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RIFT EXTENSION AND FAULT SLIP RATES IN THE SOUTHERN SAN LUIS BASIN, NEW MEXICO

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Abstract.—New estimates of a minimum, average slip rate on the Embudo fault zone (EFZ) and a minimum, average, east-west, extension rate across the southern San Luis Basin of the Rio Grande rift for the last 3 m.y. yield values of 102 m/m.y. and 83 m/m.y., respectively. The estimates are based on the vertical offset of ca. 3 Ma Servilleta Basalt flows across the EFZ southwest of the Village of Pilar, and an average slip vector for that segment of the fault zone. A previous estimate of 130 m/m.y. average, east-west Quaternary (last 1.8 Ma) extension rate across the southern San Luis Basin was based on the slip rates on the Sangre de Cristo and Los Cordovas faults. If these independent estimates of average east-west extension are approximately correct, then the rate of extension across the southern basin may have increased slightly since the late Pliocene. Several other published estimates of slip on the Sangre de Cristo fault can be used to approximate average extension rates as far back as about 28 Ma. Although some of these estimates are poorly constrained, they can be used to speculate that: 1) average San Luis Basin extension rates may have increased since rift inception; and 2) average extension rates may have been greater across the southern San Luis Basin than across the central part of the basin near the Colorado border. The first speculation is difficult to evaluate, as extension rates have certainly varied through time. The second speculation is consistent with published conclusions that the cumulative amount of extension increases northward among rift basins, and that rifting has progressed northward through Neogene time.

INTRODUCTION

The southern San Luis Basin displays some of the most impressive fault-related topographic relief in the Rio Grande rift. The Sangre de Cristo Mountains, including the highest point in New Mexico (Wheeler Peak, 13,161 ft), tower 6000 ft above the eastern rift valley (Fig. 1). The precipitous, 1000-ft-high Pilar cliffs, and the 10,000+ ft high ridges of the Picuris Mountains define the southern structural/topographic margin of the basin. The dramatic topographic relief between mountains and basin in the southeast San Luis Basin has been generated by Tertiary and Quaternary tectonic activity along the Sangre de Cristo and Embudo faults—activity that has continued into the late Quaternary. The geomorphology of the modern landscape represents the interactions of erosion and the slip rates on these two primary faults within the Rio Grande rift. Information on slip rates through time is essential for assessing seismic source characteristics and thus for evaluating seismic hazard and risks associated with large earthquakes. An understanding of the long-term variability of slip rates on rift-margin faults is also useful for interpreting the geologic evolution of the Rio Grande rift.

A number of workers have estimated rates of extension across the Rio Grande rift basins in northern New Mexico. The magnitude of Neogene (Miocene plus Pliocene) extension appears to decrease northward from at least 28% in the southern Albuquerque Basin, to at least 17% in the northern Albuquerque Basin, to only about 8 to 12% in the San Luis Basin (Kluth and Schaftenaar, 1994; Russell and Snelson, 1994; Chapin and Cather, 1994).

Most regional analyses of rift development utilize estimates of slip rates on the major rift-bounding normal faults. Slip rates have been determined in a variety of ways in northern New Mexico, including summing the cumulative slip on faults for a given period of time (Kelson and Olig, 1995; Menges, 1988, 1990), mapping the offset of a well-dated geologic marker bed (e.g., a distinct basalt flow; Miggins et al., 2002), or constructing restorable geologic cross sections from geophysical data (Kluth and Schaftenaar, 1994; Russell and Snelson, 1994).

Kelson and Olig (1995) evaluated the average late Quaternary rates of horizontal E-W extension in the Santo Domingo, Española, and San Luis Basins by summing slip rates of the primary faults in each basin. They concluded that each basin has experienced an average late Quaternary extension rate of about 100 m/m.y., and that no evidence exists for decreasing rates from south to north during the late Quaternary. They noted that the possible discrepancy between Neogene and Quaternary extension could be related to inaccuracies in estimates of fault slip rates, or, alternatively, their results could be correct if indeed rifting has progressed northward from basin-to-basin during the Tertiary.

Another technique for estimating rift extension utilizes dateable marker horizons, such as basalt flows, that are displaced across rift faults. If the age of the offset marker is known and the fault slip vector can be estimated for that period of time, then simple trigonometry yields an average extension rate. Two advantages of this technique are that slip rates are measured rather than estimated, and that the time frame is set by the age of the datum rather than estimating the length of time that faults have been active. A serious disadvantage is that a reasonable value of the plunge of the slip vector is essential for calculating net slip rates and rift extension rates. Such values are difficult to obtain without excellent fault exposures and fault kinematic data.

In this paper, we present geologic data collected along the Embudo fault zone (EFZ) in the southernmost San Luis Basin of the Rio Grande rift to estimate a long-term net extension rate for the basin. This estimate is based on well-constrained ages for displaced rock units and measurable displacements along the fault zone. This information provides an opportunity to extract the slip history of a rift accommodation zone and estimate an average rate of extension for the southern San Luis Basin for the last 3 m.y.

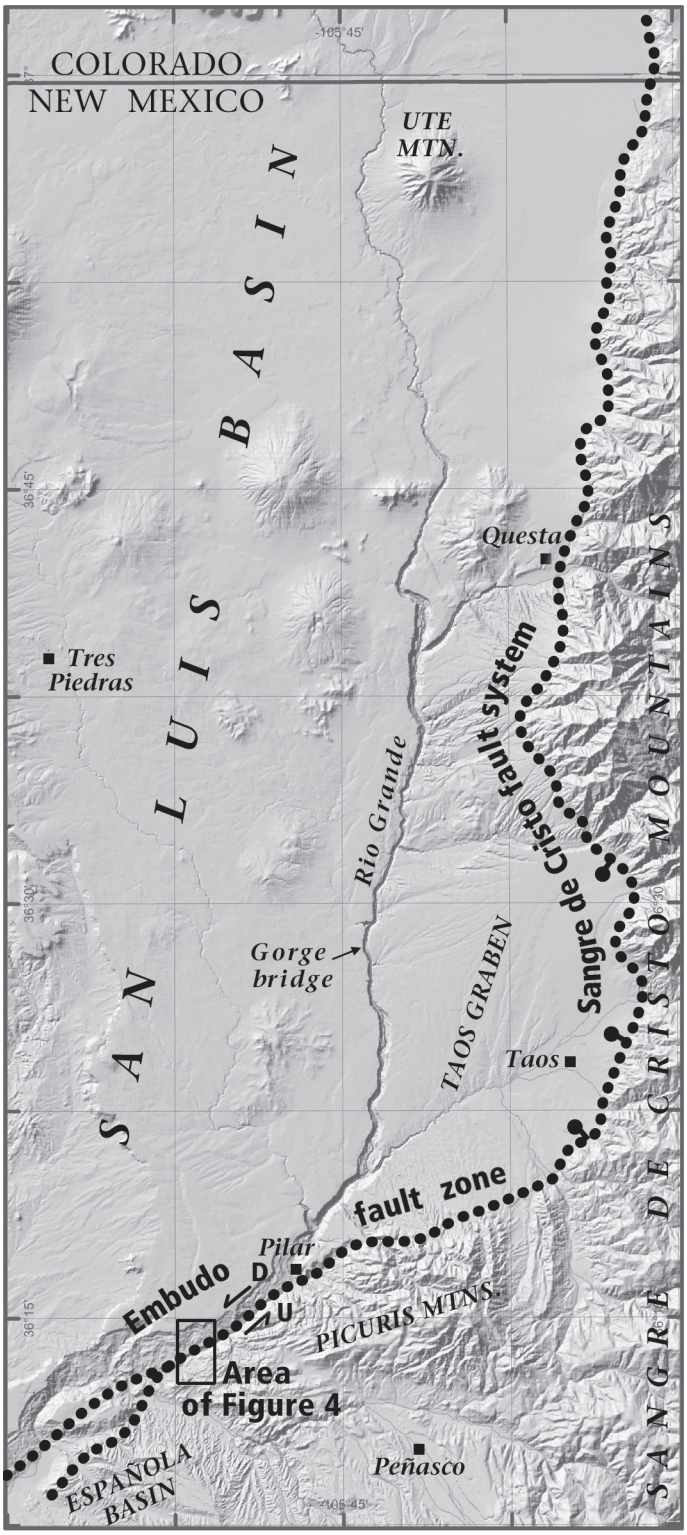


FIGURE 1. Index map of the southern San Luis Basin in New Mexico, showing the Embudo and Sangre de Cristo faults and the study area.

