Stratigraphy and depositional trends in the Santa Fe Group near Espanola, north-central New Mexico: tectonic and climatic implications

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STRATIGRAPHY AND DEPOSITIONAL TRENDS IN THE SANTA FE GROUP NEAR ESPAÑOLA, NORTH-CENTRAL NEW MEXICO: TECTONIC AND CLIMATIC IMPLICATIONS

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Abstract. — Exposures of the Miocene Tesuque and Chamita Formations and interbedded tephra zones provide a record of extensional basin evolution in the northern Española basin of the northern Rio Grande rift. Geologic studies of these strata resulted in the definition of the Cuarteles Member (new name) in both the Tesuque and Chamita Formations. The Cuarteles Member is a 180 m-thick succession of light brown to reddish yellow to pink arkosic sandstone together with granite- and quartzite-bearing conglomerate derived from the Sangre de Cristo Mountains. It was deposited in an alluvial slope environment on the eastern basin margin. Six laterally extensive tephra-bearing intervals have been mapped in the study area and correlated between measured stratigraphic sections. The age of these tephra-bearing intervals are generally well-constrained and are used to estimate rates of stratal tilting and stratal accumulation during middle and late Miocene time. Additional geochronologic controls come from middle Miocene (late Barstovian) mammal fossils in these deposits. There is a noteworthy decrease in stratal tilt rates and sediment accumulation rates after about 13-14 Ma. This decrease is generally coincident with an overall coarsening of the stratigraphic succession and basinward progradation of deposits represented by the Cuarteles Member. The rate change in both stratal tilt and stratal accumulation rate data indicates a decrease in tectonic subsidence of the Española basin after about 13-14 Ma. The overall increase in the proportion of coarse channel deposits and clast sizes, in addition to the progradation of basin-margin detritus, after 13-14 Ma does not agree with previous half-graben models that relate tectonic subsidence with deposition. These sedimentologic changes could be the result of the Española basin transitioning from an underfilled to overfilled condition as the rate of tectonic subsidence decreased. Other factors besides tectonic changes that could have influenced this coarsening and progadation include: 1) a change in climate as inferred from the emplacement of a major dune field and marine proxy records, and 2) geomorphic changes in streams draining the Sangre de Cristo Mountains.

INTRODUCTION

The Santa Fe Group consists of siliciclastic basin fill associated with the Rio Grande rift (Spiegel and Baldwin, 1963). The Española basin is one of many rift-related basins filled by the Santa Fe Group (Kelley, 1956; Spiegel and Baldwin, 1963; Chapin, 1971), and is located in north-central New Mexico between the San Luis and northern Albuquerque (Santa Domingo) Basins. The Española Basin is bordered by the Sangre de Cristo Mountains on the east and a zone of east-down faults near the town of Abiquiu on the west (Fig. 1). In the central to northeastern parts of the Española basin, the Santa Fe Group is 1-5 km thick (Cordell, 1979; cross-sections of Kelley, 1978, Koning, 2003a, Koning and Aby, 2003, and Koning and Manley, 2003) and forms the primary aquifer for the city of Española, home to about 10,000 residents (Española Valley Chamber of Commerce, 2003, community profile brochure).

This paper describes excellent exposures of the Tesuque Formation east of Española, and introduces age control for these strata using fossil data and tephra studies. We correlate these strata to the west of the city (down-dip) using a cross-section and fence diagram. Distinctive tephra beds and zones allow us to analyze thickness changes between these marker beds. These thickness data are then used to calculate tectonic tilt rates and sedimentation rates for this part of the Española basin during the middle-late Miocene.

Geologic setting

The city of Española lies in the north-central part of the Española Basin (Fig. 1). The predominance of west-tilted strata in the central and eastern parts of the basin (e.g., Kelley, 1978) indicates that the basin here is a west-tilted half-graben. The Pajarito and Santa Clara faults, in addition to possible faults to the west buried by younger volcanic rocks, probably act as master faults for the half-graben (Golombek, 1983; Harrington and Aldrich, 1984; Baldridge et al., 1994; Koning et al., 2004b). A structurally shallower

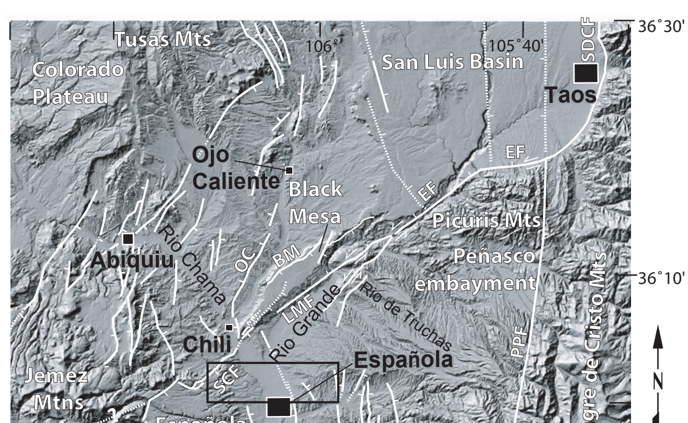

FIGURE 1. Location map of the northern Española and southern San Luis basins. The area of the geologic map of Figure 2 (the study area) is shown by the rectangle near the city of Española. Major geologic structures are shown by white lines, with the small perpendicular bars indicating throw direction of normal and normal-oblique faults. Important faults are abbreviated as: PFZ = Pajarito fault zone, SCF = Santa Clara fault, OCF = Ojo Caliente fault, BMF = Black Mesa fault, LMF = La Mesita fault, EF = Embudo fault, SDCF = Sangre de Cristo fault, and PPF = Pecos-Picuris fault.

part of the Española basin, having about 1 km of basin fill thickness (Baldridge et al., 1994), has been called the Abiquiu embayment and lies northwest of these faults. The Abiquiu embayment is bounded on its west side by a greater than 17 km-wide zone of east-down faults (Baldridge et al., 1994). Attitudes in the central Abiquiu embayment are variable, but strata consistently dip to the east-southeast near its eastern margin (Koning et al., 2004b).

Several structural domains marked by differences in dip magnitude are present in the Española basin east of the Pajarito and Santa Clara faults. However, dip direction is relatively consistent: south-southeast of Española beds dip to the west and east-northeast of Española beds dip to the northwest (Fig. 2; Koning, 2002; Koning et al., 2002; Koning, 2003a). Geologic mapping delineates numerous intrabasinal normal faults that have both east-down and west-down separation (Fig. 2; Galusha and Blick, 1971; Kelley, 1978; Borchert and Read, 2002; Koning and Maldonado, 2001; Koning et al., 2002; Koning, 2002; Koning, 2003a). In addition, there are many west-facing monoclines associated with west-down normal faults at depth, as suggested by comparison of geophysical and geologic map data to the south (Biehler et al., 1991; Koning and Maldonado, 2001).

The most important structural features within the study area, depicted in Figure 2, include the Santa Clara fault in the northwest and numerous northwest- and northeast-trending normal faults that have both east- and west-down separation. Six of these faults occur between the Martinez and Cuarteles stratigraphic sections (Fig. 2), including one informally referred to as fault A. The estimated maximum throw on fault A in Figure 2 is 25-30 m based on the displacement of the interpreted Pojoaque-Skull Ridge contact. Other faults are of comparable length and may have similar throw values. Beds in the study area dip northwest east of Española at magnitudes ranging from 9° to horizontal. West of Española, dip direction is more variable but generally to the west at magnitudes of 4-12°. West-southwest of the city is an intra-basinal structural and gravity low called the Santa Clara graben (Koning et al., 2004b).

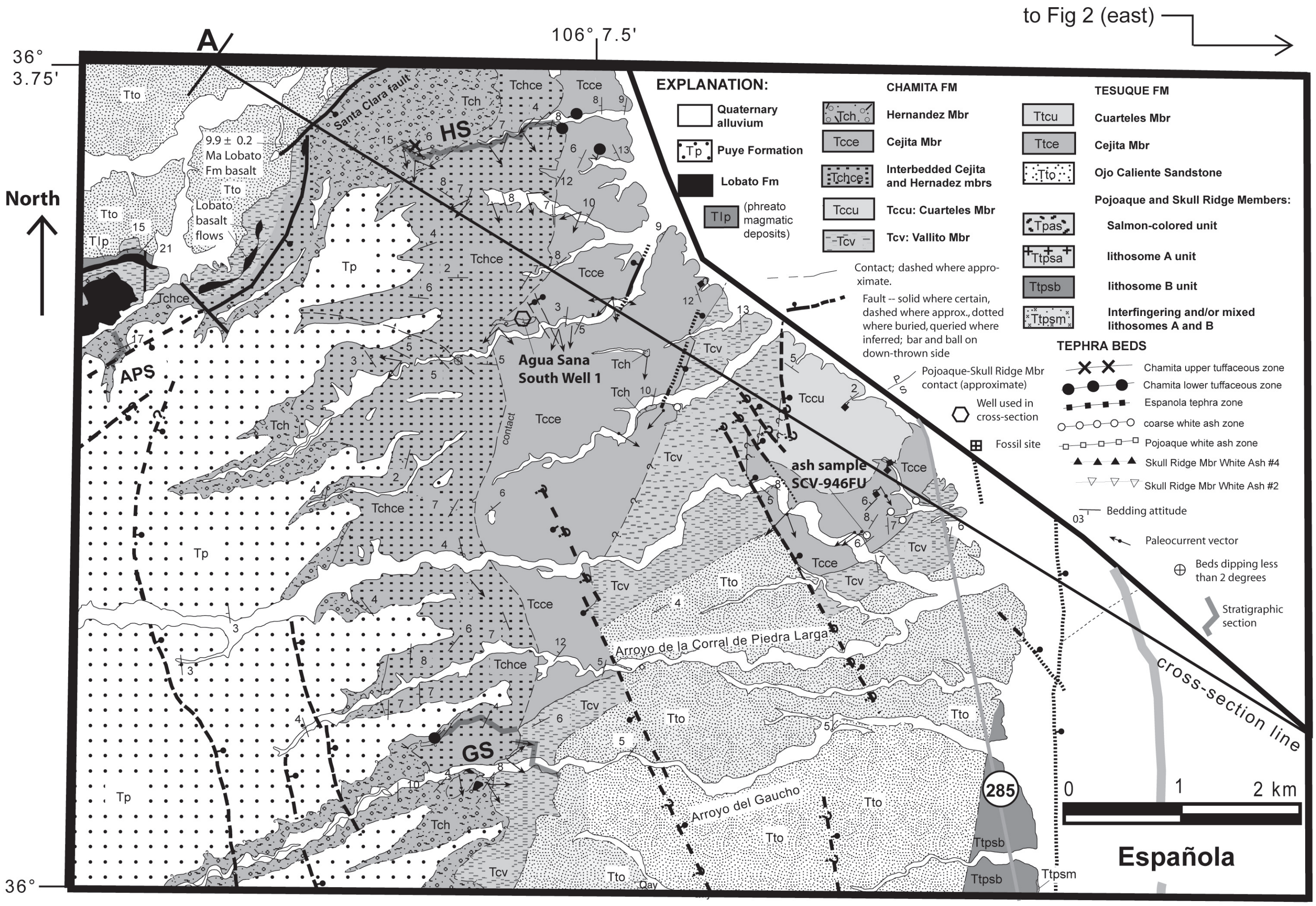

FIGURE 2. Generalized geologic map of study area illustrating major geologic units, structure, and stratigraphic sections (compiled from Koning, 2003a, Koning and Manley, 2003, and Koning et al., 2005). Quaternary terrace deposits are not shown. Stratigraphic sections shown in Figure 8 are labeled in bold and abbreviated as: MS = Martinez section, CS = Cuarteles section, LS = Llano section, and GS = Gaucho section. Two stratigraphic sections in the western part of the map mentioned in the text, but not included in Figure 8, are the Hernandez section (HS) and Arroyo de la Presa section (APS); these are discussed in Koning and Aby (this volume). The Chimayó section listed in Tables 2 and 3 is located 2.3 km east of the Martinez section and not shown on this map.

Previous stratigraphic studies

Galusha and Blick (1971) were the first to propose a comprehensive stratigraphic framework for the Española basin, in which the Tesuque Formation is unconformably overlain by the Chamita Formation. They subdivided the Tesuque Formation into several members, from oldest to youngest: Nambé, Skull Ridge, and Pojoaque Members on the east side of the basin, and the Chama-El Rito and Ojo Caliente Sandstone Members on the west side of the basin (Fig. 3). Later workers added the Dixon Member (Steinpress, 1980 and 1981), Cejita Member (Manley, 1976, 1977, 1979), and Cieneguilla Member (Leininger, 1982) to the Tesuque Formation in the northern Española basin. Cavazza (1986, 1989) subdivided the Pojoaque, Skull Ridge, and Nambé Members into lithosomes A and B; these two informal units interfinger laterally with one another (Figs. 4-5) and can be differentiated based on their composition, bedding characteristics, and paleoflow directions. No new members have been added to the Tesuque Formation in the Abiquiu embayment since Galusha and Blick (1971), but several sedimentologic and stratigraphic studies of the Chama-El Rito and Ojo Caliente Sandstone Members have been undertaken since their benchmark study (May, 1980, 1984; Ekas et al., 1984; Dethier and Martin, 1984; Dethier and Manley, 1985; Koning et al., 2004a; and Koning, 2004).

