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GEOLOGIC STRUCTURE OF THE VELARDE GRABEN AND THE SOUTHERN EMBUDO FAULT SYSTEM, NORTH-CENTRAL, N.M.

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Abstract.—The northeast-trending Embudo fault has a significant component of left-lateral slip and acts as a transfer fault in relaying extensional strain between the San Luis and Española Basins. In the northern Española Basin, the Embudo fault system links with the La Mesita and Dixon-Velarde faults of the northern Velarde graben, a 6-10 km-wide intra-rift graben. There is no evidence that a single scissors fault connects the down-to-the-northwest Embudo fault with the major down-to-the-east faults that bound the western side of the deepest parts of the central Española Basin (e.g., the Pajarito fault system). Rather, late Cenozoic slip associated with the Embudo fault appears to be partitioned amongst several major faults in the Velarde graben. In the southern Velarde graben, a lateral transfer of slip likely occurs between these faults and a major down-to-the-east fault called the Santa Clara fault. This transfer zone likely corresponds to an important fault segment boundary and is marked by transverse folds that may follow a transverse basement structure. Stratigraphic and seismic data indicate that substantial throw occurred along at least two major Velarde graben faults prior to the deposition of upper Miocene strata. This interpretation is consistent with a steepening of seismic reflectors with depth along the eastern margin of the Velarde graben. We speculate that the gravity high extending northwestward from the Picuris Mountains may correspond to a structural high related to the early development of the rift transfer zone between the Española and San Luis Basins. Subsequently, fault propagation and linkage may have formed a through-going Embudo fault system.

INTRODUCTION

The San Luis and Española Basins are two north-trending half-grabens related to the Rio Grande rift in northern New Mexico. Characterizing their common structural boundary is critical in understanding how extensional strain is transferred between the two basins. The southern San Luis Basin is approximately 30 km-wide and bordered by the Tusas Mountains on the west and the Sangre de Cristo Mountains on the east (Fig. 1). The southern San Luis Basin is tilted to the east along the Sangre de Cristo fault (Dungan et al., 1984). The Española Basin lies south of the San Luis Basin. It also is bordered by the Sangre de Cristo Mountains on the east and extends 55-65 km westward into the topographic feature known as the Abiquiu embayment.

The Abiquiu embayment lies northwest of the Pajarito fault system and Black Mesa. Its western margin coincides with a 17 km-wide zone of prominent down-to-the-east faults near Abiquiu (Fig. 1). North of the Jemez volcanic field, this fault zone is interpreted to have comprised the rift boundary until the late Miocene, when activity shifted eastward to the Pajarito and Santa Clara fault systems (Baldridge et al., 1994). This eastward shift of activity resulted in the Abiquiu embayment being relatively shallow (~1 km of basin fill thickness) compared to the rest of the Española Basin (Baldridge et al., 1994). Attitudes in the central Abiquiu embayment are variable, but strata consistently dip to the east-southeast near its eastern margin. In contrast, strata dip west-northwest in the Española Basin to the east of the Abiquiu embayment.

The various basins of the Rio Grande rift, like most studied rifts, are generally separated by structural zones that accommodate opposing tilts between adjoining basins (Chapin and Cather, 1994; Mack and Seager, 1995; Gibbs, 1984; Bosworth, 1985; Rosendahl, 1987; Ebinger et al., 1987, 1989; Ebinger, 1989; Dunkelman et al., 1988; Milani and Davison, 1988; Morley et al., 1990; Faulds and Varga, 1998). The structural boundary between the east-tilted San Luis Basin and the west-tilted Española Basin half-grabens has commonly been placed at either the Embudo fault system (Dungan et al., 1984; Muehlberger, 1979) or at a gravity high, reflecting a structural or bedrock high, that extends between the Picuris and Tusas Mountains (Kelley, 1978, Cordell, 1979) (Fig. 1).

The Embudo fault aligns with the Jemez lineament (Aldrich, 1986), and its location is probably controlled by crustal weakness associated with this lineament. Trending approximately 60°E and connecting with the Sangre de Cristo fault near Taos, the Embudo fault is dominated by left-lateral, northwest-down oblique slip (Muehlberger, 1978 and 1979; Steinpress, 1980 and 1981; Leininger, 1982). Northeast of Pilar, the fault can be divided into four sections based on geomorphic expression and inferred differences in kinematic behavior (Kelson et al., unpubl. report for the U.S. Geological Survey, 1997). The fault zone is several km wide on the north flank of the Picuris Mountains (P. Bauer, unpubl. report for NM Office of the State Engineer, 1999), but is probably narrower southwest of Pilar. Locally, it has significant components of reverse slip where it changes trend from 60°E to 90°E at the northwest corner of the Picuris Mountains (Muehlberger, 1978 and 1979; Personius and Machette, 1984; Leninger, 1982). A recent study (Kelson et al., unpubl. report for the U.S. Geological Survey, 1997) ascribes this reverse slip to local shortening and strain partitioning along a predominately strike-slip fault. Estimates of total throw along the Embudo fault between Pilar and the Sangre de Cristo fault are as much as 3 km (Muehlberger, 1979), and scarp morphology indicates late Quaternary movement on some fault strands (Kelson et al., unpubl. report for the U.S. Geological Survey, 1997). Past studies have suggested that the Embudo fault changes sense of normal slip

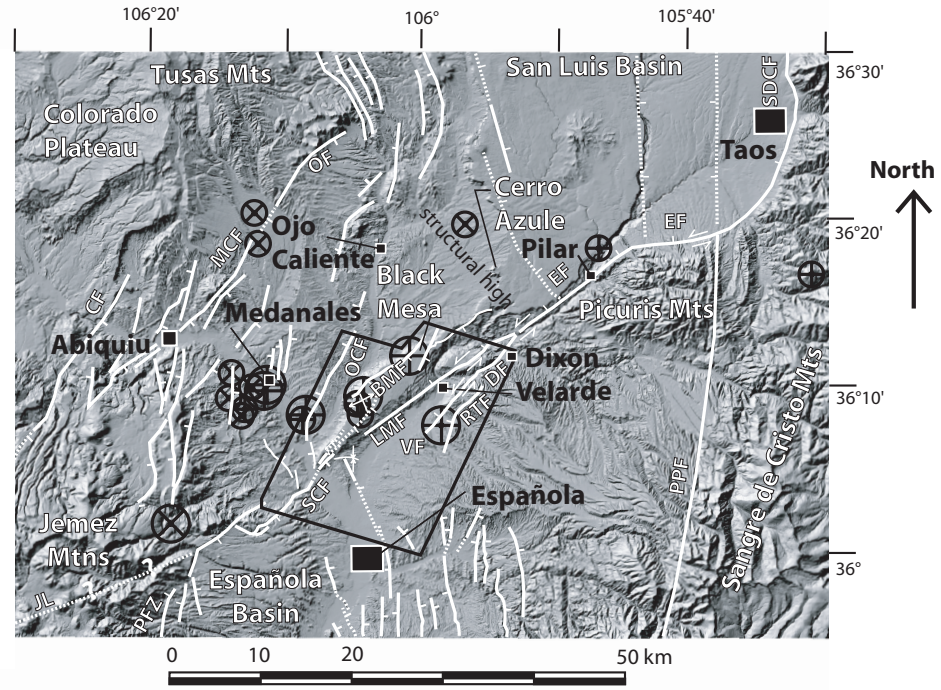


FIGURE 1. Shaded-relief map generated from 10 m-spaced DEM data. The map shows topographic features of the southern San Luis Basin and northern Española Basin in addition to towns and major faults. Bar is on down-thrown side of faults. Earthquake epicenters are also shown (from Sanford et al., 2002): epicenters denoted by crosses inside a circle are from 1962 through 1972, and epicenters denoted by X's inside a circle are from 1973-1998. Smaller circles represent earthquakes with calculated duration magnitudes of 2.0-3.0; larger circles represent duration magnitudes of 3.0-4.0. See Sanford et al. (2002) for more information regarding earthquake data and magnitude calculations. Axes of antiforms and synforms are denoted by lines with outward-facing and inward-facing arrows, respectively. Names of geologic structures are abbreviated as follows: CF = Cañones fault, OF = Ortega fault, MCF = Madera Cañon fault, JL = Jemez lineament in the Jemez Mountains, OCF = Ojo Caliente fault, BMF = Black Mesa fault, SCF = Santa Clara fault, PFZ = Pajarito fault zone, LMF = La Mesita fault, VF = Velarde fault, RTF = Rio de Truchas fault; DF = Dixon fault zone; EF = Embudo fault, PPF = Picuris- Pecos fault. Geology taken from lead author's geologic mapping and Kelley (1978).

between Pilar and Dixon, so that motion is down-to-the-southeast south of this area (Muehlberger, 1979; Leininger, 1984; Personius and Machette, 1984), although Kelley (1978) places the change southwest of Velarde under the eastern slope of Black Mesa.