BACKGROUND

Regional Geologic Setting

The San Luis Basin is the major structural element of the northern Rio Grande rift. It is approximately 240 km long, and is bordered by the Sangre de Cristo Mountains on the east, and the Tusas and San Juan Mountains on the west (Fig. 1). In the Taos area, the rift consists of a 30-km-wide, asymmetrical, Basin and Range-style basin with the major flanking fault system along the eastern border (Sangre de Cristo fault zone).

The southern part of the basin is a physiographically and geologically unique terrain known as the Taos Plateau. The plateau is composed principally of Pliocene basaltic rocks that have been only mildly deformed by intrarift tectonism. Basalt flows dip gently to the east and south. The plateau surface shows only minor dissection, although the Rio Grande and its tributaries are confined to deep canyons cut into the volcanic plateau. Near the Gorge bridge, three well-defined flow packages are at least 200 m thick. Basalt flows pinch out eastward and southward along the edges of the basin. During Pliocene time, the Picuris Mountains restricted southerly flowing lavas, and the rim of the Rio Grande canyon downstream from Pilar displays only a single, 30-m-thick package of basalt flows (Koning et al., 2004 this volume). Only the youngest flows of the Servilleta Basalt traveled as far south as the Picuris Mountains near Pilar, based on the $^{40}Ar/^{39}Ar$ age of 2.81±0.13 for a basalt flow along the Rio Grande near the Village of Rinconada (Appelt, 1998).

Rift Extension

The eastern boundary of the San Luis Basin is the 160-km-long, north-striking Sangre de Cristo fault zone (Fig. 1), which has a total west-down throw of as much as 7 or 8 km (Lipman and Mehnert, 1979). A series of prominent, segmented fault scarps show evidence for significant Pleistocene and Pliocene normal offset (Machette and Personius, 1984; Machette et al., 1998; Bauer and Kelson, 2002; Kelson et al., 2004b, this volume). Individual normal faults typically dip steeply westward, with slickenlines plunging down dip.

Lipman and Mehnert (1979) placed the beginning of rifting at ca. 26 Ma in the San Luis Valley. Similarly, Brister and Gries (1994) concluded that rift structures evolved after about 27 Ma in the northern San Luis Basin. Most recently, Miggins et al. (2002) determined that the 24.96±0.11 Ma age of the Amalia Tuff, erupted from the Questa caldera, is a more accurate estimate of rift inception. However, there is evidence that the transition from Laramide-style contractional and dextral faulting to rift-style extensional faulting was transitional over much of the Tertiary; Erslev (1999) concluded that the latest phase of north-south, strike-slip faulting is post-25 Ma in central and northern New Mexico. Similarly, Bauer and Kelson (2004, this volume) showed that strike-slip faulting was occurring in the Taos area less than about 18 Ma.

The Embudo Fault Zone

The southeastern margin of the San Luis Basin is delineated by a major Cenozoic rift accommodation zone, called the Embudo fault zone (EFZ), which separates the east-tilted San Luis Basin from the west-tilted Española Basin and Picuris Mountains basement block. A number of different interpretations of the geometry, kinematics, and timing of the fault have been published (Miller et al., 1963; Kelley, 1978; Manley, 1978, 1979; Muehlberger, 1979; Aldrich, 1986). Chapin and Cather (1994) stated that the EFZ developed where the north-trending rift intersected the pre-existing Jemez lineament of probable Proterozoic ancestry. Our recent work documents late Quaternary northwest-down, left-oblique normal slip along multiple, near-vertical fault strands (Kelson et al., 2004a, this volume, 1996, 1997; Bauer and Kelson, 1997; Kelson and Bauer, 1998; Bauer and Kelson, 2000). Our mapping indicates that the fault zone is several kilometers wide, and extends between the basement rocks of the Picuris Mountains into the basin to the north (Fig. 1). In general, our mapping shows that the oldest rocks (Proterozoic) display the most intense brittle deformation, and that the EFZ exhibits evidence of late Pleistocene, and possibly Holocene, surface faulting. Clearly, the history of faulting along the EFZ is one of episodic reactivation.

Northeast of the Village of Pilar, the EFZ is a complex system of left-oblique, north-down, strike-slip fault strands that is over two kilometers wide. West of Pilar, along the Pilar cliffs, the surface exposure of the fault zone is limited to a wide zone of brittle deformation in the Proterozoic strata of the cliffs, as the principal fault strands are hidden beneath the Rio Grande and landslides mantling the valley walls (Fig. 2). Several slickenlined fault planes and other kinematic indicators (see Kelson et al., 2004a, this volume) exist along the EFZ in rocks that range in age from Proterozoic to Miocene. Nearly all such faults are near-vertical with slip lines that plunge shallowly (generally 20°±5°) to the southwest (Fig. 3). Lower-angle fault planes with only minor slip, such as the reverse faults described by Muehlberger (1979), exist locally, although we do not consider such faults to be representative of the kinematic behavior of the EFZ. Kelson et al. (2004a, this volume) present several lines of evidence that the fault is dominated by left-lateral slip, including fault kinematic indicators in roadcut and stream bank exposures, the presence of possible left-deflected drainages along the fault, changes in geomorphic expression coincident with changes in fault strike, and the presence of local reverse faulting within a small right-restraining stepover near Pilar Mesa. Reverse fault and other secondary structures, such as positive flower structures, are typical of complex strike-slip fault zones. For the purpose of this paper, we assume an average slip vector of 20^0 towards $S60^0W$ on the EFZ between the villages of Pilar and Rinconada. Clearly,

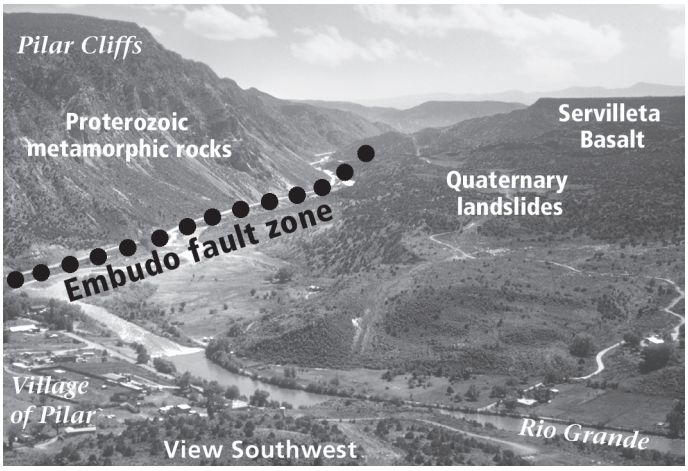


FIGURE 2. View southwest along the Embudo fault zone from Pilar mesa. The Pilar cliffs are composed of south-dipping Paleoproterozoic supracrustal rocks. The cliffs are separated from the Taos Plateau volcanic field by the Embudo fault zone, which is buried beneath the Rio Grande and surficial deposits flanking the Rio Grande valley.



FIGURE 3. View southeast across the Rio Grande to Proterozoic quartzite of the Pilar cliffs that is highly faulted and fractured along the Embudo fault zone. Kayaker for scale. The large, planar quartzite surface in photo center, above the scree slope, is a 10-m-long vertical fault plane that is dramatically striated. Slickenlines plunge approximately 20° westward. Such faults, with gently west-plunging slickenlines, document north-down, sinistral strike-slip movement on the Embudo fault zone.

however, the EFZ contains a variety of geometrical/kinematic domains along its northeastern extent (Kelson et al., 1997), and the characteristics of these domains also may have varied through time. The regional gravity map shows a strong gradient along the northern flank of the Picuris Mountains, indicating that the EFZ separates basement from basin fill over a narrow, sub-vertical deformational zone with a large amount of throw (T. Grauch, personal commun., 2004). Muehlberger (1979) estimated that throw on Proterozoic rocks across the fault is at least 3050 m (10,000 ft).

