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2004, pp. 359-373. https://doi.org/10.56577/FFC-55.359

in:

Geology of the Taos Region, Brister, Brian; Bauer, Paul W.; Read, Adam S.; Lueth, Virgil W.; [eds.], New Mexico Geological Society 55 th Annual Fall Field Conference Guidebook, 440 p. https://doi.org/10.56577/FFC-55

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MIDDLE-UPPER MIOCENE STRATIGRAPHY OF THE VELARDE GRABEN, NORTH-CENTRAL NEW MEXICO: TECTONIC AND PALEOGEOGRAPHIC IMPLICATIONS

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Abstract.—Geologic mapping and correlation of tephras in and near the Velarde graben supports the southward extension of the Cieneguilla member of Leininger (1982) into the graben, refines the stratigraphic relationships of various lithostratigraphic units, and has produced better estimates of vertical stratigraphic displacement on several graben faults. The Velarde graben is a 6-10 km-wide, northeast-trending extensional feature in the northern Española Basin of the Rio Grande rift. It coincides with a 19 km-long gravity low between the north tip of Black Mesa and the town of Hernandez to the southwest. In the general area of the Velarde graben, the Santa Fe Group is differentiated into seven lithostratigraphic units assigned to the Tesuque Formation. Some of these units were originally assigned to the Chamita Formation in previous studies. However, we propose abandoning the Chamita Formation, and reassigning its strata to the Tesuque Formation, because 1) strata assigned to the Tesuque Formation correlate into the Chamita type section, and 2) in the absence of the Ojo Caliente Sandstone Member it is not possible to map a contact between the Chamita and Tesuque formations with confidence. Vertical stratigraphic displacements along the border faults of the Velarde graben since 7.7-8.4 Ma range from as low as 65 m on the Rio de Truchas fault to 435 m on the Santa Clara fault. On the southern tip of Black Mesa, comparison of vertical slip rates for the Santa Clara fault over two time periods yields slightly higher vertical slip rate values for 3-8 Ma (48-56 m/Myr) compared to 0-3 Ma (35-48 m/Myr). On the gravity high separating the Velarde graben from another gravity low to the south, a vertical slip rate calculated for the Santa Clara fault gives 48-50 m/Myr for time after 9.9 Ma. Increasing slip rates on the Velarde graben faults in the late Miocene may have induced west-northwestward progradation of alluvial slope facies (lithosome A) derived from the Sangre de Cristo Mountains.

INTRODUCTION

This paper discusses preliminary results from recent field-based geologic investigations in the Velarde graben. The Velarde graben is a 6-10 km-wide, fault-bounded, northeast- trending graben in the northern Rio Grande rift, New Mexico (Fig. 1; Manley, 1976a, 1979b). Located in the north-central part of the Española Basin northeast of the town of Hernandez, this graben corresponds to a 19 km-long gravity low, which is differentiated from other gravity lows and associated intra-rift grabens to the south in the Española Basin (Koning et al., 2004, this volume). The Española Basin was formed due to extension associated with the Rio Grande rift (Kelley, 1956; Spiegel and Baldwin, 1963; Chapin, 1971), and is bordered by the Sangre de Cristo Mountains on the east and a zone of down-to-the-east faults near the town of Abiquiu on the west (Kelley, 1978). Strata in the eastern Española Basin are generally tilted to the west (Galusha and Blick, 1971; Kelley, 1978), in contrast to the east-tilted San Luis Basin located to the north (Dungan et al., 1984). In the northern Española Basin, the Velarde graben lies to the east of the Abiquiu embayment, a relatively shallow part of the Española Basin that extends westward to the Colorado Plateau near the town of Abiquiu. On its east side, the Velarde graben is bound by two faults: the Rio de Truchas and Velarde faults (Plate 11). Both the Velarde and the Rio de Truchas faults have normal slip. The Velarde fault also has a component of left-lateral slip, but whether this is true for the Rio de Truchas fault is not clear (Koning et al., 2004, this volume). The La Mesita fault at the north end of the graben projects southwestward to the poorly exposed, eastern slopes of Black Mesa, and is characterized by down-to-the-west and left-lateral motion (Koning et al., 2004, this volume; Koning and Aby, 2003). Lateral motion on the Velarde and La Mesita faults is consistent with map relationships that suggest these faults represent the southward continuation of the Embudo fault system (Koning et al., 2004, this volume; Aby and Koning, 2004, this volume; Manley, 1979b). The Santa Clara fault probably forms the west-northwest border of the southern Velarde graben. Seven to ten km northeast of the south tip of Black Mesa, the Santa Clara fault appears to end and extensional strain steps 1 to 3 km westward to the Black Mesa fault (Plate 11). Using the stratigraphic data presented in this paper and additional geophysical data, Koning et al. (2004, this volume) interpret that subsidence of the Velarde graben began before the late Miocene.

The Velarde graben is filled with clastic sediment of the Santa Fe Group, which is considered "a broad term including sedimentary and volcanic rocks related to the Rio Grande trough" (Spiegel and Baldwin, 1963, p. 39). Previous studies suggest that the Santa Fe Group is up to 2.2-5.0 km thick in the Velarde graben (Cordell, 1979; cross-sections of Kelley, 1978, Koning and Aby, 2003, and Koning and Manley, 2003). At Black Mesa, Miocene-age strata are overlain with angular unconformity by 1-17 m of Pliocene fluvial sandy gravel, which are in turn overlain by 3-38 m of Servilleta Basalt (Pliocene; Lipman and Mehnert, 1979) that caps Black Mesa. The absence of a strong soil or angular unconformity between the Pliocene sandy gravel and the Servilleta Basalt indicates that no significant temporal hiatus existed between the two units (Koning and Manley, 2003). Erosion generally predominated after the emplacement of the Servilleta Basalt.

Setting a general stratigraphic framework for subsequent studies, Galusha and Blick (1971) established the Tesuque Formation overlain by the Chamita Formation. They subdivided the exposed Tesuque Formation in the Velarde graben into two members: Chama-El Rito and Ojo Caliente Sandstone Members. The Cejita and Dixon members were later added to the Tesuque Formation by Manley (1976a, 1977, 1979a) and Steinpress (1980 and 1981),

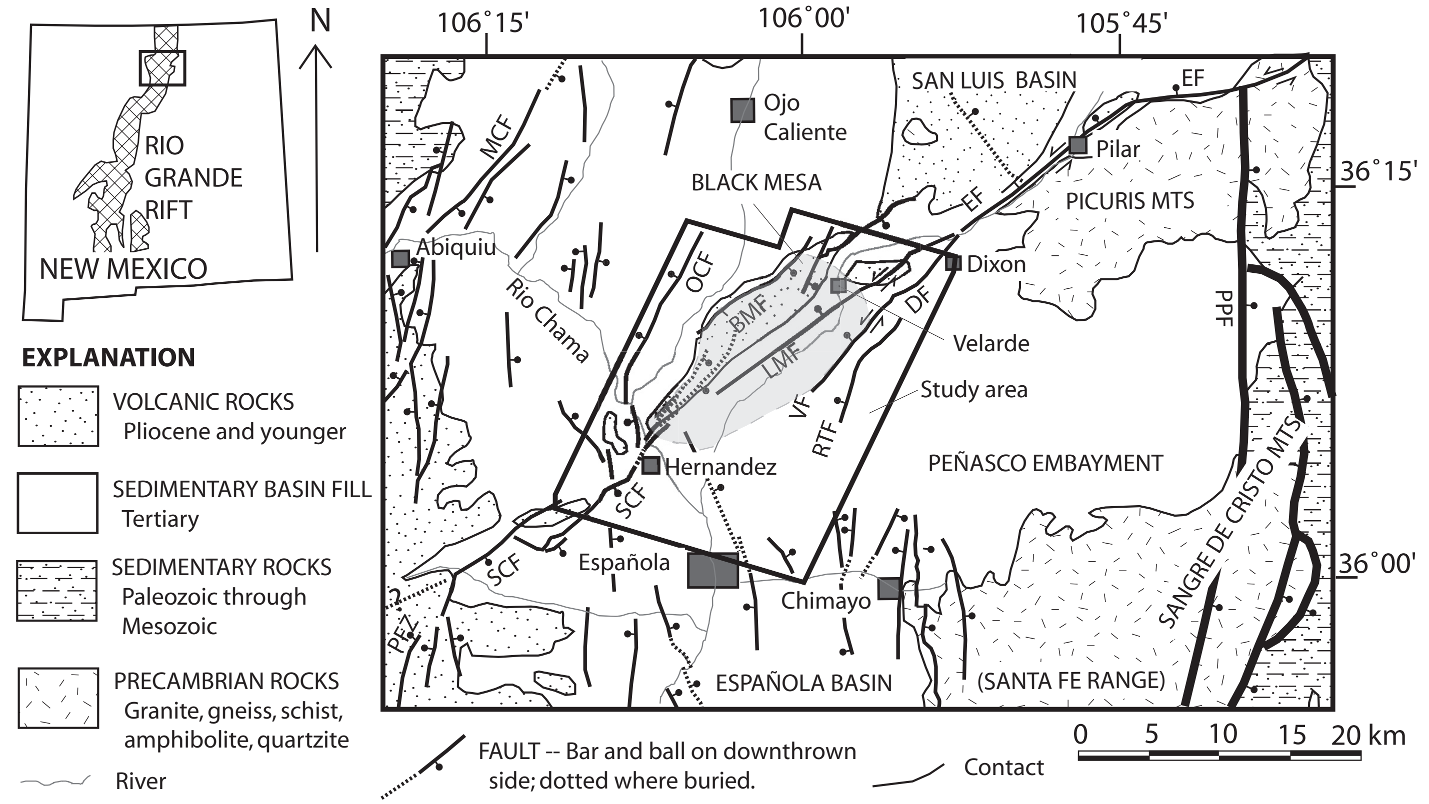


FIGURE 1. Location of study area. The Velarde graben is shown by gray shading. Fault names are abbreviated as: MCF = Madera Cañon fault; PFZ = Pajarito fault zone; SCF = Santa Clara fault; OCF = Ojo Caliente fault; BMF = Black Mesa fault; LMF = La Mesita fault, VF = Velarde fault; RTF = Rio de Truchas fault; DF = Dixon fault zone; EF = Embudo fault; PPF = Pecos-Picuris fault. Constructed in part from Kelley (1978).

respectively. Other important stratigraphic studies in and near the Velarde graben include Kelley (1978), May (1980 and 1984), Leininger, (1982), Dethier and Martin (1984), and Dethier and Manley (1985).