With its dominant left-lateral slip, the Embudo fault has been considered as an intracontinental transform fault (Muehlberger, 1978 and 1979), in which the crustal block underlying the San Luis Basin has slid westward as it was down-dropped along the master fault at the basin's eastern margin. Faulds and Varga (1998) specifically cite the Embudo fault as an example of a transfer zone, which they envision as "transversely oriented (i.e., parallel to extension direction) to moderately oblique fault zones that accommodate a large component of strike-slip motion" (Faulds and Varga, 1998, p. 6). Other workers use the term transfer zone in a broader sense to indicate an area of deformation between two normal faults that acts to conserve extensional strain (e.g., Peacock et al., 2000; Morley et al., 1990), and refer to structures like the Embudo fault as transfer faults (Gibbs, 1984; Peacock et al., 2000).

The purpose of this paper is to describe the geologic structures related to the southern terminus of the Embudo fault system in the vicinity of the Velarde graben. We then briefly discuss the nature of the structural boundary between the San Luis and Española Basins, and speculate on its evolution.

GEOLOGIC STRUCTURE IN THE VICINITY OF THE VELARDE GRABEN

Manley (1976a and 1979) applied the name Velarde graben to a 6-10 km-wide, northeast-trending intra-rift graben that is bounded on the east-southeast by the Velarde fault and on the northwest by a fault we call the Black Mesa fault (Fig. 1, Plate 11), both of which were described as normal faults. Northeast of the town of Hernandez, the Velarde graben coincides with a 19 km-long gravity low (Figs. 1 and 2). Manley (1979) and Cordell (1979) consider other gravity lows to the southwest, located west and southwest of Española between the Rio Grande and the Pajarito fault zone, to be the Velarde graben. However, Ferguson et al. (1995) distinguish three distinct sub-basins which we refer to as the Velarde, Santa Clara, and Pajarito grabens (Fig. 2). Mapping by Kelley (1978) shows a prominent down-to-the-northwest fault associated with the Embudo fault system (a strand we call the La Mesita fault; Fig. 1, Plate 11) extending along the east slope of Black Mesa and directly connecting with a prominent down-to-the-southeast fault called the Santa Clara fault (the latter fault name is from Harrington and Aldrich, 1984). This interpretation suggests that the La Mesita and Santa Clara faults behave as a single scissors fault, in which the sense of normal offset reverses across a pivot point of little or no offset. Aldrich (1986) and

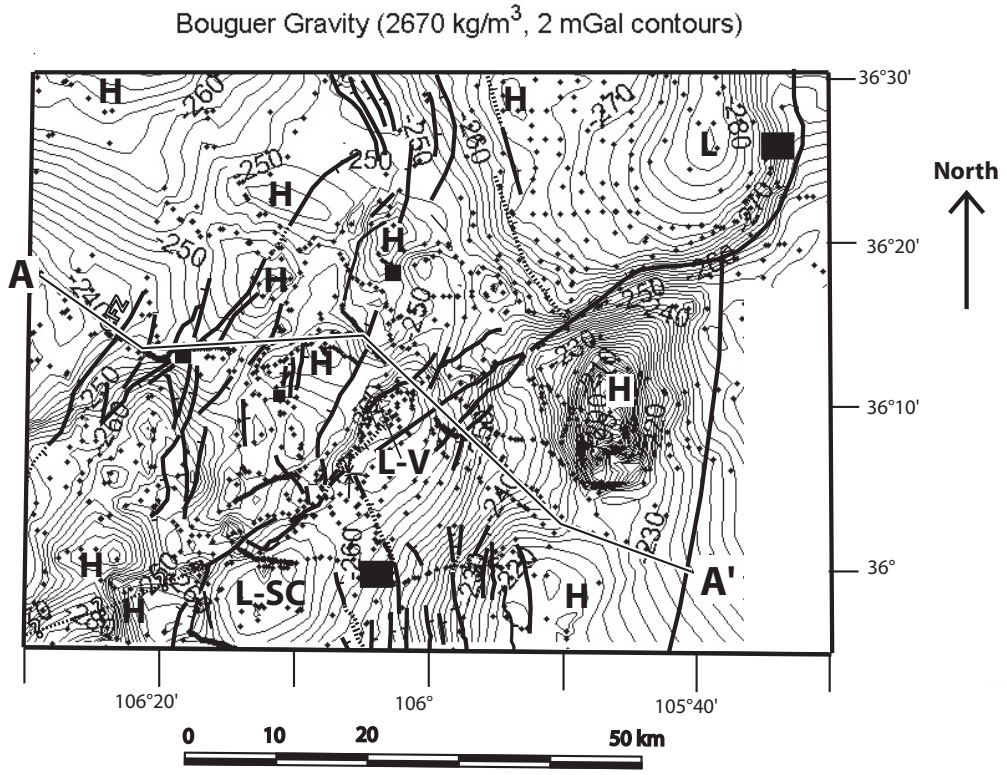


FIGURE 2. Bouguer gravity contour map for area of Fig. 1. Please see Fig. 1 for names of faults and geographic locales. H and L are written for localized Bouguer gravity highs and lows, respectively. The labels L-SC and L-V are for gravity lows corresponding to the Santa Clara and Velarde grabens, respectively (L-V is plotted 7 km southeast of the lowest part of the Velarde graben). A-A' section line for gravity profile (Fig. 4) is also depicted.

Aldrich and Dethier (1990) follow this interpretation in subsequent structural investigations of the Jemez lineament, and use the term Embudo fault to refer to the Santa Clara fault of Harrington and Aldrich (1984). Although there has been substantial normal slip on the Santa Clara fault, the direction and magnitude of lateral slip is not well established. Aldrich (1986) and Aldrich and Dethier (1990) argue for right-lateral slip. However, slickenline data of Gonzales (1993) show predominately left-lateral slip on north-trending, relatively short fault strands that connect longer, northeast-trending faults whose slickenline data are not sufficient to establish a unique direction of lateral slip. Steinpress (1980 and 1981) interprets a significant component of left-lateral motion along some strands of the Dixon fault zone near the town of Dixon (Plate 11).

Recent geologic mapping and sedimentologic investigation (Koning and Aby, 2003; Koning and Manley, 2003; Koning, 2003; Koning, 2004) in addition to geophysical investigations (Ferguson et al., 1995) by SAGE (Summer of Applied Geophysical Education – refer to Jiracek et al., 2000) have improved our understanding of geologic structures and stratigraphic relationships in the vicinity of the Velarde graben. In the following, we use these recent data to elucidate the structural aspects of the Velarde graben and their relationship to the southern Embudo fault system. The most recent interpretations of stratigraphic relationships of the Velarde graben, in addition to interpretations of throw along various faults in the graben (summarized in Table 1), are presented in Koning et al. (2004, this volume), which also summarizes past stratigraphic work.

