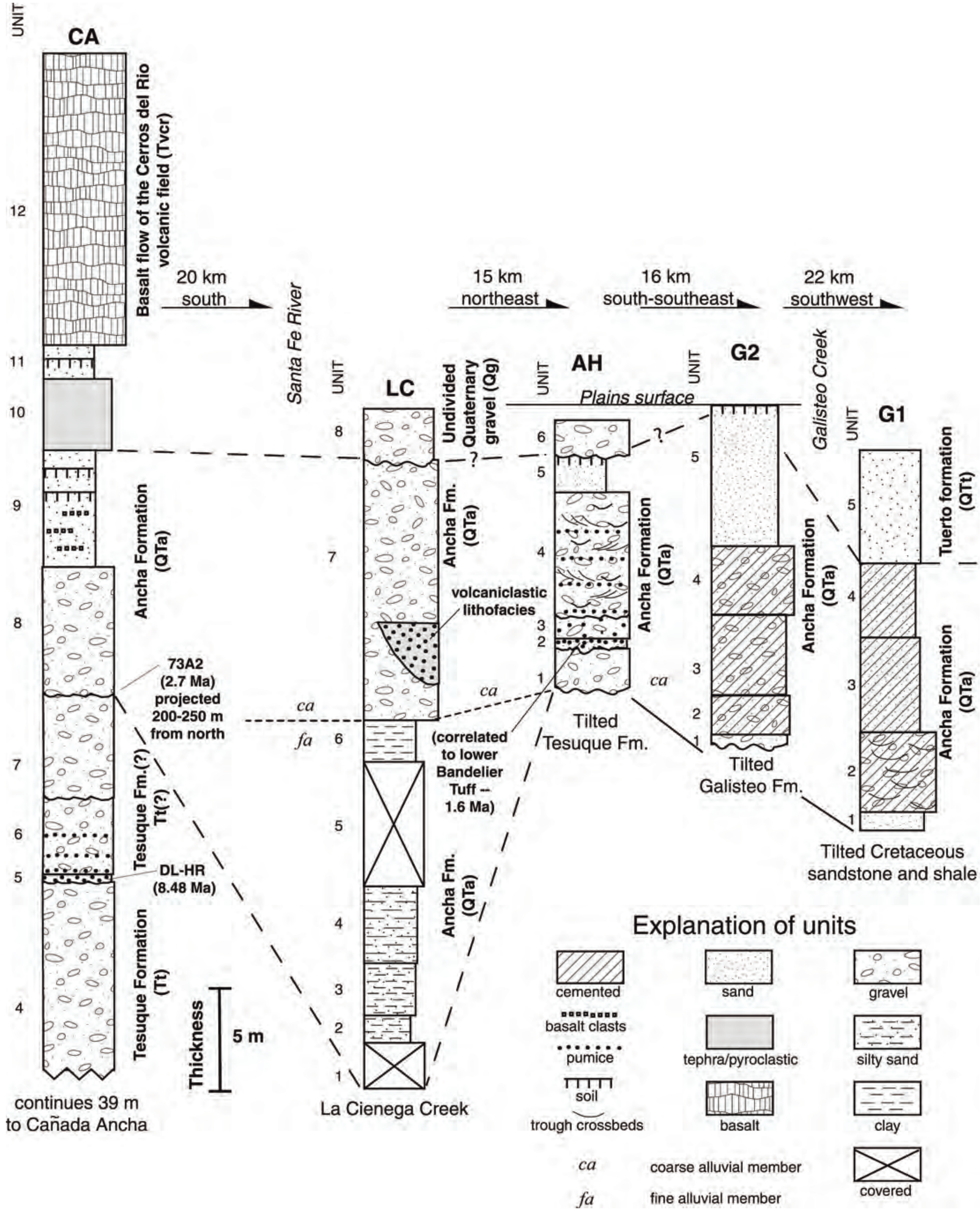

FIGURE 3—Type and reference stratigraphic sections of the Ancha Formation in the Santa Fe embayment. Sedimentologic descriptions of the Cañada Ancha type section (**CA**) are in Appendix 1. Descriptions of the La Cienega (**LC**), Arroyo Hondo (**AH**), and Galisteo #1 and #2 (**G1** and **G2**) sections are in Connell et al. (in prep.). Members labeled only for sections **LC**, **AH**, and **G2**; *ca* = coarse alluvial member; *fa* = fine alluvial member.

TABLE 1—Geochronologic data for late Tertiary and early Pleistocene tephras.