During the course of geologic mapping, we delineated tephra zones and lava flows, together with lithostratigraphic units, because they provide useful stratigraphic markers and age control. After presenting these tephras zones and flows, this paper describes seven lithostratigraphic units in the Velarde graben and their stratigraphic relationships. These units and tephra zones are then used to reconstruct late Miocene paleogeography in the northern Española Basin and determine vertical slip magnitudes and slip rates on faults in the Velarde graben.

STRATIGRAPHY OF MARKER INTERVALS

In performing correlations, several relatively distinctive tephra zones (Fig. 2) and lava flows, the latter associated with two separate eruptive episodes, provide useful stratigraphic-marker intervals. These are briefly described below, in addition to relevant radiometric age data. Most of the tephra beds show evidence of fluvial reworking. The tephra correlations are primarily field-based. To complement these field correlations, numerous tephra samples were collected and sent to New Mexico Tech for geochemical comparisons with other ashes. Weathering and diagenetic alteration rendered most ashes useless in this endeavor. Two samples (from the Chamita upper tuffaceous zone) were sufficiently pristine to allow for compositional characterization and comparison. Twenty to thirty glass shards from each ash sample were analyzed using a Cameca SX-100 electron microprobe (data tabulated in Koning and Aby, 2003). The composition of these ashes was then compared to tephra compositions for eruptions in the southwest United States (N. Dunbar, unpubl. data) using a statistical difference method (Perkins et al., 1995). It is important to note that age interpretations regarding these tephras may change with future dating efforts.

Stratigraphic thicknesses of the tephra zones include interbedded clastic sediment of the Tesuque Formation (which is generally far more abundant than the actual tephra beds). We use the term Chamita badlands to refer to the exposed terrain north of the Rio Chama, west of the Rio Grande, and east of the south tip of Black Mesa. Also, in the following text the abbreviation NALMA is used for North American Land Mammal Age.

Lava Flows

Lobato Formation Basalt Flows

Olivine-phyric tholeiite and hawaiite basalt flows associated with the Lobato Formation were erupted about 14-9 Ma from at least four vents located 12-18 km west of Española (Bailey et al., 1969; Smith et al., 1970; Dethier and Manley, 1985; Aldrich

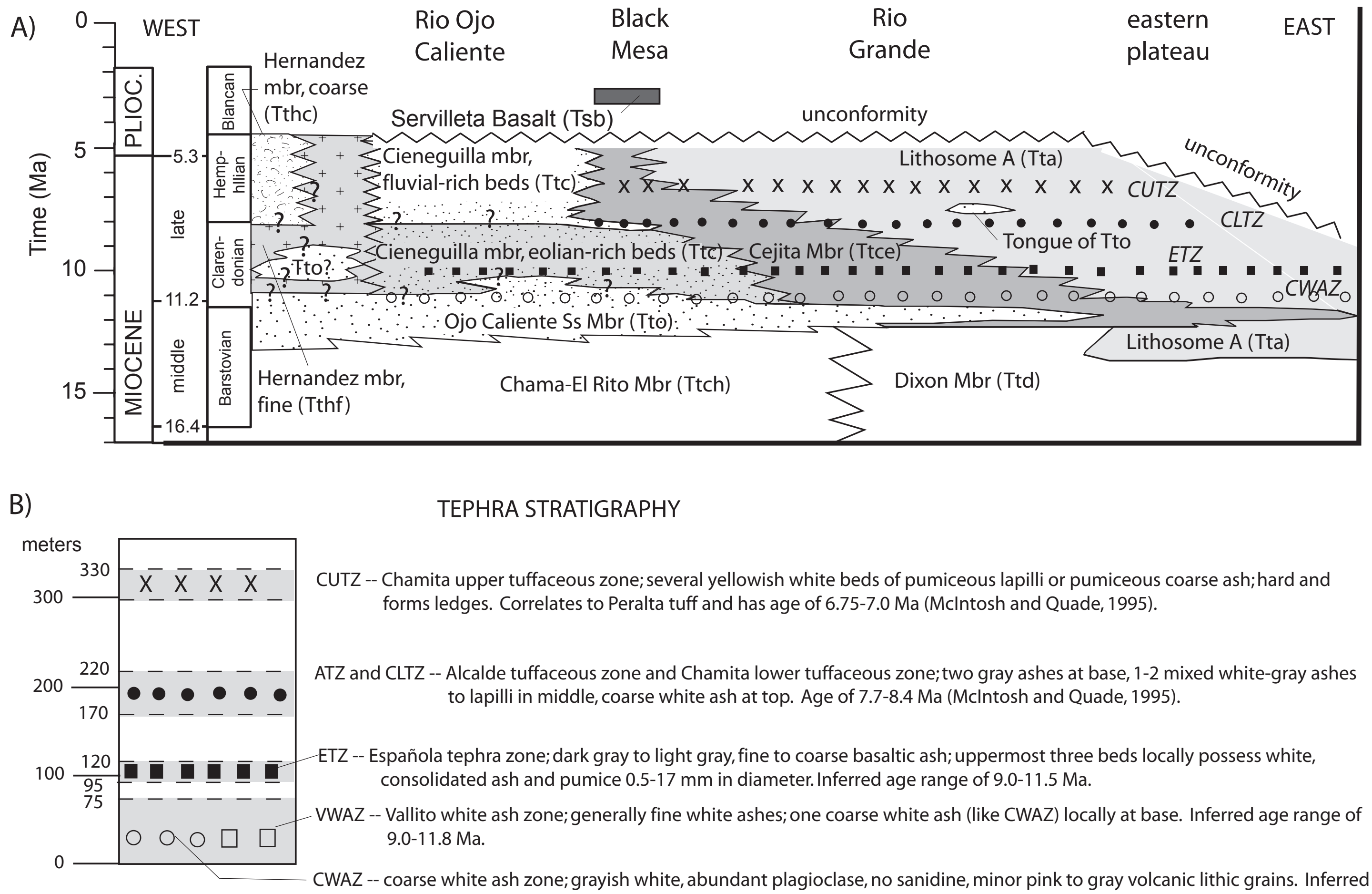


FIGURE 2. A) Stratigraphic correlation of late Tertiary units in the southern Velarde graben. Units, symbols, and shading follow the explanation on Fig. 3. B) Approximate stratigraphic positions and thicknesses of tephra zones (shaded); the Lobato Formation basalt flows and Servilleta Basalt are not included, and intervening clastic strata are not differentiated.

and Dethier, 1990; Goff et al., 1989). The Lobato volcanic field in this area was most active between 9 and 11 Ma (Aldrich and Dethier, 1990; Goff et al., 1989). Individual flows are 2-5 m thick and interfinger with clastic sediment of the Santa Fe Group (Baldridge et al., 1980; Dethier and Manley, 1985). Cumulative flow thickness is 200 m (Aldrich and Dethier, 1990).

Servilleta Basalt

The Servilleta Basalt (Lipman and Mehnert, 1979) is 3-38 m thick and caps Black Mesa and La Mesita. Most of this lava is olivine tholeiite (Dungan et al., 1984). North of the study area, several samples of this unit have been dated by the $^{40}Ar/^{39}Ar$ technique at 2.7-3.7 Ma (Appelt, 1998). In the study area, one sample gave an $^{40}Ar/^{39}Ar$ age of 3.65 ± 0.09 Ma (A.W. Laughlin et al., unpublished report for Los Alamos National Laboratory, 1993), and one returned a K-Ar age of 2.78 ± 0.44 Ma (Manley, 1976a and 1976b). For the Servilleta Basalt on Black Mesa, we include the K-Ar date for a conservative age range of 2.8-3.7 Ma.

Tephra

Coarse White Ash Zone (CWAZ)

As many as ten beds of similar-looking ash over a stratigraphic distance of 65-80 m comprise the coarse white ash zone (CWAZ) (Fig. 2). The ash is grayish white to white and consists of consolidated ash with abundant plagioclase. In addition, there are minor grains of pink to gray volcanic lithic fragments, biotite, and quartz. Locally east of Española, the upper beds of this zone have some lapilli-sized fragments of greenish dacite(?) and purplish gray volcanic lithics. On the whole, however, tephra beds in the CWAZ correspond to a coarse ash (0.06 - 2 mm diameter), and hence we use the term ash in the name. The mineralogy of the ash is similar to rhyolitic and dacitic tephra and flows of the Paliza Canyon and Canovas Canyon formations in the southern Jemez Mountains, which have an age range of ~ 9 Ma to greater than 10.8 Ma (G. Smith, personal commun., 2004; S. Kelley and Kirt Kempter, personal commun., 2004). Consequently, we infer that the CWAZ is older than 9 Ma. In Cañada de las Entrañas 2-6 km east of the study area, $^{40}Ar/^{39}Ar$ dating of ash correlated to the CWAZ yielded ages of 11.3 ± 1.2 and 11.7 ± 1.1 Ma on biotite (Gary Smith, personal commun., 2003). In exposures near the Buckman well field in the southern Española Basin, a $^{40}Ar/^{39}Ar$ age of 10.9 ± 0.2 Ma was obtained from biotite in a coarse white ash bed (William McIntosh, unpublished data) near the middle of the CWAZ. Two to four km northeast of Española High School (UTM coordinates of school: 3985000 N, 406400 E, Zone 13, NAD 27), the CWAZ lies 125-130 m above a site that yielded fossils identified as belonging to the Clarendonian NALMA (Dave Love and Gary Morgan, personal commun., 2002), which ranges from 9 to 11.8 Ma, (Tedford et al, 1987; Tedford and Barghoorn, 1993). So the CWAZ must post-date 11.8 Ma. Based on these data and relative stratigraphic positions, we assign an age range of 9.0-11.8 Ma for the CWAZ.