Structural Data from Geologic Mapping

Bedding Attitudes

In the southeast part of Plate 11, strata uniformly strike 30-70°E and dip northwest at generally 3-6°. Strikes become more northerly and dips steepen (6-12°) in the hanging wall of the Santa Clara fault south of the Rio Chama. East of the Ojo Caliente fault, Tesuque Formation strata have remarkably uniform strikes (generally 10-30° E) and dips (4-7° E). West of the town of Embudo (Plate 11), prevalent mass wasting obscures primary structural data. However, sparse attitudes west of Embudo (Aby and Koning, 2004, this volume) and the general map pattern of the upper Ojo Caliente Sandstone Member contact in the lower Rio Grande gorge suggest that beds northwest of Velarde strike northeast and dip to the southeast.

Faults

The down-to-the-west Ojo Caliente fault zone strikes 20-30°E along the western margin of the study area. Its hanging wall constitutes the eastern part of the Medanales graben (Gonzales and Dethier, 1991) in the Abiquiu embayment. Northwards, it splays

into numerous strands that each appear to have relatively small displacement (up to ~ 100 m). The fault is interpreted to have 180-240 m of normal throw in its central section (May, 1980). Slickenside data associated with this fault are sparse and indicate predominately dip slip.

Near the northwestern margin of Black Mesa, the capping Servilleta Basalt (nomenclature follows Lipman and Mehnert, 1979) is displaced 18-35 m down-to-the-southeast along the 12-14 km-long Black Mesa fault (new name). The underlying Cieneguilla member of the Tesuque Formation (nomenclature follows Leininger, 1982), specifically the eolian-rich beds of this member that have an inferred age of 8.5-11.7 Ma (Koning et al., 2004, this volume), is vertically offset by 70-80 m on the north edge of Black Mesa. Cross-sections suggest that throw magnitude increases southward to 150-180 m near the center of the fault (Table 1; Koning et al., 2004, this volume, fig. 3). Slickenline data along this fault at the north end of Black Mesa indicate almost pure dip slip (Plate 11). A right-stepping, en echelon series of 3-15 m-tall fault scarps developed on the northern tip of Black Mesa, facing both east-southeast and west-northwest, may be considered as part of the broader Black Mesa fault zone at the north end of the Velarde graben. Later movement along this fault zone clearly post-dates the 2.8-3.7 Ma Servilleta Basalt (age data from Manley, 1976b, and A.W. Laughlin et al., unpublished report for Los Alamos National Laboratory, 1993).

The La Mesita fault, formerly "Fault 1" of Steinpress (1980), is an oblique-slip fault (down-to-northwest, left-lateral slip) which has offset the basalt flow on La Mesita by as much as 60-70 m vertically and 460 m laterally (Table 1). The La Mesita and Dixon faults (the latter is discussed below) both strike northeastwards towards the Embudo fault, as mapped to the northeast by Bauer and Helper (1994), and should be considered as part of the Embudo fault system. These two strands have been individually named, however, for identification purposes in the following discussion. Based on linear features in landslide deposits, the La Mesita fault may extend at least 3.5 km south of the mouth of the Rio Grande gorge at Velarde.

The Dixon fault zone (new name) is 0.4-0.6 km wide and located in the extreme northeast corner of Plate 11. It is interpreted as a left-lateral, northwest-down oblique fault (Steinpress, 1980 and 1981). The following summarizes more detailed information presented in Aby and Koning (2004, this volume) and Koning and Aby (2003). Within the fault zone Tertiary and Proterozoic strata are tectonically imbricated and steeply tilted, and Tertiary strata are tightly folded. This deformation, in addition to a local reverse fault, indicates an element of shortening and/or transpression in this zone, as was locally noted by Steinpress (1980 and 1981). The overall shortening along the central to southern part of the fault zone is attributed to a right bend of the fault trace in Arroyo Ocole, northeast of the north end of the Velarde fault (Plate 11).

The Dixon fault is interpreted to link with the Velarde fault 3.4-3.9 km northeast of Velarde (Fig. 1 and Plate 11; Manley, 1979; Aby and Koning, 2004, this volume, fig. 1). West of the Velarde fault, there is no evidence of stratigraphic offset by a southwest-projected Dixon fault possibly buried under Quaternary alluvium in Arroyo Ocole. In exposures about 2 km northeast of Velarde, immediately south of the mouth of Cañada de las Entranas, there is unambiguous lateral interfingering of the Cejita and Cieneguilla members of the Tesuque Formation and no sign of fault-related deformation. This contrasts with the interpretation by Kelley (1978) that the Dixon fault extends through these exposures and continues into Velarde.

The Velarde fault (Manley, 1976a and 1977) strikes 30-40°E and is about 8 km long. The northern Velarde fault appears to join with the Dixon fault zone in Arroyo Ocole, as mentioned above, but vertical stratigraphic offset exposed on the south margin of this drainage is only approximately 30 m. This fault exhibits down-to-the-northwest throw, and hanging wall strata on the central part of this fault dip southeast towards the fault. Near the center of the Velarde fault, upper Miocene strata are interpreted to have been offset vertically by 95-125 m (Table 1; Koning et al., 2004, this volume). Faint slickenlines were measured on the fault plane at two locations 0.7 and 1.3 km north of the road in Rio de Truchas (shown on the same stereonet in Plate 11). These slickenside data indicate left-lateral, down-to-the-northwest oblique slip.

The Rio de Truchas fault (new name) is located 1.0-1.8 km east of the Velarde fault and has a roughly similar strike. This fault is 8.5-9.0 km long and does not appear to connect directly

TABLE 1. Vertical displacement data for Velarde graben faults (from Koning et al., 2004, this volume)

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

† See Koning et al., this vol., fig. 3); * Alcalde tuffaceous zone; **Vallito white ash zone; *** Chamita lower tuffaceous zone.

with the Embudo fault at the surface. Because it is not as linear as the adjoining Velarde fault, it may have less of a component of left-lateral slip. Shallow, upper Miocene strata are interpreted to be vertically offset by 65-100 m (Table 1; Koning et al., 2004, this volume).

Following Harrington and Aldrich (1984), we apply the name Santa Clara fault to the prominent northeast-striking fault zone present in the southern tip of Black Mesa. In exposures south of the Rio Chama, this fault zone is marked by steeply tilted (60-80°E) beds of the Santa Fe Group, with local exposures of closely spaced, steeply eastward- to southeastward-dipping fault planes. The Santa Clara fault is characterized by down-to-the-southeast motion, with a possible component of right-lateral slip (Aldrich, 1986); this sense of offset contrasts with the left-lateral, down-to-the-northwest oblique slip of the Embudo, La Mesita, and Velarde faults. This difference in kinematic behavior, plus the fact that the Santa Clara fault does not appear to form a hard-linkage with faults of the Embudo fault system, justifies applying different names to the two faults.

The Santa Clara fault appears to project to the southwest into the Valles caldera along the Jemez lineament (Fig. 1), although there is no evidence of significant offset in exposed strata west of the Pajarito fault (Aldrich, 1986). Faults associated with the Pajarito fault system join this fault about 18 km west of Española (Fig. 1). We use the name Pajarito fault system to collectively refer to the faults in the eastern Jemez Mountains near the town of Los Alamos that generally trend northwards and dip both west and east, but the majority of displacement is clearly down-to-the-east. Among others, these faults include the individual Pajarito, Rendija Canyon, and Guaje Mountain faults (Golombek, 1983; Carter and Gardner, 1995; Wong et al. (unpubl report to Los Alamos National Laboratories, 1995).

In the southern part of Black Mesa, north of the Rio Chama, the Santa Clara fault fault splits into two to three strands which collectively drop the Servilleta Basalt 125-135 m (Fig. 3, Table 1). Along the eastern strand is an alignment of topographic cones 4-13 m in height that are possible volcanic vents for some of the Servilleta Basalt in the near vicinity (Fig. 3). The locations of these vents may have been controlled by the intersection of the Santa Clara fault with a transverse structure associated with the Chamita syncline (see below). North of the Chamita syncline, vertical displacement associated with the Santa Clara fault after the emplacement of the Servilleta Basalt dramatically decreases, and surficial faults terminate northwards as east-facing monoclines in the Servilleta Basalt.