A BASALT PIERCING PLANE

Field Relations of Basalts

Along the northwestern flank of the Picuris Mountains, between the villages of Pilar and Rinconada, the EFZ is topographically distinguished by precipitous cliffs that parallel the Rio Grande and NM-68, juxtaposing Proterozoic rocks against Pliocene rocks (Fig. 2). North of the Rio Grande, approximately 30 m (100 ft) of Servilleta Basalt caps the Taos Plateau and is well exposed along the rim of the Rio Grande gorge (Fig. 4). The basalt overlies sandstone and conglomerate of the Chama-El Rito member of the Tesuque Formation, which contains clasts of Tertiary volcanic rocks (including the 25 Ma Amalia Tuff) and pebbles of Paleoproterozoic quartzite. Between these basalt outcrops along the gorge rim and the EFZ, late Quaternary deposits (i.e., landslides, alluvium, colluvium) mantle the valley walls and floor, and conceal bedrock and the EFZ. However, in the Pilar cliffs on the southeastern side of the EFZ, Bauer and Helper (1994) identified a small outcrop of Servilleta Basalt (in S 13 and 14, T23N, R10E; see Fig. 4) at an elevation of 7094 ft. The basalt is an erosional remnant of Servilleta Basalt that flowed across the EFZ and onlapped the Proterozoic and Miocene rocks of the Picuris Mountains. Subsequently, the Rio Grande incised through the basalt, stranding the basalt remnant 366 m (1200 ft) above the modern river. This is the only outcrop exposure of Servilleta Basalt known to exist on the south side of the EFZ, and therefore provides the sole field datum for estimating the post-Servilleta Basalt vertical component of slip (throw) across the EFZ.

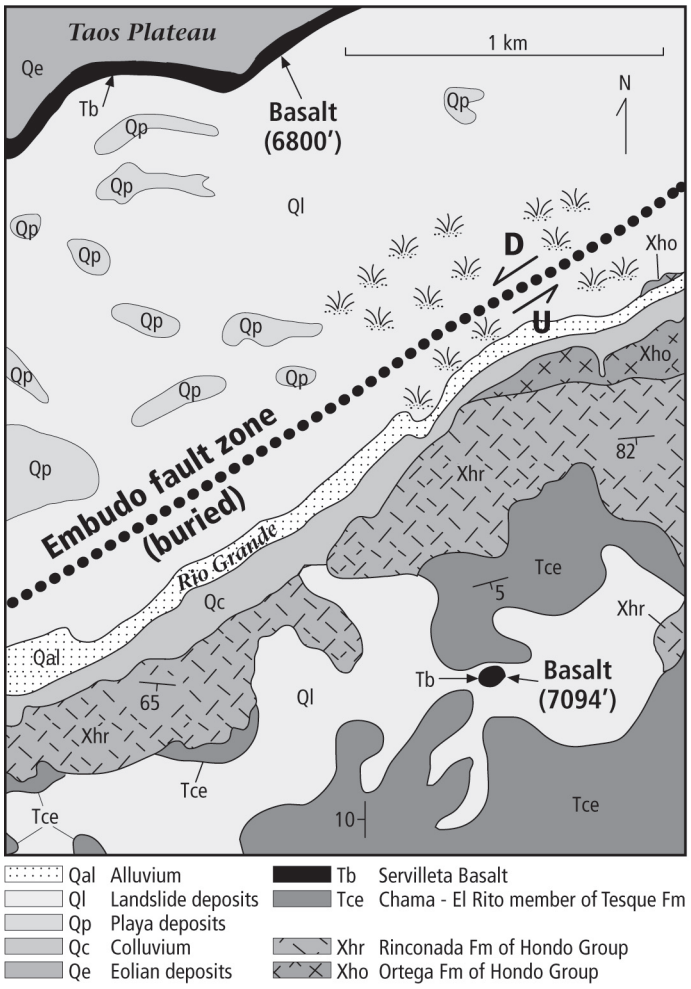


FIGURE 4. Geologic map of the northwestern Trampas quadrangle, showing the Servilleta Basalt exposures that are offset vertically by the Embudo fault zone. Map has been generalized from Bauer and Helper (1994).

The 4-m-thick outcrop consists of a single, flat-lying flow of vesicular to massive tholeiitic basalt, indistinguishable in the field from outcrops of Servilleta Basalt north of the river. This basalt flow also overlies the Chama-El Rito member of the Tesuque Formation, as on the north side of the Rio Grande. Between the base of the basalt flow and the Tesuque Formation is a thin, gray gravel composed mainly of large (up to 50 cm) rounded quartzite boulders. The origin of the gravel is unknown, but similar gravels unconformably cap high-level erosional surfaces elsewhere in the Picuris Mountains. No gravel clasts are present on top of the basalt flow.

Basalt Geochronology

We sampled the base and top of the basalt remnant south of the river (samples T-7.31.02-3 and T-7.31.02-2, respectively) for $^{40}Ar/^{39}Ar$ geochronology, and submitted the samples to the New Mexico Geochronology Research Laboratory at the New Mexico Bureau of Geology and Mineral Resources. Both groundmass analyses yielded fairly well-constrained ages of 3.41±0.50 Ma for the base, and 3.06±0.33 Ma for the top of the flow package (L. Peters, New Mexico Geochronological Research Laboratory Internal Report #NMGRL-IR-344). The low radiogenic yields of both samples decreases the confidence in the precision of these eruptive ages. Therefore, for the purposes of this study, we assign the top of the lone basalt exposure (7094 ft elevation) an approximate age of 3 Ma.

Fortuitously, the rim basalts north of the river (S11, T23N, R10E) were sampled and dated by Appelt (1998) in the New Mexico Geochronology Research Laboratory as part of his study of the Taos Plateau volcanic field. He sampled basalt from near the base of the rim exposure (sample RA-061; 2.81±0.13 Ma isochron age; moderate confidence of age) and near the top (sample RA-060; 3.39±0.32 Ma isochron age; low confidence of age). Obviously, the stratigraphically lower basalt is not younger than an overlying flow, and so we discount the low-confidence age of the top of the outcrop. Therefore, for the purposes of this study,

we assign the base of the rim exposure (6800 ft elevation) an approximate age of 2.8 Ma. Furthermore, we surmise that 3 Ma basalt, equivalent to the basalt remnant south of the river, is probably buried by landslide and talus material below the base of the rim exposure, perhaps at an elevation of approximately 6750 ft. If this is correct, then the basalt flow is a 3 m.y. timeline that is offset approximately 105 m (344 ft) by the EFZ.

ESTIMATES OF SLIP RATES AND EXTENSION RATE

Assuming an average slip vector of 20^0 on a vertical, sinistral, north-down fault, we calculate the average vertical and horizontal components (throw and heave) of slip, and the net slip across this segment of the EFZ during the past 3 m.y. (Fig. 5):

Average vertical component of slip on EFZ for past 3 m.y. (throw or uplift rate of Picuris Mountains relative to San Luis Basin)

$$= 105 \text{ m} / 3 \text{ m.y.} = 35 \text{ m/m.y.}$$

Average horizontal component of slip on EFZ for last 3 m.y. (equivalent to the map separation of Servilleta Basalt across the EFZ)