The name Chamita Formation has been applied to predominantly sand and gravel fluvial deposits that overlie the Ojo Caliente Sandstone of the Tesuque Formation – the latter is an easily identifiable cross-stratified eolianite (Galusha and Blick, 1971; Dethier and Manley, 1985; Aldrich and Dethier, 1990). However, its basal contact has been difficult to recognize and map east of the Rio Grande because the Ojo Caliente Sandstone only extends ~6 km east of this river (Koning, 2003b; Koning and Manley, 2003), leading Koning et al. (2004c) to suggest abandoning the term. More recent mapping of much of the basin west of the Rio Grande and north of Española (Koning, 2004; Koning et al., 2005) indicates that the lower contact of the Chamita Formation

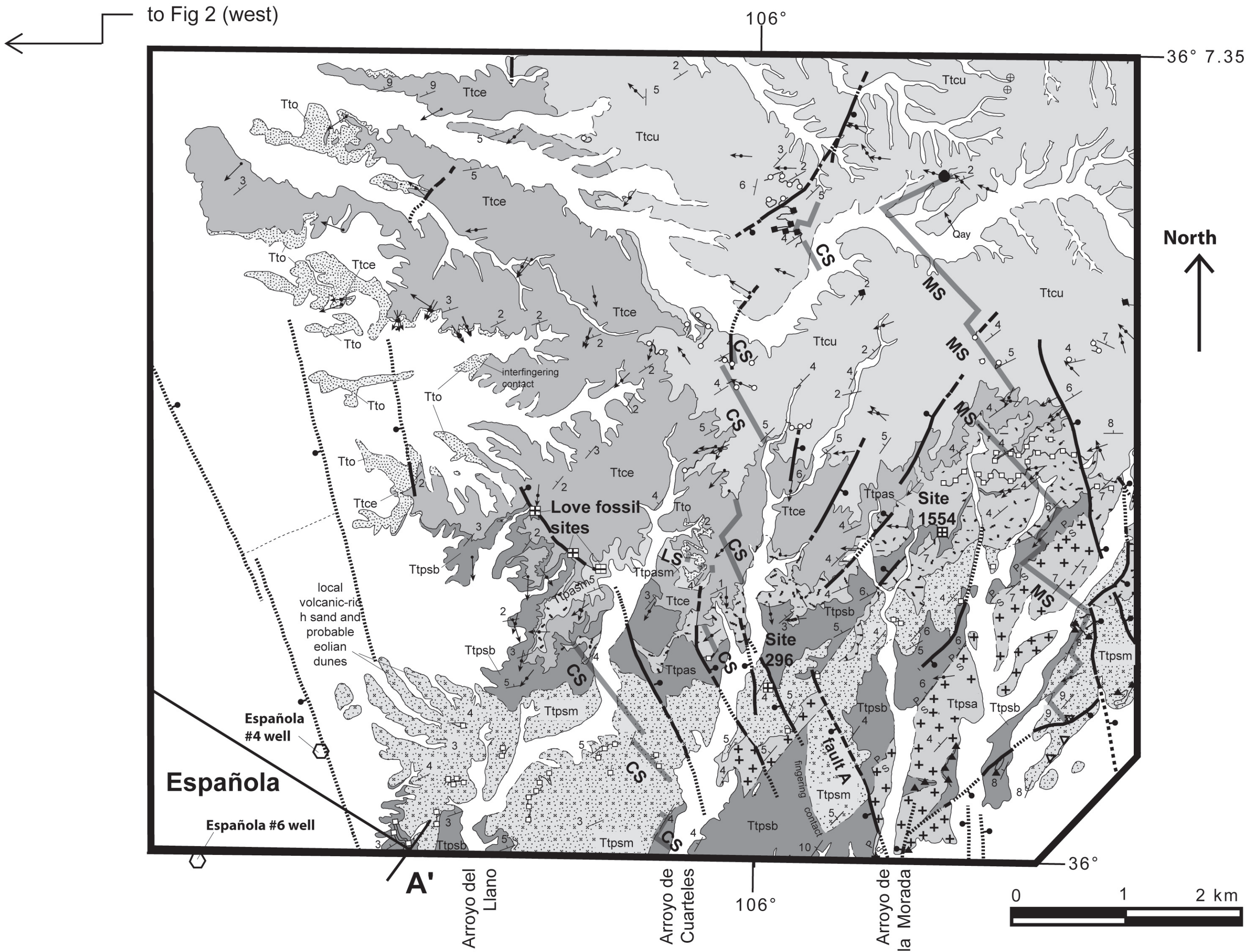

FIGURE 2. Continued.

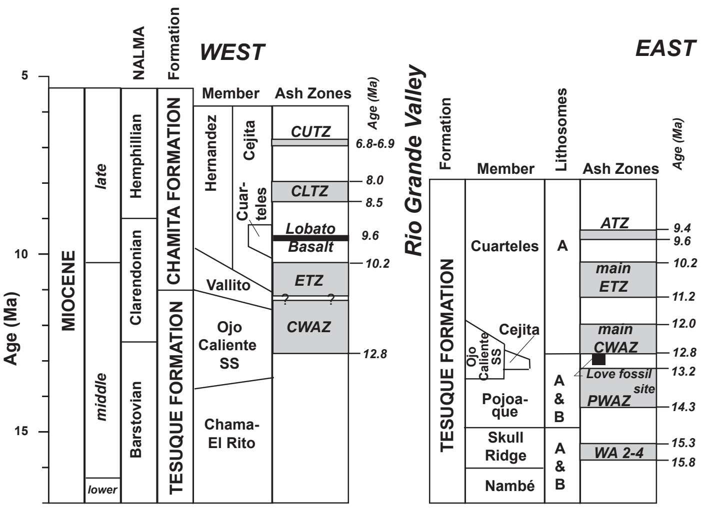

FIGURE 3. Schematic diagram illustrating the age relations of middle to upper Miocene lithostratigraphic units and tephra of the north-central and northeastern Española Basin. WA 2 = Skull Ridge White Ash #2, WA 4 = Skull Ridge White Ash #4, PWAZ = Pojoaque white ash zone, CWAZ = coarse white ash zone, ETZ = Española tephra zone, CLTZ = Chamita lower tuffaceous zone, CUTZ = Chamita upper tuffaceous zone, NALMA = North American land mammal "age."

can be readily distinguished there because of the relatively ubiquitous presence of the Ojo Caliente Sandstone. The Chamita Formation is thus retained for predominantly sand and gravel fluvial strata west of the Rio Grande, upper middle to upper Miocene in age, which overlie the Ojo Caliente Sandstone (Koning and Aby, this volume). However, time-equivalent strata are called Tesuque Formation east of the Rio Grande between Velarde and Española.

METHODS

Five stratigraphic sections were measured using an Abney level and Jacob staff. These include the Llano, Cuarteles, Martinez, and Chimayó sections east of Española (Fig. 2) plus the Gaucho section west of Española. Of these five, the Cuarteles section provides a useful representation of the stratigraphy near Española (Fig. 6). Descriptive data for the other sections east of Española are provided in Koning (2003a) and Koning and Manley (2003); the Gaucho section is depicted in Koning and Aby (this volume) and its full description provided in Koning et al. (2005). We also utilized drill cuttings descriptions and borehole geophysical logs from the Española #4, #6, #8, and #9 municipal supply wells and the Agua Sana South Well #1 (Shomaker and Assoc., unpublished consultant reports), in order to construct a northwest-southeast cross-section across the study area (Fig. 7). Figure 2 depicts the locations of these stratigraphic sections (except the Chimayó section), wells (except Española #8 and #9), and cross-section relative to the mapped geology of the area (Koning, 2003a; Koning and Manley, 2003; Koning et al., 2005).

In order to estimate the degree of tectonic tilting with time, we constructed a fence diagram (Fig. 8) of the stratigraphic sections listed above. Westward tilting rates (degrees per million years) were calculated based on thickness variations of stratigraphic intervals bounded by certain marker beds or zones (Fig. 9).

STRATIGRAPHY

Biostratigraphy

Fossil vertebrates collected in the eastern study area between 1985 and 2003 include several species of mammals that are typical of late Barstovian North American land mammal "age" (NALMA) faunas in the Española basin (Table 1**;** the Pojoaque Fauna of Tedford et al., 2004). The most fossiliferous of these sites are the Love fossil sites (Fig. 2; NMMNH sites L-5915-5920), located northeast of Española and west of Arroyo del Llano (called First Wash in Galusha and Blick, 1971). Fossils from the Love fossil sites were collected by David Love (NM Bureau of Geology and Mineral Resources) in 1985. Age-diagnostic mammals from the Love Fossil sites include: the small canid *Leptocyon vafer*, the larger borophagine canid cf. *Aelurodon* sp., the beaver *Monosaulax pansus*, the antilocaprids *Meryceros crucensis* and *Ramoceros ramosus*, and the gomphotheriid proboscidean *Gomphotherium productum*. Most of the fossils collected from site SCV-296 (Fig. 2; NMMNH sites L-5910-5912), on the east side of Arroyo de Cuarteles (called Second Wash in Galusha and Blick, 1971), are fragmentary and not diagnostic at the species level, although the tentative identifications of *Leptocyon*, a primitive hipparionine horse (cf. *Neohipparion coloradense*), and *Meryceros* also support a late Barstovian age. A mandible of a horse from site SCV-1554 (Fig. 2; NMMNH site L-5913) is identified as the late Barstovian species *Neohipparion coloradense*.

Tedford et al. (2004) gave an age range of about 12-14.5 Ma for the Pojoaque Member of the Tesuque Formation in the Española basin. Most fossils in this member have generally been collected from below the Pojoaque white ash zone (discussed below), although some have been collected within this zone (e.g., fig. 24 of Galusha and Blick, 1971). This lower part of the Pojoaque Member has produced the Pojoaque fauna of late (but not latest) Barstovian age, within magnetic polarity chrons 5AC and 5AB that range from 13.3 to 14.3 Ma (Barghoorn, 1981; Tedford and Barghoorn, 1993). Typical late Barstovian mammals from the Pojoaque fauna include several species found in the study area sites: the canine *Leptocyon vafer*, the borophagine *Aelurodon* (either *A. ferox* or *L. stirtoni*), the castorid *Monsaulax pansus*, the horse *Neohipparion coloradense*, the merycodont antilocaprids *Meryceros crucensis* and *Ramoceros ramosus*, and the gomphothere *Gomphotherium productum*. Several of the species listed above continue into younger early Clarendonian faunas in the Española Basin, such as the Round Mountain Quarry found at the base of the overlying Chamita Formation west of the Rio Grande, but the association of these taxa is more typical of the late Barstovian (Tedford and Barghoorn, 1993; Tedford et al., 2004). Although species identified at the Love fossil sites are broadly correlative to the classic Pojoaque fauna of 14.3-13.3 Ma (early late Barstovian), we do not have a sufficient number of specimens to determine whether their age is early late Barstovian or latest Barstovian. The Love fossil sites are 50 m above the Pojoaque white ashes and within the Cejita Member; this stratigraphic position strongly suggests the fossils there are latest Barstovian. Other sites in poorly fossiliferous strata of the upper Tesuque

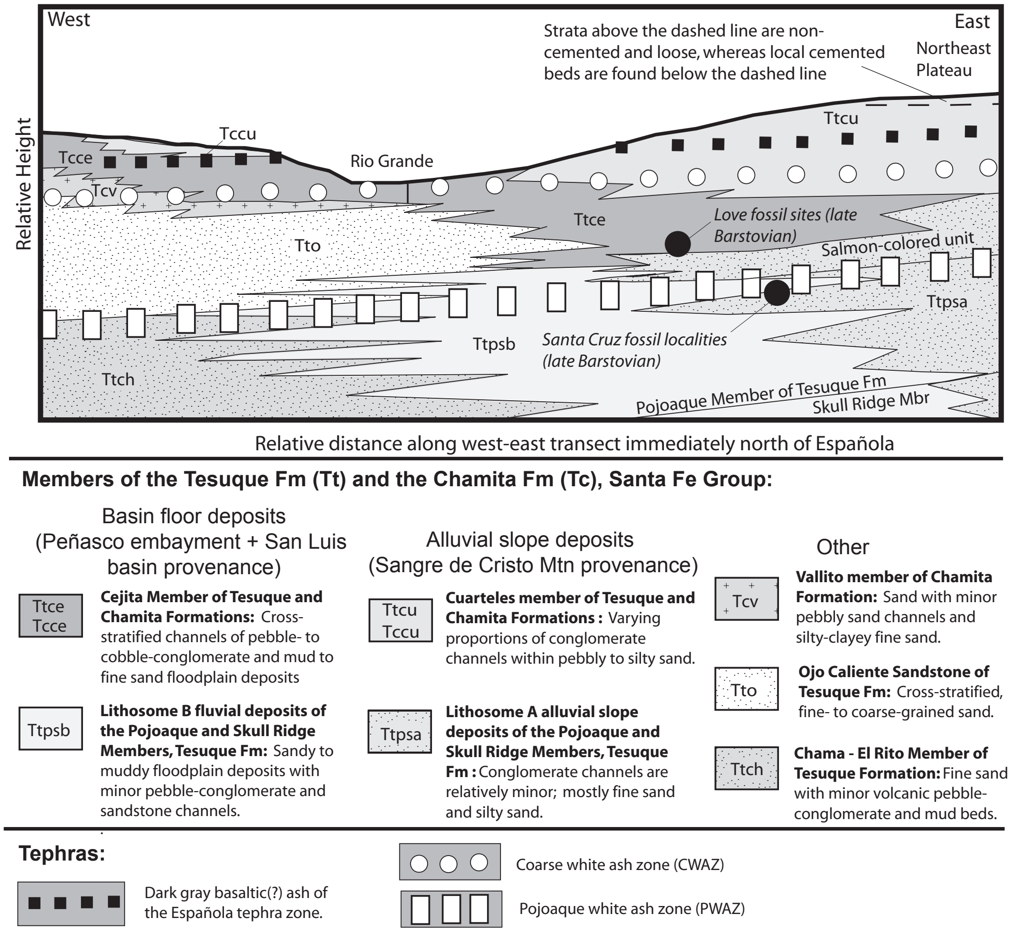

FIGURE 4. Schematic diagram illustrating the physical stratigraphic relations of middle to upper Miocene lithostratigraphic units and tephra.

Formation (e.g., Ojo Caliente Sandstone and Cejita Members) have produced late Barstovian mammals that appear to be somewhat younger than the early late Barstovian Pojoaque fauna of the Pojoaque Member (Tedford, 1981; Tedford and Barghoorn, 1993, 1997; Tedford et al., 2004).

Tephra zones

The Española basin contains numerous tephra beds that can aid the correlation of units across faults and across the basin. Many of these tephra are distinctive and occupy mappable stratigraphic zones that can be used as chronostratigraphic markers. In this section, we describe these tephra (from oldest to youngest) and discuss their age control.

