Fault geometry and Cenozoic kinematic history of the southeastern San Luis Basin near Taos, New Mexico

Paul W. Bauer[1] and Keith I. Kelson[2]

[1]*New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM 87801, bauer@gis.nmt.edu*
[2]*William Lettis & Associates, Inc., 1777 Botelho Drive, Suite 262, Walnut Creek, CA 94596, kelson@lettis.com*

Abstract

New, detailed geologic maps of Precambrian and Paleozoic bedrock, Tertiary basin fill, Quaternary surficial deposits, and the faults that cut them all, provide important controls on the geometry and kinematics of tectonism in the Taos area, from Laramide shortening to modern rifting. The three major fault systems that intersect in the Taos area are much more complex than previously described. The north-striking, 8-km-wide, strike-slip Picuris–Pecos fault system cuts Picuris Formation rocks as young as 18 Ma. The Picuris–Pecos fault is truncated by the Embudo fault, a major sinistral, antithetic rift transfer zone between the San Luis and Española rift basins. The Embudo fault is a complex system of left-oblique, north-down, strike-slip fault strands that is over 2 km wide. Pliocene basalt offset by the Embudo fault southwest of Pilar suggests a post-3-Ma minimum uplift rate of 0.04 mm/yr and a minimum average net slip rate of 0.15 mm/yr. The northeastern terminus of the Embudo fault is at the Rio Grande del Rancho drainage, where the east-striking Embudo fault system swings northward and smoothly merges with the dominantly dip-slip Cañon section of the rift-bounding Sangre de Cristo fault. The transition zone from the Embudo fault to the Sangre de Cristo fault is coincident with the Picuris–Pecos fault system and the Miranda graben. The Picuris–Pecos fault projects northward across the Taos embayment and aligns with the Questa section of the Sangre de Cristo fault. In the San Luis Basin directly north of the Embudo fault, is the buried, north-trending, 13-km-wide, 5,000-m-deep Taos graben. We speculate that this graben may be the sinistrally displaced equivalent of the Miranda graben.

Our mapping also yields information on the timing of tectonism in the southeastern San Luis Basin. Substantial strike-slip faulting occurred in the Taos area at least until 18 m.y. ago, well past the 27 Ma onset of extension in the San Luis Basin. During early extension, before development of the Embudo fault, the Picuris–Pecos fault system, and its now-buried northward extension, may have represented the eastern rift margin. The transition from Laramide shortening to rift extension overlapped in time and space, and at least some Laramide transverse faults probably evolved into rift normal faults in a transtensional(?) setting. The change to pure extension may have coincided with a middle Miocene change in crustal extensional strain rate and may have also triggered the development of the Embudo fault.

Introduction

This paper presents preliminary results of geologic mapping and structural analysis of the southeastern San Luis Basin of the Rio Grande rift where an active rift transfer fault intersects an active rift-bounding fault. In addition a third major fault system, which may be an earlier rift-margin precursor, intersects these other fault systems in a deformational "triple-point." The southeastern part of the San Luis Basin provides a unique opportunity to address the geometry and kinematics of an active rift margin because it contains excellent exposures of an active rift boundary (the Sangre de Cristo fault), the best-exposed accommodation zone of the Rio Grande rift (the Embudo fault), good exposures of the most impressive Laramide fault zone in the state (the Picuris–Pecos fault system), a unique and illuminating zone of intersection among these three fault systems, and sedimentary rocks that overlap the kinematic transition from the Laramide orogeny to Rio Grande rift extension.

Although dozens of geologic studies have been conducted within the southern San Luis Basin of the Rio Grande rift, there is no compilation of subsurface data at an area-wide scale and thus no adequate base of information for evaluating the geologic framework of the Taos Valley. Before our mapping no quadrangle-scale detailed geologic maps existed for the southern San Luis Basin. Instead there existed regional maps (Miller et al. 1963; Lipman and Mehnert 1979; Machette and Personius 1984; Garrabrant 1993; Machette et al. 1998) and thesis maps of generally small areas or specialized subjects (Chapin 1981; Peterson 1981; Leininger 1982; Rehder 1986; Kelson 1986; Bauer 1988). Kelson et al. (1997) completed a study of the earthquake potential of the Embudo fault zone for the U.S. Geological Survey's National Earthquake Hazard Reduction Program, which included detailed geomorphic mapping and kinematic analysis of faults on the Picuris Mountains piedmont from Pilar to Talpa. During the past several years we have completed 1:12,000 scale geologic maps of the Carson, Taos SW, Ranchos de Taos, and Taos 7.5-minute quadrangles, funded by the STATEMAP component of the National Cooperative Geologic Mapping Program. Development of a sound geologic understanding of the basin and its history requires collection and synthesis of surface geologic data, subsurface drill hole data, and geophysical information.

This paper synthesizes new geologic mapping with existing and publicly available geological and geophysical data in an attempt to provide a preliminary conceptual geologic model of the Taos area. In particular, we consider the following questions:

- What are the geometries and kinematic histories of each of the three major fault systems and can a geologically reasonable conceptual tectonic model of the buried bedrock basin be developed?
- What do field relations among the three fault systems suggest about the transition from Laramide shortening to Neogene extension?
- What can we infer about the evolution of the Embudo accommodation zone?

Methods

Our approach for the investigation consisted of three components: air photo analysis and geologic mapping, compilation of existing geologic/geophysical/subsurface data, and collection of domestic well data. Analysis of aerial photography included review of 1973-vintage color images at a

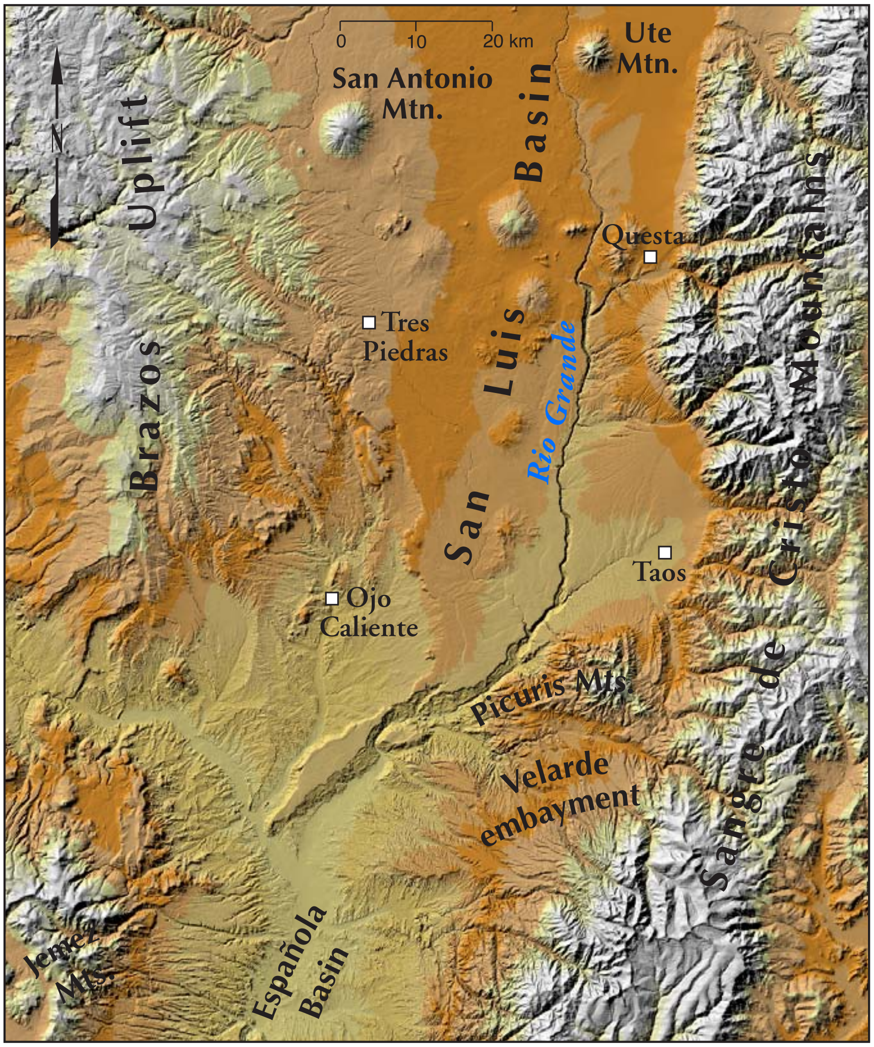


FIGURE 1—Digital shaded-relief index map of the northern Rio Grande rift in New Mexico showing major tectonic features.

scale of about 1:16,000, as well as analysis of 1:62,500-scale color-infrared images and smaller-scale satellite imagery. Following the analysis of this imagery we conducted detailed mapping of geologic units and geomorphic features at a scale of 1:12,000 (1:6,000 in the Talpa area). Analysis of faults in all units (Proterozoic through Quaternary) included evaluations of fault geometries and kinematic data. On bedrock faults, slickenlines were combined with kinematic indicators such as offset piercing lines or planes, and calcite steps to infer slip directions. In Quaternary deposits we inferred slip directions based on fault scarp geometry, map pattern of fault strands, and deflected drainages.

A primary goal was to provide a conceptual model of the large-scale geologic structure of the basin beneath the southern Taos Valley. Our approach was to first understand the surficial structural geology around the edge of the basin and then to infer subsurface basin structure using that knowledge and other data sets (boreholes, geophysics, surface structure, geomorphology, and hydrogeology). This approach allowed us to infer subsurface stratigraphy and structure over the region and to speculatively project important features such as buried faults and basalt flows into the study area. We also evaluated 250 well records along the bedrock/piedmont interface in order to better understand the shallow basin bedrock architecture in the area of the Embudo and Sangre de Cristo fault systems.