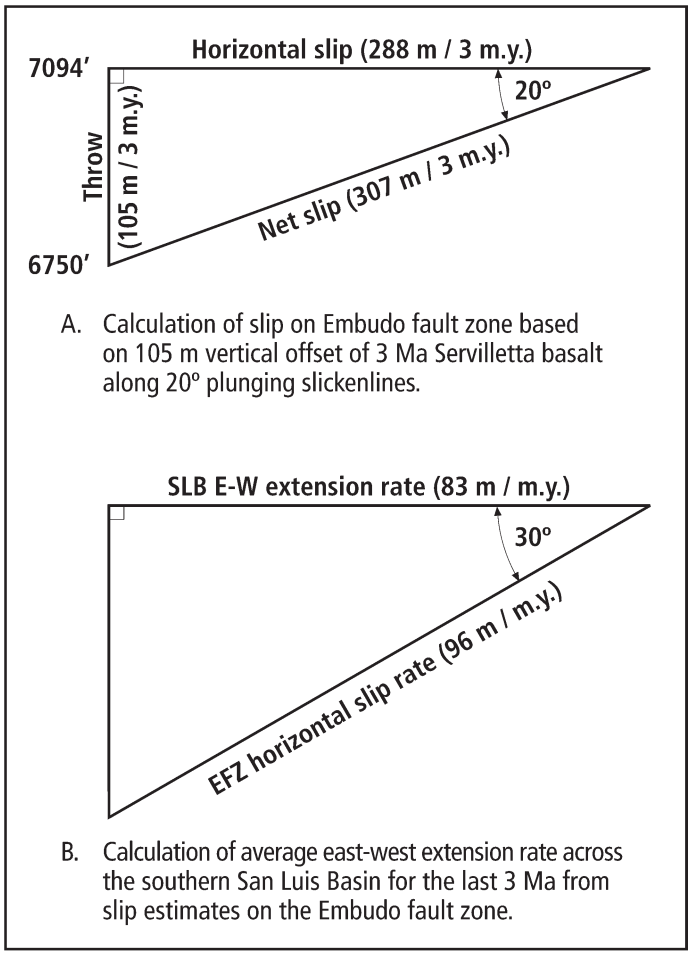


FIGURE 5. Schematic showing the vectors used to calculate slip on the Embudo fault zone (A) and east-west extension on the southern San Luis Basin (B).

$$= 105 \text{ m} / \tan 20^0 / 3 \text{ m.y.} = 288 \text{ m} / 3 \text{ m.y.} = 96 \text{ m/m.y.}$$

Net average slip rate on EFZ for last 3 m.y.

$$= 105 \text{ m} / \sin 20^0 / 3 \text{ m.y.} = 307 \text{ m} / 3 \text{ m.y.} = 102 \text{ m/m.y.}$$

Using the EFZ horizontal slip rate of 96 m/m.y., and the $N60^0E$ strike of the fault, and assuming that these values are representative of the entire northeast segment of the EFZ, we calculate an east-west extension rate across the southern San Luis Basin (Fig. 5):

Average east-west extension rate across the southern San Luis Basin

$$= (96 \text{ m/m.y.}) (\cos 30^0) = 83 \text{ m/m.y.}$$

DISCUSSION AND SPECULATION

Slip Rates on the Embudo Fault Zone

Our 3 m.y. average slip rate of 102 m/m.y. is a minimum estimate, as it does not account for any strain that was partitioned south of the basalt remnant on the southeastern side of the Rio Grande. For example, slip may have occurred on northeast-striking, sinistral, north-down, en echelon faults located 2 km southeast of the basalt remnant (Bauer and Helper, 1994). For that fault set, Hall (1988) calculated 840 m (2756 ft) of net slip, 539 m (1768 ft) of vertical slip, 643 m (2110 ft) of horizontal slip (post-Proterozoic), and concluded that these faults are part of the EFZ. The amount of slip on these faults since 3 Ma is unknown, although one of the faults appears to offset part of a Pliocene(?)/Pleistocene gravel in the Copper Hill area (Bauer and Helper, 1994).

The above calculations are sensitive to the plunge value assigned to the slip vector on the EFZ. For example, increasing the plunge from 20^0 to 25^0 changes the EFZ slip rate from 102 m/m.y. to 83 m/m.y., and the extension rate from 83 m/m.y. to 65 m/m.y. Decreasing the plunge to 15^0 results in a slip rate of 135 m/m.y. and an extension rate of 113 m/m.y. However, based on field measurements of slickenlines along the Pilar cliffs, we believe that 20^0 is a reasonable plunge estimate.

Recent work by Koning et al. (2004, this volume) along the EFZ to the southwest yields another minimum estimate of slip. Near Velarde, slip is partitioned onto four major faults whose cumulative displacement yields a minimum vertical slip rate of 45 to 62 m/m.y. for the past 7.7 to 8.4 Ma. He noted that this vertical slip rate is less than that on the Pajarito fault, (70 to 120 m/m.y.), but suspects that the lateral component of slip is being converted to vertical slip to the south, as the Pajarito fault is mostly a normal fault.

Regional gravity data suggest that Proterozoic basement is buried at a depth of approximately 2134 m (7000 ft) just north of Pilar (Cordell, 1978). Using these data, Muehlberger (1979) inferred that the structural relief across the EFZ is at least 3000 m (10,000 ft), because the Proterozoic peaks of the Picuris Mountains are over 3000 m (10,000 ft) above sea level. If so, and assuming an age of 30 Ma for initiation of the EFZ, the average rate of vertical displacement is 100 m/m.y. for the life of the accommo-

dation zone. In contrast, for the last 3 Ma, we estimate a vertical component of slip for the Picuris Mountains of only 35 m/m.y. Consequently, either: 1) the estimate for the depth to Proterozoic basement is too high; 2) our estimate of vertical separation is too low; 3) the Embudo fault has been active for longer than 30 Ma; 4) the uplift rate of the Picuris Mountains was considerably greater in the past; or 5) some combination of the above. It should be noted that Kelley (2004) deduced that some of the elevation of the Picuris Mountains was probably attained in the Laramide, although it is not known whether that included differential offset between the Picuris Mountains and the San Luis Basin (along the EFZ). However, assuming that the above estimates are reasonable, and that the EFZ is predominantly a Neogene feature, the pre-3 Ma vertical separation rates on the EFZ probably were much greater than our post-3 Ma rate of 35 m/m.y.

Extension rates across the San Luis Basin

Summary of existing data on extension rates

In this paper, we translate the estimated net slip rate on the EFZ into an east-west rate of extension across the San Luis Basin, and compare this rate with extension rates derived primarily from the rift-margin Sangre de Cristo fault. Because the San Luis Basin is east-tilted with most of the brittle extensional strain concentrated along the 60˚ west-dipping Sangre de Cristo fault (Kluth and Schaftenaar, 1994), estimates of net slip on this fault (Menges, 1988, 1990; Kelson and Olig, 1995) and net displacement (exhumation or uplift) across the fault (Miggins et al., 2002 and references therein) can be used to estimate east-west extension rates across the rift. Figure 6 summarizes the published

Fault System	Area	Reference	Data Source	Reported Components of Slip Rates (m/m.y.)			Time Period (m.y. to present)		San Luis Basin Average E-W Extension Rate (m/m.y.)		Notes
				Net	Vertical (Exhumation Rate)	Horizontal	Reported	Assigned	Reported by Author	Our Estimate	
Embudo Fault zone	SW of Pilar	This paper	Offset 3 Ma Servilleta basalt.	83-135	35	75-130	3		65-113 (median 83)		Range in slip rates based on estimated EFZ slip vector range from 15-20 degrees plunge.
	Near Velarde	Koning, 2004	Summed vertical offset across 4 fault strands.		45-62		7.7 to 8.4		na	na	Data are not suitable for extension estimate.
Sangre de Cristo fault	Taos Range	This paper	Vertical separation between Carson Conglomerate of Petersen (1969) and Picuris Fm of Bauer and Kelson (2004 this volume)		31-150		28		18-87 (median 53)		The range of slip rate values reflects our uncertainty in depth-to-Picuris Fm estimates in the Taos graben.
		Menges, 1990	Estimates of young slip on Sangre de Cristo fault scarps. Displacement rate.		30-60		Middle(?) to late Pleistocene	0.4	none reported	2.8-5.6	Menges states that slip rates from the scarps are difficult to estimate. We believe that these extension rates are geologically unreasonable.
			Estimates of long-term slip on Sangre de Cristo fault scarps. Slip rate.		115-261		Post-Pliocene	4.3	none reported	67-151 (median 109)	Machette et al. (1998) assigned a post-Pliocene age of 4 Ma for Menges data.
		Kelson and Olig, 1995	Summed estimates of fault slip on Sangre de Cristo plus Los Cordovas fault systems.		220		Quaternary	ca. 1.8	ca. 130		Assuming 60 degree west fault dip. Time period is approximate.
	Colorado border area	Miggins et al., 2002	Offset volcanic rocks at San Luis Hills and Culebra Range.		58		25		none reported	33	Vertical slip rate is reported as an exhumation rate.
			Offset 4.7 Ma Servilleta basalt at San Pedro mesa and along Rio Grande.		87		4.7		none reported	50	Earlier estimates of slip in this area were made by Lipman and Mehnert (1979) and Personius and Machette (1984). Exhumation rate.
		Lipman and Mehnert, 1979	Approximate 500 m offset of Servilleta basalt.		167		3		none reported	96	Time period is approximate.