Española Tephra Zone (ETZ)

The lowest tephra bed of the Española tephra zone occurs only a few meters above the uppermost ash bed of the CWAZ. However, the majority of the black tephra beds of the ETZ, about 5-8 in number, lie in a 23-25 m-thick interval 11-24 m above the CWAZ (Fig. 2). The tephra of ETZ are characterized by dark gray to light gray, fine to coarse basaltic ashes that are generally mixed with sandy arkosic detritus. The uppermost three beds of this zone locally possess abundant white, consolidated ash and pumice 0.5 - 17 mm in diameter; these uppermost beds may be more felsic in composition. Two to three km west of Española (Plate 11), this zone includes a basaltic phreatomagmatic bed 120 cm-thick with lapilli 30-65 mm in diameter. The coarseness of this particular phreatomagmatic bed strongly suggests derivation from vents associated with the Lobato volcanic field 12-18 km west of Española. We tentatively correlate several grayish ash beds located on the north slope of Cañada de las Entrañas, north-northwest of the mouth of Cañada de Jacinto (just east of the study area outlined in Plate 11, approximate UTM coordinates of: 3,999,500N and 420,200E, zone 13, NAD 27), to ETZ. This correlation is based on similarities in appearance and the observation of pumiceous beds (such as the Orilla pumice, see Manley, 1977) occupying the top position in the tephra beds there. A sample from a pumiceous bed that projects approximately 35-100 m stratigraphically below the Orilla pumice site returned a zircon fission-track date of 10.8 Ma (Manley, 1976a, 1977, 1979a). Based on this zircon fission-track date, the age of the Lobato volcanic field (9-14 Ma) 12-18 km west of Española, and our age range of the underlying CWAZ, we infer that the ETZ has an age range of 9.0-11.5 Ma.

Vallito WhiteAsh Zone (VWAZ)

Along the exposed, western slopes of central Black Mesa are five white ash beds that cover a stratigraphic interval of 90-100 m (Plate 11). The upper four beds consist of fine, commonly altered ashes that are medium to thick and laterally continuous. Of these four, the lowest bed is by far the thickest (up to 4.3 m) and the most laterally extensive; this bed becomes progressively more reworked with silt and sand northwards and marked the base of the Chamita Formation in the stratigraphic scheme developed by May (1980). Below these upper four ashes, the lowermost ash bed is very discontinuous and consists of fine to coarse, consolidated white ash, ~ 25% pinkish to grayish volcanic lithic fragments, and 3% biotite. The coarse white ash found in the lowermost bed is visually identical to that of the CWAZ, and stratigraphic relations depicted in cross-section D-D' of Fig. 3 suggest that the VWAZ may occupy a similar stratigraphic position as CWAZ to the south. If so, the age range of the VWAZ would be comparable to the CWAZ at 9.0-11.8 Ma. Perhaps the upper four beds of the VWAZ are finer-grained lateral equivalents to the CWAZ, but no chemical analyses have been conducted to evaluate this hypothesis due to the general alteration of these ashes.

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 lower contact of ATZ projects approximately 45-50 m above the Orilla pumice in Cañada de las Entrañas, and in a stratigraphic section on the east end of section B-B' (Fig. 3) lies 52 m above the uppermost beds of the ETZ (Daniel Koning, unpublished data). 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 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 ATZ is located in close proximity to, and probably stratigraphically above, the *Osbornoceros* fossil quarry (Plate 11), where fossils from the Hemphillian NALMA were collected (~ 4.8 - 9 Ma; Tedford and Barghoorn, 1993; Tedford et al., 1987). Thus, the ATZ very likely post-dates 9 Ma. We interpret that the ATZ correlates to the CLTZ based on this age and comparison of the lithologic characteristics of the successive beds in each (see CLTZ description below).

Chamita Lower Tuffaceous Zone (CLTZ)

The Chamita lower tuffaceous zone (CLTZ) occupies the stratigraphic interval about 85-115 m above the base of the Chamita Formation type section (fig. 29 of Galusha and Blick, 1971) in the Chamita badlands. Within this 30 m interval are three distinctive subintervals. The lowest consists of two thick beds (80-110 cm each) of grayish coarse ash and lapilli separated by 2.8 m of siltstone and fine sandstone. Approximately 9-15 m above is the middle subinterval, which is composed of two beds spaced 3 m apart. The lower of these beds consists of altered, lapilli-size clasts composed of consolidated white ash; the upper bed consists of a 40 cm-thick bed of silt mixed with poorly sorted, angular basaltic(?) lapilli and white ash consolidated into lapilli-size clasts. The upper subinterval lies 9-15 m above the middle subinterval. It is composed of a ledge-forming, 50-55 cm-thick bed of pumiceous coarse white ash with ~ 20% black biotite and hornblende(?). $^{40}Ar/^{39}Ar$ dating of a tephra (probably the upper subinterval) and revision of the Chamita Formation magnetostratigraphy of MacFadden (1977) by McIntosh and Quade (1995) indicates an age range of 7.7-8.4 Ma for this zone. The upward succession of black tephra to mixed white and dark tephra to pumiceous white tephra in the CLTZ is similar to the succession of ashes in the ATZ, although the CLTZ is overall thinner than the ATZ (30 m compared to 50 m). This upward pattern in lithologic changes, in addition to age similarities, supports the interpretation that the ATZ and CLTZ are correlative. Attempts to compare the glass and biotite composition of the ATZ and CLTZ tephras were not successful due to alteration from diagenesis and weathering. The thickness discrepancies between the ATZ and CLTZ may possibly be due to measurement error. Alternatively, the discrepancies may indicate relatively higher subsidence rates in the hanging wall of the Rio de Truchas fault during the time of deposition of the ATZ compared with the lower Chamita Formation type section. The lower Chamita Formation type section is near the gravity high defining the approximate south margin of the Velarde graben; perhaps subsidence on the southern flanks of the graben was less than in the hanging wall of the Rio de Truchas fault.

Chamita Upper Tuffaceous Zone (CUTZ)

The Chamita upper tuffaceous zone (CUTZ) occupies a 30 m-thick stratigraphic interval roughly 192-222 m above the base of the Chamita Formation type section (Fig. 2; fig. 29 of Galusha and Blick, 1971), and is well-exposed in the Chamita badlands. The CUTZ consists of several beds of yellowish white pumiceous lapilli and pumiceous coarse ash. Five of these pumiceous beds are fairly continuous in the Chamita badlands, but several other non-continuous pumice beds are also present. The tephra beds are generally thick and commonly form ledges. This tephra is felsic and mixed with various proportions of detrital sand. Microprobe analyses indicates that a similar-looking bed on the immediate hanging wall of the Velarde fault, between Cañada Ancha and Rio de Truchas (Plate 11), is chemically correlative to the CUTZ (Koning and Aby, 2003). Based on $^{40}Ar/^{39}Ar$ dating and K/Ca ratios of sanidine in the CUTZ, the CUTZ is correlative to the Peralta tuff and 6.75-7.0 Ma in age (McIntosh and Quade, 1995).

LITHOSTRATIGRAPHY OF THE TESUQUE FORMATION

Stratigraphic Nomenclature: Tesuque and Chamita Formations

The Santa Fe Group in and near the Velarde graben has been subdivided into the Tesuque and Chamita Formations by Galusha and Blick (1971). The Tesuque Formation, in turn, has been subdivided into various members in this area: Chama-El Rito Member and Ojo Caliente Sandstone Member (Galusha and Blick, 1971), Cejita Member (Manley 1976a, 1977, 1979a), and Dixon member (Steinpress, 1980 and 1981). About 12 km to the northeast of the Velarde graben, the Cieneguilla member has also been included in the Tesuque Formation (Leininger, 1982). In our mapping, we have differentiated seven lithostratigraphic units, five of which correspond with the above members of the Tesuque Formation. Three lithostratigraphic units formerly incorporated in the Tesuque Formation (Cejita Member, Cieneguilla member, and lithosome A) extend into what has been mapped as the Chamita Formation by Galusha and Blick (1971) and Dethier and Manley (1985) (Plate 11). This has complicated the previous model of a distinctive Chamita Formation overlying a distinctive Tesuque Formation.

We propose abandoning the Chamita Formation and incorporating its strata into the Tesuque Formation for two reasons. First, strata assigned to the Tesuque Formation east of the Rio Grande correlate into the Chamita type section (located in the Chamita badlands). East of the Rio Grande and south of Arroyo Ocole, there are two lithostratigraphic units representing two depositional facies; these units have been assigned to the Tesuque Formation (Manley, 1976a, 1977, 1979a). One is the Cejita Member, which represents a fluvial system derived from the Sangre de Cristo Mountains east of the Picuris-Pecos fault. The other is lithosome A (Cavazza, 1986), which represents a piedmont (or alluvial slope) facies derived from the granite-cored Sangre de Cristo Mountains south of Truchas Peaks (Kuhle and Smith, 2001), referred to by some workers as the Santa Fe Range (Fig. 1). These two units are present in the Chamita type section, and their sedimentologic and lithologic features (such as bedding, texture, and composition) are very similar, if not identical, to lithosome A and the Cejita Member east of the Rio Grande. Comparison of sedimentologic features such as channel geometries, clast sizes, and cross-stratification do not indicate that these units in the Chamita Formation type section only represent local reworking of older units east of the Rio Grande. Rather, the strata in the Chamita type section were deposited by streams comparable to those that deposited lithosome A and the Cejita Member east of the Rio Grande and south of Rio de Truchas (Koning, 2003b; Koning and Aby, 2003; Koning and Manley, 2003). In addition, fossils collected from the Osbornoceros Quarry east of the Rio Grande match those collected from the Chamita badlands (i.e., both are from the Hemphillian NALMA; Tedford and Barghoorn, 1993).