We apply the name Chili fault to the northwest-striking, down-to-the-southwest fault on the north side of the Rio Chama just downstream from the Rio Ojo Caliente (Plate 11). It has offset the base of an upper Pleistocene terrace deposit (Qtc3 of Koning and Manley, 2003) by 30 cm. At this location, measurements of five slickenlines indicate primarily normal slip, with a slight component of left-lateral motion (Plate 11). This fault (Galusha and Blick, 1971, fig. 28a) has displaced fluvial sediment associated with the upper Miocene Cejita Member (Koning et al., 2004, this volume) by at least 120 m. Furthermore, strata to the southeast strike parallel to this fault and dip 4-9°NE into the fault, strongly suggesting that they have been tilted by the fault.

Folds

Two monoclinal folds, trending west to northwest and down-to-the-south, are observed in the Servilleta Basalt that caps southern Black Mesa (Fig. 3). The south one, called the South Black Mesa monocline, has produced a topographic relief of 50-60 m on the upper surface of the Servilleta Basalt, trends approximately 70°W, and aligns with the northern limb of the west-trending Chamita syncline (see below). The northern fold, referred to as the North Black Mesa monocline, has produced a topographic relief of 16-20 m on the upper Servilleta Basalt surface and trends 50-60°W. Neither of these monoclines extends west of the Rio Ojo Caliente, nor are they apparent in the Tesuque Formation on the west slopes of Black Mesa. We do not have data demonstrating whether these folds were formed by shortening or extension. As discussed below, the South Black Mesa monocline may have formed over a blind, south-dipping normal fault (Koning et al., 2004, this volume, Fig. 3).

The Tesuque Formation on the southeast side of southern Black Mesa has been deformed into a west-trending syncline called the Chamita syncline by Koning and Manley (2003) (Fig. 3). It is best exposed for 3 km east of the Santa Clara fault, beyond which it disappears under Quaternary Rio Grande alluvium. The north limb of the syncline corresponds with the South Black Mesa monocline mentioned above. The limb extends west of the Santa Clara fault no more than a few hundred meters. Deformation along the Santa Clara fault obscures whether the axis and south limb of the syncline also extend a short ways into the footwall of the Santa Clara fault. Based on attitude data (Fig. 3; Koning and Manley, 2003), this syncline plunges to the west. This orientation has resulted in a parabolic map pattern in the Chamita upper tuffaceous zone. Cross-section C-C' presented in Koning et al. (2004, this volume, fig. 3) indicates the Chamita syncline has an approximate amplitude of 520-550 m and appears to be asymmetrical, with the northern limb steeper than the southern limb.

SAGE Gravity Data and Structural Interpretations

Methods

The gravity database contains stations from a variety of sources, particularly the U. S. Geological Survey (Cordell, 1979) and the SAGE field course. SAGE students gathered stations regionally where spot elevations were available as well as at carefully surveyed locations. In the northern Española Basin area, surveying was performed using laser EDM total stations between 1989 and 1993, but afterwards phase differential GPS was employed. Particularly dense coverage and high quality stations are found along the seismic lines (profile A to A' in Fig. 2). The data have been reduced to a complete Bouguer anomaly using 7 1/2 minute quadrangle digital elevation models from the U. S. Geological Survey. A "standard" reduction density of 2670 kg/m^3 has been used here, although 2000 to 2200 kg/m^3 would likely be best.

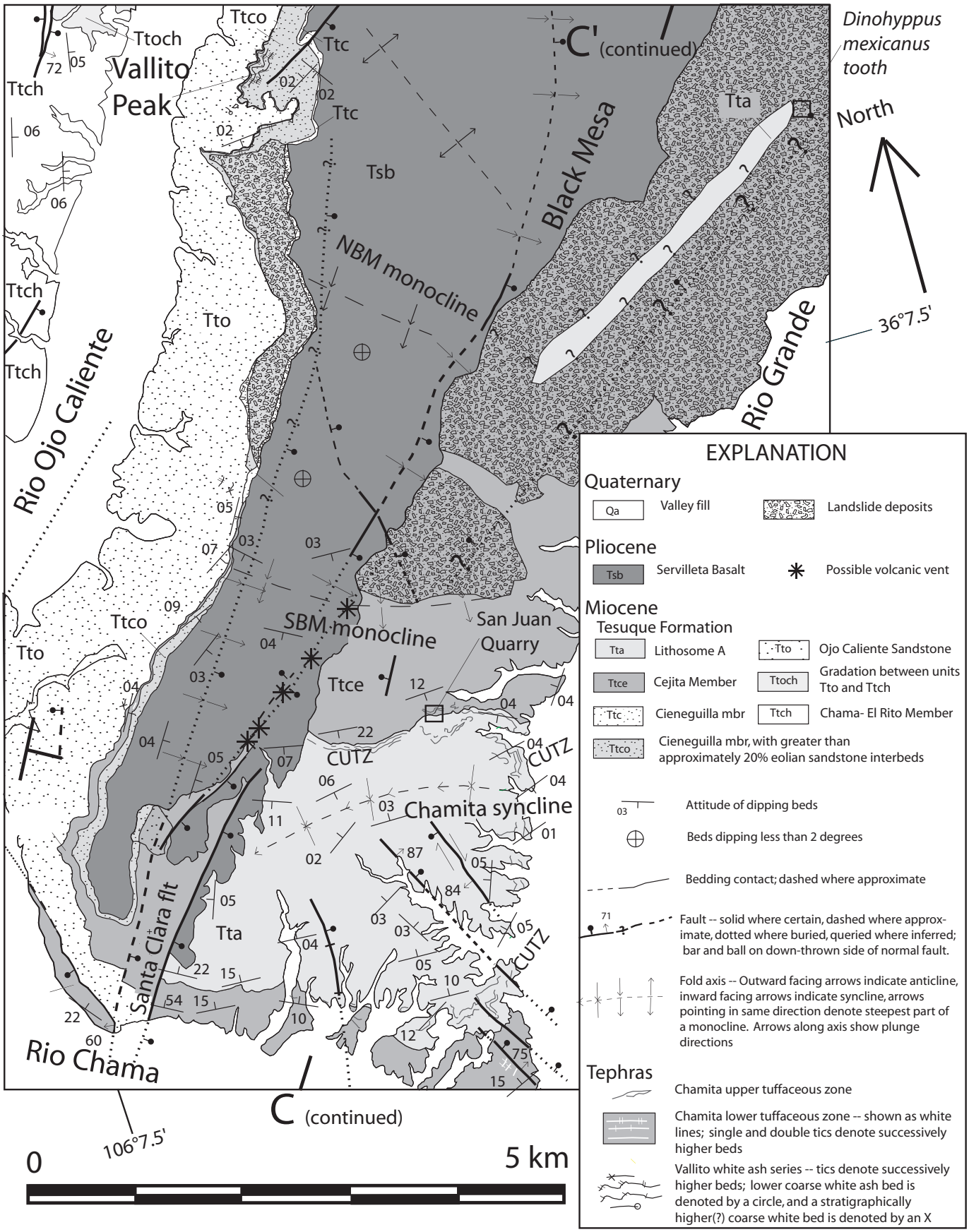


FIGURE 3. Geologic map of area around southern Black Mesa. NBM monocline = North Black Mesa monocline; SBM monocline = South Black Mesa monocline. Cross-sections B-B', and C-C' are shown in Koning et al. (2004, this volume, Fig. 3).