FIGURE 6. Summary of published estimates of slip and extension on the Embudo and Sangre de Cristo fault systems. If the authors reported net slip rates or vertical slip rates, we translated them into average extension rates using the reported or estimated time periods. Our calculations of extension rates assume that all extension was by brittle deformation that is orthogonal to the north-striking, 60° west-dipping Sangre de Cristo fault.

A.

Area	Reference	Time Period (m.y. to present)	San Luis Basin Average E-W Extension Rate (m/m.y.)
Embudo fault	Bauer and Kelson, 2004	3	83
Taos Range	Bauer and Kelson, 2004	28	53
Taos Range	Menges, 1990	4.3	109
Taos Range	Kelson and Olig, 1995	1.8	130
CO/NM border area	Miggins et al., 2002	25	33
CO/NM border area	Miggins et al., 2002	4.7	50
CO/NM border area	Lipman and Mehnert, 1979	3	96

B.

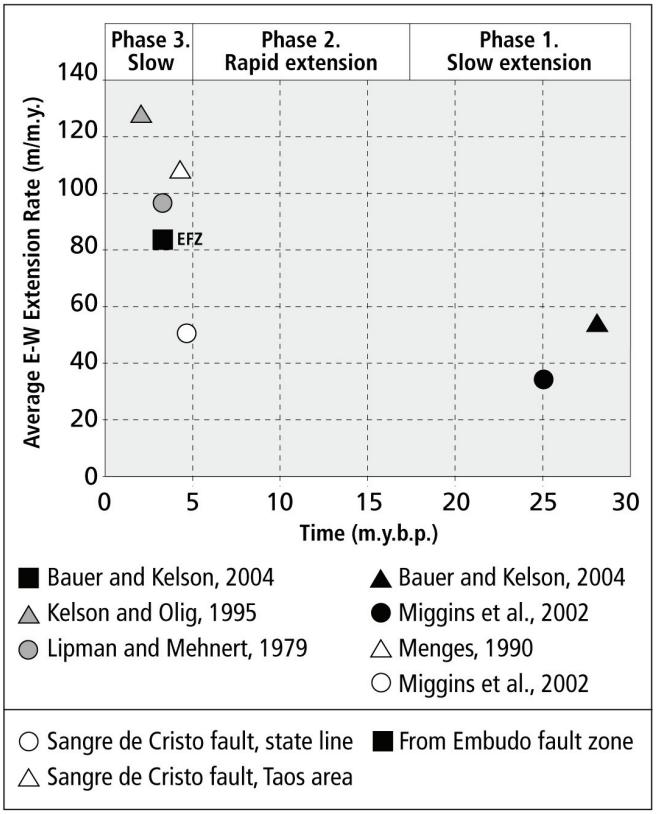


FIGURE 7. Summary chart (A) of the seven best-constrained estimates of average, east-west extension rates for the central and southern San Luis Basin. Graph (B) of average extension rates from data in 7A, coded according to geographic area and fault system. Two speculative trends can be seen on the graph. Average rates of extension appear to have increased during the last 28 Ma, and average rates have been higher in the southern part of the basin than the central part (triangles versus circles).

work on slip and extension in the southern half of the San Luis Basin. In a number of cases, previous workers reported net slip or slip rates or exhumation rates, without estimating extension rates. Where we could reasonably ascertain the time periods involved, we calculated extension rates or ranges of rates. In all cases, we assumed that all extension was by brittle deformation that is orthogonal to the north-striking, 60° west-dipping Sangre de Cristo fault. We consider only well-constrained estimates of extension that are based on a well-dated datum that is offset by the entire suite of faults along the eastern rift boundary, as summarized below (Figs. 6 and 7A).

Based on offset of middle(?) to late Pleistocene surfaces and scarp morphology in the Taos area, Menges (1988, 1990) inferred a late Quaternary displacement rate of approximately 30-60 m/m.y. for the Sangre de Cristo fault (Fig. 6). However, he stated that slip rates from Sangre de Cristo scarps are difficult to estimate. We suspect that the resulting extension rates of 2.8-5.6 m/m.y. for the last 0.4 ka are geologically unreasonable, and we have not included them in Figure 7. Menges (1988, 1990) also estimated post-Pliocene slip rates of 115-261 m/m.y. on the Sangre de Cristo fault in the Taos area, rates that are two to eight times greater than his late Quaternary rates. He noted that the differences could be due to sampling a complex seismic system, or it could actually reflect a waning of fault activity in the late Quaternary.

Kelson and Olig (1995) used an averaged vertical slip rate on the Sangre de Cristo fault of 200 m/m.y. (from Menges, 1988, 1990), plus an estimated average long-term vertical slip rate of 20 m/m.y. for the Los Cordovas faults, to determine a net east-west Quaternary (post-1.8 Ma) extension rate of 130 m/m.y. for the San Luis Basin at the latitude of Taos (Fig. 6). They acknowledged that their calculation is strictly a first approximation.

Personius and Machette (1984) originally reported minimum average rates of uplift of 60-120 m/m.y. for basalts displaced by the Sangre de Cristo fault for the past 3-4 Ma near the Colorado border. Recently, Miggins et al. (2002) refined that work, and reported exhumation rates of 58 m/m.y. for the last 25 Ma, and 87 m/m.y. for the last 4.7 Ma. We use their exhumation rates to calculate extension rates across the central San Luis Basin. The exhumation rate of 58 m/m.y. translates to a horizontal east-west extension rate of 33 m/m.y. for the last 25 Ma. The exhumation rate of 87 m/m.y. translates to a horizontal east-west extension rate of 50 m/m.y. for the last 4.7 Ma (Fig. 6).

A second long-term exhumation rate can be calculated based on the offset of the pre- to early-rift Picuris Formation, at the latitude of Taos. Bauer et al. (1999) and Bauer and Kelson (2004) presented an east-west structural cross section through the southern San Luis Basin that depicts the geometry of the Taos graben based on the geophysical depth-to-basement estimates of Keller et al. (1984). They also describe the Picuris Formation as a sec-

tion of volcaniclastic sandstones and conglomerates dated at ca. 28 Ma that contain only clasts of Tertiary volcanic rocks, and concluded that such rocks exist at depth in the Taos graben. Very similar rocks (named the Carson Conglomerate) were described by Petersen (1969) at an elevation of about 2750 m (9000 ft) on the crest of the mountain range east of Taos. We propose that the Carson Conglomerate is equivalent to the Picuris Formation, and we calculate that the unit is offset across the rift boundary by 900-4000 m (ca. 3000-13,000 ft), depending on their depth in the Taos graben. This yields an average, east-west, extension rate of 18-87 m/m.y. (median is 53 m/m.y.) for the last 28 Ma (Fig. 6).

We have chosen not to include the apatite-fission track exhumation/uplift rates that have been published for the Taos Range (Kelley and Duncan, 1984; Kelley et al., 1992: Pazzaglia and Kelley, 1998) due to the uncertainties related to assigning time values to those rates. The AFT data may record cooling of the Latir volcanic field in addition to cooling associated with exhumation.

Discussion of extension rates

Chapin and Cather (1994) envisioned a broad, three-phase history of rifting in the northern rift basins, consisting of: 1) late Oligocene to early Miocene slow extension with modest strain rates; 2) middle to late Miocene rapid extension; and 3) Pliocene to Recent slow extension. Those phases of rifting are shown on Figure 7B, a graph of the most robust estimates of San Luis Basin extension rates. The seven rates fall into two time domains, earliest rift (>25 Ma) and Pliocene (<5 Ma). This distribution is due to the relative ease of dating and correlating the volcanic rocks of the San Juan/Latir volcanic field and the Pliocene Servilleta Basalt. While keeping in mind the general lack of precision inherent in estimating extension rates in structurally complex basins, there are two notable trends. First, the two average early rift rates are generally lower than the five average Pliocene rates. Second, the two northern rates from Miggins et al. (2002) are lower than their southern old and young counterparts. Miggins et al. (2002) noted that in the central San Luis Basin the average Pliocene/Quaternary exhumation rate is greater than the average rate for the entire 25 m.y. history of rifting.