A second reason to abandon the Chamita Formation is the difficulty in recognizing and confidently mapping a contact between the Chamita and Tesuque Formations east of the Rio Grande and locally south of the Rio Chama. East of the Rio Grande, this is largely due to the absence of the Ojo Caliente Sandstone Member whose top, by definition (Galusha and Blick, 1971), forms the lower boundary of the Chamita Formation. One can argue to expand the Chamita Formation to include generally coarser strata in the Española Basin that were deposited subsequent to 13-14 m.y. ago (Koning, 2002a, 2002b, 2003a), such as the Cejita Member, and also perhaps including the Ojo Caliente Sandstone Member. Doing this, however, still does not lead to a mappable, distinctive contact in the eastern Peñasco embayment (Gary Smith, personal commun., 2003; Smith et al., 2004), located east of the Velarde graben. It is also difficult to distinguish the Chamita Formation from the Chama-El Rito Member of the Tesuque Formation south of the Rio Chama where the Ojo Caliente Sandstone Member is thin (Aldrich and Dethier, 1990). In summary, away from its type locality the lower contact of the Chamita Formation does not meet the mappability criterion of a formation-rank lithostratigraphic unit (North American Commission on Stratigraphic Nomenclature, 1983).

Description and Ages of Units

The stratigraphic relationships of the lithostratigraphic units delineated in the Velarde graben are summarized in Fig. 2, and depicted in Plate 11 and the cross-sections of Fig. 3. These units are generally weakly to well consolidated. Channels are mostly non- to weakly cemented, with 10-65% of the channels having local moderate to strong cementation by calcium carbonate. Considering the wide range of cementation and consolidation within these units, it is appropriate only locally to use the ending "stone" (e.g., sandstone or siltstone). For consistency and simplicity, we do not use "stone" when referring to this sediment. Thicknesses of these units are illustrated in the cross-sections of Fig. 3; note that the thickness of the Ojo Caliente Sandstone Member is poorly constrained. More detailed descriptions of these units are found in Koning (2003a), Koning and Manley (2003), Koning and Aby (2003), and Koning (2004).

Chama-El Rito Member (Ttch)

In the eastern Abiquiu embayment, the Chama-El Rito Member is mostly composed of pink to very pale brown, fine-grained sand interbedded with channel deposits whose medium to very coarse sand fraction is dominated by volcanic grains. The gravel assemblage of the channel deposits is generally pebble-size with local cobbles (average a and b axes of larger clasts are 19 and 14 cm, n=21), and composed of greater than 75% intermediate to felsic volcanic clasts. To the northwest of the Velarde graben, the Chama-El Rito Member grades into the Cordito(?) Member of the Los Pinos Formation (May, 1980 and 1984). Fifteen to twenty-two km south of Ojo Caliente, the upper 60-75 m of the Chama-El Rito Member interfingers laterally north and northeastward into eolian sandstone of the Ojo Caliente Sandstone Member (Koning, 2004). The unit also grades upward into the Ojo Caliente Sandstone Member (May, 1980 and 1984). Several fine white ashes are interbedded within this unit, but none have yet been dated or chemically correlated. This unit near Dixon is described in Steinpress (1980 and 1981) and Aby and Koning (2004, this volume).

The Chama-El Rito Member has been assigned an approximate age of 11-18 Ma based on fossil data (Tedford and Barghoorn, 1993), K-Ar dates on reworked volcanic clasts (Ekas et al., 1984), and overlying basalt flows and cross-cutting dikes (Dethier et al., 1986). A minimum age of ~12 Ma is preferred by May (1984) because that is the minimum age of the Cordito(?) Member. Aldrich and Dethier (1990) argue that this unit pre-dates 12.4 Ma, which is a K-Ar age of a lava flow immediately above the upper Ojo Caliente Sandstone Member contact.

Dixon Member (Ttd)

The Dixon member was deposited by a fluvial system sourced east of the Picuris-Pecos fault in the Sangre de Cristo Mountains (Steinpress, 1980 and 1981), and thus has the same provenance and composition as the Cejita Member (described below). The gross sedimentologic features of the two members are similar, but in the area south of Dixon the Cejita Member is overall coarser-grained than the Dixon member. The lower and upper contacts of the Dixon member are gradational with the Chama-El Rito Member and Ojo Caliente Sandstone Member, respectively. More information regarding the Dixon member is presented in Steinpress (1980 and 1981) and Aby and Koning (2004, this volume). The Dixon member is sedimentologically similar to lithosome B, proposed and studied by Cavazza (1986) southeast of Española, and the two units are interpreted to represent the same fluvial system. Southeast of Española, however, lithosome B has more volcanic clasts; this is probably due to progressive downstream input of volcaniclastic detritus into this fluvial by streams associated with the Chama-El Rito Member. Based on fossil data (Tedford and Barghoorn, 1993) and the age of the underlying Chama-El Rito Member near Dixon, the age of the Dixon member is interpreted to be 11.8-14 Ma.

Ojo Caliente Sandstone Member (Tto)

Much of the northwest corner of the study area is underlain by the Ojo Caliente Sandstone Member. This unit is a distinctive fine- to coarse-grained, very pale brown to pink sand that generally has meter-scale, northeast- to southeast-facing, tangential cross-stratification (laminated to very thin bedded). The sand is rounded to subrounded, well sorted, and has approximately subequal amounts of pinkish potassium feldspar and volcanic-rich lithics in its medium-sized sand fraction (finer sand commonly has more potassium feldspar). The base of this unit is gradational and interfingers with the underlying Chama-El Rito and Dixon members of the Tesuque Formation. In most areas, the Cieneguilla member and Cejita Member overlie the Ojo Caliente Sandstone Member with gradational and scoured contacts, respectively. The upper part of the Ojo Caliente Sandstone Member contains both fine white ashes in addition to the lowermost coarse white ash bed of the VWAZ. Interpreted grain flow deposits, bedding and textural factors, and its wide lateral extent indicate that this unit was deposited in a large eolian dunefield or erg, as was concluded by Galusha and Blick (1971) and May (1980).

The margin of the Ojo Caliente Sandstone Member dunefield may have begun shrinking by the start of the late Miocene (~ 11.8 Ma) because a basalt flow dated at 12.4 Ma, interbedded in the lowermost part of the proposed Hernandez member, overlies the Ojo Caliente Sandstone Member west of Hernandez (date from Aldrich and Dethier, 1990). In lower Arroyo del Pueblo, interbeds of the Ojo Caliente Sandstone Member in lithosome A near the Osbornoceros Quarry (Hemphillian in age) indicate that this unit persisted at least locally into the late Miocene. The coarse white ash that forms the lowermost bed of the VWAZ is located 12-18 m below the thick fine ash that marks the Cieneguilla – Ojo Caliente Sandstone Member contact. This ash is visually identical to the ashes in the CWAZ, so the top of the Ojo Caliente Sandstone Member along the western slopes of Black Mesa is likely in the range of 9.0-11.8 Ma (i.e., the age range of the CWAZ). In summary, although the dune field that deposited the Ojo Caliente Sandstone Member had shrunk in size, it locally persisted from 12.4 (Aldrich and Dethier's minimum age south of the Rio Chama) to 7-9 Ma (early Hemphillian).

The age of the base of the Ojo Caliente Sandstone Member is poorly constrained. Three km northeast of Española High School, a 9-10 m-thick finger of the unit lies below the CWAZ but above aforementioned site yielding fossils correlated with the Clarendonian NALMA, which has an age of 11.8-9.0 Ma (Tedford et al., 1987; fossil site is ~ 2 km northeast of Española High School). If this finger represents the furthest eastward extent of the Ojo Caliente Sandstone Member, then its age is approximately 11.5-11.8 Ma. This age is slightly at odds with Aldrich and Dethier (1990), who interpret that Ojo Caliente Sandstone Member was deposited between 12.4 and14 Ma. Our best age estimate for the beginning of the Ojo Caliente Sandstone Member deposition is 12-13 Ma, which generally agrees with Tedford and Barghoorn (1993).

Lithosome A (Tta)

Lithosome A occupies most of the southeast part of the study area and extends into the Chamita badlands (Plate 11). This unit consists of a finer extra-channel facies of silty sand and a subordinate coarser channel facies. The sand in the extra-channel facies is pink to very pale brown, very fine- to coarse-grained, and arkosic. The channel gravel is clast-supported, contains pebbles with subordinate cobbles (abundance of cobbles increases towards the Sangre de Cristo mountain front), and composed of granite with varying amounts of subordinate quartzite. In the Chamita badlands, the average a and b axes of the larger clasts are 12 and 8 cm (n=30). Lithosome A grades westward from a sandy gravel at the foot of the Sangre de Cristo Mountains to mostly a silty sand and silt (with subordinate channels of medium-very coarse sand and gravel) in its most distal reaches. Paleocurrent data indicate a general west to northwest flow (Manley, 1977; Koning, 2003a; Koning and Manley, 2003; Koning and Aby, 2003).

This unit is similar to the lithosome A described and proposed by Cavazza (1986) to the southeast in the Nambé, Skull Ridge, and Pojoaque members of the Tesuque Formation. However, the stratigraphically higher lithosome A in the study area is overall coarser than that described by Cavazza and will likely be proposed as a new member by the senior author. Along the eastern boundary of the study area, in Rio de Truchas and Cañada de las Entrañas, quartzite commonly exceeds granite in abundance. For convenience, we have included this quartzite-rich sediment with lithosome A.