Sample no. (Fig. 1)	Map unit (Fig. 2)	Location, UTM, NAD83, zone 13S (m)	Description	NMGRL No.	WM K/Ca ratio ± N	Number of sanidine crystals (MSWD)	WM ± 2N age (Ma)
T-318	Qaϒ	N: 3,933,270 E: 400,520	< 10 cm lapilli bed interbedded with pebbly sand along south margin of Bonanza Creek.	51220	24.8 ± 1.3	2 (n.a.)	1.25 ± 0.06
T-264	QTa	N: 3,940,320 E: 406,300	White, 80 cm thick, pebbly pumice bed overlain by 50 cm of pumiceous sand in west roadcut just south of I–25.	51222	29.4 ± 6.7	7 (0.88)	1.48 ± 0.02
BS-2∝	QTa	N: 3,953,470 E: 404,420	Intersection of I–25 and Richards Avenue. About 1–6 m below eroded Ancha Fm. surface.	9778, 9779, 9780	34.5 ±12.4	38 (2.66)	1.61 ± 0.02
BS-1∝	QTa	N: 3,942,350 E: 415,900	About 1 m below eroded Ancha Fm. surface north of Arroyo Hondo.	9777	31.2 ± 16.5	13 (5.07)	1.67 ± 0.03
T-40	QTa	N: 3,941,940 E: 404,305	120 cm thick, white ash and pumice mixed with sand and sandy gravel in roadcut by aquaduct. Overlies soil with Bt horizon.	51221	60.8 ± 12.7	14 (0.82)	1.63 ± 0.02
DL-HR*	Tt	N: 3,956,680 E: 399,870	White lapilli bed ~20 m below basalt flow and ~9 m below QTa(?) at Cañada Ancha section.	6049	0.06 ψ	n.a.	8.48 ± 0.14
73A2**	QTa	N: 3,956,893 E: 399,807	2 m thick, white pumice interbedded in arkosic sand and granitic gravel near base of Ancha Fm. 200–250 m downstream of Cañada Ancha stratigraphic section.	n.a.	n.a.	n.a.	2.7 ± 0.4

Tephras analyzed by the New Mexico Geochronological Research Laboratory (NMGRL; Peters, 2000, and Winick, 1999) by the laser total fusion method, except for samples DL-HR* and 73A2** (see below). Locations of tephra sample localities given in Figure 1. Geographic coordinates (Universal Transverse Mercator, 1983 North American Datum) are rounded to the nearest 5 m (16 ft). Single asterisk (*) indicates sample analyzed by incremental-heating-age-spectrum method on hornblende grains. Double asterisk (**) indicates sample analyzed by zircon fission-track dating method (Manley and Naeser, 1977). (ψ) indicates K/Ca ratio measured from graphs because tabulated data were not available. (ϒ) Qa = Quaternary alluvium inset into QTa. (∝) = data from Read et al. (1999 and 2000).

would be correlative to the Tuerto formation. Thus, the arkosic sand and granitic gravel deposited by the ancestral Galisteo Creek, as observed at the Galisteo #1 section, would approximate the southern limit of the Ancha Formation.

Near the Santa Fe River, approximately 4–5.5 km (2.5–3.5 mi) north of La Cienega (Fig. 1), Ancha Formation strata with rounded quartzite pebbles are interbedded with basalt flows of the Cerros del Rio field. Furthermore, colluvial deposits overlying these basalt flows contain locally derived basaltic deposits mixed with fine- to coarse-grained sand composed of potassium feldspar and quartz interpreted to be derived from the Sangre de Cristo Mountains (Koning and Hallett, 2000). There is also local granitic lag gravel on basalt flows approximately 3 km (2 mi) west of La Cienega (D. Sawyer, pers. comm. 2001). These last two observations indicate that the Ancha Formation once extended over part of the eastern Cerros del Rio volcanic field, which is consistent with westward projection of the Plains surface (cross section in Fig. 2).

North of the Santa Fe River, the Ancha Formation pinches out against the Tesuque Formation but extends under the Cerros del Rio volcanic field (Figs. 1, 2). The Tesuque Formation in the Santa Fe uplands, particularly at Tano Point, is topographically higher (by as much as 80–100 m [262–328 ft]) than the northward projection of the Plains surface. The Ancha Formation extends north of the Santa Fe River along the southwestern flank of the Santa Fe uplands to the head of Cañada Ancha (Fig. 2). From here, it continues northwestward toward the Rio Grande as a 10–20(?)-m-thick (33–66-ft-thick) deposit under the Cerros del Rio volcanic field, as discussed previously.