Although possible trends suggested by Figure 7B are intriguing, we acknowledge that the amount of uncertainty in the estimates of slip rates and extension rates could be large. We note that, if early rates were very low (e.g., less than 20 m/m.y.), then the extension rates of the two long-term points at 25 Ma and 28 Ma will have been skewed downward, representing the effect of averaging slow phase one extension with fast phase two extension, plus moderate phase three extension.

If the five Pliocene rates are broadly accurate, and Chapin and Cather's (1994) model of the three phases is correct, then we can infer that rates of extension during phase two (ca. 18-5 Ma) were probably considerably higher than the mean of the Pliocene rates, which is approximately 90-100 m/m.y. of east-west extension. In a qualitative way, this is supported by the Chapin and Cather (1994) interpretation that the most rapid phase of regional extension was middle to late Miocene. Similarly, Miggins et al. (2002) concluded that the central San Luis Basin experienced a major episode of uplift and block faulting during the middle Miocene (around 15 Ma).

If extension rates have been faster in the southern San Luis Basin than the central San Luis Basin, this supports the general perception that rifting has progressed northward through Tertiary time (Chapin and Cather, 1994). Such a trend is also consistent with the observation that net extension decreases northward from rift basin to rift basin (Chapin and Cather, 1994).

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REFERENCES

Aldrich, M. J., Jr., 1986, Tectonics of the Jemez lineament in the Jemez Mountains and Rio Grande rift: Journal of Geophysical Research, v. 91, no. B2, p. 1753-1762.

Appelt, R. M., 1998, 40Ar/39Ar Geochronology and volcanic evolution of the Taos Plateau Volcanic field, northern New Mexico and southern Colorado [MS thesis]: Socorro, New Mexico Institute of Mining and Technology, 207 p.

Bauer, P. W. and Helper, M., 1994, Geology of the Trampas 7.5-minute quadrangle, Taos County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map GM-71, scale 1:24,000.

Bauer, P. W. and Kelson, K. I., 1997, Geology of the Taos SW 7.5-minute quadrangle, Taos County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map OF-GM 12, scale 1:24,000.

Bauer, P. W., Kelson, K. I., Lyman, J., Heynekamp, M. R., and McCraw, D. J., 2000, Geology of the Ranchos de Taos 7.5-minute quadrangle, Taos County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map OF-GM 33, scale 1:24,000.

Bauer, P. W. and Kelson, K. I., 2001, Geology of the Taos 7.5-minute quadrangle, Taos County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-File Geologic Map OF-GM 43, scale 1:24,000.

Bauer P. W. and Kelson, K. I., 2004, Cenozoic structural development of the Taos area, New Mexico: New Mexico Geological Society, 55th Field Conference, Guidebook, p. 129-146.

Bauer, P. W., Johnson, P. S., and Kelson, K. I., 1999, Geology and hydrogeology of the southern Taos Valley, Taos County, New Mexico: Final Technical Report for the New Mexico Office of the State Engineer, January 1999, 56 p.

Brister, B. S. and Gries, R. R., 1994, Tertiary stratigraphy and tectonic development of the Alamosa basin (northern San Luis Basin), Rio Grande rift, south-central Colorado: in Keller, G. R. and Cather, S. M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Geological Society of America, Special Paper 291, p. 39-58.

Chapin, C. E. and Cather, S. M., 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift, *in* Keller, G. R. and Cather, S. M., eds.,

Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting, Geological Society of America, Special Paper 291, p. 5-25.

Cordell, L., 1978, Regional geophysical setting of the Rio Grande rift: Geological Society of America Bulletin 89, p. 1073-1090.

Erslev, E. A., 1999, Multistage, multidirectional horizontal compression during Laramide and mid-Tertiary deformation east of the Rio Grande rift, north-central New Mexico: New Mexico Geological Society, 50th Field Conference, Guidebook, p. 22-23.

Faulds, J. E. and Varga, R. J., 1998, The role of accommodation zones and transfer zones in the regional segmentation of extended terranes: *in* Faulds, J. E. and Stewart, J. H., eds., Accommodation Zones and Transfer Zones: The Regional Segmentation of the Basin and Range Province: Geological Society of America, Special Paper 323, p. 1-45.

Hall, M. S., 1988, Oblique slip faults in the northwestern Picuris Mountains of New Mexico—An expansion of the Embudo transform zone [M.S. thesis]: Austin, University of Texas, 69 p.

Kelley, V. C., 1978, Geology of the Española Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 48, scale 1:125,000.

Kelley, S. A. and Duncan, I. J., 1984, Tectonic history of the northern Rio Grande rift derived from apatite fission-track geochronology: New Mexico Geological Society, 35st Field Conference, Guidebook, p. 67-73.

Kelley, S. A., Chapin, C. E., and Corrigan, J., 1992, Late Mesozoic to Cenozoic cooling histories of the flanks of the northern and central Rio Grande rift—Colorado and New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 145, 39 p.

Kelley, S.A., 2004, Laramide to post-Laramide cooling history of the Miranda graben: New Mexico Geological Society, 55th Field Conference, Guidebook, p. 61-62.

Keller, G.R., Cordell, L., Davis, G.H., Peeples, W.J. and White, G., 1984, A geophysical study of the San Luis Basin: New Mexico Geological Society, 35th Field Conference, Guidebook, p. 51-58.

Kelson, K. I., Unruh, J. R. and Bott, J. D. J., 1996, Evidence for active rift extension along the Embudo fault, Rio Grande Rift, northern New Mexico (abs.): Geological Society of America, Abstracts with Program, v. 28, no. 7, p. A377.

Kelson, K. I., Unruh, J. R., and Bott, J. D. J., 1997, Field Characterization, Kinematic Analysis, and initial Paleoseismic assessment of the Embudo fault, northern New Mexico: Final Technical Report to the U.S. Geological Survey from William Lettis and Associates, Inc., 48 p.

Kelson, K. I. and Bauer, P. W., 1998, Geology of the Carson 7.5-minute quadrangle, Taos County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Geologic Map OF GM-22, scale 1:24,000.

Kelson, K. I. and Olig, S. S., 1995, Estimated rates of Quaternary crustal extension in the Rio Grande rift, northern New Mexico: New Mexico Geological Society, 46th Field Conference, Guidebook, p. 9-12.

Kelson, K. I., Bauer, P.W., Unruh, J.R., and Bott, J.D.J., 2004a, Late Quaternary characteristics of the northern Embudo fault, Taos County, New Mexico: New Mexico Geological Society, 55th Field Conference, Guidebook, p. 147-157.

Kelson, K. I., Bauer, P. W., Connell, S. D., Love, D., Rawling, G., and Mansell, M., 2004b, Initial paleoseismic and hydrogeologic assessment of the southern Sangre de Cristo fault at the Taos Pueblo site, Taos County, New Mexico: New Mexico Geological Society, 55th Field Conference, Guidebook, p. 289-299.

Koning, D. J., Ferguson, J., Jackson-Paul, P., and Baldridge, S., 2004, The geologic structure of the northern Española Basin and the southern Embudo fault system: New Mexico Geological Society, 55th Field Conference, Guidebook, p. 158-171.

Kluth, C. F. and Schaftenaar, C. H., 1994, Depth and geometry of the northern Rio Grande rift in the San Luis Basin, south-central Colorado: *in* Keller, G.R. and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Geological Society of America, Special Paper 291, p. 27-37.

Lipman, P. W. and Mehnert, H. H., 1979, The Taos Plateau volcanic field, northern Rio Grande rift, New Mexico: *in* Riecker, R. C., ed., Rio Grande rift – Tectonics and magmatism: American Geophysical Union, Washington D.C., p. 289-311.

Machette, M. N. and Personius, S. F., 1984, Quaternary and Pliocene faults in the eastern part of the Aztec quadrangle and the western part of the Raton quadrangle, northern New Mexico: U.S. Geological Survey, Map MF-1465-B, scale 1:250,000.

Machette, M. N., Personius, S. F., Kelson, K. I., Haller, K. M., and Dart, R. L., 1998, Map and data for Quaternary faults in New Mexico: U.S. Geological Survey, Open-File Report 98-521, 443 p.