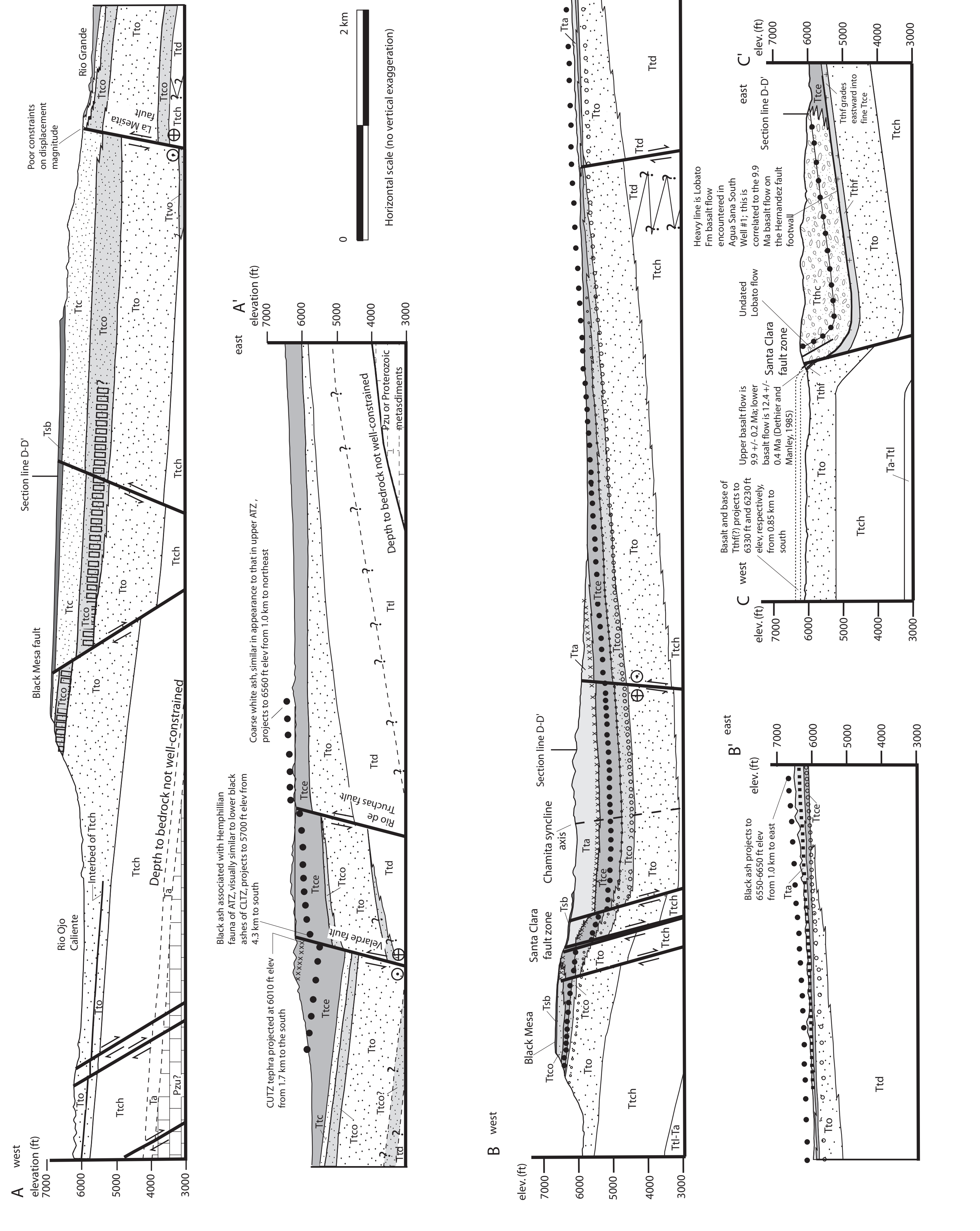
Lithosome A was deposited on an alluvial slope flanking the western-northwestern granite-cored Sangre de Cristo Mountains (Fig 1), and interfingers laterally with the Cejita Member to the north (Manley, 1976a, 1977, 1979a). Because of a northwestward progradation of this facies in the middle to late Miocene, this unit gradationally overlies the Cejita Member over much of the study area (Koning, 2002a, 2002b, 2003a; Koning and Manley, 2003). Interbedded within lithosome A in lower Arroyo del Pueblo is a unit of eolian sand and fluvially reworked eolian sand, 6-15 m-thick and 1 km long, that we correlate to the Ojo Caliente Sandstone Member (Plate 11).

In the study area, lithosome A was deposited throughout the late Miocene. The ATZ, CLTZ, and CUTZ are interbedded in lithosome A across the study area (Fig. 2 and Plate 11), and interbeds of CWAZ are present 1-3 km south of the east end of the B-B' section line (Koning, 2003a; Koning and Manley, 2003). In the central Velarde graben about 6 km southwest of Velarde, a fossilized horse tooth was found in lithosome A. This tooth is interpreted to belong to *Dinohyppus mexicanus*, which has an age of ca. 4.8-5.5 Ma (identification and age of species from Gary Morgan of the New Mexico Museum of Natural History and Science, written communication, 2004). Based on the interpreted ages of these tephra and this horse tooth, lithosome A in the Velarde graben is 12 – 5 Ma in age. Paleomagnetic data of MacFadden (1977), as reinterpreted by McIntosh and Quade (1995), indicate that lithosome A in the Chamita badlands is as young as 5.0-5.5 Ma.

Cejita Member (Ttce)

The Cejita Member (Manley, 1976a, 1977) consists of light brown to light yellowish brown to pink floodplain deposits that are interbedded with various proportions of coarser channel deposits of gravel to sand. It is similar to the underlying Dixon member (Fig. 2) but overall is coarser. Channel gravel is dominated by quartzite and green-gray Paleozoic limestone, sandstone, and siltstone (with minor quartz, felsic to intermediate volcanic rocks, Pilar phyllite, and granite). Cobbles are common in the northeast part of the study area (where the average a and b axes of the larger clasts are 20 and 13 cm, n=27) but less abundant in the southwest part of the study area (where the average a and b axes of the larger clasts are 12 and 9, n=32). The Cejita Member interfingers to the south-southeast with lithosome A (Manley, 1976a, 1977; Koning and Aby, 2003), and to the northwest with the Cieneguilla member of Leininger (1982) (Fig. 2 and Plate 11; Koning and Aby, 2003). The member is predominately sandy gravel south of Dixon, but fines noticeably to the southwest (downstream) so that in the Chamita badlands it consists mostly of floodplain deposits with subordinate sandy gravel channels. The base of this unit is commonly sharp or scoured, and is best observed 3 km south of Dixon and 1.5-3 km northeast of Española High School.

The Cejita Member was deposited in the late Miocene by a river sourced in the Sangre de Cristo Mountains east of the Picuris-Pecos fault (Manley, 1976a, 1977, 1979a; Koning and Aby, 2003; Aby and Koning, 2004, this volume). This river generally flowed west until it passed the Velarde fault. Near the center of the Velarde graben, the river generally flowed to the southwest, based on the map pattern of the unit (Plate 11) and paleocurrent


A
west
elevation (ft)
7000
6000
5000
4000
3000
Rio Ojo Caliente
Interbed of Ttch
Black Mesa fault
Section line D-D'
Tsb
Poor constraints on displacement magnitude
La Mesita fault
Rio Grande
Tto
Ttch
Ttc
Ttco
Ttvo
Ttd
Ta
Pzu?
Depth to bedrock not well-constrained
0
2 km
Horizontal scale (no vertical exaggeration)
CUTZ tephra projected at 6010 ft elev from 1.7 km to the south
Black ash associated with Hemphillian fauna of ATZ, visually similar to lower black ashes of CLTZ, projects to 5700 ft elev from 4.3 km to south
Coarse white ash, similar in appearance to that in upper ATZ, projects to 6560 ft elev from 1.0 km to northeast
Velarde fault
Rio de Truchas fault
Ttce
Ttl
Depth to bedrock not well-constrained
Pzu or Proterozoic metasdiments
A'
east
elevation (ft)
B
west
elev. (ft)
Black Mesa
Santa Clara fault zone
Chamita syncline axis
Section line D-D'
Tta
Ttl-Ta
B'
east
elev. (ft)
Black ash projects to 6550-6650 ft elev from 1.0 km to east
C
west
elev. (ft)
Basalt and base of Tthf(?) projects to 6330 ft and 6230 ft elev, respectively, from 0.85 km to south
Upper basalt flow is 9.9 +/- 0.2 Ma; lower basalt flow is 12.4 +/- 0.4 Ma (Dethier and Manley, 1985)
Santa Clara fault zone
Undated Lobato flow
Heavy line is Lobato Fm basalt flow encountered in Agua Sana South Well #1; this is correlated to the 9.9 Ma basalt flow on the Hernandez fault footwall
Section line D-D'
Tthf grades eastward into fine Ttce
Tthc
Tthf
Ta-Ttl
C'
east
elev. (ft)