Observations

Several features of the contoured Bouguer gravity map (Fig. 2), generated from the gravity data base, are important to note. First, there is a prominent gravity high that extends northwest from the western front of the Picuris Mountains, through Cerro Azule, and into exposed Proterozoic rock northwest of the town of Ojo Caliente (Figs. 1 and 2). Second, there is a pronounced gravity low that corresponds to the Velarde graben of Manley (1976a, 1979). The low Bouguer anomaly values coincide spatially with the topographic high of Black Mesa. A steep gravity gradient on the west side of the gravity low probably corresponds with a fault and is discussed in more detail below. Third, a gravity saddle is present for ~ 10 km northwest of Española. This saddle separates the Velarde graben to the north from the Santa Clara graben to the south.

SAGE Seismic Reflection Data and Structural Interpretations

Methods

The seismic reflection/refraction data at SAGE has been collected using Vibroseis (c) sources (usually two vibrators). From 1989 to 1991, a recording system with about 270 channels belonging to the ARCO Oil and Gas Company was employed (Baldridge, et al., 1994). From 1994 to 1997, a 48 channel system owned by the Colorado School of Mines was used. Source and receiver intervals of 110 feet were recorded for common midpoint (CMP) processing of reflections (presented in Fig. 4). In addition, wide angle reflection and refraction data were always recorded, which has been invaluable for modeling and lithologic characterization. For this study, we present three seismic lines that lie along or near

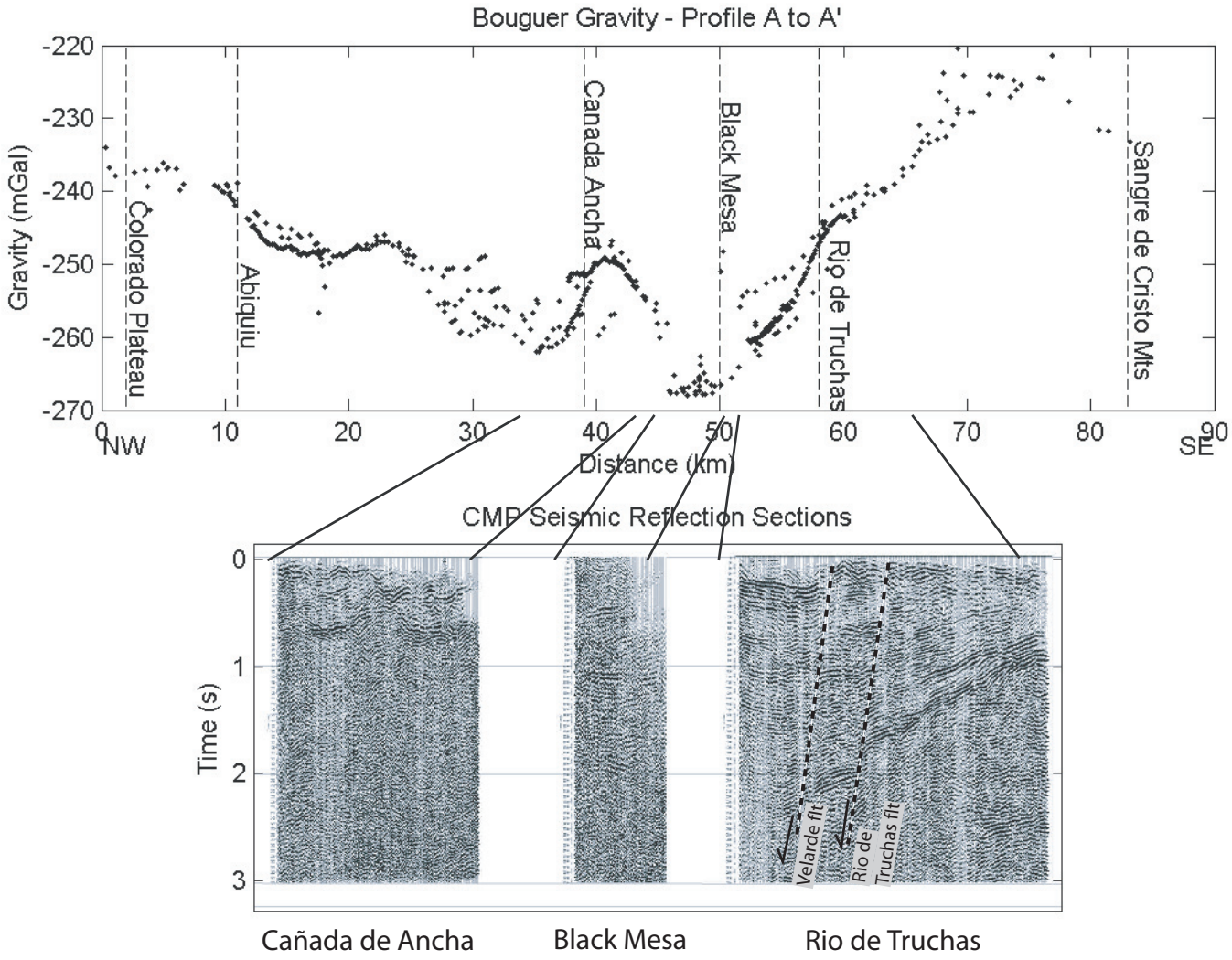


FIGURE 4. Top: gravity profile of section A-A' (see Figure 2); bottom: CMP (common midpoint) seismic reflection sections; the location of each section relative to the overlying gravity profile is shown by tie lines. The seismic reflection sections are labeled as they are referred to in the text.

a single transect through the northern Española Basin. These are, from east to west, the Rio de Truchas, Black Mesa, and Cañada de Ancha lines (Fig. 4). All times related to the seismic profiles are two-way travel times.

Observations and Interpretations of Seismic Lines

The Rio de Truchas reflection line follows the lower 6 km of Rio de Truchas (Plate 11; Fig. 4), and extends northwestward 1.0 km from the mouth of Rio de Truchas to the Rio Grande. Reflectors generally dip to the left (northwest), similar to what is observed near the eastern basin boundary farther to the south (Biehler et al., 1991). Heavy reflectors are found at 0.7-1.7 seconds on the east side of the line. These probably represent bedrock below the rift basin fill; the bedrock is possibly composed of either Paleozoic strata or Proterozoic metasediments. Reflectors from the overlying Tesuque Formation appear to have steeper dips with depth. The two significant faults mapped in the lower Rio de Truchas are expressed well in the seismic data (Fig. 4). The Velarde fault is manifested by discordance in the reflectors, on either side of which the reflectors generally have opposing slopes. To the east, preliminary correlation of reflectors across the Rio de Truchas fault suggests a possible vertical displacement of 0.28-0.30 sec at the base of the Tesuque Formation (approximately 300-400 m depending on subsurface density and velocity assumptions). Resolution of deeper seismic horizons on the hanging wall of the Velarde fault is too poor to constrain throw across it, but since the Velarde fault is of similar length to the Rio de Truchas fault their throw values may also be similar.

The Black Mesa seismic line is about 3.3-3.4 km in length and trends north to south. The south end of the line is 3 km northwest of the northwest end of the Rio de Truchas line. Lack of roads in addition to basaltic talus and landslide deposits prevented a direct seismic survey between this and the Rio de Truchas line. Although the presence of 10-30 m-thick basalt on top of Black Mesa reduced reflection resolution from much of the underlying Tesuque Formation, two strong reflectors are present at about 0.50-0.55 and 1.05-1.10 seconds. These may represent clayey intervals in the Tesuque Formation. Another reflector at 1.8-2.0 seconds is interpreted to correlate to the strong lower reflectors on the adjoining Cañada de Ancha and Rio de Truchas lines, which probably represent the top of Proterozoic or Paleozoic rock. This reflector clearly dips to the southeast and is consistent with surface attitudes in the hanging wall of the Velarde fault east of the Rio Grande (Plate 11). Comparing this strong lower reflector to its interpreted correlative on the Cañada de Ancha line suggests a vertical offset of about 1.0-1.6 km along the Black Mesa fault, based on reasonable velocity and density assumptions for the graben basin fill.