Manley, K., 1978, Cenozoic geology of the Española basin: New Mexico Bureau of Mines and Mineral Resources, Circular 163, p. 201-210.

Manley, K., 1979, Stratigraphy and structure of the Española basin, Rio Grande rift, New Mexico, *in* Riecker, R. E., ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union, Washington D.C., p. 71-86.

Menges, C. M., 1988, The tectonic geomorphology of mountain front landforms in the northern Rio Grande rift, New Mexico [Ph.D. dissertation]: Albuquerque, University of New Mexico, 140 p.

Menges, C. M., 1990, Late Cenozoic rift tectonics and mountain-front landforms of the Sangre de Cristo Mountains near Taos, northern New Mexico: New Mexico Geological Society, 41st Field Conference, Guidebook, p. 113–122.

Miggins, D. P., Thompson, R. A., Pillmore, C. L., Snee, L. W., Stern, C. R., 2002, Extension and uplift of the northern Rio Grande rift: Evidence from 40Ar/39Ar geochronology from the Sangre de Cristo Mountains, south-central Colorado and northern New Mexico: Geological Society of America, Special Paper 362, p. 49-66.

Miller, J. P., Montgomery, A., and Sutherland, P. K., 1963, Geology of part of the Sangre de Cristo Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 11, 106 p.

Muehlberger, W. R., 1979, The Embudo fault between Pilar and Arroyo Hondo, New Mexico: an active intracontinental transform fault: New Mexico Geological Society, 30th Field Conference, Guidebook, p. 77-82.

Pazzaglia, F. J. and Kelley, S. A., 1998, Large-scale geomorphology and fission-track thermochronology in topographic and exhumation reconstructions of the southern Rocky Mountains: Rocky Mountain Geology, v. 33, no. 2, p. 229-257.

Personius, S. F. and Machette, M. N., 1984, Quaternary faulting in the Taos Plateau region, northern New Mexico: New Mexico Geological Society, 35th Field Conference, Guidebook, p. 83-90.

Petersen, J. W., 1969, Geology of the Tienditas Creek-La Junta Canyon area, Taos and Colfax Counties, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 82 p.

Russell, L. R. and Snelson, S., 1994, Structure and tectonics of the Albuquerque Basin segment of the Rio Grande rift: insights from reflection seismic data: Geological Society of America, Special Paper 291, p. 83-112.

PLATE 1: LANDSAT ETM+ IMAGE – SOUTHERN SAN LUIS BASIN

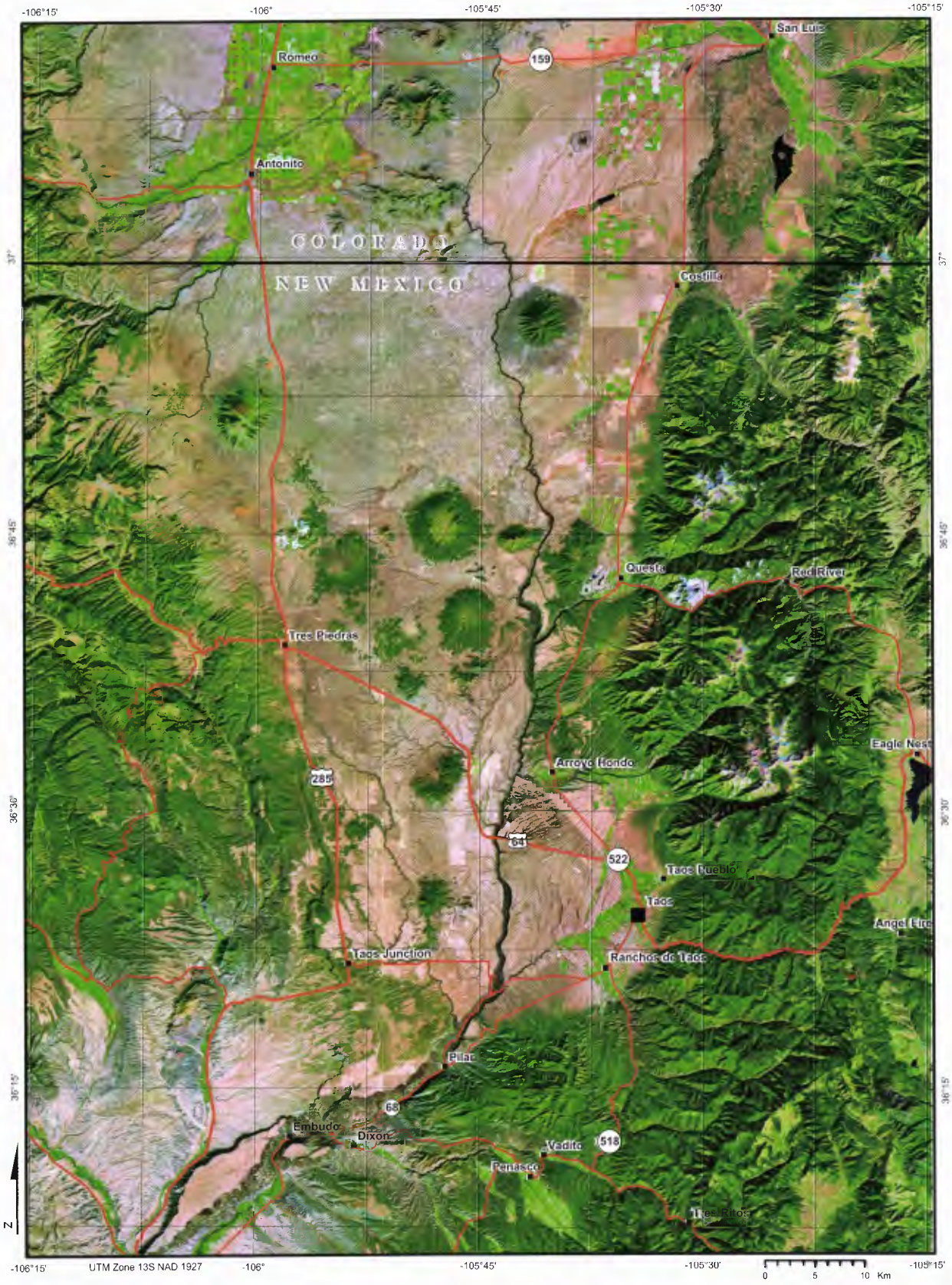


PLATE 1. LANDSAT 7 ETM+ image of the southern San Luis Basin from two scenes acquired 14-Oct-1999. Image processing by Sawyer et al. (2004 – see roadlog references). Bands 7-4-2 (RGB) panchromatically sharpened with 15-meter Band 8 data.