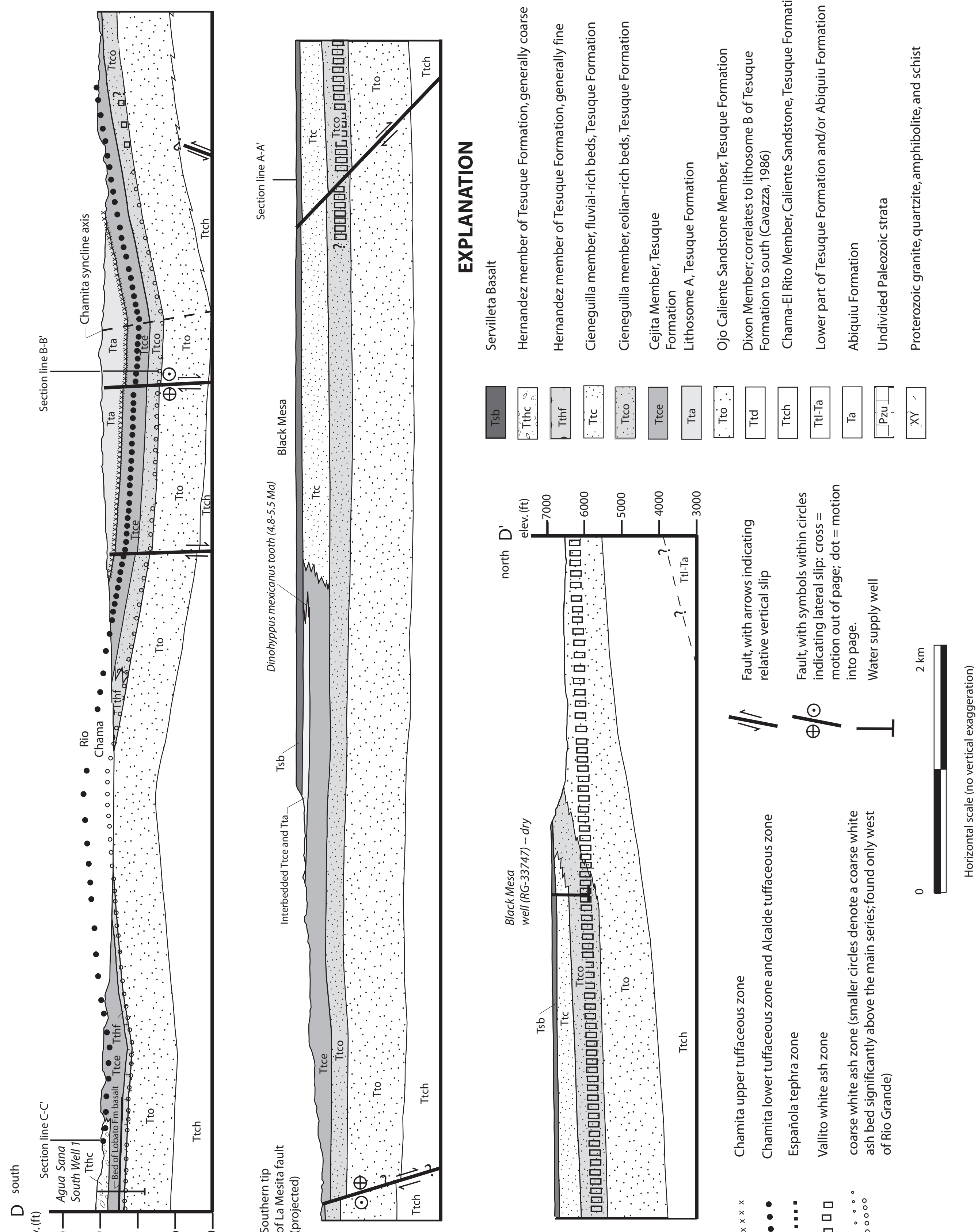


FIGURE 3. Cross-sections across the Velarde graben. Sections A-A', B-B', and C-C' trend northwest-southeast. Section D-D' is a northeast-trending longitudinal cross-section. Their locations are shown on Plate 11. Positions of contacts below ~ 500 m (1600 ft) depth are less constrained compared to those above; deep structure on east A-A' based on Ferguson et al. (1995).

data (Manley and Koning, 2003; Koning and Aby, 2003). The Cejita Member interfingers with lithosome A on either side of the Rio Grande and so is of similar age. Thus, we interpret that the Cejita Member spans approximately 12 to 5 Ma.

Overlying the Ojo Caliente Sandstone Member on the west-northwest slope of Black Mesa, 2 km north of its southern tip, is a 23 m-thick fluvial deposit with a clast assemblage similar to the Cejita Member, although the clast size is generally smaller than coarse pebbles (Plate 11). Here, about 10 m above the base of the deposit is a thin bed of black ash that is interpreted to correlate to the CLTZ. This correlation is based on fossils collected in this fluvial unit that typify the early Hemphillian NALMA, which ranges approximately 7-9 (Tedford and Barghoorn, 1993; Tedford et al., 1987). Other than those of the CLTZ, there are no black ashes in strata of the Chamita Formation type section and Chamita badlands that have been assigned an age correlative to the early Hemphillian (MacFadden, 1977; Tedford and Barghoorn, 1993; and McIntosh and Quade, 1995). Correlation of the black ash on the west-northwest slope of Black Mesa with the CLTZ is the most reasonable tephra correlation given the fossil data.

Cieneguilla Member (Ttc)

We provisionally extend the Cieneguilla member of Leininger (1982) into the north-northwest part of the Velarde graben. Here, the member is characterized by interbedding of cross-stratified eolian sand (correlative to the eolian Ojo Caliente Sandstone Member in terms of bedding, textures, and composition) with fluvially reworked Ojo Caliente Sandstone Member, very fine to medium sand and silty sand (interpreted as fluvial), pebbly sand channel deposits, and minor tabular beds of claystone and mudstone. Particularly good exposures of this member are found near Vallito Peak, on the western margin of Black Mesa. In the study area, this member is further subdivided into eolian-rich and fluvial-rich beds. This subdivision is based on the relative abundance of eolian Ojo Caliente Sandstone Member interbeds, with approximately 10% chosen as the demarcation. The eolian-rich beds characteristically have a very pale brown to light yellowish brown color. The lesser abundance of eolian sandstone in the fluvial-rich beds gives it a browner or redder color. Three km west of Embudo, which is well up on the northern flank of the gravity low defining the Velarde graben (Koning et al., 2004, this volume, Fig. 2), the fluvial-rich beds of the Cieneguilla member overlies Ojo Caliente Sandstone Member with angular unconformity. In most places in the Velarde graben, however, the eolian-rich beds are in a stratigraphic interval that generally lies near the base of the Cieneguilla member and grade upward into the fluvial-rich beds.

The Cieneguilla member in the study area is interpreted as a basin floor facies that grades laterally into the alluvial fan facies described by Leininger (1982) adjacent to the Picuris Mountains. The fluvial very fine to medium sand and silty sand are commonly massive or in medium to thick, tabular to broadly lenticular beds; this sand lacks cross-bedding or ripple marks, although it locally is planar-laminated. The pebbly sand deposits are in medium to thick, broadly lenticular beds with common planar-lamination and low-angle cross-lamination generally less than 10 cm thick. Pebbles are subrounded and generally very fine to medium in size (with minor coarse pebbles). No very coarse pebbles or cobbles have been observed, nor is there significant clast imbrication. The pebbles are composed of greenish to brownish Paleozoic sandstone, felsic to intermediate volcanic clasts, quartzite, and pink to brown granite; there are minor amounts of Pilar phyllite, vein quartz, a gray quartz-porphyritic silicic rock (rhyolite?), and gray-white granite to granodiorite (Koning and Aby, 2003, table 1). These clasts were compared with the bedrock geology of the Taos Range and southern Tusas Mountains using field reconnaissance, inspection of geologic maps (New Mexico Bureau of Geology and Mineral Resources, 2003), and clast counts of Quaternary terrace gravel deposits derived from these highlands (Koning and Aby, 2003, table 1). This comparison suggests that most of the sediment of the Cieneguilla member in the study area came from the San Luis Basin, with some contribution from the Picuris Mountains and northeastern Abiquiu embayment. Paleocurrent analyses is not possible due to the lack of clast imbrication, cross-stratification, ripple marks, or exposures of steep-sided channel margins. Based on the small clast sizes and low thickness of the cross-stratification in the pebbly sand, the channelized streams in this unit were probably shallower and of lower energy than those in the underlying Chama-El Rito and Dixon members. Also, the fact that much of the very fine to medium sand lacks internal bedding, such as cross-stratification and ripple-marks, may suggest high bioturbation and/or low sedimentation rates.

The clast composition of the Cieneguilla member in the study area, particularly the presence of Paleozoic sandstone, supports our interpretation that the member here represents a basin floor facies, as opposed to the alluvial fan facies found in its type locality adjacent to the Picuris Mountains (Leininger, 1982). In its type locality, the Cieneguilla member has been subdivided into a lower, finer part and upper, coarser part. The former is interpreted to represent distal alluvial fan faices and the latter proximal alluvial fan facies (Leininger, 1982). Other than some differences in clast composition reflecting provenance, the lower Cieneguilla member adjacent to the Picuris Mountains and the Cieneguilla member found in the Velarde graben are sedimentologically similar. Consequently, we did not feel it is practical to differentiate distal the alluvial fan facies and basin floor facies as two separate members, although this may possibly change with future mapping north of the Velarde graben.

The Cieneguilla member interfingers laterally with the Ojo Caliente Sandstone Member and Cejita Member. Exposures south of the mouth of Cañada de las Entrañas, 1 km east of Velarde, show that the Cieneguilla member interfingers with the Cejita Member of the Tesuque Formation (Plate 11). On the west-northwest slope of central Black Mesa, the eolian-rich beds of the Cieneguilla member are 90-120 m thick and appear to gradationally overlie Ojo Caliente Sandstone Member, with a thick fine white ash (the second ash from the bottom in the VWAZ) chosen as the base of this unit. Here, the Cieneguilla member corresponds with the Chamita Formation as mapped by May (1980) and Galusha and Blick (1971). Southwest of Vallito Peak by 4.0-4.1 km, in an area of many landslide deposits, what appears to be this same thick ash is within cross-stratified Ojo Caliente Sandstone Member and the base of the eolian-rich beds of the Cieneguilla member has climbed higher up-section (approximately 65-70 m higher than near Vallito Peak). On the north-northwest slope of Black Mesa 6 km northeast of Vallito Peak (Plate 11; May, 1980, Koning, 2004), a thick ashy silt that appears to project to the VWAZ is also interbedded within the Ojo Caliente Sandstone Member. Based on these field-based ash correlations, the eolian-rich beds of the Cieneguilla member interfinger laterally with, and perhaps downwind of, the Ojo Caliente Sandstone Member in the Velarde graben. Similar interfingering of the Ojo Caliente Sandstone Member and Cieneguilla member has also been noted near the Picuris Mountains to the north (Leininger, 1982; Dungan et al., 1984.

In contrast to these earlier workers, we are not convinced of an unconformity at the base of the member on the west-northwest slope of central Black Mesa. Here, we have not observed any corresponding soils, sharp contacts, or angular unconformities suggesting a hiatus in deposition. The basal contact seems to be sharper within ~ 3 km of the south tip of Black Mesa, and there an unconformity seems more plausible.

On the west-northwest slopes of Black Mesa, the fluvial-rich beds of the Cieneguilla member correspond to the 29-34 m of strata exposed immediately below the Servilleta Basalt near Vallito Peak. About 5 km to the northeast of Vallito Peak, the fluvial-rich beds pinch out. South-southwest of Vallito Peak, the fluvial-rich beds project towards the previously described exposures of Cejita Member on the west-northwest slope of Black Mesa, about 2 km north of the southern tip of the mesa. However, the 23 m-thick Cejita Member here is overlain by 40-50 m of eolian-rich beds of the Cieneguilla member, in contrast to the general trend elsewhere of the eolian-rich beds underlying predominately fluvial facies.

The lower, eolian-rich beds of the Cieneguilla member along the west-northwest slope of Black Mesa contains the VWAZ. According to our interpreted age range of the VWAZ, the Cieneguilla member would then postdate 11.8 Ma in this area. As previously mentioned, the overlying fluvial-rich beds of the Cieneguilla member appear to project to the fine-grained Cejita Member exposed on the west-northwest slope of Black Mesa. In these strata Tedford and Barghoorn (1993) report fossils that typify the early Hemphillian NALMA (9-7 Ma), so both of these units are interpreted to be 7-9 Ma on the west-northwest slopes of Black Mesa. We preliminarily assign the underlying eolian-rich beds of the Cieneguilla member exposed on Black Mesa an age range of 8.5-11.7 Ma (pre-dating much of the early Hemphillian and post-dating the beginning of the VWAZ).