The Cañada de Ancha seismic line_follows its namesake for 10 km from its mouth near the Rio Ojo Caliente to the northwest. Strong seismic reflectors at 0.60-0.80 sec are interpreted to represent Paleozoic or Proterozoic rock. This package of strong reflectors is relatively flat-lying and found at approximately 1 km depth. No faults with significant throw are observed in this line. This is consistent with the interpretation that faults mapped on the surface probably have less than 100 m of displacement, and the resolution of the seismic reflection data is an order of magnitude better than that. About 3 km upstream from the mouth of Cañada de Ancha there is a discontinuity of the lower package of strong reflectors. This discontinuity is interpreted to represent a buried volcanic vent because such vents (basaltic) are exposed in nearby Tesuque Formation outcrops (May, 1980).

DISCUSSION

The Embudo Fault System in the Velarde Graben

The Embudo fault is a major, relatively continuous structure that bounds the northern and western flanks of the Picuris Mountains (Fig. 1) and has a significant component of left-lateral slip (Muehlberger, 1978 and 1979; Steinpress, 1980 and 1981; Personius and Machette, 1984; Kelson et al., unpubl. report for the U.S. Geological Survey, 1997; Koning and Aby, 2003; Aby and Koning, 2004, this volume). Our investigation adds new insight on the extension of this important fault to the south in the northern Española Basin.

Approximately 2 km north of Dixon, the Embudo fault splits into two strands: the La Mesita fault on the northwest and the Dixon fault zone on the southeast (Fig. 1; Koning and Aby, 2003). The Dixon fault zone continues for 4 km southwest of Dixon before probably joining the Velarde fault. We interpret that a right bend in this fault 2.3 km southwest of Dixon acted as a restraining bend, and has resulted in shortening and uplift of Proterozoic rock west of Dixon (Aby and Koning, 2004, this volume). The La Mesita fault appears to project northeastward into the Embudo fault and exhibits similar motion as the Embudo fault. Cross-section A-A' of Koning et al. (2004, this volume, fig. 3) suggests a poorly constrained, down-to-the-west throw of ~160 m in upper Miocene strata where this fault projects 2 km southwest of Velarde. This sense of offset and relatively low throw magnitude is consistent with comparison of seismic reflectors between the Rio de Truchas and Black Mesa seismic lines. Based on its strike near Velarde, the La Mesita fault would project into the western part of the well-exposed Chamita badlands east of the south tip of Black Mesa. Here, however, there is no evidence of the La Mesita fault, nor is there evidence of a down-to-the-west structure or a scissors fault that has offset the basalts of Black Mesa. Consequently, the La Mesita fault terminates somewhere northeast of the Chamita badlands and southwest of Velarde (Plate 11; Fig. 3).

West of Dixon, there may be a transferring of slip from the Dixon to the La Mesita fault because of the restraining bend in the southern Dixon fault. However, a component of slip seems to step back to the Velarde fault from the La Mesita fault within 2 km N-NE of Velarde. Here, attitude data indicate a south-facing ramp structure between the two faults (Plate 11). Some motion associated with the La Mesita fault may also step westward onto two short down-to-the-northwest faults in the middle of Black Mesa and to the Black Mesa fault (Plate 11).

We interpret that both the Velarde and Rio de Truchas faults comprise the north part of the southeastern border of the Velarde graben. These faults terminate southwestwards as fault-tip mono-

clines at locations of 2.3-2.4 km and 3.5-3.6 km south of Rio de Truchas, respectively (Plate 11). Southwest of the Velarde fault tip and its associated west-facing monocline, there is a complex zone of relatively small faults (Koning and Manley, 2003), many of them nearly vertical, which may be related to slip transfer from the Velarde fault to either the Chamita syncline (discussed below) or possibly a buried, north-south structure underneath the Rio Grande Quaternary alluvium. If the latter exists, however, it does not seem to continue south of the Chamita syncline based on geologic mapping and available aeromagnetic data (USGS et al., 1999; Koning and Manley, 2003).

The predominately normal-slip Black Mesa fault does not continue significantly north of the Velarde graben and has experienced up to 35 m of vertical displacement since the emplacement of the Servilleta Basalt. Relatively recent activity (i.e., <2.8-3.7 Ma) on this fault is consistent with the inference that a component of dip-slip has been transferred to that structure from the comparably recent Embudo fault system.

In summary, geologic mapping indicates that the Embudo fault zone splays into the La Mesita and Dixon-Velarde faults as it enters the Velarde graben. Some dip-slip may have been partitioned to the Black Mesa and Rio de Truchas faults on the northwest and southeast sides of the Velarde graben, respectively, as these structures seem to have little or no lateral motion. It is important to note that the Velarde fault does not link with the down-to-the-west Pojoaque-Road fault system and Los Barrancos monocline found in the central Española Basin (Koning, 2002a; Koning and Maldonado, 2001). Rather, the Pojoaque-Road fault, which coincides with a pronounced aeromagnetic lineament, appears to switch sense of normal offset northwest of Española and continues into the Chamita syncline as the down-to-the-east San Juan Pueblo fault (Plate 11; Koning and Manley, 2003).

Pre-late Miocene Activity on the Velarde Graben Faults

Previous workers have suggested that the Velarde graben was primarily created between 5-2.8 Ma (Manley, 1976a and 1979; Steinpress, 1980 and 1981). However, integration of our geologic map and geophysical data indicates that the Velarde graben was also an active structure in the middle to late Miocene, and possibly earlier (also see discussion in Koning et al., 2004, this volume). On the east end of the Rio de Truchas line, seismic reflectors for the lower-middle basin fill (upper Oligocene-early Miocene?) and upper bedrock contact dip more steeply northwestward than those of the upper-middle basin fill (middle?-upper Miocene). Considering that rift sedimentation in the Española Basin and Abiquiu embayment began in the late Oligocene (Smith, 2000; Smith et al., 2002), we interpret that syndepositional tilting of the Rio de Truchas fault footwall occurred between the late Oligocene and late Miocene. In addition, at least two faults of the Velarde graben are interpreted to be growth faults because younger strata are offset significantly less than older strata. Vertical displacement of the basin fill-bedrock contact is interpreted to be in the range of 1.0-1.6 km along the Black Mesa fault. Along the Rio de Truchas fault, the base of the basin fill is probably vertically offset 300-400 m. These throw values are significantly greater than those obtained from upper Miocene strata (65-180 m; Table 1), and this indicates growth faulting and tectonic activity in the Velarde graben before the late Miocene and subsequent to initiation of Santa Fe Group deposition.

Relationship of the Santa Clara Fault to the Santa Clara and Velarde Grabens

We think it is important to differentiate the Velarde graben from other inner grabens located to the south. West of Española, bedding dips increase to 6-12° west, compared with 3-6° NW east of Española (Koning and Manley, 2003; Koning, 2003). This increase in dip corresponds spatially with a slight steepening of the westward-sloping gravity gradient associated with the Santa Clara graben (Fig. 2). The western boundary of the Santa Clara graben coincides with the Pajarito and southern Santa Clara faults. A gravity saddle (relative gravity high) near the Rio Chama separates the Santa Clara graben from the Velarde graben to the north (Fig. 2).

The Santa Clara fault zone continues north of the Rio Chama and splays northward into 2 to 3 strands that have displaced both the Tesuque Formation and overlying Servilleta Basalt on Black Mesa. Seven to ten km northeast of the south tip of Black Mesa, the deformation of the Servilleta Basalt attributed to these faults appears to end. About 2 km to the northwest is the southern Black Mesa fault; this step to the Black Mesa fault coincides with a 2-3 km left-step of the steep gravity gradient bounding the west side of the Velarde graben (Fig. 2). The southern terminus of the La Mesita fault may be about 1 km to the east, although landslide deposits obscure exactly where it ends.