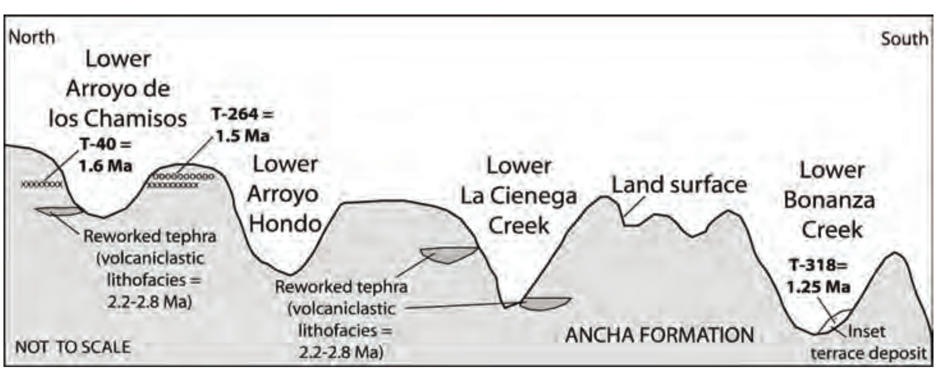

FIGURE 4—Schematic and generalized sketch showing stratigraphic relationships of tephra sample localities in the northwestern Santa Fe embayment. Vertically exaggerated and not to scale.

Pleistocene alluvial deposits with weakly developed soils are recognized near the mouths of major arroyos draining the front of the Sangre de Cristo Mountains. These deposits overlie or partly grade into the Ancha Formation but generally are not distinguishable from the Ancha Formation.

Age of the Ancha Formation

Tephras collected at five localities from early Pleistocene deposits in the Santa Fe embayment and one from a prominent pumice bed in the Cañada Ancha section (unit 5) were dated by the $^{40}Ar/^{39}Ar$ method and correlated to known tephras in the region (Table 1; Winick, 1999; Peters, 2000). The stratigraphic relationship for three tephra localities in the Santa Fe embayment are schematically illustrated in Figure 4. The five samples from the Santa Fe embayment yield weighted mean ages between 1.25 ± 0.06 Ma and 1.67 ± 0.03 Ma. The results of the $^{40}Ar/^{39}Ar$ analyses indicate that the samples are age equivalent to tephras derived from the neighboring Jemez volcanic field and are interpreted to include the Guaje Pumice Bed (1.61 Ma; Izett and Obradovich, 1994), Cerro Toledo Rhyolite (1.62–1.22 Ma; Spell et al., 1996), and Tsankawi Pumice Bed (1.22 Ma; Izett and Obradovich, 1994).

These tephra ages and stratigraphic relationships indicate that the Ancha Formation was aggrading in the north part of the embayment during early Pleistocene time. A bed of lapilli near the interchange of I–25 and NM–14 (sample T-264; Table 1, Figs. 1, 4) temporally correlates to one of the Cerro Toledo Rhyolite events. This tephra is approximately 7–11 m (23–36 ft) below the projection of the Plains surface. Located in the same general stratigraphic interval, tephra beds that are age equivalent to the Guaje Pumice Bed are recognized in at least two localities in the Santa Fe embayment (samples T-40, BS-2, and possibly BS-1; Table 1, Figs. 1, 4). These tephra are approximately 4–18 m (13–59 ft) below projections of the Plains surface. Other tephra in similar stratigraphic positions to these sampled beds, and thus probably Cerro Toledo Rhyolite or the Guaje Pumice Bed, are scattered throughout the northern part of the Santa Fe embayment. North of the middle reach of Arroyo Hondo, between samples T-264 and BS-2, these tephra are overlain by as much as 12–15 m (39–49 ft) of Ancha Formation, indicating significant deposition occurred at least locally after their emplacement. These tephra have not been recognized in the southern part of the embayment, suggesting that deposition ceased before 1.6 Ma in the south, deposits younger than ~1.6 Ma have been eroded, or that tephra correlative to the Guaje Pumice Bed or Cerro Toledo Rhyolite were not deposited in the south. In the lower reach of Bonanza Creek near the west side of the Santa Fe embayment, pumice lapilli from a deposit of pebbly sand, interpreted to be inset against the Ancha Formation, is approximately 20–25 m (66–82 ft) below the projected Plains surface (sample T-318; Table 1, Figs. 1, 4). A sample from a single pumice lapilli bed here yields a range of ages between 1.25 and 2.6 Ma. Seventy-five percent of the analyzed sanidine crystals of this youngest tephra yield ages between 1.48 and 2.6 Ma, indicating that significant recycling of older Ancha Formation deposits was underway by 1.25 Ma. Thus, the Ancha Formation generally ceased aggrading between 1.48 Ma and 1.25 Ma. The cessation was probably a response to incision of this area by drainages associated with the Santa Fe River. The Santa Fe River may have experienced an increase in incision rate at this time because it had succeeded in cutting through relatively resistant rocks of the Cerros del Rio volcanic field, or because of incision of the Rio Grande at White Rock Canyon (Dethier, 1997; Dethier and Reneau, 1995).