Regional geologic framework

The Rio Grande rift in northern New Mexico is composed of a series of north-trending, elongate topographic and structural basins, including the San Luis and Española Basins (Fig. 1). The basins are broad half grabens that are tilted to either the east or west and typically have a relatively active, north-striking fault along one border as well as many lesser faults within the basin. Current tectonic models based on geologic, geophysical, and drill hole data suggest that the basins of the northern Rio Grande rift are separated by northeast-trending zones that accommodate the differential sense of basin tilting (Chapin and Cather 1994). The San Luis Basin is one of the major structural elements of the 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. The southern part of the basin is a physiographically and geologically unique terrain known as the Taos Plateau. The plateau is composed mostly of Pliocene basaltic rocks that were erupted locally and have only been mildly deformed by rift processes. Basalt flows dip very gently to the east, at about 6 m/km or 0.4° (Lipman and Mehnert 1979). The plateau surface shows only minor dissection, although the Rio Grande and its two major tributaries are confined to deep canyons cut through the volcanic rocks. The 300-m-deep Rio Grande gorge contains good exposures of Tertiary volcanic rocks, as well as the interlayered sands and gravels of the Chamita Formation that represent westward-prograding alluvial fans of the Taos Range (Peterson 1981; Dungan et al. 1984). Based on surface mapping and drill-hole data, the basalt flows pinch out eastward and southward toward the edge of the basin.

In the Taos area, the Rio Grande rift is a 30-km-wide, asymmetrical basin with the major flanking fault system along its eastern border (Sangre de Cristo fault). The total throw on the Sangre de Cristo fault system may be as much as 7 or 8 km (Lipman and Mehnert 1979). Gravity data indicate that, at the latitude of Taos, the basin consists of a deep north-south graben, the Taos graben, perhaps > 5 km deep along the eastern edge of the rift (Cordell 1978). The western edge of the graben (the Gorge fault) lies beneath the Rio Grande (Cordell and Keller 1984), resulting in a graben that is less than half the width of the topographic valley. The structural bench west of the Taos graben rises gently to the Tusas Mountains and is cut by numerous small-displacement normal faults. To the north the bench becomes an intra-rift horst with Oligocene volcanic rocks exposed in the middle of the rift at the San Luis Hills of southern Colorado (Lipman and Mehnert 1979).

Our work focused on the intersection of the southern Sangre de Cristo fault and the northern Embudo fault in the southern San Luis Basin (Fig. 1). The Sangre de Cristo and Embudo faults form the eastern and southern boundaries of the basin, respectively, and intersect in a manner characteristic of continental rift systems (Rosendahl 1987; Morley et al. 1990). The Sangre de Cristo fault is a north-striking, west-dipping normal fault that accommodates asymmetric subsidence of the late Cenozoic San Luis Basin. The Sangre de Cristo fault exhibits geomorphic evidence for multiple surface-rupturing events in the late Quaternary (Machette and Personius 1984; Menges 1990). The 64-km-long Embudo fault strikes northeast-southwest and can be interpreted as a transfer fault or accommodation zone (Rosendahl 1987; Morley et al. 1990; Faulds and Varga 1998) that allows differential subsidence between the San Luis Basin to the northeast and the Española Basin to the southwest. Detailed field mapping and geomorphic investigations document late Quaternary and possibly Holocene surface rupture along the northeastern Embudo fault (Kelson et al. 1997). The Embudo fault, in particular, is an excellent example of an active accommodation zone in the northern Rio Grande rift.

Rocks and deposits

Previous workers have shown that rocks in the southern Rocky Mountains of northern New Mexico record a complex tectonic history, from Early Proterozoic crustal genesis, to the Paleozoic Ancestral Rocky Mountain orogeny, to the Cretaceous/Tertiary Laramide orogeny, to Neogene rifting and contemporary extension and sedimentation. The rocks of the Taos area contain evidence of all of these events. The Taos area straddles the boundary between Proterozoic and Paleozoic basement rocks of the Sangre de Cristo and Picuris Mountains and Cenozoic sedimentary and igneous rocks of the southern San Luis Basin (Fig. 1). In this paper we emphasize the Cenozoic history, although it is likely that earlier geologic events produced structures that helped focus Laramide and later rift deformation. Detailed descriptions of rock units and deposits are available in Bauer et al. (1999) and references therein. The following discussion of stratigraphy focuses on general stratigraphic and field relationships plus new data and radiometric ages from the pre- to syn-rift Picuris Formation. Figure 2 is a composite stratigraphic section for the study area.

Proterozoic rocks

The great variety of Early and Middle Proterozoic rocks exposed in the Taos Range and Picuris Mountains is also present in the subsurface of the San Luis Basin. These units are important because in some cases they are a source of information on the provenance of Cenozoic basin-fill units. In general, the Taos Range contains large areas of plutonic and gneissic complexes (including greenstones), whereas the northern Picuris Mountains are composed of metasedimentary rocks (quartzite, schist, phyllite) in fault contact with granite to the east. The eastern granite, known as the Miranda granite, is exposed in the ridges between Arroyo Miranda and Rio Grande del Rancho. For more information on the local Proterozoic rocks, see references cited in Montgomery (1953, 1963), Condie (1980), Lipman and Reed (1989), Bauer (1988, 1993), and Bauer and Helper (1994).

Paleozoic rocks

Most of the bedrock exposed in the Taos area consists of Paleozoic sedimentary strata of Mississippian and Pennsylvanian age. For detailed stratigraphic information on the Mississippian strata, see Armstrong and Mamet (1979, 1990). In the Talpa area, near Ponce de Leon Spring, a thin section of the Mississippian Arroyo Peñasco Group rests unconformably on the Proterozoic Miranda granite. Pennsylvanian strata exposed from the top of the Mississippian section on Cuchilla del Ojo near Ponce de Leon Spring eastward into the Sangre de Cristo Mountains are probably entirely Desmoinesian Flechado Formation—a thick sequence of marine, deltaic, and continental sediments equivalent to part of the Madera Group—although a series of large, north-striking faults have repeated and/or deleted parts of the section.

Although only a small part of the study area contains Paleozoic rocks at the surface, it is likely that much of the area is underlain at depth by these rocks. Baltz and Myers (1999) proposed that the Pennsylvanian Taos trough actually continues northwestward near Taos, and that a thick section of Pennsylvanian rocks could underlie parts of the southern San Luis Basin. They imply that Pennsylvanian facies therefore do not necessarily thin toward the former Uncompahgre uplift in a simple geometry.

Tertiary rocks

Ingersoll et al. (1990) noted, “Cenozoic stratigraphic nomenclature of the study area is extraordinarily complex……due to interfingering of distantly and locally derived nonmarine units of widely differing provenance and lithology. There are many examples of published geologic maps with different stratigraphic units mapped in the same places by different geologists. This confusion of nomenclature results from both the complex stratigraphy and poor exposure of some slightly consolidated lithologies.” Although we concur, we also believe that the Tertiary units of the study area generally are consistent with previous stratigraphic schemes published by Manley (1976), Muehlberger (1979), Steinpress (1980), Leininger (1982), Dungan et al. (1984), Aldrich and Dethier (1990), and Ingersoll et al. (1990). Below, we summarize two important Tertiary units in the area—the Picuris Formation and the Santa Fe Group.

Picuris Formation—The oldest known Cenozoic unit in the area is the Picuris Formation, a local sequence of mostly volcaniclastic sedimentary rocks that represents pre-rift and early-rift activity. Baltz (1978) stated that the early shallow rift basins of northern New Mexico were initially infilled by a combination of volcanic eruptions and volcaniclastic alluvial fans with sources in the San Juan volcanic field to the north. Rehder (1986) previously divided the Picuris Formation into three members: a lower member, the Llano Quemado breccia member, and an upper member, on the basis of 11 scattered exposures north and east of the Picuris Range. This work was a major contribution to understanding this important unit, but we are uncertain of the validity of some of the interpretations mainly because of new isotopic ages and the extensive faulting of the area. Although the Llano Quemado breccia is an excellent marker bed, it crops out in the Talpa area as a scattering of fault-bounded exposures that complicate straightforward stratigraphic reconstructions. Nonetheless, we have retained and refined Rehder’s stratigraphy.