PLATE 2: GENERALIZED GEOLOGIC MAP – SOUTHERN SAN LUIS BASIN

COMPILED BY: ADAM S. READ, REN A. THOMPSON, AND MARK M. MANSELL

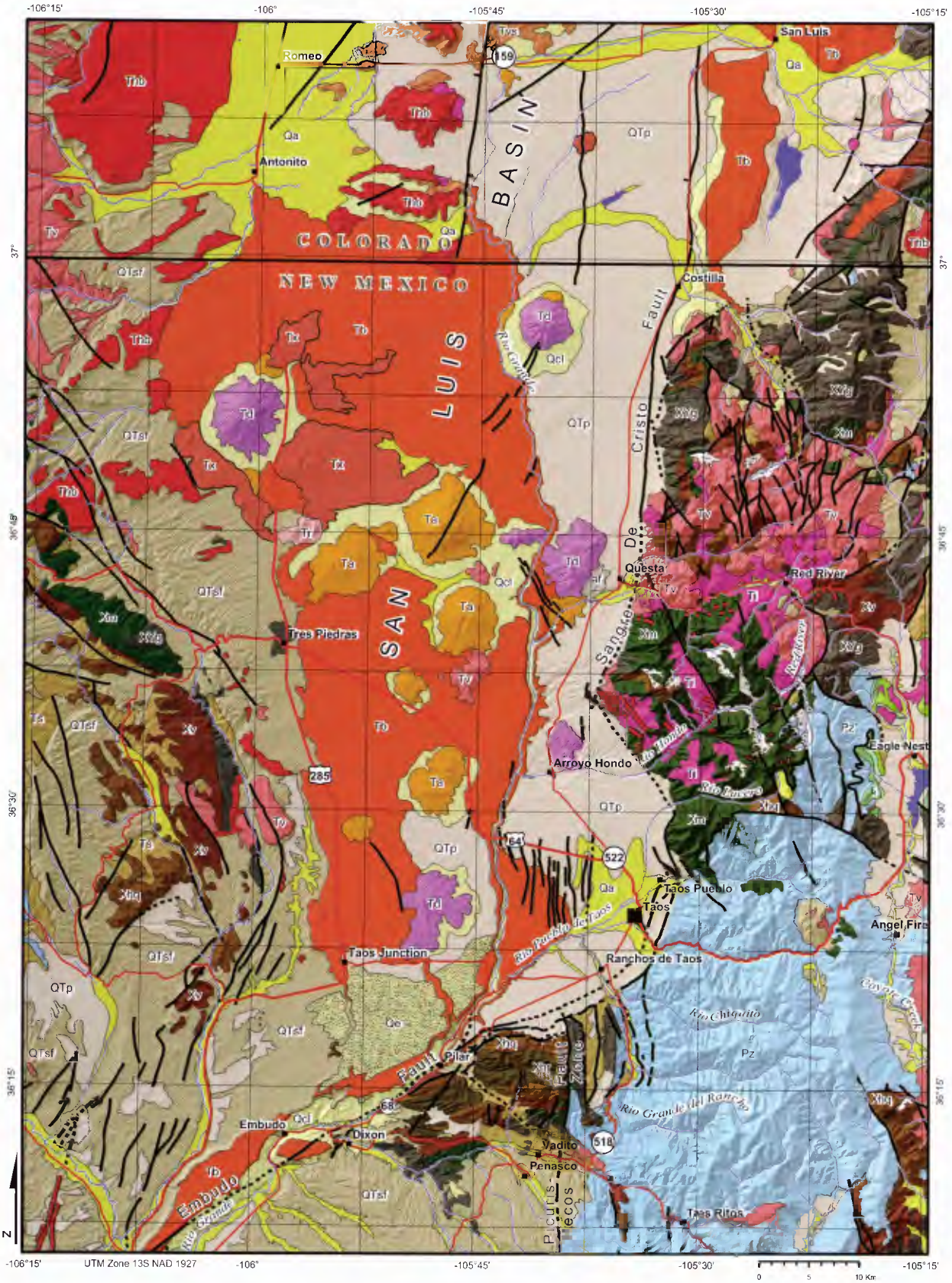
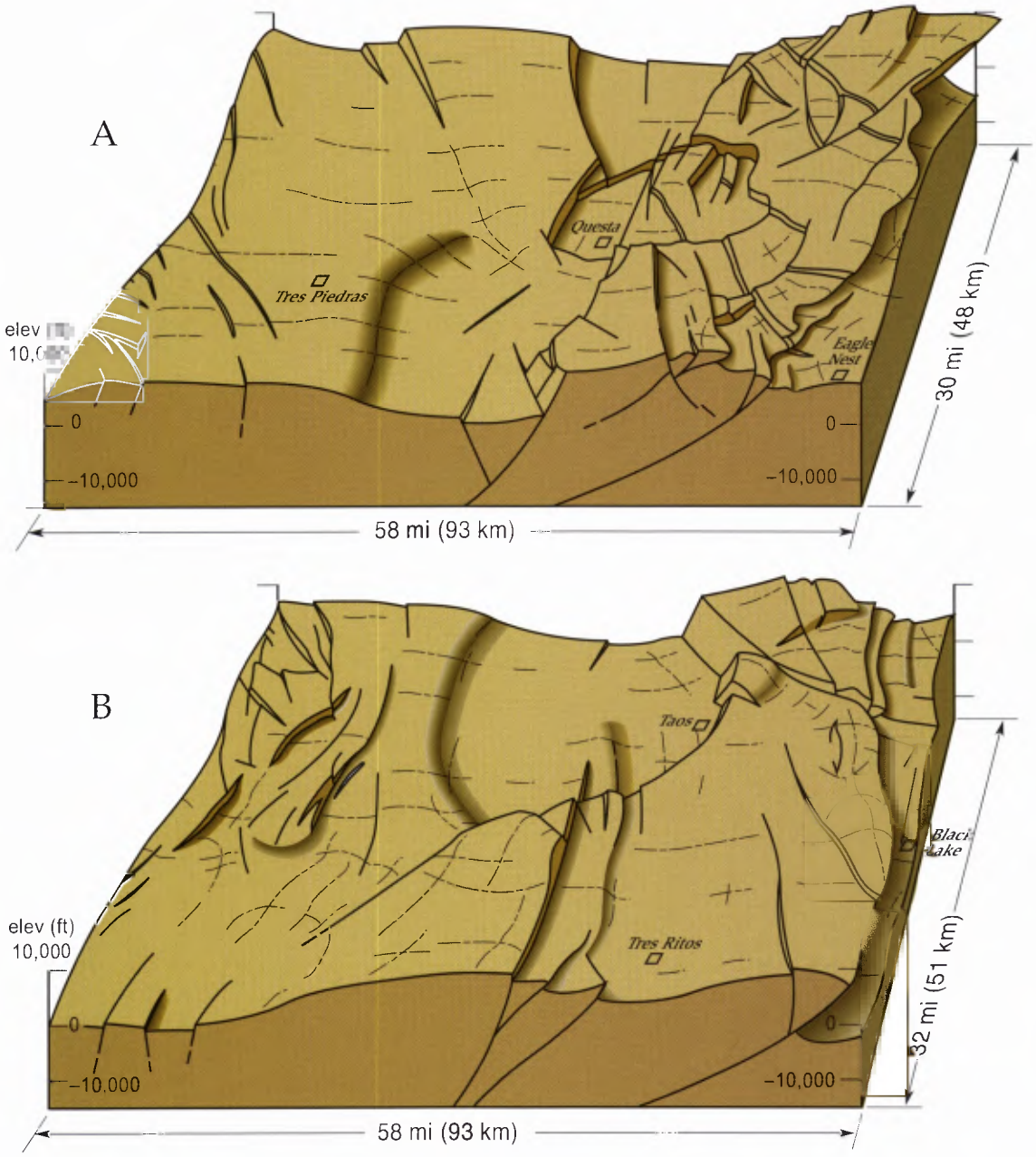


PLATE 2. Geologic map and block diagrams of the southern San Luis Basin area. The geologic map is based largely on 1:500,000 geologic maps of New Mexico and Colorado (NMBGMR, 2004; Tweto, 1979). Taos Plateau volcanic field geology from R.A. Thompson (unpublished mapping) and Taos valley geology from Bauer et al. (Plate 6, this volume). The block diagrams depict the modern configuration of the Proterozoic basement at 2x vertical exaggeration (modified from Plate 2 of Baltz and Myers, 1999).



Legend

- fault-approximately located
- fault-exposed
- fault-concealed
- Tertiary dikes
- Neoproterozoic dike

Quaternary

- water
- artificial fill (tailings)
- Qa alluvium
- Qe eolian deposits
- Qcl colluvium and landslides
- Qd glacial deposits (Pleistocene)
- QTp piedmont deposts
- QTsf Santa Fe Group (Miocene to Pleistocene)

Tertiary

- Tv volcanic rocks-undifferentiated
- Tx xenocrystic basaltic andesite (Pliocene)
- Td dacite (Pliocene)
- Tb Servilleta Basalt (Pliocene)
- Tr rhyolite of No Agua Peak (Pliocence)
- Ta olivine andesite (Pliocene)
- Thb Hinsdale Basalt (upper Oligocene to Pliocene)
- Ti intrusive rocks and dikes
- Tvs volcaniclastic rocks and sediments
- Ts sedimentary rocks-undifferentiated

Mesozoic

- K sedimentary rocks-undifferentiated
- J sedimentary rocks-undifferentiated
- Ŧ sedimentary rocks-undifferentiated

Paleozoic

- Pz sedimentary rocks-undifferentiated

Proterozoic

- XYg granitic rocks
- Xhr Rinconada Fm. of Hondo Group
- Xhq Ortega Fm. of Hondo Group
- Xv Vadito Group
- Xm mafic plutonic/volcanic rocks