Skull Ridge white ash #2

The white ash #2 bed of the Skull Ridge Member is a relatively extensive ash that is commonly underlain by at least 4 m of reddish mudstone and fine-grained sand. The ash is white and fine, as much as 80 cm thick, contains 1-3% fine biotite crystals, and is generally altered. The source of the ash has not been published. It was dated at 15.5 ± 0.07 Ma using $^{40}Ar/^{39}Ar$ methods (Izett and Obradovich, 2001), but magnetic-polarity stratigraphy work by

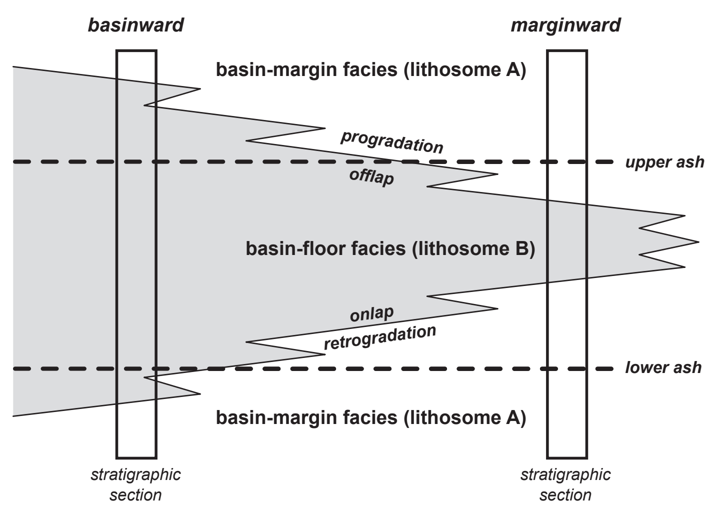

FIGURE 5. Schematic diagram illustrating the interfingering stratigraphic relations of lithosomes A and B of the Pojoaque, Skull Ridge, and Nambé Members of the Tesuque Formation. Stratigraphic positions of synchronous ash-bed markers and retrogradational and progradational sequences of lithosome A are also depicted.

Barghoorn (1981) and Tedford and Barghoorn (1993) suggests an approximate age of 15.8 Ma. We use an age range of 15.5-15.8 Ma for this ash bed in this paper.

Skull Ridge white ash #4

The White Ash #4 bed of the Skull Ridge Member is one of the most extensive and thickest tephra beds in the Española basin. It is composed of white, commonly hard, fine ash that is 70-250 cm thick. The basal part of the ash may be massive, but overlying ash is commonly planar-laminated to thinly planar-bedded. The source of this ash has not been published. This ash was dated at 15.3 ± 0.05 Ma (Izett and Obradovich, 2001) and 15.45 ± 0.06 Ma (McIntosh and Quade, 1995) using $^{40}Ar/^{39}Ar$ methods; magnetic-polarity stratigraphy work by Barghoorn (1981) and Tedford and Barghoorn (1993) indicates an approximate age of 15.2-15.3 Ma. We use an age of 15.3-15.4 Ma in this paper based on the $^{40}Ar/^{39}Ar$ ages.

Pojoaque white ash zone (PWAZ)

The Pojoaque white ash zone (PWAZ) consists of numerous, thin to thick, tabular beds of fine, white ashes. Ash beds may be reworked and mixed with detrital sand, have a thickness of 10-100 cm, and are commonly internally planar- to wavy-laminated. These ashes are generally altered and contain very sparse to sparse glass shards and up to 7% biotite. Gray ashes locally preserved in the Pojoaque Member type section to the south (Galusha and Blick, 1971, fig. 21) are not observed in the study area. Chemical comparisons suggest that most beds in the PWAZ came from the Southern Nevada volcanic field (A. Sarna-Wojcicki, written commun., 2005). Based on magnetic-polarity stratigraphy work by Barghoorn (1981) and the revised geomagnetic polarity time scale of Cande and Kent (1995), the PWAZ was probably deposited between 14.0 Ma and 13.2 Ma; this age is consistent with the early late Barstovian fossils found within and below the PWAZ. An $^{40}Ar/^{39}Ar$ age of 13.7 ± 0.18 Ma (Izett and Obradovich, 2001)

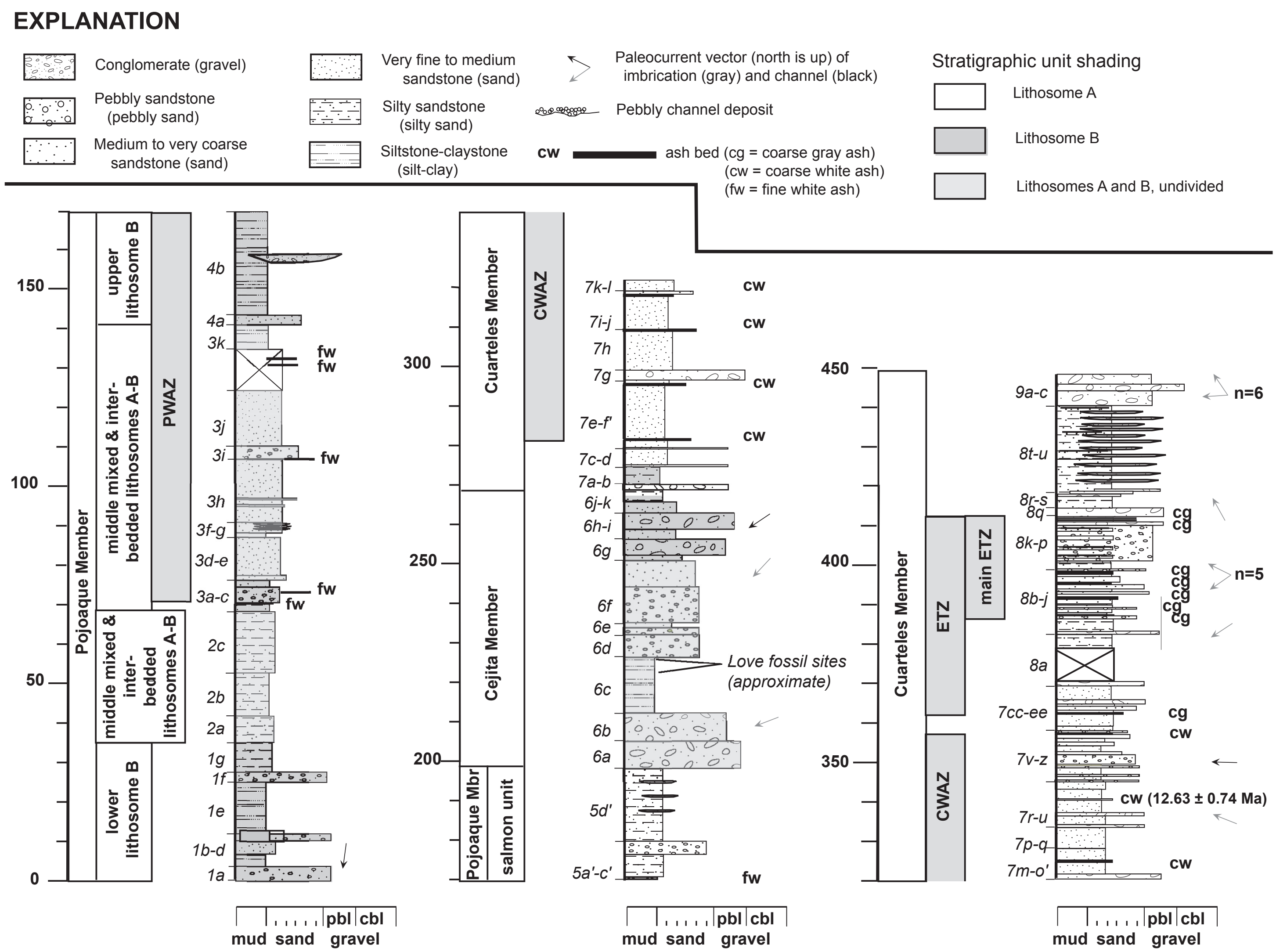

FIGURE 6. Graphic columns illustrating the Cuarteles stratigraphic section. The width of these columns depicts the general texture of the units. Descriptive data is provided in Koning and Manley (2003) and Koning (2003a). PWAZ = Pojoaque white ash zone, CWAZ = coarse white ash zone, ETZ = Española tephra zone.

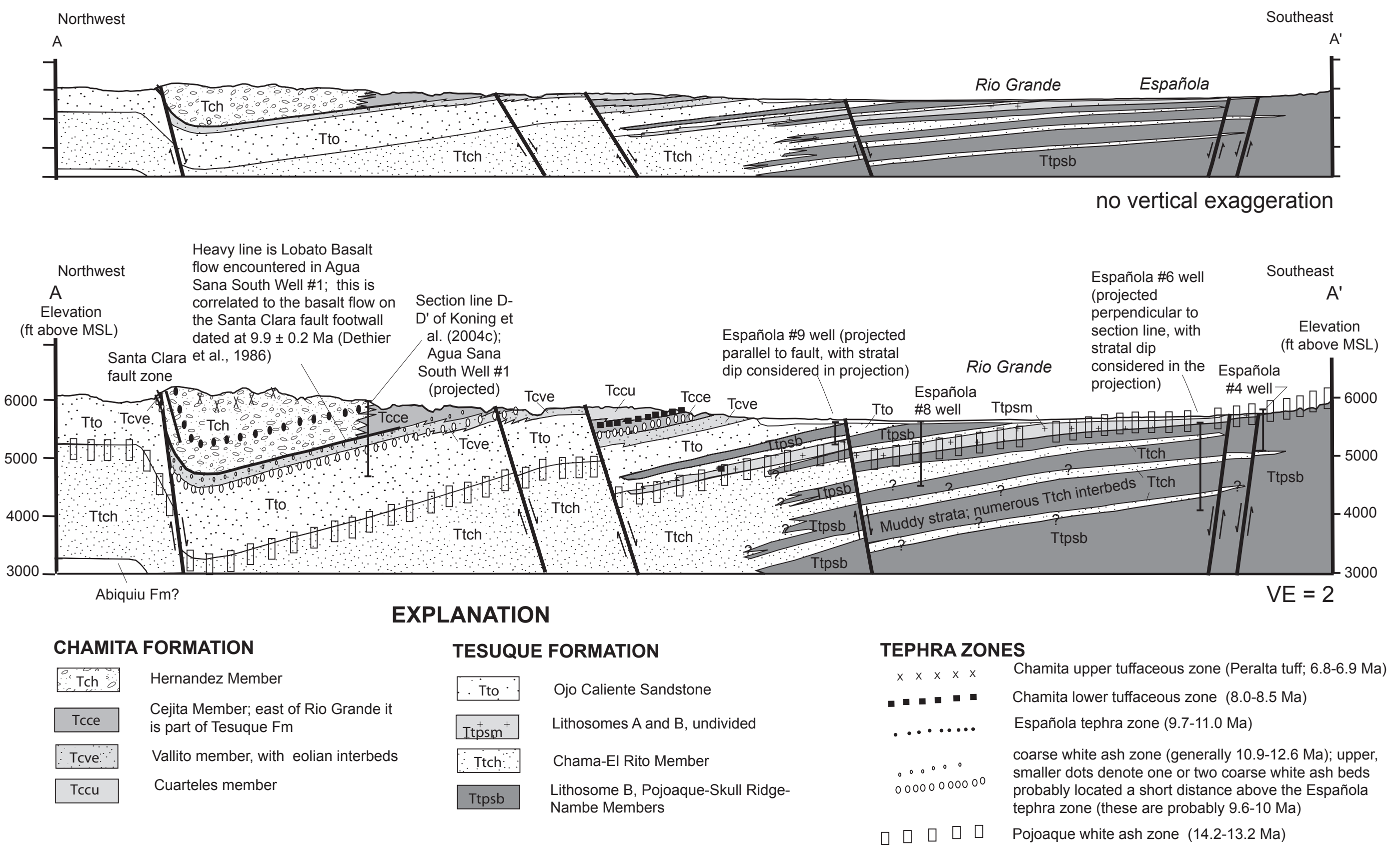

FIGURE 7. Northwest-southeast cross-section through the study area. End points shown on Figure 2.

was obtained from an ash bed located in the lower middle part of the PWAZ (G. Izett, written commun, 2004) in the Pojoaque Member type section, located ~9 km south of the study area.

Coarse white ash zone (CWAZ)

The coarse white ash zone (CWAZ) contains as many as ten similar-looking ash beds that are recognized over a stratigraphic interval of 50-75 m. As described in Koning et al. (2004c), these grayish white tephra consist of consolidated ash with abundant plagioclase. In addition, there are minor grains of altered pink to gray volcanic lithic fragments, biotite, and quartz. In the Cuarteles stratigraphic section, the upper beds of this zone locally contain greenish dacite(?) lapilli and purplish gray volcanic lithic grains. On the whole, however, coarse ash dominates and hence we apply the term of coarse ash to these white tephra beds.