Within the study area, the lower member of the Picuris Formation appears to consist of a basal boulder and cobble conglomerate and conglomeratic sandstone interbedded with thinly bedded sandstones. The boulder unit is distinctive, composed of well-rounded, poorly sorted, mostly clast supported, Proterozoic quartzite clasts with minor altered clasts of intermediate Tertiary volcanic rocks and Paleozoic sedimentary rocks. The boulder unit fines upward to less-indurated pebble conglomerate and conglomeratic sandstone and variegated green, red, and white siltstone and mudrock. Local layers of primary(?) white to gray to yellow to brown air-fall ash are well sorted and contain sanidine and biotite crystals. This member was interpreted as a sequence of debris flow and alluvial fan deposits derived from the Sangre de Cristo Mountains and Latir volcanic field to the north and northeast (Rehder 1986). However, the deposit (34–27 Ma, see new ages below) cannot be older

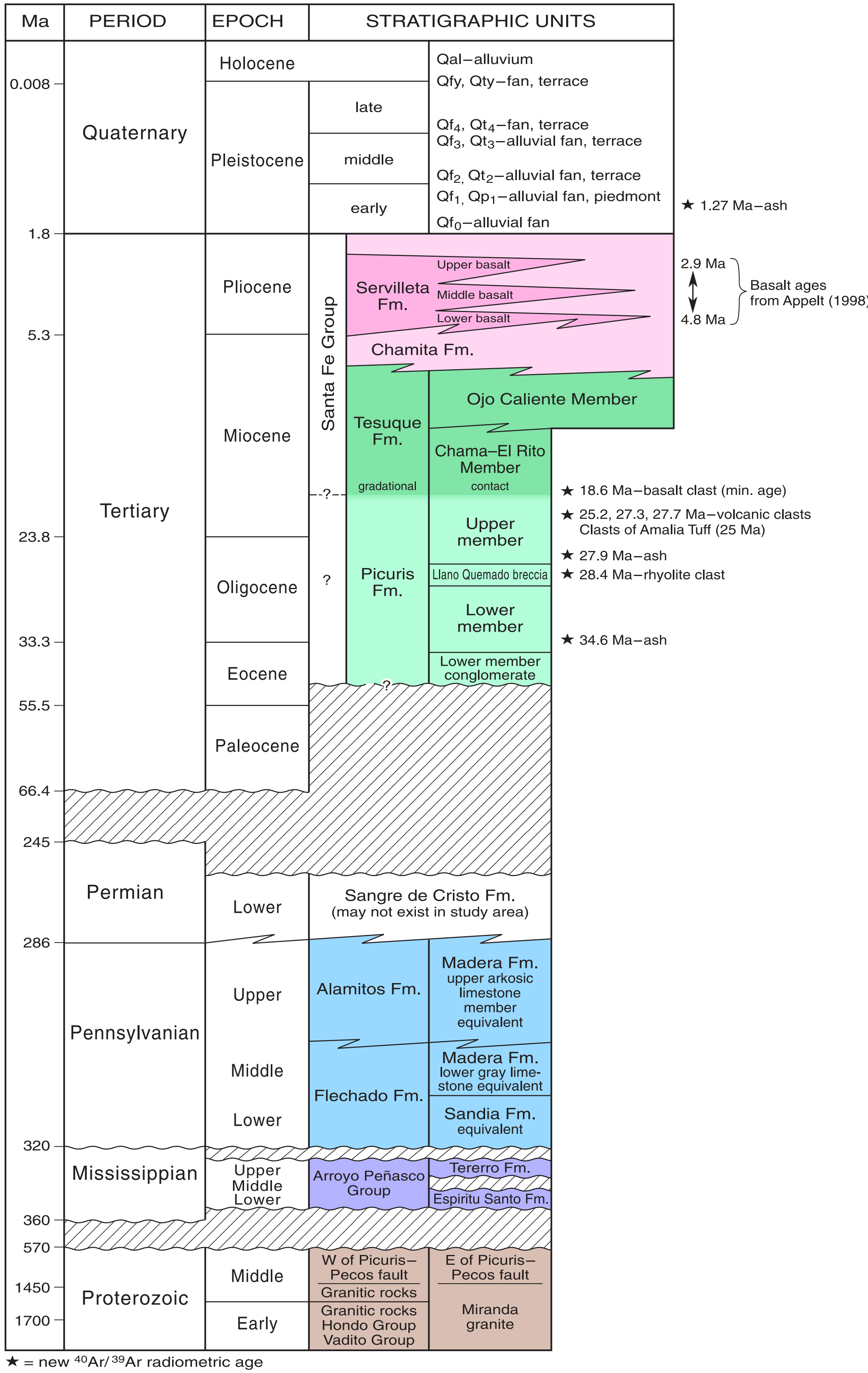


FIGURE 2—Composite stratigraphic section for the Taos/Talpa area, north-central New Mexico. New $^{40}Ar/^{39}Ar$ radiometric ages are listed on right.

than the source (ca 26 Ma), and the volcanic component of the unit was probably derived from an older San Juan volcanic field to the north and northwest. Alternatively the source could be an unrecognized (buried or eroded) older volcanic unit from the Latir field.

The Llano Quemado breccia is a monolithologic volcanic breccia of distinctive, extremely angular, poorly sorted, light-gray, recrystallized rhyolite clasts in a reddish matrix. Rhyolite clasts contain phenocrysts of biotite, sanidine, and quartz. The rock is a highly indurated ridge-former. The breccia was interpreted as a series of flows from a now buried, presumably local, rhyolite vent (Rehder 1986). However, excellent exposures in Arroyo Miranda display sedimentary layering and crossbedding that indicate that at least parts of the unit are locally reworked volcaniclastic sediments.

The upper member of the Picuris Formation is a gray to pinkish-gray, immature, pumice-rich, ashy, polylithologic, conglomeratic sandstone. It consists mainly of sandstones with gravel-sized clasts of pumice and silicic volcanic rocks (mostly 25.1 Ma Amalia Tuff) and minor Precambrian quartzite and intermediate composition volcanic rocks (including the 26.0 Ma Latir Peak quartz latite). Most of the gravel-sized fraction is pumice with some clasts as much as 25 cm in diameter. Most clasts are rounded to well rounded. Some cobble-rich conglomerates are interlayered with easily eroded, weakly cemented pebble conglomerates. Paleoflow measurements indicate a source to the north, and Rehder (1986) interpreted the unit as an alluvial fan deposit derived from the Latir volcanic field at around 26 Ma (Rehder 1986). Our new radiometric age of a basalt clast in this unit (see below) suggests that the upper member likely accumulated until at least 18 m.y. ago. Based on our mapping along the northern Picuris Mountains piedmont of tilted Tertiary rocks, we interpret a continuous section of Picuris Formation to Tesuque Formation, perhaps punctuated locally by unconformities.

The New Mexico Bureau of Geology and Mineral Resures' New Mexico Geochronology Research Laboratory recently provided several new $^{40}Ar/^{39}Ar$ radiometric ages for the Picuris Formation that have greatly expanded both the known age range of the unit and its importance in constraining the tectonic history. Some of our important geochronological findings are:

A white ash that crops out near Talpa, and is interbedded with clastic sediments of the lower Picuris Formation, yielded an age of 34.64 ± 0.16 Ma. The oldest exposed part of the Picuris Formation (Tplc, the basal quartzite boulder conglomerate near Talpa) is therefore older than 34.6 Ma. A second ash from the Picuris Range foothills south of Pilar yielded a similar age of 34.5 ± 1.2 Ma, indicating that the Picuris Formation underlies all(?) of the high piedmont along the northern Picuris Range.

A rhyolite clast from the Llano Quemado breccia, in the middle part of the formation, yielded a plateau age of 28.35 ± 0.11 Ma. This probably represents the eruptive age of a rhyolite dome that was later eroded or buried. The breccia therefore is older than any rock known from the Latir volcanic field, the oldest of which is a 26.0 Ma quartz latite that was interpreted as a pre-caldera feeder (Czamanske et al. 1990). Because we believe that the breccia is actually a sedimentary rock, the clast age is a maximum age for the unit.

A poorly indurated white ash from Arroyo Miranda in the northeast corner of the range (1.5 km south of hill) was dated at 27.93 ± 0.08 Ma. This confirms that other parts of the Picuris Formation are approximately time equivalent to the Llano Quemado breccia.

Additional control on the age of the Picuris Formation comes from a vesicular basalt clast from the upper Picuris Formation on the west side of Arroyo Miranda collected by D. McDonald of the University of Texas at Dallas. Our date of 18.59 ± 0.70 Ma from the clast is a maximum age for deposition and indicates that the Picuris Formation deposition continued into the Miocene and possibly overlaps in time with the Tesuque Formation (18–14 Ma for the Chama–El Rito Member in the Dixon area, according to Steinpress 1980). Preliminary data from our mapping along the southern flank of the Picuris Range support possible interfingering between the upper Picuris Formation and the Dixon member of the Tesuque Formation of the Santa Fe Group.