We assume that the southern Santa Fe embayment also ceased aggrading in response to incision during the early Pleistocene. However, this area is drained by tributaries to Galisteo Creek, such as Gallina Arroyo, which may have a different incision history than the Santa Fe River drainage system.

Regional stratigraphic relationships and radioisotopic ages constrain the lower age limit of the Ancha Formation to approximately 2.7–3.5(?) Ma. The base of the Ancha Formation is locally older than 2.2–2.8 Ma flows of the Cerros del Rio volcanic field (Stearns, 1979; Bachman and Mehnert, 1978; Koning and Hallett, 2000; WoldeGabriel et al., 1996; Manley, 1976a; Sawyer et al., 2001) and younger than the 8.48 Ma tephra in the Tesuque Formation at the Cañada Ancha stratigraphic section. Near the mouth of Cañada Ancha, the Ancha Formation (unit Ta of Dethier, 1997) lies below a basalt flow that gave an $^{40}Ar/^{39}Ar$ age of 2.49 ± 0.03 Ma (Dethier, 1997; WoldeGabriel et al., 1996). Here, these deposits are also interbedded with phreatomagmatic deposits of the Cerros del Rio volcanic field, which was active following 2.8 Ma (Bachman and Mehnert, 1978; WoldeGabriel et al., 1996; Sawyer et al., 2001). A 2.7 ± 0.4 Ma zircon fission-track age (Manley and Naeser, 1977) from a pumice bed probably correlative to the basal Ancha Formation (K. Manley, pers. comm. 2002) is consistent with the above data and indicates that the Ancha Formation near Cañada Ancha began aggrading at about 2.7 Ma.

In the northern Santa Fe embayment, there is evidence that the lower Ancha Formation is diachronous, with the base being older in the west and younger to the east. North of La Cienega, at least 25 m (82 ft) of Ancha Formation underlies a 2.3–2.8 Ma basalt flow of the Cerros del Rio volcanic field (Koning and Hallett, 2000), compared to 12 m (39 ft) at the Ancha Formation type section, so it is likely that the Ancha Formation near La Cienega is older than at Cañada Ancha, possibly extending back to 3.5(?) Ma. Near the mountain front at the Arroyo Hondo reference section, only 2 m (7 ft) of Ancha Formation underlies pumiceous sediment that correlates to the 1.6 Ma Guaje Pumice Bed (Fig. 3; Read et al., 2000). Thus, the lower age of the Ancha Formation probably ranges from 2.7 to 3.5(?) Ma in the northwestern Santa Fe embayment but may be as young as ~1.6 Ma to the east near the Sangre de Cristo Mountains.

Discussion

The stratigraphic relationships at the Cañada Ancha stratigraphic section, where Pliocene deposits correlative to the Ancha Formation unconformably overlie Tesuque Formation strata containing 8–9 Ma tephra, are similar to the previously mentioned exposure in Bayo Canyon (see top of p. 78; Fig. 1). This similarity suggests that the associated unconformity is regional in extent and that aggradation of the Tesuque Formation continued to about 8 Ma in the southern Española Basin.