The felsic mineralogy of the CWAZ ashes, their coarseness, and their stratigraphic abundance suggest they might be related to the Canovas Canyon Rhyolite and the dacites of the Paliza Canyon Formation in the Jemez Mountains. Radioisotopic dates bracketing the age of the Canovas Canyon Rhyolite (excluding the lowest "pink tuff", whose associated pink tephra does not seem to extend to the study area) range from 12.4 ± 2.0 Ma (Goff et al., 1990) to 8.8 ± 0.7 Ma (Goff and Gardner, 2004). In Cañada de las Entrañas (Truchas quadrangle), 15-18 km northeast of the study area, an $^{40}Ar/^{39}Ar$ age of 11.7 ± 1.1 Ma (Smith et al., 2004) was obtained from biotite of an ash bed tentatively correlated to the CWAZ based on hand sample comparison of minerals, lithic fragments, and texture. This particular ash was also correlated to a typical bed of the CWAZ exposed 5.8 km northeast of Chimayó on the basis of the phenocryst suite and refractive indices of glass and hornblende phenocrysts (Manley, 1976); the ash northeast of Chimayó has been dated at 12.7 ± 1.8 Ma using zircon fission-track dating (Manley, 1976 and 1979). In exposures near the Buckman well field in the southern Española Basin (White Rock quadrangle), an $^{40}Ar/^{39}Ar$ age of 10.9 ± 0.2 Ma was obtained from biotite in a coarse white ash bed (W.C. McIntosh, unpublished data). Tephras similar to the CWAZ have not been observed above a 9.6 ± 0.2 Ma basalt flow located 1 km south of the town of Chili, nor above another basalt flow from which a K-Ar age of 9.93 ± 0.20 Ma was obtained. In three beds of the CWAZ immediately northwest of Española (samples SCV-946FU, SCV-948-251102, and SCV-1014-051202 in Fig. 2), $^{40}Ar/^{39}Ar$ ages from biotite respectively are: 13.03 ± 0.40 Ma, 11.98 ± 0.67 Ma, and 12.7 ± 2.40 Ma (L. Peters, unpublished reports NMGRL-IR-365 and NMGRL-IR-398 for the NM Geochronological Research Laboratory, 2004 and 2005). A sample from unit 7u of the Cuarteles section returned an $^{40}Ar/^{39}Ar$ age of 12.63 ± 0.74 Ma using biotite (L. Peters, unpublished report NMGRL-IR-398 for the NM Geochronological Research Laboratory, 2005; sample label SCV-318-230702-djk). No beds of the CWAZ have been observed in the well-exposed bluffs near the Pojoaque type section (fig. 21 of Galusha and Blick, 1971), which is located about 9 km south and 2 km west of the Cuarteles section. The height of the basal CWAZ above the salmon unit at the Cuarteles section is 83 m (Fig. 6). At the Pojoaque type section, a height of 83 m above the salmon unit

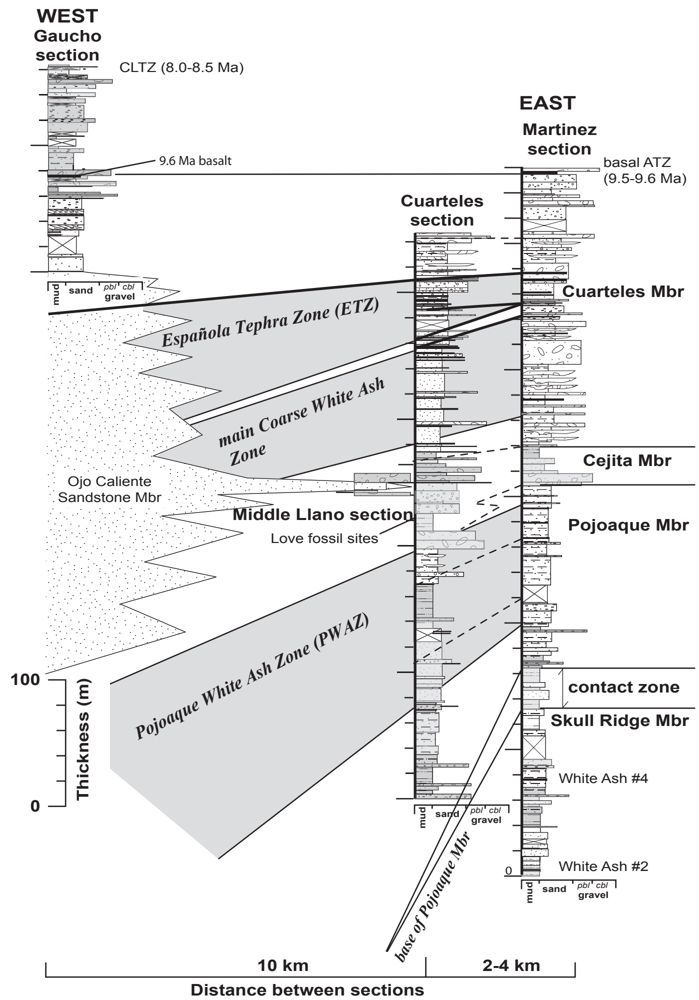

FIGURE 8. Fence diagram of stratigraphic sections in the study area. Thick black lines are temporal tie lines that bound tephra zones, and dashed lines correlate individual beds or contacts. Section locations are shown in Fig. 2. Descriptive data for Martinez section given in Koning (2003a). Descriptive data for Gaucho and Hernandez sections given in Koning and Aby (this volume) and Koning et al. (2005).

corresponds to gravelly sediment correlated to magnetic polarity chron 5An.2n of the Magnetic Polarity time scale, which is less than 12.8 Ma (Barghoorn, 1981; Tedford and Barghoorn, 1993; Cande and Kent, 1995). Based on the above age control, we use an age range of 10.9-12.8 Ma for the CWAZ, with the majority of the ashes (particularly those lying below the Española tephra zone, which we will refer to as the main CWAZ) being 12.0-12.8 Ma.

Española tephra zone (ETZ)

The Española tephra zone (ETZ) consists of one to eight dark gray to light gray, coarse ash beds. In the study area, these generally lie in a 24 m-thick interval 28-52 m above the CWAZ (an interval called the main ETZ), with the exception of a lone gray ash bed located only 3 m above the uppermost bed of the CWAZ in the Cuarteles stratigraphic section (Fig. 6). The tephra of the ETZ contains fine to coarse, dark gray (basaltic?) ashes that are generally mixed with sandy arkosic detritus. Dark gray ash beds in the upper part of the zone, in particular units 8p and 8j (Figure 6), locally contain abundant white, consolidated ash and pumice (0.5 - 17 mm in diameter) that may be of intermediate composition. Pumiceous beds in the upper ETZ may correlate to a dacitic pumice bed located 14 km to the northeast (windmill-72035 tephra of Manley, 1976) that lies about 20 m above gray, coarse ashes similar to those in the ETZ (Koning et al., 2004c). This northeastern pumice bed is 35-100(?) m above a down-dip projection of a pumice bed that has been dated at 10.8 ± 1.6 Ma using zircon fission-track methods (Orilla-72027 tephra of Manley, 1976 and 1979) and 11.3 ± 1.2 Ma using $^{40}Ar/^{39}Ar$ methods on biotite (Smith et al., 2004). Two to three kilometers west of Española, the ETZ zone includes a basaltic phreatomagmatic bed, 120 cm-thick, with lapilli 30-65 mm in diameter (Fig. 2). The coarseness of this particular phreatomagmatic bed strongly suggests derivation from vents associated with the eastern Lobato volcanic field 12-18 km west of Española. In the far west part of the study area, the oldest dated phreatomagmatic deposit from this field appears to lie below a basalt flow dated at 12.4 ± 0.4 Ma (Manley, 1985; Dethier et al., 1986). Also, the highest bed of the ETZ lies ~30 m below the 9.6 ± 0.2 Ma basalt located 1 km south of Chili (Koning et al., 2005) and in the uppermost CWAZ there. This particular, highest bed has not been directly dated, but it is probably no younger than 10.2 Ma, the youngest of extensive basalt flows in the eastern Lobato volcanic field other than the flows overlying this ash; these overlying flows have been dated at 9.6 ± 0.2 Ma and 9.9 ± 0.2 Ma (Dethier and Manley, 1985, and Dethier et al., 1986). These constraints support an age range of 10.2 to 12.5 Ma for the ETZ, with the upper part of the zone (the main ETZ) interpreted to be 10.2-11.2 Ma.

Alcalde tuffaceous zone (ATZ)

Found in outcrops east of the Rio Grande and northeast of the town of Alcalde, this tuffaceous stratigraphic interval is approximately 50 m thick and consists of three subintervals (Fig. 2). The lowest subinterval in the ATZ consists of one to two, thin to thick ash beds (separated by 9-12 m) that are black to gray, fine to coarse (mostly coarse), and basaltic(?). These basaltic(?) ashes are laterally extensive. The middle subinterval consists of a ~10 cm-thick bed of mixed soft, gray to dark gray coarse ash and white coarse ash. The top of the upper subinterval contains

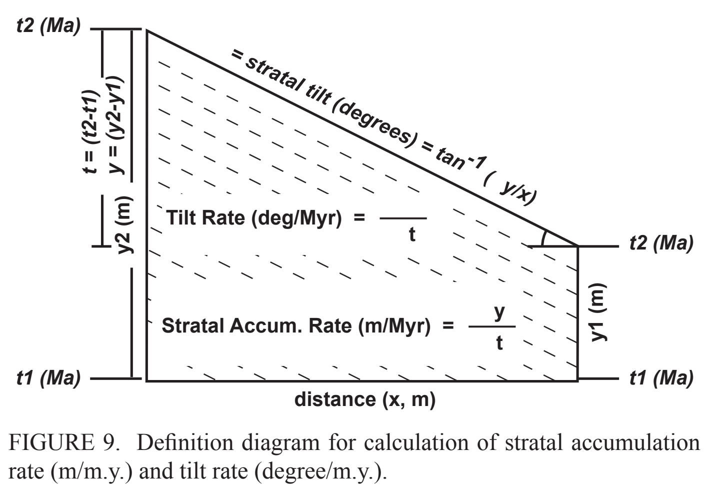

FIGURE 9. Definition diagram for calculation of stratal accumulation rate (m/m.y.) and tilt rate (degree/m.y.).

a 2-20 cm-thick bed of coarse white ash and fine, white, pumiceous lapilli. It lies 1.5-2.0 m above a 120 cm-thick interval of ashy sand similar to the CWAZ. The pumiceous lapilli returned an $^{40}Ar/^{39}Ar$ age of 9.40 ± 0.46 Ma (Lisa Peters, unpublished internal report NMGRL-IR-398 for the NM Geochronological Research Laboratory, 2005). The ATZ is located in close proximity to, and probably stratigraphically above, the *Osbornoceros* fossil quarry, previously inferred to correlate to the Hemphillian NALMA were collected (~ 4.8 - 9 Ma; Tedford and Barghoorn, 1993; Tedford et al., 1987). However, we cannot confirm that there are any species or association of species from this quarry restricting its age to the Hemphillian NALMA (as opposed to the earlier Clarendonian NALMA). The ATZ was previously interpreted as correlating with the CLTZ based on the previously inferred Hemphillian NALMA fauna and comparison of the lithologic characteristics of the successive beds in each (Koning et al., 2004c). However, the $^{40}Ar/^{39}Ar$ age of 9.40 ± 0.46 Ma may negate this correlation and suggests an age range of 9.4-9.6 Ma for the ATZ.

Chamita lower tuffaceous zone (CLTZ)

In the northwestern study area, there are two beds that are similar in appearance to the lower and middle intervals of the Chamita lower tuffaceous zone found in the Chamita Formation type section to the north (Fig. 2; Galusha and Blick, 1971; Koning et al., 2004c; Koning and Aby, this volume). The lowest bed consists of gray, coarse ash to fine lapilli (1-8 mm in diameter) of probable dacitic composition. The middle bed is approximately 13 m above the lower near the Santa Clara fault (Hernandez section of Koning and Aby, this volume) and in the Chamita Formation type section. This bed consists of white coarse ash and fine lapilli that is laminated to very thin, planar-bedded. Tephra of the middle bed is composed of consolidated white ash, 1-10 mm in size, with 7-20 percent gray (and minor pink, green, and black) dacite(?) lithics that are 1-15 mm-long. The coarseness of the CLTZ strongly suggests a local source, such as the Jemez volcanic field, but that has yet to be confirmed by chemical comparison. An $^{40}Ar/^{39}Ar$ age of 7.7 ± 0.3 Ma from a tephra bed in the lower part of the CLTZ in the Chamita Formation type section, and revision of the Chamita Formation stratotype magnetostratigraphy of MacFadden (1977) by McIntosh and Quade (1995), indicates an age range of 7.7-8.4 Ma for this zone (Koning et al., 2004c). We favor an age of 8.0-8.5 Ma, which is consistent with revision of the magnetostratigraphic data of MacFadden (1977) by McIntosh and Quade (1995) using the revised geomagnetic polarity time scale of Cande and Kent (1995).

Chamita upper tuffaceous zone (CUTZ)

The Chamita upper tuffaceous zone has only been observed in the upper Hernandez Member (Fig. 2), where it is in a single, 15 cm-thick bed and consists of pumiceous, coarse, white ash altered to clay. Its pumiceous texture and stratigraphic position supports its correlation to the Chamita upper tuffaceous zone in the Chamita type section, 5-7 km to the northeast. There, three samples of this tephra have been dated ($^{40}Ar/^{39}Ar$) between 6.75 ± 0.05 and 6.93 ± 0.05 Ma (McIntosh and Quade, 1995) and geochemically correlated to the 6.8-6.9 Ma Peralta Tuff (Koning et al., 2004c). The Peralta Tuff is a member of the Bearhead Rhyolite, an upper Miocene eruptive in the southeastern Jemez Mountains (Goff and Gardner, 2004).

Pojoaque and Skull Ridge Members, Tesuque Formation

The Pojoaque and Skull Ridge Members have been informally subdivided into two distinct lithologic units called lithosomes A and B (Koning and Maldonado, 2001; Koning, 2002; Koning et al., 2002; Koning, 2003a; Koning and Manley, 2003), following Cavazza (1986). These two units interfinger laterally (Fig. 5). Lithosome A consists of arkosic sandstone and silty sandstone plus minor gravel consisting largely of granite and quartzite clasts. It represents basin-margin facies that were deposited on an alluvial slope flanking the Sangre de Cristo Mountains (Fig. 5; Smith, 2000). Lithosome B consists of sandstone, siltstone, and claystone with minor conglomeratic units that are dominated by pebbles of Paleozoic sandstone and limestone in addition to Proterozoic quartzite. Interpreted provenance, based on clast and sand composition (App. 1; Cavazza, 1986), is likely a mix between the Sangre de Cristo Mountains near the eastern Peñasco embayment and the southern San Luis basin. A partial San Luis basin source, abundant floodplain deposits, and south-southwest paleoflow indicators (Fig. 6; Cavazza, 1986) that are only slightly oblique to the basin axis support the interpretation that this lithosome represents basin-floor deposits in the study area. We differentiate lithosomes A and B in our stratigraphic sections and mapping, in addition to a third unit consisting of mixed and/or interbedded lithosomes A and B (Figs. 4-6). These units are relatively fine-grained and are described below. The presence of the PWAZ within the Pojoaque Member in the study area indicates an approximate age of 14.5-13.0 Ma for the strata in the Cuarteles stratigraphic section (Fig. 6), consistent with the late Barstovian fossils collected in Arroyo del Llano in the Pojoaque Member (i.e., Santa Cruz fossil collecting locality of Galusha and Blick, 1971). The contact between the Pojoaque and Skull Ridge Members is found in the southeast part of the study area (Fig. 2), and is manifested by a stratigraphic interval of lithosome B channel sandstones or floodplain deposits overlying a fine-grained interval of lithosome A. This contact has been interpreted as an unconformity based on magnetic-polarity stratigraphy (Barghoorn, 1981; Tedford and Barghoorn, 1993; Tedford et al., 2004), but we are skeptical of this interpretation because in places the contact appears gradational. Lithosomes A and B are generally similar in both the Pojoaque and Skull Ridge Members; refer to Kuhle and Smith (2001) for more description of the Skull Ridge Member.