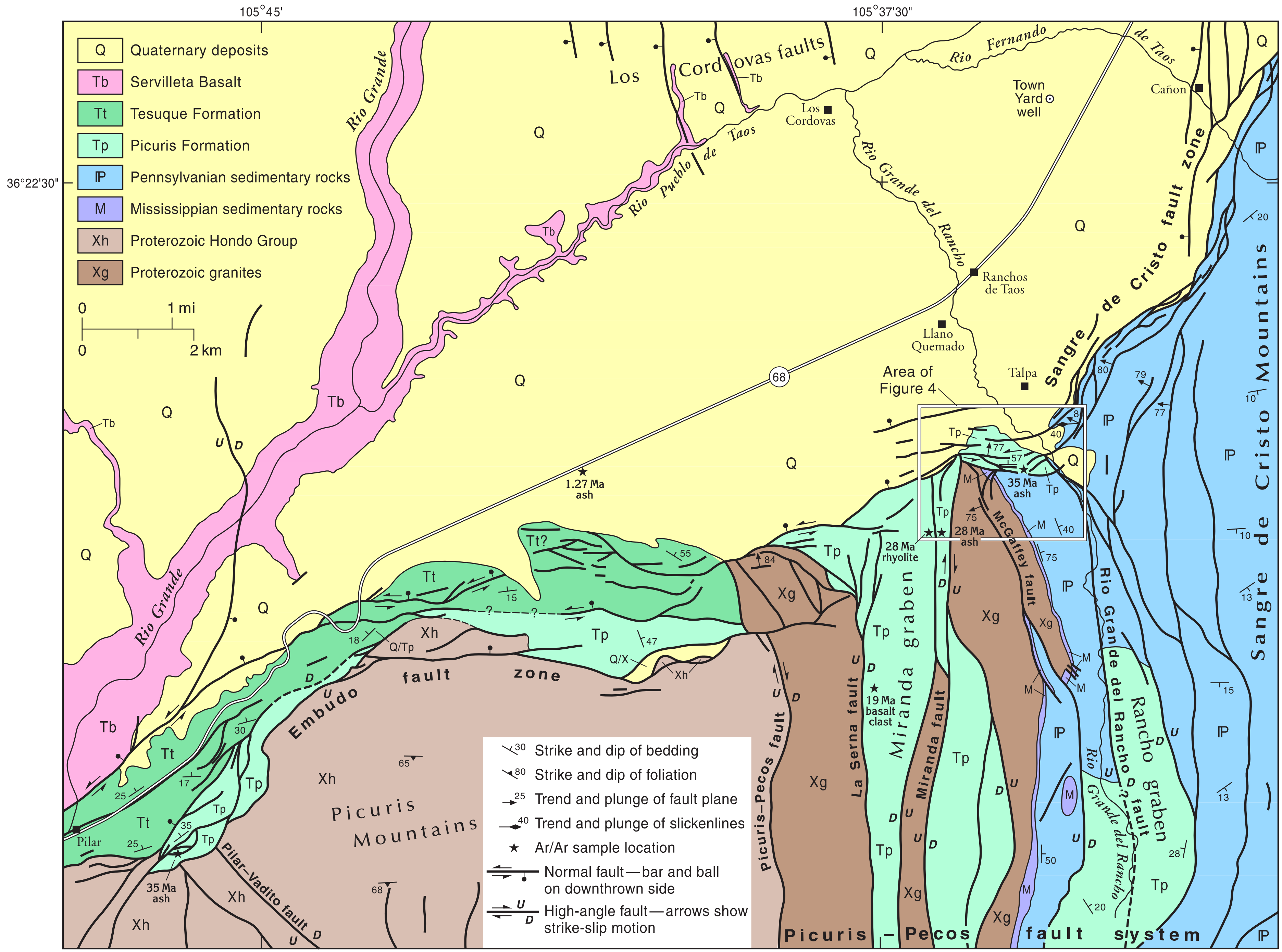
In summary, in the study area, our stratigraphy generally agrees with that of Rehder (1986). The base of the Picuris Formation is exposed just west of the mouth of the Rio Grande del Rancho where a quartz-cobble conglomerate is faulted against Pennsylvanian strata. The conglomerate fines upward to a sequence of quartz-pebble conglomerates, sandstones, and siltstones. This part of the section is cut extensively by north- and northeast-striking faults. Well data indicate that the basal boulder conglomerate has west-down vertical separation across a series of faults within the Embudo fault zone. The middle member of the Picuris Formation crops out in the western map area, generally west of Arroyo Miranda, where it is extensively faulted by both the Miranda and La Serna faults.

Santa Fe Group—Because the Santa Fe Group is not exposed in the study area, the exact nature of the unit is unknown. Borehole data in the San Luis Basin indicate that relatively thin Quaternary deposits are underlain by thick Tertiary sand and gravel. Cuttings from deep exploration boreholes in the Taos area suggest the presence of the Chamita, Ojo Caliente, and Chama–El Rito Members in the subsurface (P. Drakos pers. comm. 2000). At present because of the heterogeneity of the Santa Fe Group and the paucity of petrographic analysis of the cuttings, we believe that within the map area the data are insufficient for constructing well-constrained isopach or structure contour maps of any of the Santa Fe Group sedimentary subdivisions.

Along the western flank of the Picuris Mountains, the oldest Tesuque Formation unit is the Chama–El Rito Member, composed predominantly of volcanic-rich, non-fossiliferous sandstone and conglomerate with minor mudrock interbeds. The Chama–El Rito Member, thought to be 18–14 Ma, represents braided stream deposits on a distal alluvial fan derived from a volcanic terrain to the northeast (Steinpress 1980). The thickness in the Dixon area was estimated to be 480 m (Steinpress 1980).

The Chama–El Rito Member is conformably below, and interfingers with, the Ojo Caliente Sandstone Member of the Tesuque Formation west of the study area along Rito Cieneguilla near Pilar (Leininger 1982; Kelson and Bauer 1998). The Ojo Caliente is a buff to white, well-sorted eolian sandstone consisting mostly of fine sand. Tabular crossbeds are common with some sets over 4 m in height. Transport was from southwest to northeast at approximately 13–12 Ma (Steinpress 1980). The Ojo Caliente is not exposed in the study area but probably exists in the subsurface. Based on lithologic interpretations from well cuttings and downhole geophysics, the town of Taos exploration well RP-2000 along the Rio Pueblo in the northwestern corner of the study area penetrated what appears to be a 200-m interval of primarily Ojo Caliente sands (Drakos and Lazarus 1998).

In late Miocene time high-angle rift faulting produced


105°45'
105°37'30"
36°22'30"
Q Quaternary deposits
Tb Servilleta Basalt
Tt Tesuque Formation
Tp Picuris Formation
IP Pennsylvanian sedimentary rocks
M Mississippian sedimentary rocks
Xh Proterozoic Hondo Group
Xg Proterozoic granites
0 1 mi
0 2 km
Strike and dip of bedding
Strike and dip of foliation
Trend and plunge of fault plane
Trend and plunge of slickenlines
Ar/Ar sample location
Normal fault—bar and ball on downthrown side
High-angle fault—arrows show strike-slip motion
Los Cordovas faults
Sangre de Cristo fault zone
Sangre de Cristo Mountains
Rio Grande
Rio Pueblo de Taos
Rio Grande del Rancho
Rio Fernando de Taos
Los Cordovas
Town Yard well
Cañon
Ranchos de Taos
Llano Quemado
Talpa
Area of Figure 4
1.27 Ma ash
35 Ma ash
28 Ma ash
28 Ma rhyolite
19 Ma basalt clast
McGaffey fault
Miranda graben
Miranda fault
La Serna fault
Picuris–Pecos fault
Rio Grande del Rancho fault
Rancho graben
Picuris – Pecos fault system
Embudo fault zone
Pilar–Vadito fault
Picuris Mountains
Pilar
68
Q/Tp
Q/X
Tt?

deep, narrow, fault-bounded basins that filled with great thicknesses of clastic sediments and volcanic rocks. In the Taos/Pilar area the clastic sediments are named the Chamita Formation, and the volcanic unit is named the Servilleta Formation. The thickness of the Chamita Formation is highly variable and difficult to estimate at any given location. It is also difficult to distinguish from overlying Quaternary alluvial deposits and underlying Tesuque Formation, a fact that poses a problem when interpreting formational contacts based solely on well cuttings. The thickness has been estimated to range from 100 to 230 m in the Pilar area (Steinpress 1980). However, in the Town of Taos exploration well RP-2000 along the Rio Pueblo, the thickness of the Chamita Formation below the lower Servilleta basalt was estimated to be 284 m (Drakos and Lazarus 1998).

Nearly flat-lying basalts of the Pliocene Servilleta Formation cap the Taos Plateau over much of the southern San Luis Basin. The Servilleta basalts have been encountered in many test and exploration wells near Taos, and the eastward lateral extent of at least the uppermost basalt flows can be approximated in map view (Fig. 3). The basalt is a dark-gray, diktytaxitic olivine tholeiite that erupted as thin, fluidal, widespread, pahoehoe basalt flows. Individual flows, which are as much as 12 m thick, are grouped into sequences of from one to ten flows, and separated by 0.3- to 4.5-m-thick sedimentary intervals (Leininger 1982). Dungan et al. (1984) identified three basalt sequences at the Gorge Bridge, a classification that has been adopted by most workers. A lower basalt sequence consists of two sets of flows totaling 51 m that locally are separated by as much as 4 m of Chamita sediments. A 36-m-thick middle basalt is separated by a relatively thick, 30-m sedimentary interval from an upper basalt sequence of 30 m. The relative thicknesses of the various basalt sequences, individual flows, and intervening sediments are variable. Limited exposure of the basal basalt in the gorge suggests that flows erupted onto a nearly flat surface of the Chamita Formation. Five central vents to the north are the sources of the flows (Lipman and Mehnert 1979), which dip gently, thin, and pinch out to the east and southeast. A recent study has shown a range in ages of the Servilleta basalts from 4.81 ± 0.04 to 3.12 ± 0.13 Ma at the Gorge Bridge, and from 4.33 ± 0.02 to 2.93 ± 0.14 Ma at the Dunn Bridge (Appelt 1998).

Quaternary deposits

Quaternary deposits in the Taos area provide a means to assess the locations of Quaternary active faults and to estimate the senses and relative amounts of Quaternary displacement. The area contains a variety of coalescent alluvial-fan, stream channel, and terrace deposits that range in age from early(?) Pleistocene to Holocene. In the southwestern part of the study area, high alluvial fans derived from the Picuris Mountains interfinger with alluvial terrace deposits along Rio Grande del Rancho north of Talpa. The alluvial fans grade to the highest Servilleta Formation basalt along the southern rim of the Rio Pueblo de Taos gorge (Kelson 1986). In the central and eastern parts of the study area, near-surface Quaternary units consist of coarse-grained fluvial sediments deposited by major streams and coarse- to fine-grained alluvial-fan sediments derived from small, mountain-front drainages. The area contains fluvial and alluvial-fan deposits that range in age from early to middle(?) Pleistocene to recent.