We concur with most previous mapping of the Ancha Formation except for the inclusion of Oligocene monzonite or diorite gravels on the flanks of the Cerrillos Hills (e.g. Bachman, 1975). Rather, we propose that the Ancha Formation be restricted to deposits whose gravel contain more than 5% granite clasts. This serves to clearly differentiate porphyry- and monzonite-bearing Tuerto formation, which was deposited by streams draining the Cerrillos Hills and Ortiz Mountains, from the granite-bearing Ancha Formation, which was deposited by streams draining the southern Sangre de Cristo Mountains. Within and north of the Santa Fe uplands, topographically high-level stream gravels are preserved as terraces. The highest terrace deposits probably predate the Ancha Formation (Koning and Maldonado, 2001), but lower terrace deposits may be partly concomitant with Ancha Formation aggradation (Koning and Maldonado, 2001). However, it is difficult to correlate these terrace deposits among different drainages, and aside from a few dated terraces it is difficult to correlate these deposits with the Ancha Formation. Thus, we concur with Manley (1979a) that these upland gravel deposits should not be assigned to the Ancha Formation. This flight of relatively thin terrace deposits indicates long-term, post-late Miocene fluvial dissection for that landscape. In contrast, south of the Santa Fe River there appears to have been general aggradation, as manifested by the thicker Pliocene–early Pleistocene deposits preserved there. The Pliocene–early Pleistocene deposits in these two areas reflect markedly different environments, one of general aggradation and the other of landscape degradation, and this justifies the concept of keeping the Ancha Formation confined to the Santa Fe embayment and extending it northwest beneath the Cerros del Rio volcanic field.

Aggradation of the Ancha Formation probably began around 2.7–3.5(?) Ma and continued into the early Pleistocene, when regional incision occurred over much of the Santa Fe embayment. We interpret that large-scale aggradation likely began as a response to a relative rise in base level because the western, distal part of the basin appears to have aggraded significantly before the eastern margin. Later aggradation near the Pliocene–Pleistocene boundary appears to have been concentrated in the eastern Santa Fe embayment and may have been more influenced by sediment supply and discharge factors in the Sangre de Cristo Mountains than local base level control. The relative rise in base level at the beginning of Ancha Formation aggradation was probably driven by a combination of Cerros del Rio volcanism and to a lesser degree by Pliocene tectonism. Basalt flow thickness, geologic map relations, and $^{40}Ar/^{39}Ar$ ages in the Tetilla Peak quadrangle (Sawyer et al., 2001) suggest that particular Cerros del Rio basalt flows, dated at ~2.6–2.7 Ma, may have raised local base level by 20–50 m (66–164 ft). The projected base of the Ancha Formation is lower than the base of the basalts (Fig. 2, geologic cross section), so these flows may not wholly account for Ancha aggradation, but the top of the basalts is higher than the projected Plains surface. Moreover, Cerros del Rio volcanism proba-