Lithosome A

Lithosome A (unit Ttpsa, Fig. 2) lies in the eastern part of the Pojoaque Member. In the study area, it consists of pink to very pale-brown, very fine- to medium-grained sandstone and silty sandstone that form broadly lenticular to tabular beds. Within the finer-grained sandstone beds are minor channel fills of fine- to very coarse-grained, arkosic sandstone. These channels are lenticular in form, and become progressively more conglomeratic to the east. Gravel is dominantly granite pebbles, with cobbles becoming more common eastward. Gravels are subrounded to subangular and moderately to poorly sorted. Channel trends support a general westward flow direction away from the Sangre de Cristo Mountains (Koning, 2003a). This unit is very similar to deposits of lithosome A described in the underlying Skull Ridge Member, which have been interpreted as being deposited on a westward-sloping alluvial slope (Kuhle and Smith, 2001; Smith, 2000). The abundance of granite detritus in generally west-directed paleochannels indicates a western Sangre de Cristo Mountains provenance for lithosome A, as noted by Cavazza (1986).

Lithosome B

Lithosome B (unit Ttpsb, Fig. 2) is generally exposed west of lithosome A and consists of very fine- to fine-grained sandstone, siltstone and claystone that represent floodplain deposits of an axially aligned stream or river system. Lithosome B has subordinate channel fill deposits of light gray to pale brown sand with minor conglomerate. The sand is litharenite to lithic arkose in composition. In the sand fraction, lithic grains containing Paleozoic detritus commonly exceed pink potassium feldspar grains in abundance. Lithosome A, in contrast, contains relatively abundant pink potassium feldspar and generally no Paleozoic detritus. Lithosome B channels may contain local gravel (generally pebbles) consisting of Paleozoic sandstone, siltstone, and limestone, with 5-20% Proterozoic quartzite, 1-20% felsic-intermediate volcanic rocks (10-26% in clast count data of Cavazza, 1986), and 1-5% granite (Appendix 1; Fig. 10). Pebbles are subrounded and moderately to poorly sorted. Paleocurrent data indicate a general south- to southwest-directed flow (Fig. 2; Koning and Manley, 2003; Koning, 2003a), consistent with data of Cavazza (1986). Dominant provenance is interpreted to be from Paleozoic sedimentary strata and Proterozoic quartzite rocks exposed in the eastern Peñasco embayment (Fig. 1), with contribution of sediment from river(s) draining the southern San Luis basin (Cavazza, 1986). The volcanic clasts and grains in this unit could have been derived from mixing of detritus from drainages associated with the Chama-El Rito Member in the Abiquiu embayment, erosion of the older, volcaniclastic Picuris Formation from the Picuris Mountains, or from river(s) exiting the southern San Luis basin.

Interfingering and mixed lithosomes A and B

We recognize intervals of interfingering and mixed deposits that have characteristics of lithosomes A and B (Ttpsm, Fig. 2). These deposits have been differentiated in the Cuarteles section and the geologic map (Figs. 2 and 6). This compositionally mixed interval generally consists of very fine- to fine-grained sandstone and silty sandstone that form tabular to broadly lenticular, medium to thick beds. Sandstone is arkosic and may contain greenish quartz grains likely eroded from Paleozoic sandstone. Local thick, tabular beds consisting of well sorted and subrounded sand may be eolian, particularly in unit 3j of the Cuarteles section (Fig. 6). Locally near the city of Española (Fig. 2), these tabular beds are internally cross-stratified; foresets are approximately 20-50 cm thick and generally face east. Very sparse, coarse-grained channel fills contain clasts that are consistent with either lithosome B or lithosome A provenance. However, interbedded in eolian deposits immediately adjacent to the city of Española (Fig. 2) are minor sand lenses with abundant volcanic grains that are likely derived from the Abiquiu embayment or southern San Luis basin. Over most of the map area, this unit represents deposition near the transition between the basin floor (lithosome B) and distal portions of the alluvial slope (lithosome A). Incorporation of sediment from various source areas, as well as eolian sedimentation, may account for the mixed composition of this unit.

Salmon-colored unit of Pojoaque Member

A distinctive pink to reddish yellow to light brown, silty sandstone characterizes the salmon-colored unit of lithosome A (Ttpas, Fig. 2), which was also informally recognized as the salmon-colored beds by Galusha and Blick (1971). In this unit, fine-grained sandstone is intercalated with sparse, pebbly medium- to very coarse-grained sandstone channel fills. The sandstone is arkosic and the gravel is dominated by granite with subordinate quartzite. Channels are oriented west-east, and are consistent with west-flowing streams draining the Sangre de Cristo Mountains (Koning, 2003a). We do not know for sure why this unit has a distinctive salmon color, but perhaps the reddening is related to increased oxidation of iron-bearing minerals. Although this unit can be grouped with the stratigraphically lower lithosome A, we distinguish it because of its distinctive color, precedence (cf. Galusha and Blick, 1971), and stratigraphic position at the uppermost part of the Pojoaque Member. In the study area, this unit overlies lithosome B sediment. However, progressively eastwards of the study area the lower contact of this unit becomes increasingly difficult to recognize because it overlies older lithosome A strata of the Pojoaque Member. The salmon-colored unit is interbedded with the lowermost Cejita Member to the west, but is sharply overlain by this member to the east.

Ojo Caliente Sandstone, Tesuque Formation

The Ojo Caliente Sandstone (Tto, Fig. 2) of the Tesuque Formation is a distinctive eolianite recognized in the west-central and northwestern parts of the Española basin. In the study area, the Ojo Caliente Sandstone is commonly cross-bedded, with tangential foresets that are up to 70 cm thick. Sandstone is generally very pale-brown, well to moderately sorted, subrounded, and consists of quartz with 12-18 percent orangish-colored grains and 12-15 percent volcanic-dominated lithic grains. The orangish-colored grains are probably orthoclase (May, 1980; Steinpress, 1980 and 1981) along with stained quartz. The unit exhibits a slight coarsening-upward trend in its sand-size fraction, from fine-upper and medium-lower in its lower part to predominantly medium-lower to coarse-lower in the middle to upper part of the unit. The lower Ojo Caliente Sandstone is interpreted to interfinger eastward with the mixed lithosome A-B unit of the upper Pojoaque Member (unit Ttpsm); this is based on the presence of eolian sediment in the westernmost part of the latter unit near Española (Fig. 2).

The age of the Ojo Caliente Sandstone is constrained by fossil and tephra data. The base of the Ojo Caliente Sandstone at the Conical Hill fossil quarry, 8 km southeast of Abiquiu, has a number of species that are typical members of latest Barstovian assemblages in the Great Plains, and thus is probably 13.5-12.5 Ma (Tedford and Barghoorn, 1993; Tedford et al., 2004). About 1-2 km east-northeast of the Española Municipal Airport, geologic mapping indicates that the middle-upper Ojo Caliente Sandstone interfingers eastward with the Cejita Member (western part of Fig. 2b). This interfingering of the Ojo Caliente and Cejita Members is present near the Love fossil sites, which have yielded fauna consistent with the latest Barstovian North American land mammal "age" (Table 1). One to two kilometers south of the town of Chili (Fig. 1), the uppermost part of the Ojo Caliente Sandstone has beds of the CWAZ, and thus is probably 10.9-12.8 Ma in age.

Cejita Member, Tesuque and Chamita Formations

The Cejita Member (Ttce and Tcce, Fig. 2) of Manley (1976, 1977, 1979) shares much of the same provenance as lithosome B of the Pojoaque Member but is coarser, especially in its lower portion, and its middle to upper parts contain more quartzite clasts than in the Pojoaque Member (compare Appendix 1 to table 5 of Koning and Aby, this volume). We concur with Manley's assignment of the Cejita Member to the Tesuque Formation east of the Rio Grande, but include it in the Chamita Formation west of the Rio Grande because: 1) there it overlies the Ojo Caliente Sandstone, consistent with the definition of the lower contact of the Chamita Formation (Galusha and Blick, 1971; Koning and Aby, this volume), and 2) it occupies the lower half of the Chamita Formation type section (Koning and Manley, 2003; Koning and Aby, this volume). The lower Cejita Member pinches out very close to the east boundary of the study area, and it commonly overlies lithosome B of the Pojoaque Member (to the west) or the salmon-colored unit of the Pojoaque Member (to the east) (Fig. 2). East of Arroyo de Cuarteles, the basal contact of the Cejita is a conspicuously scoured. The lowermost Cejita Member generally interfingers with the salmon-colored unit of the Pojoaque Member (Fig. 2), although this interfingering is less evident to the east.

The lower part of the Cejita Member, exposed east of the Rio Grande and lying below the CWAZ, differs dramatically from underlying strata in its abundant coarse-grained channel deposits (Fig. 6). Channel complexes are generally tabular and thick (up to 6 m); internal bedding is very thin to medium and planar, lenticular, planar- to tangential- cross-stratified with local epsilon cross-bedding (with foresets up to 250 cm thick), or channel-shaped. Preserved channel depths are as great as 180 cm and channels commonly fine upward. Channel conglomerate consists of pebbles with minor cobbles, with the largest intermediate-axis clast sizes commonly ranging between 7 and 18 cm in diameter (Fig. 11). Gravel is clast-supported, locally imbricated, subrounded to rounded, and poorly to moderately sorted. Gravel composition is dominated by Paleozoic limestone, sandstone, and siltstone, with minor quartzite, quartz, felsic to intermediate volcanic rocks, and granite (Fig. 10). Near its eastern margin, however, granite clasts can locally exceed 50% because of input of detritus from adjacent alluvial slope tributary drainages to the east (i.e., the Cuarteles Member). Except for the uppermost unit of lithosome B (unit 4 of the Cuarteles section; Fig. 6), the gravel of the Cejita Member is larger than that of lithosome B of the underlying Pojoaque member (Fig. 11). Cross-stratification as thick as 2.5 m indicates the presence of locally deep channels. Such thick cross-stratification was not observed in underlying strata. The lower Cejita Member interfingers with the Ojo Caliente Sandstone near the Love fossil sites (Figs. 2 and 8). Situated within or above the CWAZ, the middle-upper part of the Cejita Member is grossly finer than the lower part and is preserved west of the Rio Grande. West of the Rio Grande, the CWAZ is found near the base of the Cejita Member, whereas east of the Rio Grande the Cejita Member generally lies below the CWAZ. This indicates that the Cejita Member migrated laterally westward during emplacement of the CWAZ (10.9-12.8 Ma). The middle-upper part of the Cejita Member interfingers with the Hernandez Member west of the Rio Grande. In this interfingering zone the gravel of the Cejita Member consists of pebbles, with generally no cobbles. The presence and relative positions of the PWAZ, CWAZ, ETZ, and CLTZ in or near the Cejita Member indicates that it ranges in age from 13.2-7 Ma in the study area.

TABLE 1. Medial Miocene (late Barstovian NALMA) mammalian fossils from three sites in eastern part of study area. "X" indicates presence. "X?" indicates tentative identification. "—" indicates absence of species.

Taxa	Love fossil site *NMMNHS L5915-5920* Cejita Mbr	Site SCV-296 *NMMNHS, L5910-5912* uppermost lithosome B of Pojoaque Mbr	Site SCV-1554 *NMMNHS, L5913, 5914* uppermost lithosome B of Pojoaque Mbr
Carnivora			
Canidae			
Leptocyon vafer	X	X?	—
Aelurodon sp.	X?	—	—
Rodentia			
Castoridae			
Monosaulax pansus	X	—	—
Perissodactyla			
Equidae			
Neohipparion coloradense	—	X?	X
Artiodactyla			
Camelidae			
large species of camelid	X	X	X
Antilocapridae	X	X?	—
Meryceros crucensis	X	—	—
Ramoceros ramosus	—	X	—
Ruminantia			
very small ruminant			
Proboscidea			
Gomphotheriidae			
Gomphotherium productum	X	—	—

Cuarteles Member (new name), Tesuque and Chamita Formations

The Cuarteles Member (Ttcu and Tccu, Fig. 2) of the Tesuque Formation is a new term defined at and north of Arroyo de Cuarteles (Fig. 6; the name of the arroyo and town is spelled Quarteles on the San Juan Pueblo 7.5-minute topographic map, but the local population spells it as Cuarteles and that convention is followed here). The Cuarteles Member consists of ~180 m of arkosic silty sand interspersed with coarse channel deposits containing granite and quartzite gravel; these coarse channel fills generally exceed 10-20% of the sediment volume. The upper contact of the Cuarteles Member is an unconformity locally overlain by Quaternary gravels, and its lower contact is gradational with the underlying Pojoaque and Cejita Members of the Tesuque Formation. The lower part of the Cuarteles Member was previously included in the upper 50 m of the Pojoaque Member type section (Galusha and Blick, 1971, fig. 21). Its extent is shown in recent mapping, where it has informally been called the "coarse upper unit of the Tesuque Formation" (Koning and Maldonado, 2001; Koning, 2002; Koning and Manley, 2003; Koning, 2003a; Koning and Aby, 2003; Koning, 2004) or "piedmont lithofacies of the Tesuque Formation" (Manley, 1976, 1977, 1979). The Cuarteles Member shares the same alluvial slope depositional environment and general provenance as older lithosome A deposits. The Cuarteles Member extends eastward to the Sangre de Cristo Mountains and interfingers with, and partly overlies, the Cejita Member (Figs. 3-4; fig. 5 of Koning and Aby, this volume). It is included with the Chamita Formation west of the Rio Grande, where it gradationally overlies the Cejita Member in the Chamita type section (fig. 4 of Koning and Aby, this volume). In the study area east of the Rio Grande, the Cuarteles Member is included in the Tesuque Formation and overlies the Cejita Member of the Tesuque Formation. Near and east of the eastern boundary of the study area, the Cuarteles Member overlies the salmon-colored unit of the Pojoaque Member, and its lower contact becomes increasingly indistinct towards the Sangre de Cristo Mountains to the east. Throughout much of the Española basin, the Cuarteles Member is coarser grained than the Pojoaque Member, which it overlies across a 6-60 m-thick gradational zone, and is generally differentiated from the Pojoaque Member by having greater than 10-20% channel deposits of medium to very coarse sand and gravel. Immediately adjacent to the mountain front, the Cuarteles Member is still coarser than the Pojoaque Member, but the Pojoaque Member there may contain more than 10-20% coarse channels. The Cuarteles Member is similar to underlying lithosome A units in bedding style and composition. However, gravel becomes progressively more quartzite-rich in a northeast direction. On the northeast side of Rio de Truchas (Fig. 1), quartzite generally is the dominant gravel constituent because the Proterozoic quartzite-cored Truchas Peaks served as the main provenance for alluvial slope drainages in that area (Koning, 2003a). We provisionally include these quartzite-dominated, alluvial slope deposits with the Cuarteles Member because the lateral change from granite-dominated gravel to quartzite-dominated gravel is very gradational.