Fluvial sediments are present primarily along the Rio Grande del Rancho, Rio Chiquito, Rio Pueblo de Taos, and Rio Fernando valleys. These poorly sorted sands and gravel contain subrounded clasts of quartzite, slate, sandstone, schist, and granite and are laterally continuous in a downvalley direction (Kelson 1986). Soils developed on these deposits associated with older, higher stream terraces (i.e., the terrace beneath the village of Llano Quemado) contain well-developed (stage III to IV) calcic horizons. Younger terraces are associated with lesser amounts of soil development (stage I to II calcic horizons; Kelson 1986).

Alluvial-fan deposits in the central and eastern parts of the study area are derived mostly from smaller mountain-front drainages developed in Pennsylvanian sandstone and shale. In general, these deposits are coarse-grained sands and gravels near the mountain front and are finer-grained with distance to the north or west. The alluvial-fan deposits likely are laterally discontinuous and moderately heterogeneous. Older fan deposits are associated with well-developed soils (stage III to IV calcic soils), whereas younger deposits contain moderately developed soils (stage I to II calcic horizons) or lesser-developed soils. The younger fans in many places bury older fan deposits, such that subsurface conditions probably vary considerably across the mountain-front piedmont.

North of Rio Pueblo de Taos, in the northwestern corner of the study area, the Servilleta basalt is overlain unconformably by fine-grained deposits that likely are: 1) the distal parts of older alluvial fans shed from the Sangre de Cristo Mountains, and/or 2) derived from the ancestral Rio Grande (Kelson 1986). These highly oxidized and weathered deposits are probably early to middle Pleistocene in age and appear to have been saturated throughout most of the eastern Taos Plateau. These deposits most likely were deposited before the development of the Rio Grande gorge (Wells et al. 1987) and reflect alluviation on the plateau before regional incision.

Descriptions of primary fault systems

Three major fault systems intersect in the southeastern corner of the Taos Plateau: 1) the Picuris–Pecos fault system; 2) the Embudo transfer fault; and 3) the rift-bounding Sangre de Cristo fault zone (Fig. 3). Additionally, a 7-km-wide zone of west-down faults, originally mapped by Lambert (1966) and termed Los Cordovas faults by Machette and Personius (1984), exist on the plateau along the northern projection of the Picuris–Pecos fault. The geometries and kinematics of all four of these fault zones provide insight into the geometry and history of the southeastern San Luis Basin.

Picuris–Pecos fault system

Montgomery (1953) recognized the Picuris–Pecos fault (originally named the Alamo Canyon tear fault) in the Picuris Mountains. The fault has been traced for more than 60 km, from the northern Picuris Mountains south of Taos to near the village of Cañoncito east of Santa Fe. From Cañoncito it can be traced southward into the Estancia Basin for an additional 24 km, yielding a documented trace of 84 km.

As summarized by Bauer and Ralser (1995) the history of the Picuris–Pecos fault system includes:

FIGURE 3—Generalized geologic map of the southern Taos Valley, New Mexico. This compilation is based on 1:12,000-scale maps of the Ranchos de Taos quadrangle (Bauer et al. 2000), Taos SW quadrangle (Bauer and Kelson 1998), Carson quadrangle (Kelson and Bauer 1999), Taos quadrangle (Bauer and Kelson 2002), and Los Cordovas quadrangle (Kelson and Bauer 2003). Quaternary deposits are lumped on this compilation. Members of the Picuris Formation and Tesuque Formation are not shown. The Miranda graben and Rancho graben (in the Picuris–Pecos fault zone) are interpreted as fault-reactivated, Laramide to early rift structural basins that were filled with Eocene to Miocene volcaniclastic sediments of the Picuris Formation. Note that the Picuris–Pecos fault is merely the westernmost strand of a complex 10-km-wide fault system.

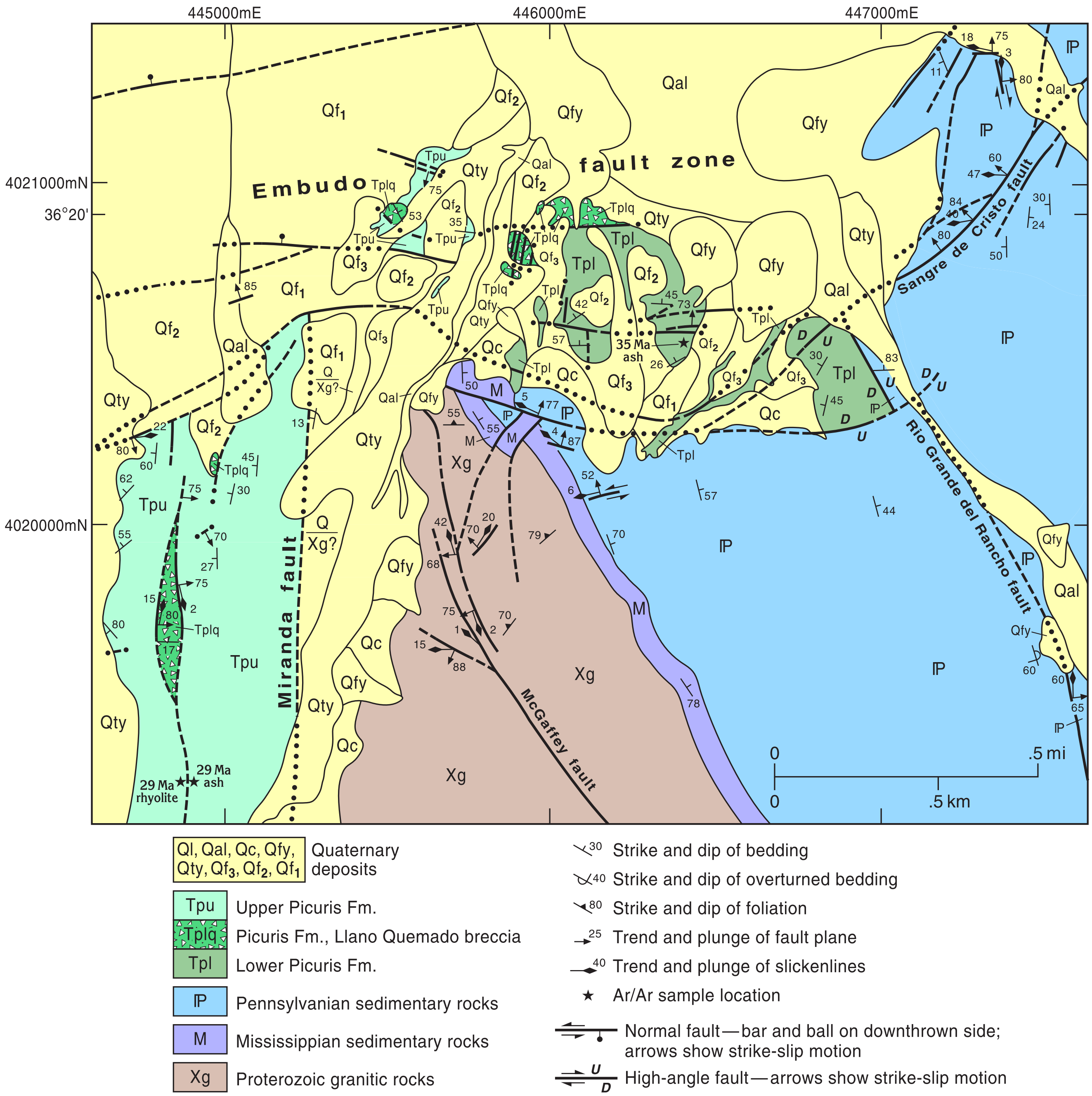


FIGURE 4—Detailed geologic map of the Talpa area where the Embudo, Picuris–Pecos, and Sangre de Cristo fault systems intersect. The zone of intersection consists of highly faulted blocks of Proterozoic through Tertiary rocks. The transition zone from the Embudo fault system to the Sangre de Cristo fault system is gradual, and we have chosen to place the boundary between these two faults at the Rio Grande del Rancho Canyon where fault kinematics suggest a change from dominantly strike slip to dominantly dip slip. Although exposures of the Picuris Formation are poor, it appears that Embudo and Sangre de Cristo faults cut the Picuris–Pecos faults. The map is compiled from 1:6,000-scale mapping in the Ranchos de Taos quadrangle (Bauer et al. 1999).

1) Proterozoic(?), post-1.4 Ga displacement resulting in an unknown amount of right slip (perhaps 11 km?) and deflection and attenuation of Proterozoic supracrustal rocks and older ductile structures;
2) As noted by Sutherland (in Miller et al. 1963) a series of Mississippian and Pennsylvanian west-up movements on the Picuris–Pecos fault resulted in deposition of sediments along the northern part of the fault. Although no strike-slip component is documented, some amount is likely;
3) During the Laramide orogeny, at least 26(?) km of right-slip occurred on the Picuris–Pecos fault, with coeval, subsidiary displacement on north-striking, high-angle faults east and west of the main fault. The overall geometry of the fault system is a positive flower structure with dip-slip displacement dominating some subsidiary faults. Strike-slip, oblique-slip, and dip-slip fault striae all developed contemporaneously on different fault strands;
4) During the Neogene rift-related faulting occurred in the Santa Fe Range, rather than the Picuris Mountains, perhaps caused by greater extension in the southern

Española Basin versus the northern Española Basin (Chapin and Cather 1994). Normal faulting may have been distributed over many reactivated(?) high-angle faults in the southernmost Sangre de Cristo Mountains.