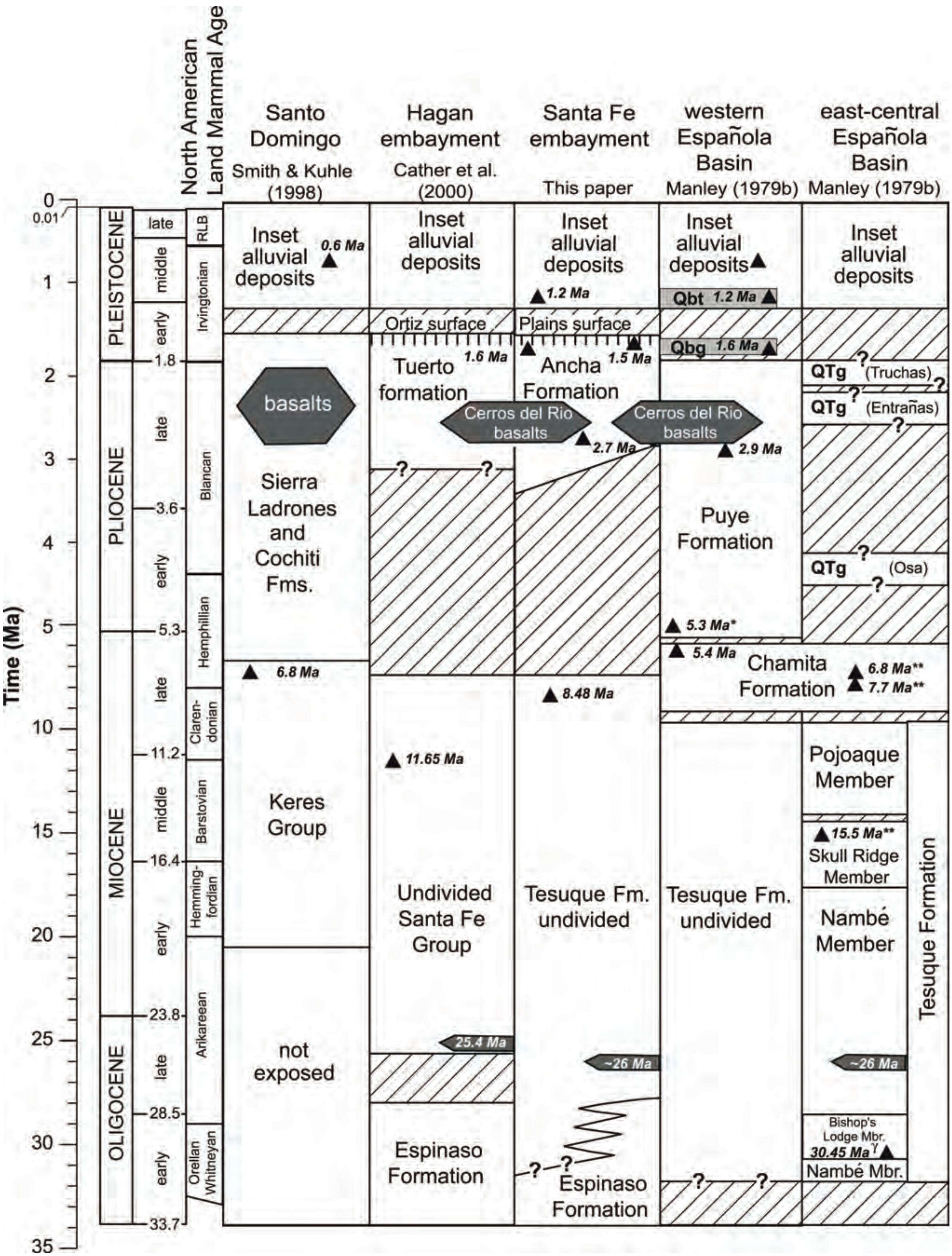

FIGURE 5—Correlation and comparison of stratigraphic units used in this report to stratigraphic sections in the Española and Albuquerque Basins. **QTg** = Quaternary and Tertiary high-level gravel deposits, **Qbt** = Tsankawi Pumice Bed, **Qbg** = Guaje Pumice Bed. Ages of Tsankawi and Guaje Pumice Beds from Izett and Obradovich (1994). Age followed by (*) from WoldeGabriel et al. (2001); ages followed by (**) from McIntosh and Quade (1995); age followed by (γ) from Smith (2000). Pattern composed of diagonal lines represents missing stratigraphic section and an associated unconformity.

bly did not affect deposition in the southernmost Santa Fe embayment because paleo-drainages there likely flowed into the ancestral Galisteo Creek and then around the basalt flows and into the Albuquerque Basin (Fig. 2).

Neogene tectonism appears to have restricted the aggradation and preservation of thick late Pliocene–early Pleistocene alluvial deposits to the Santa Fe embayment. The Santa Fe uplands to the north were likely a topographic high during Ancha Formation deposition, which explains why the Ancha Formation pinches out northward against them. The uplands may have formed by differential uplift of the rift hanging wall during the late Miocene–Pliocene (Koning and Maldonado, 2001; Smith and Roy, 2001). Between 2.7 and 0.5 Ma, as much as 500 m (1,640 ft) of offset occurred along the middle part of the La Bajada fault, and the footwall experienced relative uplift (Sawyer et al., 1999). Consequently, the Ancha Formation thins against the Espinaso and Galisteo Formations in the footwall west of La Cienega (Fig. 2, geologic cross section).

The Pliocene–Pleistocene Ancha, Puye, and Tuerto formations are generally gravelly and unconformably overlie older, generally tilted, and finer strata of the Santa Fe Group (Fig. 5). Pliocene sand and gravel successions are recognized in the upper Arroyo Ojito and Sierra Ladrones Formations in the adjacent Albuquerque Basin (Fig. 5; Connell et al., 1999; Smith and Kuhle, 1998; Maldonado et al., 1999). The coarse-grained character of these upper Santa Fe Group units, which are exposed over a wide area and in different structural basins, suggests that significant regional erosion and accompanying deposition may have been triggered by paleoclimatic factors that increased stream discharge and competence. However, we interpret that late Tertiary tectonic factors and emplacement of the Cerros del Rio volcanic field were largely responsible for the significant differences of stratal thickness between the Santa Fe embayment versus the piedmont regions near the Ortiz Mountains south of the embayment and the generally degraded upland regions to the north of the embayment.