The sediment of the Cuarteles Member is dominated by pink to light brown to reddish yellow, very fine- to very coarse-grained, arkosic sandstone and silty sandstone whose beds are commonly broadly lenticular to tabular. This sand is interspersed with subordinate coarse channel complexes, except near the mountain front where coarse channel complexes predominate. In the study area, gravel consists of more than 50 percent granite and less than 40 percent quartzite (Fig. 10 and Appendix 1). Conglomerates are commonly clast-supported in sandy gravel beds, subangular to subrounded, and poorly sorted. Clast sizes are highly variable, but the intermediate clast axis may reach 19 cm in the study area. The coarse-grained channel complexes are marked by planar-laminated to cross-stratified, arkosic sand and thin to thick, lenticular or channel-shaped gravel beds. Channel margins generally trend to the west-northwest (Fig. 6).

The age of the lower Cuarteles Member in the study area is constrained by the coarse white ash zone (CWAZ), which is found in the lowest part of this member and indicates an age of about ~12.8 Ma for the basal contact. The upper part of this member is outside the study area beneath Black Mesa (Morgan et al., this volume) and in the Chamita Formation stratotype (Koning and Aby, this volume). In the study area, a gray, coarse-grained ash is found in the uppermost part of the unit (Fig. 8). This ash is correlated to the Alcalde tuffaceous zone (ATZ) because it projects to similar gray, coarse ashes at the *Osbornoceros* quarry 7-8 km to the north (Koning et al, 2004c; Koning, plate 11 in Brister et al., 2004). Accordingly, we assign an upper age limit of 9.0-9.6 Ma for the top of the Cuarteles Member east of the Rio Grande.

Vallito Member, Chamita Formation

The Vallito Member of the Chamita Formation (new name proposed in Koning and Aby, this volume) consists of very pale brown to light yellowish brown to light brown, fine to medium sand and silty sand. Locally, it has volcanic pebbles that are scattered or in thin lenses. This unit possesses minor intervals of cross-stratified, relatively clean sand that are probably eolian -- based in part on lithologic comparison with the Ojo Caliente Sandstone. In the Gaucho stratigraphic section, this member contains a bed from the CWAZ and lies about 15-16 m below a projected basalt flow having an $^{40}Ar/^{39}Ar$ age of 9.6 ± 0.2 Ma (Fig. 2; fig. 9 of Koning and Aby, this volume; Dethier et al., 1986; Dethier and Manley, 1985; Koning et al., 2005). Immediately northwest of Española, to the east of the Gaucho stratigraphic section, this member lies below the Cejita Member and the uppermost CWAZ (Fig. 2). Thus, this unit probably ranges in age between 13 to 9.6 Ma. The Vallito Member is discussed in more detail in Koning and Aby (this volume).

Hernandez Member, Chamita Formation

The Hernandez Member of the Chamita Formation (new name; Koning et al., 2004c) consists of silty very fine- to medium-grained sand and mud deposits interbedded with sandy gravel (some pebbly sand) channel fills (Koning and Aby, this volume). Gravel is subrounded to rounded, and consists primarily of inter-

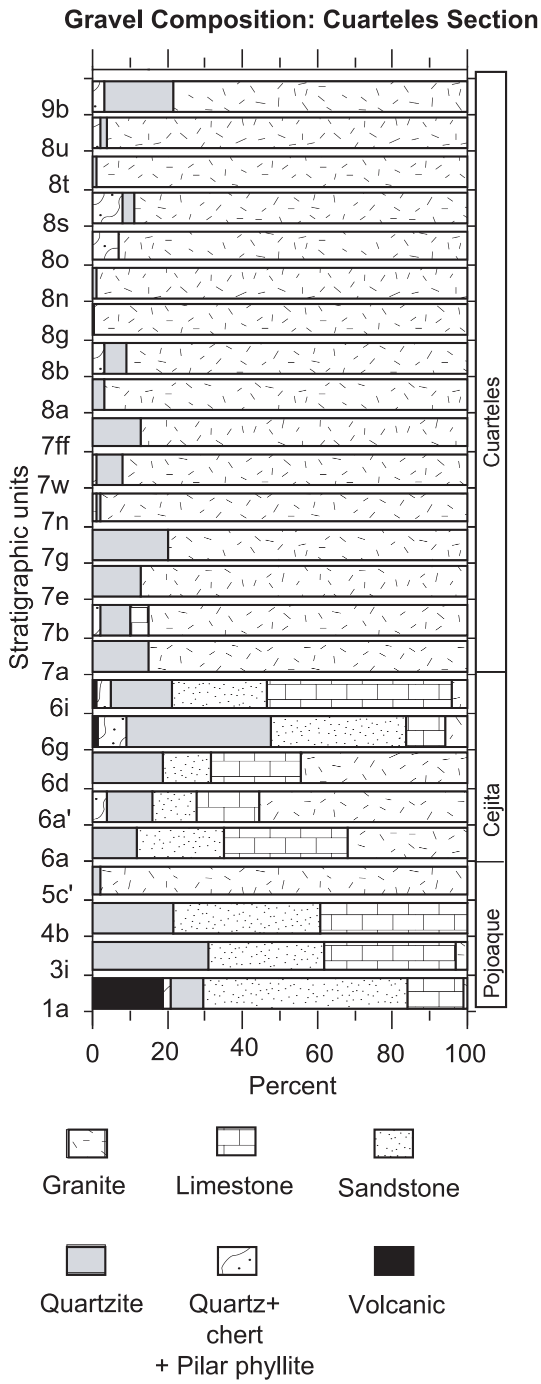

FIGURE 10. Clast compositions of units in the Cuarteles stratigraphic section (see Appendix 1).

mediate volcanic rocks with minor quartzite, basalt to basaltic andesite, rhyolite, and felsic tuffs. Channels are in medium to thick channel complexes. Internal bedding of these channels is commonly planar-laminated (sand) or in thin to thick, lenticular to broadly lenticular beds (gravel). This unit is described in more detail in Koning and Aby (this volume), who note that coarse channel deposits increase up-section, as does the percentage of quartzite. The Hernandez Member overlies a basalt flow dated at 11.9 ± 0.3 Ma near the western boundary of the study area (Arroyo de la Presa section in Fig. 2; fig. 11 of Koning and Aby, this volume). In the Gaucho section, the base of the Hernandez Member lies about 15-16 m below a projected basalt flow having an $^{40}Ar/^{39}Ar$ age of 9.6 ± 0.2 Ma (fig. 9 of Koning and Aby, this volume; Dethier et al., 1986; Dethier and Manley, 1985). About 100 m below its uppermost strata adjacent to the Santa Clara fault is a bed interpreted to correlate to the CUTZ (6.8-6.9 Ma). These constraints allow us to assign an age range to the Hernandez Member of 12 to 6 Ma.

DISCUSSION

Geologic mapping, lithostratigraphy, tephra correlation and geochronology, and biostratigraphy allow us to correlate strata across the study area. This study reveals a marked upward coarsening across the basin and westward progradation of basin-margin deposits of the Chamita and Tesuque Formations beginning about 13-14 Ma. In this section, we explore these stratigraphic correlations, vertical and lateral trends in deposition, and tectonic and climatic inferences drawn from our data.

Upward-coarsening trends

The Cuarteles and Cejita Members are noticeably coarser than the underlying middle-lower Pojoaque Member and the Skull Ridge Member, as manifested by an increase in the abundance of conglomeratic beds and in clast sizes. East of the Rio Grande in the study area, the Pojoaque and Skull Ridge Members generally consist of very fine- to medium-grained sandstone and silty sandstone, with only sparse conglomeratic channel deposits of pebbly medium- to very coarse-grained sandstone (Figs. 6 and 8). The uppermost lithosome B unit of the Pojoaque Member (unit 4 in Fig. 6) has relatively sparse coarse channel fills, but the clast sizes in these channels are the largest observed in the entire Pojoaque Member succession (Fig. 11). The finer-grained Pojoaque Member is overlain by conglomeratic deposits of the lower Cejita Member (Figs. 4, 6, and 8). The coarse-grained Cejita Member is in turn overlain by the Cuarteles Member (Fig. 6). The Cuarteles Member contains fewer coarse channel deposits than the Cejita Member, but nonetheless is coarser grained than the lithosome A and lithosome B units of the lower to middle Pojoaque Member and the Skull Ridge Member (Fig. 8). West of the Rio Grande in the Cejita and Hernandez Members, clast-size data show an upward-coarsening trend which coincides with an upward increase of conglomeratic channel facies in the Hernandez Member (Koning and Aby, this volume, figs. 9 and 12).

Relation of Ojo Caliente Sandstone with Pojoaque and Cejita Members

Stratigraphic relations on the map, cross-section, and fence diagram (Figs. 2 and 7-8) illustrate the lateral stratigraphic relations of the Ojo Caliente Sandstone with the Pojoaque and Cejita Members. The Ojo Caliente Sandstone extends eastward to the middle Llano section (Fig. 2 and 8), and outcrops northeast of Española indicate an interfingering relation between this member and the Cejita Member (Fig. 2). Possible eolian sand sheets within the PWAZ in the Cuarteles section, in addition to interpreted eolian sediment in the mixed and/or interbedded lithosomes A-B unit immediately northeast of Española (Fig. 2), indicates that the lower, slightly finer part of the Ojo Caliente Sandstone interfingers with the upper part of the Pojoaque Member within the PWAZ (13.2-14.0 Ma). An interfingering contact relationship of the Ojo Caliente Sandstone with the upper Pojoaque Member is also supported by the presence of the Ojo Caliente – Chama-El Rito contact (Figs. 4 and 7) within a zone of fine white ashes in the Abiquiu embayment (Koning et al., 2004a; Koning, 2004); this ash zone is within strata yielding late Barstovian fauna (Tedford and Barghoorn, 1993) and so it likely correlates to the PWAZ. Given this stratigraphic relationship, the notable increase in gravel size in the uppermost lithosome B unit of the Pojoaque Member (Fig. 11) is coeval with the development of the large dune field represented by the Ojo Caliente Sandstone. Moreover, the coarser, channel-dominated, lower Cejita Member above the overall finer Pojoaque Member may coincide temporally with the middle to upper Ojo Caliente Sandstone, which has slightly larger grain sizes than the lower Ojo Caliente Sandstone (Koning, 2004; Koning et al., 2005). Thus, both the lithosome B/Cejita fluvial system and the Ojo Caliente Sandstone eolian system coarsen during their concomitant deposition.

Progradation of the Cuarteles Member

Major basinward progradation of the Cuarteles Member (e.g., Figs. 4-5; Koning and Maldonado, 2001; Koning, 2002) which, like lithosome A, represents basin-margin, alluvial slope deposits derived from the Sangre de Cristo Mountains, commenced immediately prior to the emplacement of the CWAZ at approximately 12.8 Ma. In the Cuarteles and Martinez sections, the CWAZ lies

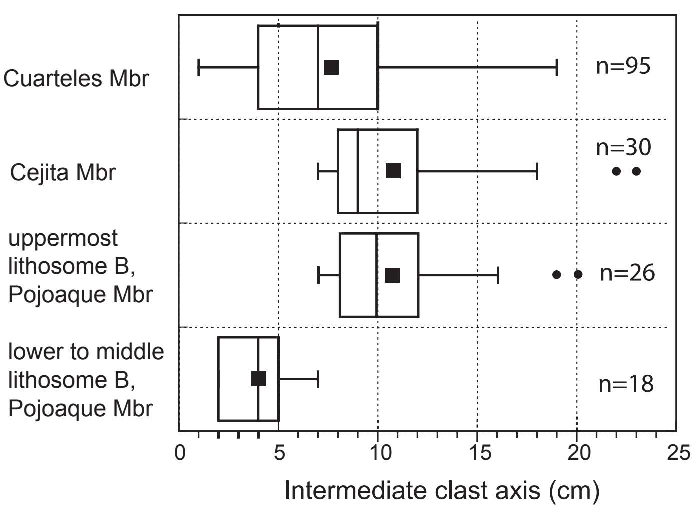

FIGURE 11. Box and whisker plot of clast size data (intermediate axis) of the Cuarteles stratigraphic section. Small, filled square represents the mean, the vertical line in the larger rectangle is the median, the length of the larger rectangle represents the upper and lower quartile (25% above and 25% below the median), the bracket(s) represent the 95% range, and filled circles are outliers.

above the Cejita Member, but west of the Rio Grande the CWAZ is within the basal Cejita Member (Figs. 2-4 and 7), demonstrating this westward migration of lithofacies. Thus, at 10.9-12.8 Ma, the time of emplacement of the CWAZ, the boundary between the river depositing the Cejita Member and the toe of the alluvial slope laid between these exposures west of the Rio Grande and exposures near the Cuarteles section (Figs. 2-4). However, the Cuarteles Member had prograded west of the present position of the Rio Grande about or shortly after the time the ETZ was emplaced (10.2-12.5 Ma) because a lapilli bed of the ETZ is present 15-20 m below the Cuarteles Member basal contact northwest of Española (Fig. 2). Examination of data from the Española #6 municipal water-supply well did not indicate that this well encountered arkosic (granite-bearing) lithosome A sediment in the Pojoaque and Skull Ridge Members (Fig. 7); this is also true for deep wells south of the study area (D. Koning, unpublished data). In summary, alluvial slope sediment of lithosome A below the Cuarteles Member (i.e., lithesome A in the Skull Ridge and Pojoaque Members) did not prograde beyond ~6 km west of the eastern border of the study area.