Near its northern end, south of Taos, the Picuris–Pecos fault systems consists of five parallel north-striking fault zones (Fig. 3). From west to east they are: Picuris–Pecos, La Serna, Miranda, McGaffey, and Rio Grande del Rancho fault zones. Herein, these fault zones are collectively referred to as the Picuris–Pecos fault system. Each fault zone consists of high-angle, anastomozing zones of distributed brittle shear. The major faults are located in valleys because of pervasive brittle deformational structures (fractures, fault gouge, fault breccia) that are relatively easily weathered and eroded. We suspect that all of the fault zones share similar kinematic histories of multiple reactivations, as described by Bauer and Ralser (1995).

The Picuris–Pecos fault is a major crustal boundary that has experienced enough slip to juxtapose very different Proterozoic rock sequences. West of the fault is the Hondo Group, a metasedimentary terrane of quartzite and schist. East of the fault is a distinctive medium-grained, orangish granite (Miranda granite) that is similar in appearance to the granite exposed at Ponce de Leon Spring. To the south, offset Paleozoic strata indicate that the Picuris–Pecos fault has a Phanerozoic east-down separation. Slickenlines are typically strike-slip or shallow oblique-slip on steep fault planes.

Approximately 1.3 km east of the Picuris–Pecos fault is the east-down La Serna fault, which has placed the Miranda granite on the west against the Picuris Formation on the east. The Picuris Formation occupies a graben between La Serna fault and the west-down Miranda fault, located about 1.4 km to the east. The main strand of the Miranda fault is inferred beneath Arroyo Miranda, based on water-well records and the juxtaposition of Picuris Formation and granite. Good exposures in the Talpa/Llano Quemado area, where the Miranda fault zone cuts Picuris Formation, display numerous north-striking, strike-slip faults with map separations measured on the order of meters to hundreds of meters (Fig. 4). Importantly, the < 18 Ma middle Picuris Formation is cut by strike-slip faults within the Miranda and La Serna fault zones, suggesting that strike-slip faulting occurred during the Neogene, which is generally accepted to be dominated by rift extension.

Approximately 1 km east of the Miranda fault is a set of west-down branching fault splays (the McGaffey fault) located on the bedrock ridge of Cuchilla del Ojo. The McGaffey fault offsets Proterozoic and Paleozoic rocks, but appears to have considerably less throw than adjacent fault zones. Strike-slip slickenlines are common on north-striking, high-angle minor fault planes. Notably, the high-discharge Ponce de Leon warm springs are located at the intersection of the McGaffey and Embudo faults (Fig. 4).

Approximately 1.5 km east of the McGaffey fault is the kilometer-wide, west-down Rio Grande del Rancho fault zone, a complex family of branching faults along, and east of, the Rio Grande del Rancho valley. Most of the main strand of the fault zone is buried in the alluvial valley, but excellent exposures in the valley walls show extensive strike-slip breccia/fracture zones in Pennsylvanian strata. At the northern end of the valley Pennsylvanian bedding has been rotated into a vertical orientation along a west-down fault involving the Picuris Formation.

Embudo fault zone

The Embudo fault zone is a sinistral, antithetic transfer zone (see Faulds and Varga 1998) that forms the border between the west-tilted Española Basin and the east-tilted San Luis Basin of the Rio Grande rift. The 64-km-long fault links the west-down southern Sangre de Cristo fault with the east-down Pajarito fault and appears to be a high-angle fault with different senses of vertical separation along strike (Kelley 1978; Muehlberger 1979; Leininger 1982; Machette and Personius 1984; Kelson et al. 1997). The fault is thought to be part of the Jemez lineament, a regional structural/volcanic trend that may have been a zone of crustal weakness since late Precambrian time (Muehlberger 1979). Aldrich (1986) stated that major transcurrent movement occurred on the Embudo fault zone during the Pliocene and has subsequently slowed.

Machette et al. (1998) identified two sections of the fault based on a reversal of throw near the village of Embudo (Kelley 1978; Personius and Machette 1984). The 36-km-long northern section (the "Pilar section" of Machette et al. 1998) was mapped in detail by Kelson et al. (1997), Bauer and Kelson (1997), and Kelson and Bauer (1998). The fault section extends from a change in sense of vertical separation near the town of Embudo (Machette and Personius 1984) to an intersection with the Sangre de Cristo fault near the village of Talpa. Notably, the transition from the Embudo fault to the Sangre de Cristo fault is coincident with the Picuris–Pecos fault system and the Miranda graben. The northern Embudo fault is characterized by left-lateral slip (Muehlberger 1978, 1979; Steinpress 1980; Leininger 1982; Hillman 1986; Hall 1988; Bradford 1992; Kelson et al. 1997). Along the northern margin of the Picuris Mountains, the fault zone is as much as 2 km wide (Bauer and Kelson 1997). Muehlberger (1979) estimated that structural relief across the fault is at least 3,050 m.

The northern Embudo fault shows evidence of displacement possibly as young as late Pleistocene or early Holocene. Muehlberger (1979) and Personius and Machette (1984) noted faulted Pleistocene alluvium in a road cut near the village of Pilar. Our detailed mapping along the fault (Kelson et al. 1997; Bauer and Kelson 1997; Kelson and Bauer 1998) shows additional evidence of late Pleistocene displacement and identifies two localities where young, possibly early Holocene alluvial fans may be faulted.

In Proterozoic bedrock units the major strands of the Embudo fault are well-developed, high-angle, brittle deformation zones. Some are many tens of meters wide, typically consisting of central zones of intense strain (breccia, fault gouge, closely spaced fractures) flanked by wide zones of fractured rock. Fractures typically are open with only minor carbonate cementation. Commonly, the massive sandstone and conglomerate beds contain through-going fractures, whereas the interlayered, more ductile, shales are unfractured. In bedrock slickenlines are common and generally plunge gently westward on near-vertical fault planes (Fig. 5). Tracing the fault zone eastward into the Cañon section of the Sangre de Cristo fault, slickenlines plunge steeper and steeper until they are downdip on the west-dipping Sangre de Cristo fault. Where the fault is exposed in Tertiary rocks, the bedrock has been reduced to a clay-rich fault gouge that contains a strong tectonic foliation with clasts rotated into the foliation plane (Fig. 6). Away from the fault plane, the gouge zones grade into altered and fractured bedrock and then into relatively unstrained country rock. Where the faults cut Quaternary deposits, the alluvium is laced with thin, anastomosing, calcite-filled fracture veins (Fig. 7). Alteration zones are common, and gravel clasts are rotated into the foliation plane. However, the overall degree of deformation is considerably less in the Quaternary deposits than in older units.

An estimate of slip for the last 3 m.y. is based on the only known outcrop exposure of Servilleta basalt south of the Rio Grande in the Picuris Range (Bauer and Helper 1994). The

FIGURE 5—View south across the Rio Grande of Proterozoic quartzite that is highly faulted and fractured along the Embudo fault zone. The large, planar quartzite surface in photo center, above the scree slope, is a 10-m-long vertical fault plane that is strongly striated. Slickenlines plunge approximately 25° westward. Such faults with gently west-plunging slickenlines document north-down, sinistral strike-slip movement on the Embudo fault system.

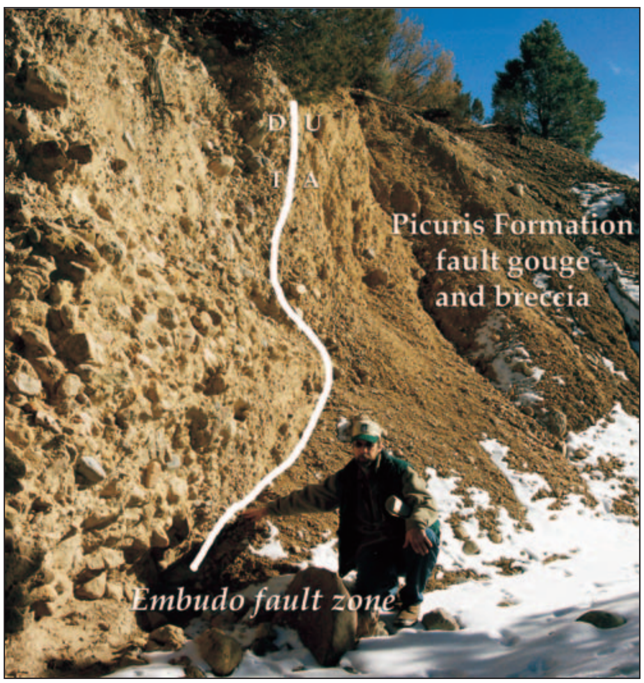


FIGURE 6—View east showing a strand of the Embudo fault south of the village of Llano Quemado. The view is along the fault plane, which separates Quaternary gravel on left from highly deformed Picuris Formation on right. The deformed zone is approximately 15 m (49 ft) wide, and consists of clay-rich fault gouge and tectonically imbricated clasts. The 3-m-wide (10-ft-wide) gouge zone characterized by extensive shearing and clast rotation grades into relatively undeformed Picuris Formation siltstone to the right edge of the photo.

small exposure is located in the Carson quadrangle on hill 7,094′ in T23N R10E S13. The base of the basalt remnant is at approximately 2,161 m elevation. It is not known with which flow it correlates to the north of the river, but for a minimum estimate of throw we can use the uppermost Servilleta unit at an elevation of 2,042 m. Assuming a 15° slickenline on a vertical fault, the minimum average slip rate is 0.15 mm/yr, with an uplift rate of 0.04 mm/yr, and a map

FIGURE 7—View east showing the style of deformation associated with the Embudo fault in middle(?) Pleistocene alluvial-fan deposits south of the village of Llano Quemado. The deformation consists of vertical calcite-filled anastomosing fractures and small-displacement faults.

separation of at least 480 m during the last 3 m.y. The average slip rate of 0.15 mm/yr can be compared with regional rates of late Quaternary rift extension, as compiled by Kelson and Olig (1995). Given a regional strike of N60°E for the Embudo fault, a sinistral net slip rate of 0.15 mm/yr contributes approximately 0.13 mm/yr of pure east-west extension. This value compares favorably with the estimated Quaternary slip rate of 0.03–0.26 mm/yr for the Sangre de Cristo fault and of 0.12 mm/yr for the Pajarito fault at the southwestern end of the Embudo fault. Thus a post-3 Ma estimated net slip rate of 0.15 mm/yr for the Embudo fault, based on geologic map relations, appears to be consistent with regional Quaternary strain rates in the northern Rio Grande rift.