Conclusions

Recent mapping and sedimentologic study in and near the Santa Fe embayment, along with $^{40}Ar/^{39}Ar$ dating of tephra layers, demonstrate that the lower three-quarters of the Ancha Formation partial type section of Spiegel and Baldwin (1963) encompasses the Tesuque Formation. Consequently, we restrict the type section to include 12 m (39 ft) of arkosic sediment located above the Tesuque Formation and below deposits and flows of the Cerros del Rio volcanic field. We also propose a granite clast content of 5% for differentiation of the granite-rich Ancha Formation from the granite-lacking Tuerto formation. Paleoclimatic influences may be responsible for deposition of regionally extensive, coarse-grained, Pliocene–early Pleistocene strata. However, preservation of thick deposits in the Santa Fe embayment may be attributed to a relative rise of local base level because of Cerros del Rio volcanic flows and Neogene tectonism. Based on $^{40}Ar/^{39}Ar$ dating of tephras, the Ancha Formation aggraded until regional incision occurred between 1.25 and 1.48 Ma.

Outcrop and subsurface data suggest that the Ancha Formation is generally 10–90 m (33–295 ft) thick and pinches out against older and topographically higher Tesuque Formation deposits north of the Santa Fe River. The suite of thin terrace deposits in the uplands north of the Santa Fe River should not be included in the Ancha Formation because of correlation ambiguities. Instead, the Ancha Formation should be restricted to Pliocene–early Pleistocene, arkosic, basin-fill sediment within the Santa Fe embayment and extending beneath the Cerros del Rio volcanic field.

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Appendix 1

Measured section of Ancha Formation partial type section of Spiegel and Baldwin (1963). Measured and described along west slope of Cañada Ancha, from floor of arroyo to top of cliff-forming basalt of the Cerros del Rio volcanic field by D. J. Koning on October 17, 2000. Base at N: 3,956,720 ± 20 m, E: 399,955 ± 20 m (zone 13, NAD 83), Horcado Ranch 7.5-min quadrangle, Santa Fe County, New Mexico. Colors determined dry. Numerical unit designations established upsection, but listed in descending stratigraphic order.