Tectonic interpretations

The presence of laterally extensive tephra zones permits stratigraphic and chronologic correlation across the north-central portion of the Española basin. These and other age-constrained marker beds allow for calculation of stratal rotation and sedimentation rates near Española. Results of these calculations yield important information on how basin subsidence in this area influenced sedimentation and sediment distribution patterns.

In the study area, the highest rates of stratal tilting and thickening occurred between the middle of the PWAZ (13.7 Ma) and the base of the Pojoaque Member (14.6-15.0 Ma), and near the middle of the Skull Ridge Member (15.8-15.3 Ma) (Fig. 8 and Table 2). A possible unconformity at the Pojoaque-Skull Ridge Member contact is inferred by Barghoorn (1981) and Tedford and Barghoorn (1993); this unconformity is incorporated in the age range of the base of the Pojoaque Member (14.6-15.0 Ma, Tables 2 and 3). The presence of such an unconformity does not substantially change stratal tilt and accumulation rate estimates. Average stratal tilt rates calculated using the stratigraphic sections are 1.5-2.4°/m.y. for the two time periods measured between 15.8-13.7 Ma (Table 2). Average stratal tilt rates (Table 2) in younger strata decreased by over an order of magnitude to 0.1-0.7°/m.y. between 13.7 and 12.0 Ma, and generally remained at 0.03-0.2°/m.y. for the time interval between 9.5-12.0 Ma. Based on these data, we interpret that rift tectonic activity decreased significantly during and after the emplacement of the PWAZ at 13.2-14.0 Ma. This interpretation is consistent with a post-14 Ma decrease in rift tectonic activity inferred from apatite fission-track data (House et al., 2003) and somewhat agrees with temporal changes in stratal tilt rates elsewhere in the Rio Grande rift (e.g., Socorro basin of central New Mexico; Cather et al., 1994).

Stratal tilt rates calculated using simple thickness variations between marker beds or zones could be affected by possible syndepositional faulting in the area. Indeed, three west-down and three east-down faults are present between the Cuarteles and Martinez sections. Our best estimate of the throw on one of these faults (fault A in fig. 2) is approximately 25-30 m using stratigraphic offset of the interpreted Skull Ridge and Pojoaque Member contact.

Because possible syndepositional faulting between the sections complicate interpretations of half-graben tilt rates, bedding dips were also tabulated between various marker beds or zones. Bedding dips were taken from maps of Koning and Manley (2003) and Koning (2003a) within 2 km of the stratigraphic sections for beds whose strike azimuths are between 300-350°, and were not used for beds immediately adjacent to faults. Figure 12a summarizes the bedding dips between various marker beds or intervals as a function of time. Stratal dips decrease progressively from 8-9° between the white ash #2 and #4 beds of the Skull Ridge Member (15.8-15.3 Ma) to 2-3° between the Española tephra zone (10.2-11.2 Ma) and the Alcalde tuffaceous zone (9.4-9.6 Ma). Using these data, the rate of dip change decreases around 13-14 Ma. This method of calculating tectonic tilt rates is independent of tilt rates calculated using thickness changes in the stratigraphic sections (Fig. 8 and Table 2), and both methods support a decrease in half-graben tilting after about 13-14 Ma.

Stratal accumulation rates also support changes in stratal tilts. These rates are calculated from stratigraphic thickness data and available age control (Table 3 and Fig. 12b). As expected considering the geometry of half-graben basins, stratal accumulation rates may be higher for the western (basin marginal) Cuarteles section than the eastern (basinward) Martinez section for a given time interval. Stratal accumulation rates calculated for both stratigraphic sections suggest a general decrease in accumulation that is roughly coincident with the interpreted decrease in stratal tilt rates at 13-14 Ma. For example, stratal accumulation rates in the Martinez section are generally 2 times higher in pre-14.6 Ma strata compared to post-15 Ma strata. A decrease in stratal accumulation rates between 12.8 and 10.2 Ma coincides with the westward (basinward) progradation of the Cuarteles Member. Stratal accumulation rates have not been adjusted for compaction. Given that accumulation rate estimates decreased as the section coarsened upwards, we suspect that compaction would not strongly influence this rate. For the lower, finer grained strata, compaction adjustments would only serve to increase apparent stratal accumulation rates. That stratal accumulation rates generally decrease during a time of decreased tilting or tectonic subsidence of the half-graben is not unexpected. Drainage integration of streams in the Cuarteles and Cejita Members is poorly understood at present but might influence accumulation rates.

In summary, our calculations indicate a decrease in stratal tilt rates during and after the PWAZ was emplaced (Tables 2-3 and Fig. 12). One would expect an overall upward decrease in the magnitude of stratal tilts in an actively subsiding basin such as the Española basin, which has undergone tectonic subsidence into Plio-Pleistocene time. However, our data demonstrate a marked

TABLE 2. Data used for calculations of stratal tilt rates. Mean values denoted by "**Avg**" and preferred values by "**Pr**." Preferred stratigraphic height (*thickness*) indicated by **bold** type.

Marker Units[µ]	Stratigraphic height, Cuarteles & other sections (m)* (thickness)	Stratigraphic height, Martinez section (m) (thickness)	Age (Ma)**	Distance between sections (m)	Westward thickness increase (m)	Tilt (°)	Stratal tilt rate (°/m.y.)
Main ETZ top, Main ETZ base	411 387 (24)	476 453 *(23)*	10.2 11.2 (1.0)	980	1	0.03	0.03 **Avg: 0.03**
Main CWAZ top, CWAZ base	357 281 *(76)*	**441** **364** to 377 *(52-**74**)*	12.0 12.8 *(0.8)*	2040	**2**-24	**0.06**-0.7	0.08 - 0.9 **Avg: 0.5** **Pr: 0.08**
CWAZ base, Love fossil site	281 24 *(57)*	**364** to 377 308 *(**56**-69)*	12.8 12.9-13.2 (*0.1-0.4*)	2300	<**1**	<**0.02**	0-0.2 **Avg: 0.1** **Pr: 0.1-0.2**
Love fossil site, PWAZ (middle)* **	224 107 *(117)*	308 216-222 *(86-92)*	12.9-13.2 13.7 *(0.5-0.8)*	3900	25-31	0.4-0.5	0.5-1.0 **Avg: 0.7** **Pr: 0.7**
PWAZ (middle), Pojoaque mbr base	107 -80 to -90 *(187-197)*	216-222 132-164 *(52-90)*	13.7 14.6-**15.0** *(1.1-**1.3**)*	4100	97-145	1.4-2.0	1.1-1.8 **Avg: 1.5** **Pr: 1.1-1.5**
White Ash #4, White Ash #2	54* 0* *(54)*	76 4 *(72)*	15.3-15.4 15.5-15.8 (*0.1-0.5*) **Pr: 0.3**	2300	18	0.4	0.8-4 **Avg: 2.4** **Pr: 1.3**

[µ] Abbreviations are as follows: ETZ = Espanola tephra zone, CWAZ = coarse white ash zone, and PWAZ = Pojoaque white ash zone; see text for more discussion of these marker units. White ashes 2 and 4 are in the Skull Ridge Member; this member underlies the Pojoaque Member and is approximately 16.1 to 15 Ma (Barghoorn, 1981; Izett and Obradovich, 2001; Koning et al., 2002; Koning, 2003).

** Age control for PWA and CWAZ discussed in the text. Age control for Pojoaque Member base is from Barghoorn (1981), Tedford and Barghoorn (1993), and Izett and Obradovich (2001).

* Lowest row for this column is from the Chimayo stratigraphic section, located 2300 m to the east of study area, and the highest row is for the Gaucho stratigraphic section.

*** We chose the ash at 107 m in the Cuarteles section because it is in a similar relative position as the ash dated by Izett and Obradovich (2001) at 13.7 Ma.

TABLE 3. Data from stratigraphic sections used for calculations of stratal accumulation rates (not adjusted for compaction). Mean values denoted by "**Avg**" and preferred values by "**Pr**." Preferred stratigraphic height (*thickness*) indicated by **bold** type.

Marker Units[µ]	**Age (Ma)*** ***(Age difference, m.y.)***	**Stratigraphic height, Cuarteles & other sections (m)**** ***(thickness)***	**Stratal accummulation rate, Cuarteles & other sections (mm/yr)**	**Stratigraphic height, Martinez section (m)** ***(thickness)***	**Stratal accummulation rate, Martinez section (mm/yr)**
ATZ base	9.5-9.6			*556*	0.1
ETZ top	10.2			*472*	**Avg: 0.1**
	(0.6-0.7)			*(84)*	
Main ETZ top	10.2	411	0.03	476	0.02
Main ETZ base	11.2	387	**Avg: 0.03**	453	**Avg: 0.02**
	(1.0)	*(24)*		*(23)*	
Main CWAZ top	12.0	357	0.1	**441**	0.08 - **0.1**
CWAZ base	12.8	281	**Avg: 0.1**	**364** to 377	**Avg: 0.09**
	(0.8)	*(76)*		*(64-77)*	**Pr: 0.1**
CWAZ base	12.8	281	0.1-0.6	**364** to 377	0.1-0.7
Love fossil site	12.9-13.2	224	**Avg: 0.4**	308	**Avg: 0.4**
	(0.1-0.4)	*(57)*	**Pr: 0.1-0.2**	*(**56**-69)*	**Pr: 0.1-0.2**
Love fossil site to	12.9-13.2	224	0.1-0.2	308	0.1-0.2
PWAZ (middle)***	13.7	107	**Avg: 0.15**	216-222	**Avg: 0.15**
	(0.5-0.8)	*(117)*		*(86-92)*	
PWAZ (middle) ***	13.7	107	0.1-0.2	216-222	0.04-0.1
Pojoaque Mbr base	14.6-**15.0**	-80 to -90	**Avg: 0.15**	132-164	**Avg: 0.07**
	*(0.9-**1.3**)*	*(187-197)*		*(52-90)*	
Pojoaque Mbr base	14.6-15.0			132-164	0.07-0.3
White Ash 4	15.3-15.4			76	**Avg: 0.2**
	(0.3-0.8)			*(56-88)*	
White Ash 4	15.3-15.4	54**	0.1-0.5	76	0.1-0.7
	15.5-15.8	0**	**Avg: 0.3**	4	**Avg: 0.4**
White Ash 2	*(0.1-0.5)*	*(54)*	**Pr: 0.2**	*(72)*	**Pr: 0.2**
	(Pr: 0.3)				

[µ] Abbreviations are as follows: ATZ = Alcalde tuffaceous zone, ETZ = Española tephra zone, CWAZ = coarse white ash zone, and PWAZ = Pojoaque white ash zone. White ashes 2 and 4 are in the Skull Ridge Member, which underlies the Pojoaque Member and is approximately 16.1 to 15.0 Ma (Barghoorn, 1981; Izett and Obradovich, 2001; Koning et al., 2002; Koning, 2003). **Avg** = average of above number range. **Pr** = preferred value or range.

* Age control for CWAZ, PWAZ, white ash 4, and white ash 2 discussed in the text. Age control for Pojoaque Member base is from Barghoorn (1981), Barghoorn and Tedford (1993), and Izett and Obradovich (2001).

** Lowest row for this column is from the Chimayo stratigraphic section, located 2300 m to the east of study area. *** We chose the ash at 107 m in the Cuarteles section because it is roughly in a similar relative position as the ash dated by Izett and Obradovich (2001) at 13.7 Ma.

change in the rate of stratal tilting at 13-14 Ma. It is important to note that our data was collected in the north-central part of the Española basin, and it is not yet clear if these tilt rate changes are recorded elsewhere in the basin.

Paleoclimatic and fluvial-geomorphic inferences

It is difficult to isolate basin subsidence (tectonics) versus climatic influences (possibly manifested by erosion rates and paleostream discharge) on sediment distribution because both can result in similar sedimentary successions. For example, after ~13 Ma coarse channel deposits became more abundant throughout the Española basin (this work; Koning, 2002; Koning and Maldonado, 2001), but this phenomena could be the result of overfilling a basin (e.g., Cather, 2004) or due to increases in discharge to streams because of climatic changes.

One could argue that paleoclimatic changes occurred at 13-14 Ma and affected deposition and drainage system locations in the basin. The marine stable isotope record indicates a major change in marine water composition at about 13-14 Ma (Fig. 13), which coincides with the change in stratal tilt and accumulation rates discussed above. Studies of marine sediments indicate a major decline in sea level with the onset of major glaciations in Antarctica during Miocene time (Zachos et al., 2001). However, our understanding of the marine-continental climate system is not clear for time prior to the formation of the isthmus of Panama and North Atlantic deepwater formation, which began during the Pliocene (e.g., Haug and Tiedemann, 1998; Zachos et al., 2001).