Sangre de Cristo fault

The Sangre de Cristo fault is a west-dipping normal fault that forms the border between the Sangre de Cristo Mountains on the east and the San Luis Basin on the west. The southern Sangre de Cristo fault within Colorado and New Mexico is divided into five primary sections and many subsections based on fault-trace complexity and mountain-front and fault-scarp morphologic data (Menges 1988; Machette et al. 1998). From north to south these are the San Pedro Mesa, Urraca, Questa, Hondo, and Cañon sections (Machette et al. 1988). The northern three of these sections (i.e., the San Pedro Mesa, Urraca, and Questa sections) strike generally north-south and extend from Costilla Creek in southern Colorado to San Cristobal Creek about 25 km north of Taos. The boundary between the Questa and Hondo sections is at a large bedrock salient of the Sangre de Cristo Mountains. In contrast to the northern sections the Hondo section strikes about N30°W and extends to the Rio

Pueblo de Taos. The Cañon section strikes about N20°E, and extends from Rio Pueblo de Taos to Rio Grande del Rancho. Together the Hondo and Cañon sections of the southern Sangre de Cristo fault border a 30-km-long, 10-km-wide, crescent-shaped re-entrant in the Sangre de Cristo range block, herein referred to informally as the Taos embayment. Our research focused on the 14-km-long Cañon section between the Rio Pueblo de Taos and the Rio Grande del Rancho (Fig. 1), where the Sangre de Cristo fault intersects the Embudo fault (Machette et al. 1998; Kelson et al. 1997).

The southern Sangre de Cristo fault shows prominent geomorphic evidence of late Quaternary surface rupture including scarps across alluvial fans of various ages (Fig. 8), air-photo lineaments, springs, and alignments of vegetation. Machette and Personius (1984) and Personius and Machette (1984) profiled several scarps along the Cañon section, and suggested a Holocene age for the most recent movement. Kelson (1986) mapped late Quaternary deposits and some fault strands along this section and showed faulted late Pleistocene alluvial-fan deposits. Menges (1990) conducted detailed morphometric analyses of the range front and fault scarps and suggests the possibility of early Holocene to latest Pleistocene movement along the Cañon section. Our recent geologic mapping along the fault supports these previous age estimates. Based on scarp morphology data, Menges (1988, 1990) estimated a recurrence interval of about 10–50 k.y., and Quaternary slip rates ranging from 0.03 to 0.26 mm/yr.

Our mapping shows that the Cañon section is a complex system of branching faults that is as much as 2 km wide (Fig. 3). With the exception of the Rio Fernando area, fault scarps in Quaternary deposits are mostly confined to the mountain front where Quaternary deposits are in fault contact with Pennsylvanian rocks. Individual fault planes typically dip steeply west to northwest (Fig. 9) with slickenlines plunging moderately to steeply westward. The transition from strike-slip to dip-slip is gradational with a prevalence of oblique-slip (plus some strike-slip) faults in the bedrock just southeast of Talpa. In Pennsylvanian rocks near the Rio Grande del Rancho faults dip between 60° and 80° northwest with moderately west plunging slickenlines. North of the Rio Fernando, faults dip between 70° and 89° westward with generally downdip slickenlines. In general field measurements of Sangre de Cristo fault plane dips are consistently steeper than estimates based on geophysics in the northern San Luis Basin of 40-60° by Tandon (1992) and 60° by Kluth and Schaftenaar (1994).

Los Cordovas faults

Previous workers described a 5- to 8-km-wide zone of north-striking faults in the Taos Plateau (Lambert 1966; Machette and Personius 1984). The Los Cordovas fault zone consists of perhaps ten or more individual fault strands that generally are approximately 10 km long and have fairly regular spacings of 1.0–1.5 km. The western margin of the fault zone is roughly coincident with the east-down Gorge fault (Fig. 10) near the Rio Grande gorge. Where separation is greatest, these west-down faults juxtapose piedmont-slope alluvium against older Servilleta Formation basalt. Machette and Personius (1984) stated that the fault offset is greater than the 15–30-m-high erosional scarps that now define the surface expression and that faulting may be as old as early Pleistocene but could be as young as middle(?) Pleistocene (Fig. 11). Profiles of stream terraces along the Rio Pueblo de Taos suggest that the faults displace the early(?) to middle Pleistocene piedmont surface but not a middle Pleistocene terrace (Kelson 1986; Machette et al. 1998). Our mapping suggests that these faults may extend southward from the Rio Pueblo de Taos and may deform high alluvial-fan deposits that are derived from the Picuris Mountains.

FIGURE 8—View north (along strike) of a natural exposure of the Sangre de Cristo fault located about 2.5 km northeast of Taos. Late Quaternary coarse gravel exposed on left (west) has well-developed soil structure and carbonate morphology and is in fault contact with bedded alluvial-fan deposits on the right (east). The fault dips steeply to the northwest (N40°E, 80°NW). Topographic profiling of adjacent fault scarp indicates at least 6 m of net vertical surface displacement; presence of scarp bevel suggests recurrent late Quaternary movement.

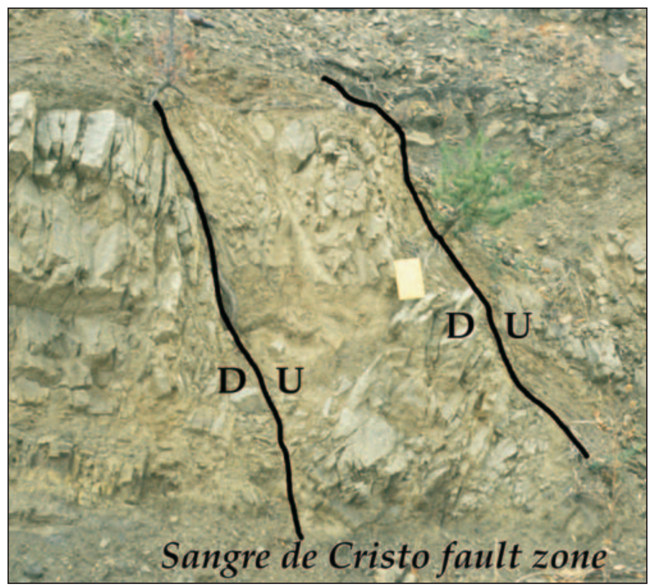
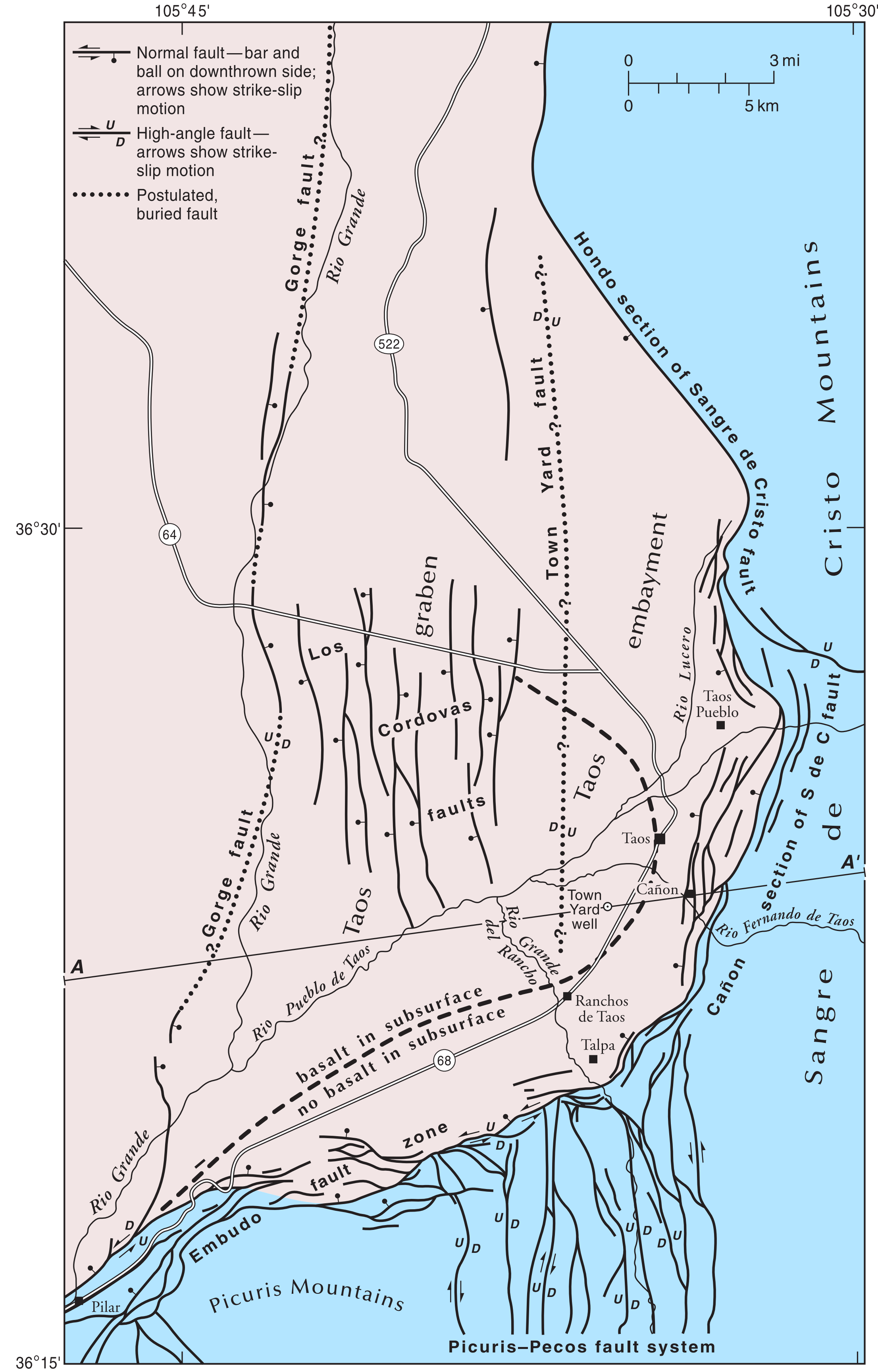