Hernandez Member (Tthc and Tthf)

The proposed, informal Hernandez member is exposed south of Black Mesa (Plate 11) and observed only in reconnaissance. Although detailed work on this unit is pending, including the designation of a stratotype, we provisionally include it here because it extends a short ways into the area discussed in this paper. The member is composed of light yellowish brown to very pale brown floodplain deposits of siltstone, very fine-grained sandstone, and mudstone interbedded with varying proportions of medium to thick channels of pebbly sandstone to clast-supported sandy pebble-conglomerate. Based on our limited observation, the Hernandez member exhibits a coarsening-upward trend. Finer deposits of this member, exposed in the footwall of the Santa Clara fault, are somewhat similar to the Cieneguilla member in terms of bedding and texture. However, the gravel consists mostly of felsic to intermediate volcanic pebbles possibly derived from reworking of older volcaniclastic units (e.g., the Chama-El Rito Member of the Tesuque Formation and Los Pinos formations to the northwest). In stratigraphically higher strata exposed in the hanging wall of the Santa Clara fault there are noticeably more coarse channel deposits and more cobbles (Plate 11). In addition, casual observation suggests that the relative abundance of quartzite may possibly increase up-section, but this needs to be more thoroughly examined. We propose differentiating these volcaniclastic strata as a new member in order to distinguish it from lower, older volcaniclastic strata of the Chama-El Rito Member, the latter which lies below or interbedded within the Ojo Caliente Sandstone Member. Our proposed Hernandez member was formerly assigned to the now-abandoned Chamita Formation by Dethier and Manley (1985), probably because it generally overlies the Ojo Caliente Sandstone Member.

The finer part of the Hernandez member was likely deposited by small streams locally sourced in the Abiquiu embayment, and is best exposed about 5 km west of Hernandez in the footwall of the Santa Clara fault. It is interbedded with Lobato Formation basalt flows flows; using available ages for these flows in the area of interbedding (12.5-9.5 Ma based on Dethier and Manley, 1985; Dethier et al., 1986; Aldrich and Dethier, 1990) supports an approximate age of 12.5-9.0 Ma for the finer part of the member south of the Rio Chama. This finer portion of the Hernandez member is not preserved north of the Rio Chama. However, the western edge of the Cieneguilla member commonly has a high abundance of volcanic pebbles. We speculate that relatively small streams carrying reworked volcanic pebbles were present north of the Rio Chama and west of the Cieneguilla fluvial system throughout the late Miocene, although these streams were probably eroding rather than aggrading.

The coarse part of the member was deposited by a relatively high-energy river, probably equivalent to the ancestral Rio Chama, capable of transporting a significantly coarser sediment load. This coarser sediment interfingers with the Cejita Member (Koning and Manley, 2003), and this can be observed 2-3 km southwest of Hernandez. In the Cejita Member near this interfingering zone are two gray ash beds possibly correlative to the CLTZ. Upon comparing the thickness of the sediment above these ashes (section C-C' of Fig. 3) with the thickness of sediment above the CLTZ in the Chamita badlands (section B-B' of Fig. 3), the uppermost part of the Hernandez member appears to be of similar age to the lower three-fourths of the Chamita type section, which is 9-6.5 Ma according to McIntosh and Quade (1995).

DISCUSSION

Paleogeographic Changes with Time

In the middle Miocene before 13 Ma, the study area was occupied by two depositional systems: one associated with the Chama-El Rito Member to the west and one associated with the Dixon member and lithosome B of Cavazza (1986) to the east. After 13 Ma, three important depositional changes occurred in the middle to late Miocene (Fig. 4). First, the Ojo Caliente Sandstone Member probably extended over the central and western parts of the Velarde graben sometime between 12-13 Ma, as discussed above. Second, the Ojo Caliente Sandstone Member dune field shrank at the beginning of the late Miocene and concurrently the Cejita Member prograded northwestward over the south-south-east part of the Velarde graben. This is observed in the Chamita badlands and southern Black Mesa, where the Cejita Member overlies the Ojo Caliente Sandstone Member. Concurrently,

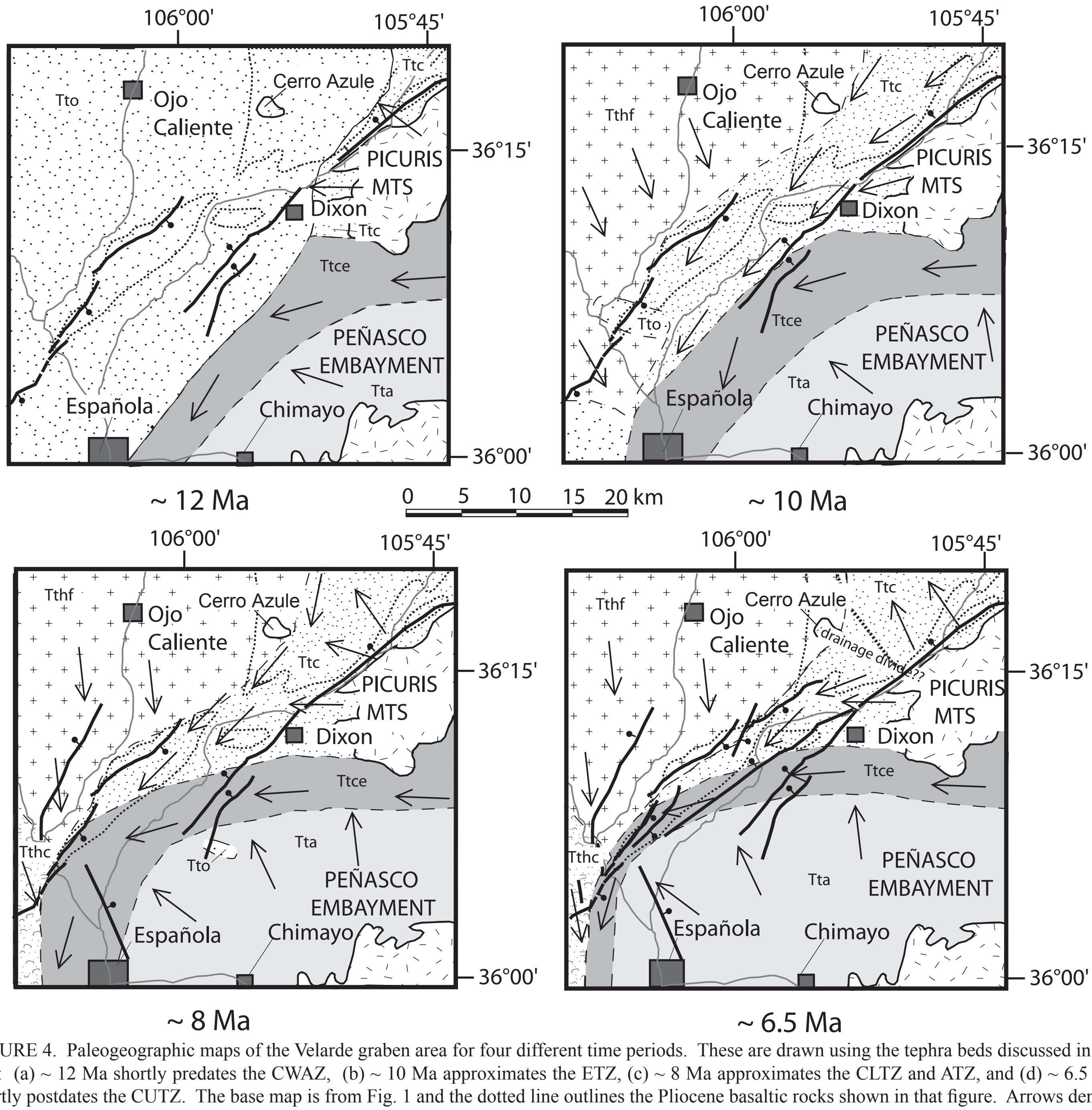


FIGURE 4. Paleogeographic maps of the Velarde graben area for four different time periods. These are drawn using the tephra beds discussed in the text: (a) ~ 12 Ma shortly predates the CWAZ, (b) ~ 10 Ma approximates the ETZ, (c) ~ 8 Ma approximates the CLTZ and ATZ, and (d) ~ 6.5 Ma shortly postdates the CUTZ. The base map is from Fig. 1 and the dotted line outlines the Pliocene basaltic rocks shown in that figure. Arrows denote paleocurent directions (summarized from Manley, 1977; Steinpress, 1980 and 1981; Dethier and Manley, 1985; Koning, 2003a; Koning and Aby, 2003; Koning and Manley, 2003). Shading and symbols follow the explanation of Fig. 3.

TABLE 1. Vertical displacement data for Velarde graben faults

Location and relevant cross-section	Marker strata	Age of strata (Ma)	Vertical displacement (m)	Vertical displacement rate (m/Myr)
Rio de Truchas fault, A-A'	ATZ	7.7-8.4	65-100	8-13
Velarde fault, A-A'	ATZ	7.7-8.4	95-125	11-16
La Mesita fault north of Velarde	Servilleta Basalt	2.8-3.7	60-70	17-25
Black Mesa fault, A-A'	VWAZ	10.0-11.5	150-180	13-18
Black Mesa fault, A-A'	Servilleta Basalt	2.8-3.7	18-35	5-13
Santa Clara fault, B-B'	CLTZ	7.7-8.4	404-434	48-56
Santa Clara fault, B-B'	Servilleta Basalt	2.8-3.7	125-135	35-48
Santa Clara fault, C-C'	Lobato Fm basalt	9.9	480-495	48-50

sediment associated with the Cieneguilla member of Leininger (1982) filled the north-northwest part of the Velarde graben and interfingered with the Cejita Member to the southeast.