A climate change at 13-14 Ma could have resulted in drier conditions and decreased vegetative stabilization in the basin that would promote the development of dune fields. However, the development of the Ojo Caliente Sandstone dune field at ~13 Ma roughly coincides with the marked increase in gravel size in the fluvial systems (Fig. 11). Although one may perhaps infer drier climatic conditions during deposition of the Ojo Caliente Sandstone, stream competence and stream power must have increased in order to transport the larger gravels in the uppermost lithosome B unit of the Pojoaque Member and in the lower Cejita Member. One may speculate changes in regional circulation patterns accompanying such a climate change, which in turn

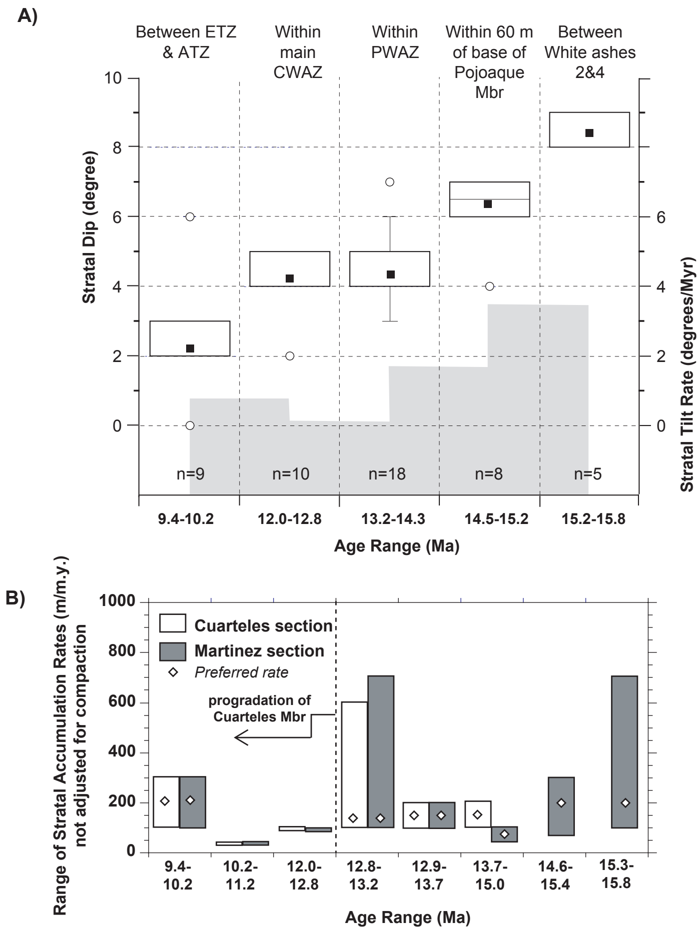

FIGURE 12. A) Box and whisker plot of stratal dips from bedding attitudes measured within 2 km of the Cuarteles and Martinez stratigraphic sections (from maps of Koning, 2003a, and Koning and Manley, 2003). Small, filled square represents the mean, the horizontal line in the larger rectangle is the median, the length of the larger rectangle represents the upper and lower quartile (25% above and 25% below the median), the bracket(s) represent the 95% range, and circles are outliers. At bottom is number of data in each interval; average rate of dip change between the intervals is illustrated by length of shaded bars. PWAZ = Pojoaque white ash zone, CWAZ = coarse white ash zone, ETZ Española tuffaceous zone, ATZ = Alcalde tuffaceous zone. B) Range of stratal accumulation rates calculated from Table 3.

might have changed the distribution (and seasonality) of precipitation. As a hypothetical example, orographic effects might lead to increased precipitation and stream discharge in the Sangre de Cristo Mountains if the dominant source of moisture was from the southeast. Such a scenario could produce a local rain shadow in the eastern Española basin. This scenario is not supported by the present data and is provided only to promote discussion of the different mechanisms that would possibly create the unexpected relation of an eolian dune field (i.e., Ojo Caliente Sandstone) interfingering with the lower Cejita Member, one of the coarsest fluvial units in the basin.

Alternatively, the increase in gravel size and proportion of coarse channels could possibly be attributed to incision and integration of upland drainages in the uplifted hanging wall block of the Sangre de Cristo Mountains after 13-14 Ma. Increased incision might allow more groundwater recharge to drainages, effectively increasing discharge and allowing larger grain sizes to be transported. If progressive stream incision exposed previously buried, relatively non-permeable rocks in the source area, increased discharge could change stream power values in the streams (e.g., Kelson and Wells, 1989). Drainage expansion would also increase drainage area and consequently increase discharge to the channels.

Drainage incision and drainage-network expansion likely occurred in the western Sangre de Cristo Mountains throughout middle Miocene and late Miocene time. One may approximately estimate drainage incision by comparing the proportion of Proterozoic quartzite and Paleozoic sedimentary rock in the gravel fraction of the Cejita Member and lithosome B of the Pojoaque Member. Most of the sediment in both of these units is interpreted to be derived from the Sangre de Cristo Mountains near Truchas Peaks and the Peñasco embayment. The proportion of quartzite gravel in the gravel fraction progressively increased from ~5% in the middle Skull Ridge Member (clast count 1 of the Martinez section; Koning, 2003) to 8-9% in the lower-middle Pojoaque Member (clast counts 2 and 3 of the Martinez section, Koning, 2003, and unit 1a of the Cuarteles section, Appendix 1). The proportion continued to increase from 12-16% in the uppermost lithosome B of the Pojoaque Member and the Cejita Member (Appendix 1) to 30-65% in the middle to upper Cejita Member

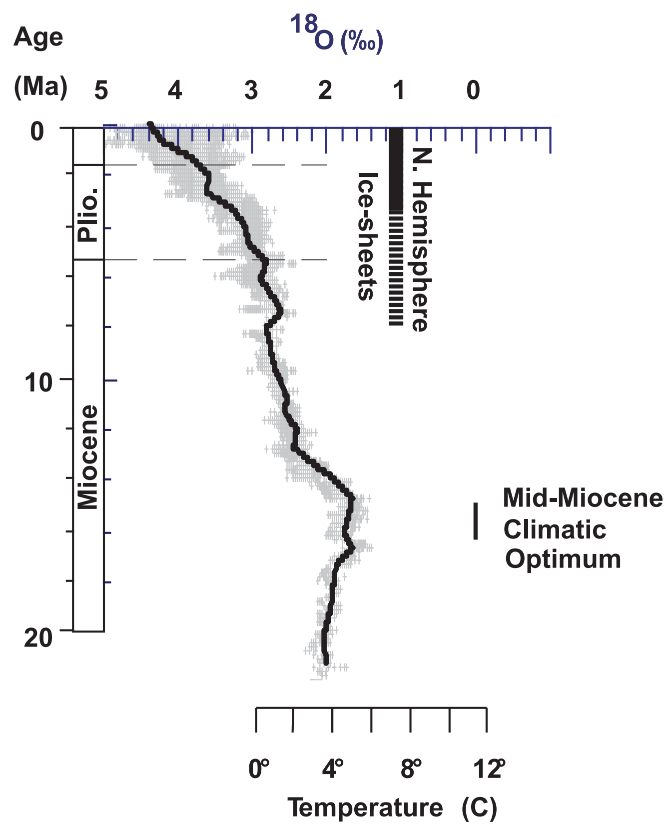

FIGURE 13. Plot of stable isotopes of oxygen and climatic interpretations; modified from Zachos et al. (2001).

(Koning and Aby, this volume). We interpret this increase in the proportion of durable quartzite clasts as indicating a progressive unroofing of Paleozoic strata from Sangre de Cristo Mountains around the Peñasco embayment; alternatively, one may argue that this could be due to greater erosion of the Proterozoic-cored Picuris Mountains on the north side of the Peñasco embayment. In either case, this unroofing or erosion probably involved greater incision of streams and perhaps expansion of drainage basins. Stream capture would likely result in abrupt changes in clast composition rather than the progressive trend we observe, in which quartzite appears to increase by approximately 3-4% per Ma (given our present age control). In addition, clast sizes are larger in the lower part of the coarser strata (i.e., uppermost lithosome B unit of the Pojoaque Member and the lower Cejita Member), which contain fewer (12-16%) quartzite clasts, as compared to the middle-upper Cejita Member, which contains 30-60% quartzite. Thus, the coarsest clasts do not coincide with the stratigraphic interval having the greatest proportion of quartzite. While increased incision or drainage expansion in the absence of external variables, such as tectonics or climate, could result in increased discharge and coarser sediment, such a scenario does not fully explain the widespread coarsening of strata and basinward migration of stream systems after about 13-14 Ma. We would argue that climatic factors or effects of overfilling the basin (discussed below) must also be considered.

Basin Sedimentation Patterns

Most models of basin filling commonly have focused on the behavior of deposits associated with the basin floor and footwall uplifts (e.g., Leeder and Gawthorpe, 1987; Blair and Bilodeau, 1988; Mack and Seager, 1990; Peakall et al., 2000); however, fewer studies relate depositional responses of the hanging wall to changes in basin deformation, discharge, and sediment supply (e.g., Paola et al., 1992). Conceptual models of basin filling that focus on sediments derived from an uplifting footwall block in an internally drained basin indicate that the footwall-derived sedimentary wedge remains close to the basin-bounding fault while the fault is active. Distal hanging wall ramp sediment is thought to prograde basinward towards the master fault during times of increased fault activity and asymmetric-basin tilting (e.g., Leeder and Gawthorpe, 1987). During times of reduced differential subsidence, coarse footwall-derived detritus progrades away from the footwall and distal hanging wall ramp sediment shifts away from the basin-bounding fault (e.g., Mack and Seager, 1990, fig. 1). A diffusion-based numerical model of basin formation developed by Paola et al. (1992) considered an input of sediment from a single source on the distal hanging wall ramp. This simulation indicated that the hanging wall ramp sediment prograded towards the basin center during times of increased tilting or increased sediment flux. The results from our study do not support basinward progradation of distal hanging wall ramp sediment during times of increased asymmetric basin subsidence. Rather, our observations indicate basinward (westward) progradation of the distal hanging wall ramp deposits (i.e., Cuarteles Member) during times of decreased asymmetric basin subsidence.

Internally drained basins tend to be underfilled and contain most of the siliciclastic record of sedimentation as well as abundant finer-grained deposits, whereas in overfilled (or fluvially integrated) basins much of the sedimentary fill may be transported out of the basin (e.g., Leeder, 1997), leaving a record of relatively coarser grained strata (for more discussion on coarsening during times of decreased tectonic rates, see Blair and Bilodeau, 1988, Beck et al., 1998, and Cather, 2004). Similarly, the transition of the Española basin from a relatively underfilled basin condition (that probably existed during times of high rates of half-graben tilting and tectonic subsidence) to an overfilled condition (that probably commenced during or after a decrease in tectonic subsidence rates) could account for the coarsening and westward progradation of the hanging wall ramp strata after about 13-14 Ma. An important element in this scenario would be the presence of a river that could transport sediment out of the Española basin to basins further south. Such a river is interpreted based on examination of exposures near the Buckman well field in the southern Española basin (White Rock quadrangle; Read et al., 2005), where deposits of the Tesuque Formation are ~11 Ma based on the presence of beds correlated with the CWAZ ($^{40}Ar/^{39}Ar$ age of 10.9 ± 0.2 Ma; W.C. McIntosh, unpublished data). A decrease in asymmetric basin subsidence rates after 14 Ma may have led to an overfilled condition of the Española basin, and would better explain the coarsening and basinward progradation of post-13-14 Ma strata than purely autocyclic fluvial geomorphic factors. Possible paleoclimate change during this time hinders us from isolating a single factor in explaining these important and intriguing sedimentation patterns.

CONCLUSIONS

Geologic mapping and stratigraphic study of middle to upper Miocene deposits of the Tesuque and Chamita Formations in the northern Española basin provide a record of sedimentation and sediment distribution patterns. Relatively distinct tephra beds, whose ages are constrained by geochronologic studies, together with biostratigraphic data provide synchronous marker beds or intervals that allow enhanced understanding of the stratigraphic relations of these deposits.

The Cuarteles Member of the Tesuque Formation is a newly defined, relatively coarse lithostratigraphic unit east of the Rio Grande consisting of granite and quartzite gravel and arkosic sand deposited between 12.8 and 8 Ma. This unit records an important depositional event where coarse clastic sediment from the Sangre de Cristo Mountains prograded basinward across most of the eastern Española Basin.

Westward (basinward) thickness changes for dated stratigraphic intervals support independent bedding attitude data in indicating a marked decrease in half-graben tilt rates after about 13-14 Ma. A slight decrease in sediment accumulation rates coincides with a westward progradation of the hanging wall ramp deposits between 12.8 and 10.2 Ma. For both alluvial slope and basin floor deposits, our data indicate that strata post-dating 13-14 Ma are coarser than strata pre-dating 13-14 Ma. Given that half-graben tilt rates slowed after about 13-14 Ma, coarsening was not due to an increase in the tectonic slope of the half-graben. Paleoclimatic factors or geomorphic evolution of upland catchments might explain this coarsening. However, the change from an underfilled basin, accompanying relatively high tectonic subsidence and tilting rates, to an overfilled basin with a through-going river, accompanying relatively lower tectonic subsidence and tilting rates, may also explain the westward progradation of the hanging wall ramp deposits and general coarsening of strata.

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APPENDIX 1. CLAST COUNT DATA FOR CUARTELES STRATIGRAPHIC SECTION

Strat section Unit	Member	Granite	Paleozoic limestone	Paleozoic sandstone and siltstone	Proterozoic quartzite	Felsic to intermediate volcanics	Vein quartz	Pilar phyllite	Other
9b	Cuarteles	77			18		3		2
8u (est)	Cuarteles	96			2		2		
8t	Cuarteles	99			1				
8s	Cuarteles	89			3		8		
8o	Cuarteles	93			0		7		
8n	Cuarteles	99			1				
8g (est)	Cuarteles	99-100			Tr-1%				
8b	Cuarteles	91			6		3		
8a (est)	Cuarteles	97			3				
7w	Cuarteles	92			7		1		
7n	Cuarteles	98			1		1		
7g (est)	Cuarteles	80			20				
7ff	Cuarteles	86			13			1	
7e (est)	Cuarteles	85-90			10-15				
7b	Cuarteles	85	5		8		2		
7a	Cuarteles	85			15				
6i	Cejita	4	49	25	15	1	4		1
6g	Cejita	4	7	24	26	1	5		4
6d	Cejita	45	24	13	19				
6a'	Cejita	56	17	12	12		4		
6a	Cejita	32	33	23	12				
5c' (est)	Pojoaque, salmon unit	98			2				
4b	Pojoaque, upper lith B	0	38	38	16	0	5	0	1 muscovite-schist 1 porphyritic silicic rock*
3i	Pojoaque, mixed lith A-B	3	35	31	19	0	12	0	
1a	Pojoaque, middle lith B	1	15	55	8	19	2	0	1 chert

Notes: * biotite phenocrysts.