A steep gravity gradient on the northwest side of the northeast-trending Velarde graben (Fig. 2) has been attributed to a major fault structure (Cordell, 1979; Manley, 1979), and we concur. The Black Mesa and Santa Clara faults are obvious candidates for such a major structure. There are no down-to-the-west structures exposed along the west slopes of Black Mesa, nor are there significant offsets of stratigraphic projections across the Rio Ojo Caliente (Koning et al., 2004, this volume, cross-section A-A' in Fig. 3). Based on available data, the gravity gradient appears to bend in the same way as the western margin of the basalts capping Black Mesa, although there is no exposed fault that directly ties the western strand of the Santa Clara fault with the Black Mesa fault. There may be a fault here buried beneath the Servilleta Basalt that accounts for the gravity gradient. If so, this fault has not been active north of the South Black Mesa monocline since the emplacement of the Servilleta Basalt (2.8-3.7 Ma based on ages from Manley, 1976a and 1976b; Appelt, 1998). This postulated buried fault may have become inactive if northward propagation of the eastern fault strand of the northern Santa Clara fault (along the eastern side of Black Mesa) caused the western fault to fall into a stress shadow zone.

Chamita Syncline and Black Mesa Segment Boundary

The Chamita syncline and South Black Mesa monocline are part of a rather anomalous, but significant, east-west transverse

structure immediately north of the gravity saddle that defines the south end of the Velarde graben (Figs. 2 and 3; Plate 11). The Chamita syncline appears to have formed largely after the emplacement of the 6.75-7.0 Ma Peralta tuff (Chamita upper tuffaceous zone; correlation by McIntosh and Quade, 1995), because this tuffaceous stratigraphic interval has been tilted as much as 22 degrees on the north and south limbs of the syncline and there is no compelling evidence that older beds are, as a whole, more deformed than this interval (Plate 11). Such an interpretation agrees with Manley (1976a, 1979).

We conclude that there is a fault segment boundary related to the northern terminus of the Santa Clara fault, which we refer to as the Black Mesa segment boundary. This boundary encompasses the general area from the Chamita syncline to about 5 km north of its axis. Here, extensional strain is transferred between the Santa Clara fault and the La Mesita, Black Mesa, and Velarde faults. Exactly how this strain is transferred requires further study, but the coincidence of the Chamita syncline in this boundary suggests it plays an important role. We speculate that the Chamita syncline may correspond to a pre-existing east-west basement structure. In particular, there may be a blind, south-dipping normal fault beneath the north limb of the syncline and the South Black Mesa monocline, as shown in cross-section C-C' of Koning et al. (2004, this volume; fig. 3). This transverse structure may also be involved in relaying slip from the southern terminus of the Velarde fault to the Santa Clara fault.

Formation of the Chamita syncline also may be due to rotation of blocks within the Española Basin (Fig. 5); this rotation may produce strike-slip motion on faults in the southern Velarde graben, including the Santa Clara fault. Calculations by Salyards et al. (1994) based on the paleomagnetic data of MacFadden (1977) gave 13.2 ± 3.5° of counterclockwise rotation (along a northeastward, steeply plunging rotation axis) for the Tesuque Formation close to the syncline axis. This counter-clockwise motion may be reflected in the southwestward bend of the Chamita syncline axis (Fig. 3). As previously noted, Aldrich (1986) and Aldrich and Dethier (1990) interpret a component of right-strike slip along the main Santa Clara fault south of the Rio Chama. It may be that the hanging wall of the Santa Clara fault is rotating counter-clockwise, perhaps accounting for the right-strike slip, and that this rotation is creating an extensional sag in the area of the Chamita syncline. Also, it is possible that the magnitude of left strike-slip is greater on the La Mesita fault than the Velarde fault, and this is causing clockwise rotation between the Velarde and La Mesita faults. This model(s) would imply different translation or rotational motion between the basin floor south of the Chamita syncline versus north of the syncline and versus the footwall of the Santa Clara fault, but examples of differential rotation have been documented elsewhere in the Española Basin (Salyards et al., 1994). It is worth noting that there are several north-northeast striking faults on the south limb of the syncline and that these have dips greater than 80 degrees. The northernmost of these faults may have right-lateral normal oblique slip, based on sparse slickenside data (Fig. 3). There may be a component of lateral slip associated with the other steep faults as well, but more study is needed to determine how this slip relates with either rotation or stresses involved in the Black Mesa fault segment boundary.

Assuming the Chamita syncline is related to the Black Mesa segment boundary and related to lateral motion along the southern Embudo fault system, then the formation of the Chamita syncline may constrain the initiation of left-lateral movement along the Embudo fault system in the Velarde graben. Since we interpret the Chamita syncline formed after 7 Ma, this would indicate that significant left-lateral motion along the Embudo fault also postdates 7 Ma. Perhaps it took until the latest Miocene for fault propagation to achieve hard-linkage of the Velarde graben faults with the Embudo fault system to the north, after which the lateral slip associated with the Embudo fault was transmitted to the Velarde and La Mesita faults in the Velarde graben. Initiation of major left-lateral slip after 7 Ma is consistent with interpretations of Leininger (1982), Dungan et al. (1984), and Aldrich (1986), but we feel more data are needed to fully address this issue.

Neotectonic activity seems to be occurring today in the general vicinity of the Black Mesa segment boundary, and is likely related to the propagation of slip across this area. This neotectonic activity has been documented by recent leveling surveys, seismic epicenter data, and geologic mapping. Analysis of repeated leveling surveys indicates as much as 4.9 cm of subsidence between the years of 1934 and 1939 that has been attributed to crustal deformation (Reilinger and York, 1979). This subsidence occurred over a distance of 19 km between the towns of Española and Medanales. The maximum subsidence occurred in the immediate hanging wall of the Santa Clara fault. A cluster of seismic epicenters, having duration magnitudes between 2.0-4.0 (Fig. 1), is recorded along the western boundary of the ground subsidence near Medanales (Sanford et al., 2002). Another cluster of seismic epicenters of similar magnitude occurs at the Black Mesa fault segment boundary (Sanford et al., 2002; Fig. 1) and two earthquakes plot on the southern Ojo Caliente fault.

The Chili fault appears to link the Ojo Caliente fault with the Santa Clara fault and has been active in the Quaternary. At its west end, displacement associated with the Chili fault probably steps leftward onto the Ojo Caliente fault. At its east end, the Chili fault turns sharply southward and appears to merge with the Santa Clara fault zone. In addition to the offset base of a late Pleistocene terrace deposit, longitudinal profiles of several Quaternary terraces along the Rio Ojo Caliente (Newell et al., 2004, this volume) show a noticeable deflection across the Chili fault. Consequently, we interpret that the Chili and Ojo Caliente faults have shunted a component of slip from the Santa Clara fault during the Quaternary.

Transfer of Slip Between the Embudo and Pajarito Fault Systems

The Embudo and Pajarito fault systems are major faults that have been active in the late Quaternary (e.g., Wachs et al., unpubl. report for Los Alamos National Laboratory, 1988; Kolbe et al., unpubl. report for Los Alamos National Laboratory, 1994 and 1995; Olig et al., 1996; Kelson et al., 1996; Kelson et al., unpubl. report for the U.S. Geological Survey, 1997). Workers have calculated a slip rate of 0.15-0.17 mm/yr (oblique slip) for