Third, throughout the late Miocene (11.8-5 Ma) the lithosome A alluvial slope progressively prograded west-northwestward in the southern Velarde graben (Fig. 3, cross-section B-B'; Fig. 4), while the area associated with Cejita Member deposition also shifted slightly northwestward and likely narrowed (Fig. 4). The boundary between the Cejita Member and lithosome A depositional systems was restricted to east of the Rio Grande (northeast of Española) around the time of the ETZ (9-11.5 Ma) because here the ETZ extends laterally across the interfingering Cejita-lithosome A contact. By the time the CUTZ was emplaced at 6.75-7.0 Ma, the boundary between the two depositional systems had shifted westward into the Chamita badlands west of the Rio Grande. In the eastern Chamita badlands, the Cejita – lithosome A contact is ~ 15 m below the CUTZ, and in the western Chamita badlands this contact is within the CUTZ – which is consistent with westward migration of this depositional boundary. At the close of the Miocene, the interfingering Cejita-lithosome A contact had extended into the central part of the Velarde graben, due west of the mouth of Cañada Ancha. Here, a fossilized horse tooth correlated to *Dinohyppus mexicanus* was found in lithosome A, as noted in the description of lithosome A. After 4.8-5.5 Ma (age of *Dinohyppus mexicanus* tooth) and before the emplacement of the Servilleta Basalt at 2.8-3.6 Ma, there was general erosion in the Velarde graben during tectonic activity. This produced the angular unconformity between the Pliocene gravels beneath the Servilleta Basalt and the uppermost Tesuque Formation.

Tectonic Influence on Depositon

The west-northwest progradation of lithosome A during the late Miocene may be due to an increase in vertical slip rates along the master faults of the Española Basin half-graben east of the Abiquiu embayment (i.e., the Pajarita, Santa Clara, Black Mesa, and Velarde faults), which increased the slope of the west-tilted eastern Española Basin floor and shifted the zone of maximum subsidence towards the master faults. However, this progradation would also likely be influenced by erosion and sediment flux rates, which in turn may be dependent on climate and relief of the highland source areas. Past research regarding controls of tectonic tilting on the distribution of sedimentary facies in half-grabens is discussed in Leeder and Gawthorpe, 1987, Alexander and Leeder, 1987, Blair and Bilodeau, 1988, Mack and Seager, 1990, and Cather et al., 1994).

Fault Throw and Slip Rates

Four cross-sections (Fig. 3) were constructed using our geologic map data and tephra correlations. These cross-sections allow improved estimates of throw and vertical slip rates along the major faults of the Velarde graben. Vertical displacement magnitudes and rates are summarized in Table 1. Note that the amount of displacement for the Velarde fault depends on our correlation of the ATZ with the CLTZ. Also, for the Santa Clara and Black Mesa faults we measured the vertical stratigraphic displacement at a location corresponding with the western edge of Black Mesa; this was done to include the effects of monoclinal folding and drag associated with these faults.

Landslides obscure observation of primary structural relationships and effects of tectonic-related faulting along most of the eastern slopes of Black Mesa. For the Santa Clara fault on the south tip of Black Mesa (cross-section B-B', Fig. 3), however, we argue that the Servilleta Basalt has been displaced primarily by tectonic-related fault movement rather than mass wasting processes, and consequently this basalt can be used constrain the throw magnitude on this fault. First, we do not observe the significant back-rotation of basalts or extensive tensile fractures that are present in landslide deposits to the north. Second, a strong consistency in strikes of Tesuque Formation strata is not consistent with significant mass wasting or landslide activity in the Chamita badlands. Third, the Rio Grande, which to the north is a major agent in undercutting the toe of the landslides and inducing further movement, is twice as far away from the edge of the basalt-capped mesa here compared to where landslides are present to the north. Given these arguments, the vertical displacement of the Servilleta Basalt across the Santa Clara fault zone west of the Chamita badlands is 125-135 m.

On the gravity high that divides the Velarde graben from another intra-rift graben to the south (the Santa Clara graben, Koning et al., 2004, this volume), vertical displacement along the

Santa Clara fault was calculated using a basalt flow of the Lobato Formation and cross-section C-C' (Fig. 3). The Agua Sana South Well #1 encountered a basalt flow at 183-186 m depth, which is within or at the top of the finer, lower portion of the Hernandez member and 45 m above the top of the Ojo Caliente Sandstone Member (units interpreted from data in J. Shomaker, unpubl. report for Agua Sana Water Users Association, 1998). On the footwall of the Santa Clara fault south of the Rio Chama, where it is crossed by section C-C', there are two basalt flows associated with the Lobato Formation that yielded K-Ar ages of 12.4 ± 0.4 Ma (lower flow) and 9.9± 0.2 Ma (upper flow) (Dethier and Manley, 1985). The upper flow is approximately 35-45 m above the top of the Ojo Caliente Sandstone Member within the finer, lower part of the Hernandez member. We surmise that the basalt flow encountered in the Agua Sana South Well #1 is the same 9.9 Ma flow observed on the surface, based on its similar stratigraphic position in the two localities. Consequently, relations in cross-section C-C' indicate a vertical displacement of 480-495 m along the Santa Clara fault (Table 1).

Vertical slip rates of the Santa Clara fault are within the range of 35-50 m/Myr for the time markers represented by the 9.9 Ma basalt flow of the Lobato Formation, CLTZ (7.7-8.4 Ma), and Servilleta Basalt (2.8-3.7 Ma) (Table 1). The slip rate after 2.8-3.7 Ma is about 80% of the late Miocene-early Pliocene slip rate. There may possibly have been a slight increase in vertical slip rates between 9.9 and 7.7-8.4 Ma compared to before 9.9 Ma. Although more data is needed to substantiate this slight increase, perhaps it was a factor in the west-northwestward progradation of lithosome A.

ACKNOWLEDGEMENTS

We thank Kim Manley, Sean Connell, and Dave Love for reviews of this manuscript. Geologic mapping in the northern Española Basin was supported by the New Mexico Bureau of Geology and Mineral Resources (Dr. Peter Scholle, Director) and the National Cooperative Geologic Mapping Program (STATEMAP). San Juan Pueblo and local property owners allowed access into the Chamita badlands.

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PLATE 11: GEOLOGIC MAP OF THE VELARDE GRABEN – NORTHERN ESPAÑOLA BASIN

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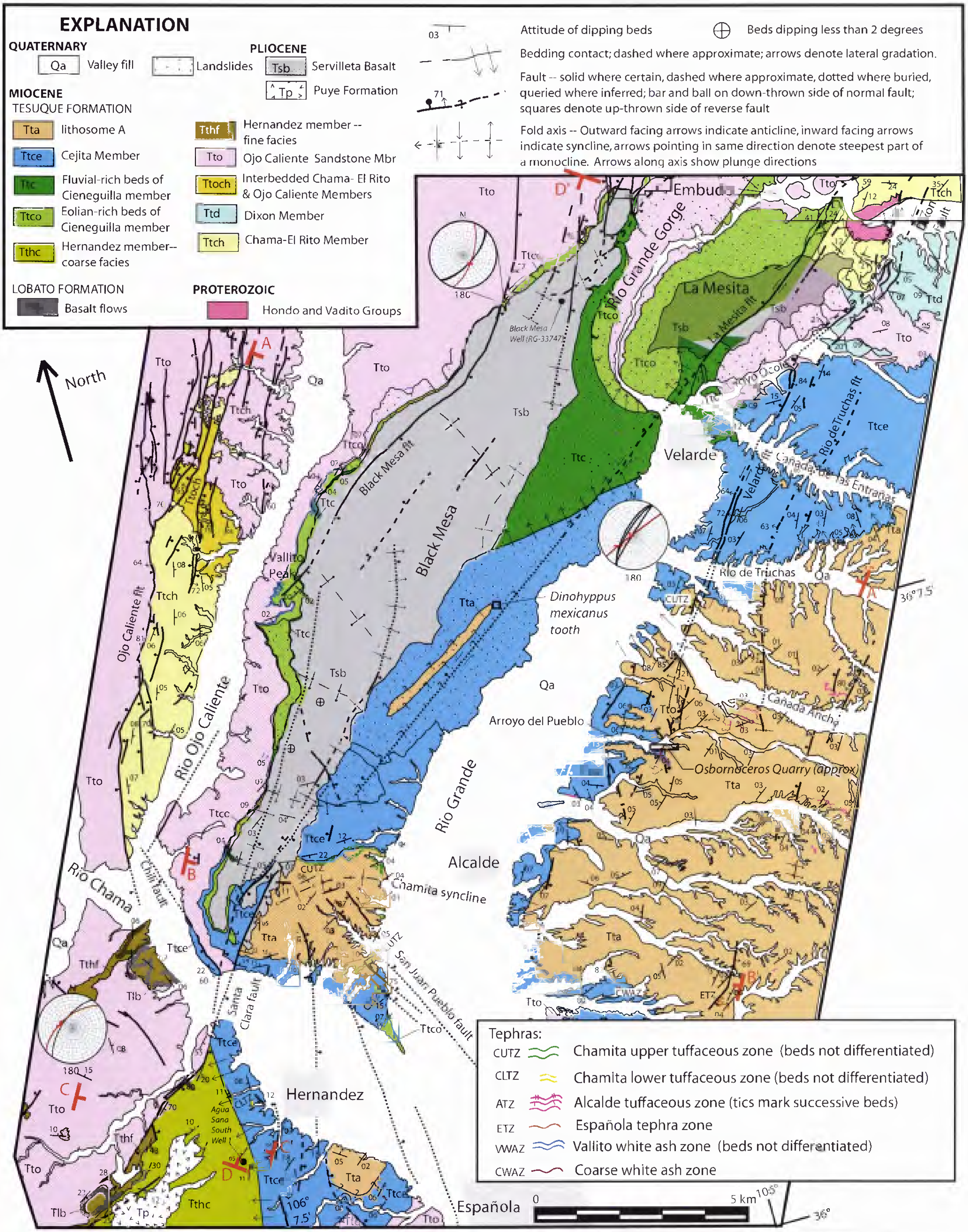

PLATE 11. Geologic map of the Velarde graben, northern Española Basin. Map compiled from Koning (2004), Koning and Aby (2003), Koning (2003), Koning and Manley (2003), with southwest part modified from Dethier and Manley (1985). Neogene terrace deposits are not shown. Stereonets of fault slickenside data are in Wulf equal-area projections. Black lines = measured fault planes. Red lines = best fit to data. Red, T-shaped lines show ends of cross sections discussed in Koning et al. (2004, this volume).