Unit	Description	Thickness (m)	(ft)
Basalt and pyroclastic deposits of the Cerros del Rio volcanic field (25 m):			
12.	Basalt; basalt flows underlain by 60–70 cm of planar laminated to thinly bedded, welded, sand-size lapilli; some beds are wavy; lower 0.5–3 m of basalt flows are flow breccia; sharp lower contact; no quartzite or granitic clasts are seen on top of the flows.	14.0	45.9
11.	Sandy silt, very pale brown (10YR 8/2); massive; contains 5% very fine to medium basaltic pebbles with 10% granitic pebbles; paleosol with a stage II calcium carbonate horizon is present 60–90 cm below top of unit; upper 60 cm is light brown (7.5YR 6/4) and contains a possible Bt soil horizon overprinted by contact thermal alteration from overlying basalt; sharp lower contact. Interpreted as a bioturbated eolian deposit.	1.6	5.2
10.	Basaltic lapilli, black; in very thin, even, and tabular beds or planar laminations; some beds are wavy; sand-size lapilli may be welded; minor bombs as much as 25 cm in diameter are on top of some beds and form load depressions on the underlying sediment; lapilli are poorly to well sorted and may contain as much as 20% granitic pebbles and sand grains; sharp lower contact. Interpreted as ash-fall deposits related to phreatomagmatic eruptions.	3.5	11.5
Ancha Formation (12 m):			
9.	Silty sand with 10–15% pebbles, pale-brown (10YR 6/3); massive and matrix-supported with 2–3% very thin to thin, planar beds or lenses of basaltic lapilli; pebbles are very fine to medium, subrounded, and have ~40% granite and ~60% basalt; sand is very fine to very coarse grained, poorly sorted, lithic-rich (~4:6, feldspar:lithics ratio), and subrounded (lithic grains) to subangular (feldspar grains); abundance of granitic clasts decreases to < 5% in the upper half of the unit; lower contact not well exposed; loose to moderately consolidated. The tops of two prominent buried paleosols are 89 cm and 200 cm below the top.	5.6	18.3
8.	Gravelly sand (very poorly exposed), light yellowish-brown (10YR 6/4); surface gravel are cobbles and pebbles consisting of 3–5% quartzite, 25% granite, and 70% basalt clasts (some or all of latter is slough from overlying units); sand is subangular to subrounded, arkosic, and loose with strong effervescence in dilute hydrochloric acid. Composition, stratigraphic position, and weakly consolidated nature suggest correlation to Ancha Formation of Spiegel and Baldwin (1963). Basal contact is generally covered, but presumably disconformable. Gravel contains slight increase in quartzite compared to underlying units.	6.1	20.0
Tesuque Formation (55 m):			
Note: Sand is very fine to very coarse, poorly sorted & subangular to subrounded, unless noted otherwise. Interpreted as fluvial piedmont deposits, unless noted otherwise.			
7.	Sandy cobble and pebble conglomerate, strong-brown to yellowish-red (5–7.5YR 5/6); very thin to thin and vague beds; gravel is clast supported, with subequal pebbles to cobbles and 1–3% quartzite, 5% amphibolite, <1% basalt(?) clasts; sand has trace to 10% clay, is moderately to poorly sorted, and arkosic; sand has 5% lithics but no basalt or pumice identified; scoured lower contact; loose to moderately consolidated. This is correlated to Tesuque Fm. because of gross similarities with unit 4; however, its cobbles and quartzite % are characteristic of Pliocene deposits in the vicinity.	5.0	16.4
6.	Pebbly sandstone and sandy pebble conglomerate; similar to unit 4 except unit is mixed with varying amounts of sand-size pumice (< 20%) and volcanic lithic (5–7%) fragments. Unit contains 10% slightly (< 5%) muddy and pebbly sand, pink to very pale brown (7.5–10YR 7-8/3); these beds are lenticular (over 10s of meters distance) and medium to thick (25–80 cm); mostly matrix supported; have 10–15% very fine to medium pebbles with ~60% granite and ~40% pumice; sand is poorly to moderately sorted and contains 20% pumice, 10% lithics, and 70% arkosic grains; sharp but relatively planar lower contact; generally loose to moderately consolidated.	3.7	12.0
5.	Pumice lapilli; white (5Y 8/1) pumice bed with scattered gravel; probably lenticular and lacks sedimentary fabric; clast supported; a:b axis ratio is 9–11:7–9 cm; pumice is mixed with 1–3%, 0.5–6-mm-diameter clasts of granite and rhyolite(?); lower contact is scoured; weakly to moderately consolidated; interpreted to be slightly fluvially reworked. Sample of pumice taken near N: 3,956,680 m; E: 399,869 m (UTM zone 13S, NAD 83) is dated using the $^{40}Ar/^{39}Ar$ method at 8.48 ± 0.14 Ma (NMGRL Lab#50512-01).	0.3	1.0
4.	Pebbly sandstone and sandy pebble conglomerate, reddish-yellow (5YR 6/6); lenticular and very thin to medium (2–35 cm) beds; gravel has about 5% cobbles and is clast supported, poorly to moderately sorted, and consists of 1% quartzite, 1–2% amphibolite, 97–98% granitic clasts, and trace dacite(?); sand is generally coarse to very coarse, moderately sorted, and has 5–10% lithic fragments (mostly basalt, pyroxene(?), or olivine), 10–15% quartz, 10–15% plagioclase, and 60–75% potassium feldspar; 3% of sediment is well cemented by 2–15-cm-thick, discontinuous layers of calcium carbonate (which are more common near the bottom of the unit); lower contact is scoured and slightly wavy (~5 cm of relief on lower contact); loose to weakly consolidated. Trace of sediment is yellowish-red (5YR 5/6) clayey sand.	27.0	88.6
3.	Pebbly sandstone, very pale brown (10YR 7/4) and slightly (< 5%) muddy; bed is lenticular and internally massive; clast and matrix supported; pebbles compose 5–10% of sediment, are poorly sorted, and consist of granitic clasts; sand consists of 3% pumice, 30–50% lithic fragments (basalt(?), pyroxene(?), olivine), 10–15% quartz, 20% potassium feldspar, and 15–40% plagioclase grains; moderately consolidated; lower contact slightly wavy and scoured (5–10 cm of relief).	0.4	1.3
2.	Pebbly sandstone and sandy pebble conglomerate, light-brown (7.5YR 6/4); beds are thin to medium (9–14 cm); gravel is clast supported, subangular to subrounded, poorly sorted, and consists of granitic clasts with trace basalt(?), trace amphibolite, and trace quartzite; arkosic sand; lower contact not exposed; loose.	0.5	1.6
1.	Covered; probably same as unit 2 except for one exposed bed of pumiceous sandstone about 11 ± 1 m above the base. This bed is a 30-cm-thick pebbly sand, pale-brown to light yellowish-brown (10YR 6/3–4), poorly sorted, and matrix-supported; about 10–15% granitic pebbles; a lithic-rich feldspathic wacke sand with 10–15% pumice grains. Base not exposed.	18.0	59.1