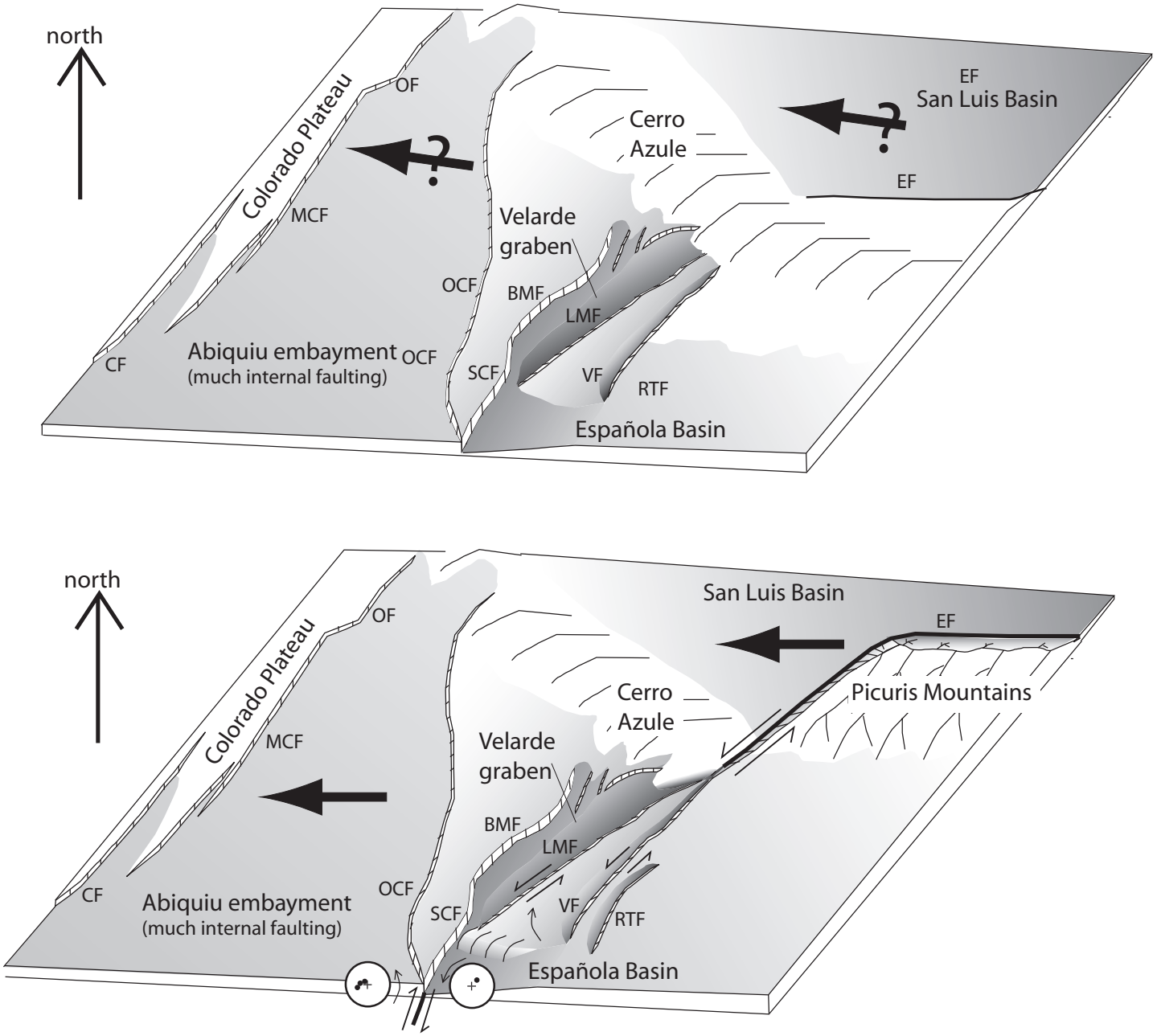


FIGURE 5. Schematic, simplified diagram showing the general structure of the region around the Velarde graben (i.e., northern Española Basin and the Abiquiu embayment). The diagram also illustrates our speculative model regarding the development of the structural boundary between the San Luis and Española Basins. Top and bottom figures respectively represent time periods before and after the Embudo fault was hard-linked to the Velarde graben faults. Darker shading indicates greater depths to Proterozoic crystalline rocks. Basin fill not shown. Circles at bottom of lower figure show net rotation axes; the left one is from data of Brown and Golombek (1985) and the right one from data of MacFadden (1977), as calculated by Salyards et al. (1994). Curved arrows around these circles indicate rotation direction. Strike-slip vectors are shown for the Embudo, Velarde, La Mesita, and Santa Clara faults (latter follows interpretations of Aldrich, 1986). Faults are labeled as in Fig. 1. Heavy dark arrows show approximate general extension direction.

the Embudo fault (Bauer and Kelson, 2004, this volume) and ~ 0.07-0.12 mm/yr (dip slip) for the Pajarito fault (Gardner and House, 1987;Wong et al., unpubl. report for Los Alamos National Laboratory, 1995; Olig et al., 1996).

The Santa Clara fault and faults associated with the Velarde graben provide an important link between the Embudo and Pajarito faults. Throw along the Santa Clara fault after the emplacement of the Servilleta Basalt is 35-48 m / Myr (Table 1), which compares favorably with a vertical displacement of .04 mm/yr for the Embudo fault southwest of Pilar (Bauer and Kelson, 2004, this volume). These values are lower than the vertical slip rates of 0.07-0.12 mm/yr on the Pajarito fault. This discrepancy is probably explained by the conversion of lateral slip along the Embudo fault system southward to pure dip slip on the Paja-

rito fault system. We do not know how the lateral motion of the Embudo fault system is accommodated through the southern part of the Velarde graben, but it may be related to counterclockwise rotation south of the Chamita syncline. There may also be a component of slip being shunted off from the Pajarito fault towards faults by Medanales; this may account for the modern subsidence boundary and microseismic activity there, which coincidently is along-trend of the Pajarito fault to the south (Fig. 1).

We conclude that there is no single fault that transfers motion from the Embudo to the Pajarito fault system, but rather that the extensional strain is being taken up by numerous faults in the Velarde graben and southern Abiquiu embayment. Important faults along which this motion is transferred in the late Miocene to present include the Santa Clara, Black Mesa, La Mesita, and Velarde faults.

The Structural Boundary Between the San Luis and Española Basins

Extending northwest from the Picuris Mountains is a pronounced gravity high (Fig. 2). Along this gravity high are two small topographic highs associated with Proterozoic rocks: quartzite at Cerro Azule and granite near the town of Ojo Caliente. A steep north-south gravity gradient, perhaps coinciding with a fault buried by the Servilleta Basalt, on the western margin of the San Luis basin turns and follows the northeast flank of this gravity high and terminates against the Embudo fault. Also, faults associated with the western margin of the Velarde graben and eastern-central Abiquiu embayment do not to cross this gravity high as continuous structures. We agree with Cordell (1979) and Kelley (1978) that this gravity high should be the structural feature that separates the San Luis and Española basins, as opposed to the entire length of the Embudo fault.

Speculated Temporal Changes of the Structural Boundary of the Española-San Luis Basins

The structural high defined by the gravity data northwest of the Picuris Mountains is appropriate for a rift structural boundary characterized as an anticlinal, oblique antithetic accommodation zone (terminology of Faulds and Varga, 1998) or an overlapping conjugate convergent transfer zone (terminology of Morley et al., 1990). Specifically, the structural high trends obliquely to the ends of two overlapping boundary fault zones in the respective basins: the Sangre de Cristo fault-Embudo fault on the east side of the San Luis Basin and north of the Picuris Mountains, and the Madera Cañon-Ortega fault zones that form the northwestern boundary of the Abiquiu embayment. We speculate that the boundary between the Española and San Luis Basins may have been characterized by such an accommodation or transfer zone prior to the development of a through-going Embudo fault system (Fig. 5). Although this model is consistent with the relative geometry of these structural features, there is no evidence that a structural high affected southward-flowing streams during deposition of the Chama-El Rito or Cieneguilla members from ca. 18-8 Ma. If this model has validity, the rate of uplift of the structural high must have been sufficiently low as not to noticeably influence stream flow or sedimentation during ca. 18-8 Ma. Another possibility is that the structural high was formed before or after ca. 18-8 Ma (for which there is no sedimentologic record exposed in the vicinity except on the western flanks of the Picuris Mountains). Sparse attitude data on the map of Kelley (1978) do not indicate that the Santa Fe Group on this structural high was significantly deformed during the latest Miocene or Pliocene. Future mapping efforts in the area around the structural high will further test this preliminary model.

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