FIGURE 9—View north of a roadcut exposure of Sangre de Cristo fault deformation along U.S. Highway 64, 1 km southeast of the village of Cañon. Pennsylvanian sandstone and shale are highly fractured and contorted with brecciation and gouge formed along anastomosing fault planes. Field book for scale.

An excellent exposure of the eastern fault strand recently was found just north of the Rio Pueblo in an arroyo that cuts across the fault scarp. In the exposure Servilleta basalt and overlying Quaternary fan deposits are faulted on a plane that dips 45° west with downdip slickenlines, rotated cobbles, and minor synthetic and antithetic normal faults. Overlying young (Holocene) colluvial gravels are not faulted. A distinctive red to yellow faulted clay horizon that rests on the basalt is interpreted to be a lake deposit, based on clay mineral analysis (G. Austin pers. comm. 2001).

Taos graben

The Taos graben, which was first recognized by Cordell (1978) from gravity data as a major structural feature in the Taos area, is critical to deciphering the kinematic history of


105°45'
105°30'
36°30'
36°15'
Normal fault—bar and ball on downthrown side; arrows show strike-slip motion
High-angle fault—arrows show strike-slip motion
Postulated, buried fault
0 3 mi
0 5 km
Gorge fault
Rio Grande
Town Yard fault
Hondo section of Sangre de Cristo fault
Sangre de Cristo Mountains
Los Cordovas faults
Taos graben
Taos embayment
Rio Lucero
Taos Pueblo
Taos
Cañon
Town Yard well
Rio Fernando de Taos
Cañon section of S de C fault
Rio Grande del Rancho
Rio Pueblo de Taos
Ranchos de Taos
Talpa
basalt in subsurface
no basalt in subsurface
Embudo fault zone
Picuris Mountains
Picuris–Pecos fault system
Pilar
522
64
68
A
A'
U
D

the southern San Luis Basin. At the latitude of Taos the north-south graben is approximately 13 km wide and over 5,000 m deep (Keller et al. 1984). The western edge of the graben is a buried fault zone (the Gorge fault) that is approximately coincident with the Rio Grande gorge (Fig. 12). The Dunn Bridge fault, which is exposed in the gorge near the Dunn Bridge, is a normal, east-down, north-striking, 35-m-high scarp that has formed in the last 3.5 m.y. (Dungan et al. 1984). An unnamed east-down fault mapped by Kelson and Bauer (1998) lies along the southern extension of the Dunn Bridge fault. This fault branches from the Embudo fault near Pilar and coincides with a change in strike of the Embudo fault from east-west to northeast–southwest (Kelson et al. 1997). This fault branch probably marks the southern intersection of the Taos graben against the Embudo transfer zone.

The eastern edge of the Taos graben correlates with mapped and inferred structures of the Sangre de Cristo fault zone. Gravity data, as interpreted by Reynolds (1992), show a complex eastern fault zone that generally steps down into the graben. Reynolds (1986, 1992) also performed shallow seismic reflection surveys over parts of Taos Pueblo and interpreted a complex system of buried faults along the Cañon section of the Sangre de Cristo fault zone including some small-scale horst and graben geometries. Drill hole evidence exists for a southward extension of such structures. In 1996 the "Town Yard" exploration well (Fig. 3) encountered Pennsylvanian limestone, shale, and sandstone from a depth of 219 m to the bottom of the hole at 311 m. Before this well was drilled no control points existed for the location of the Paleozoic section in the Taos Valley. Because the well is located nearly 3 km from the nearest surface exposures of Pennsylvanian rocks, the Town Yard well shows that Paleozoic strata exist in the subsurface of the basin and, in places, at shallow depths. The presence of abundant fossiliferous limestone in the well cuttings suggests that the rocks encountered at depth might come from higher in the Pennsylvanian section, perhaps in the upper Flechado Formation or the overlying Alamitos Formation. If so then Proterozoic Basement could be as much as several thousand meters deeper, because the Alamitos Formation can be over 1,219 m thick. Based on this information we speculate that there is north-northeast-trending, subsurface structural bedrock high (informally called the Town Yard bench) beneath the eastern part of the Taos Plateau. We do not know the exact configuration of the structural bench and have shown a speculative location on Figures 10 and 12. However the western margin of this bench likely represents the eastern margin of the Taos graben as suggested by regional gravity data (Keller et al. 1984).

FIGURE 10—Speculative tectonic map of the southeastern San Luis Basin showing mapped structures and inferred subsurface structures related to Laramide and rift-related deformation. The inferred Gorge fault connects known Pliocene/Pleistocene-age faults along the Rio Grande gorge, and corresponds with the western geophysical expression of the Taos graben. The Town Yard fault zone corresponds with eastern geophysical expression of the Taos graben and is constrained to the east by the shallow Pennsylvanian rocks encountered in the Town Yard well. The "basalt/no basalt" line is based on the occurrence of basalt in well records and represents the approximate extent of Servilleta Formation basalt flows. The Taos graben is interpreted as the Pliocene/Pleistocene expression of the Picuris–Pecos fault system. The Los Cordovas faults are interpreted as the surface expression of a section of rift-reactivated Picuris–Pecos fault system, offset westward by rift-related extension. The crescent-shaped Taos embayment is interpreted as a shallow rift sub-basin that formed when the rift margin migrated eastward, perhaps related to activity on the Embudo fault system. The Los Cordovas faults are approximately located based on the 1:250,000-scale map of Machette and Personius (1984).

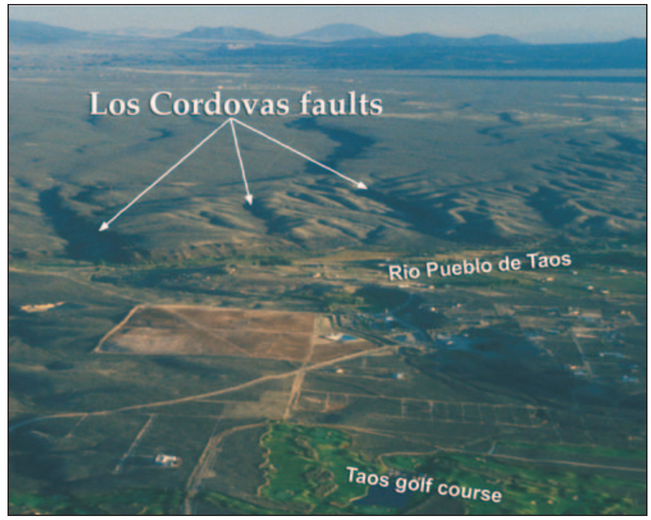


FIGURE 11—Early morning, low-altitude, oblique aerial view (looking north) of the surface expression of Los Cordovas faults on the Taos Plateau. The Rio Pueblo de Taos flows from right to left across the lower half of the photo with agricultural lands occupying its young river terraces. The several north-trending west-facing scarps (in shadow) represent offset of Servilleta Formation basalt and old alluvial-fan deposits (unit Q1p of Kelson 1986) that are offset by the sub-parallel series of west-down Los Cordovas faults. The older alluvial-fan deposits overlie basin-fill alluvium that pre-dates the present-day location and elevation of the Rio Grande and may have been deposited in a pre-incision closed basin.

The Taos graben was mostly formed by the time the lower Servilleta basalt erupted about 4.5 m.y. ago. On the Taos Plateau the Rio Grande was superposed on the plateau after eruption of the youngest Servilleta basalts (ca 3 Ma) and began to rapidly entrench upon integration of the river system at about 0.5 Ma (Wells et al. 1987). Although most of the high-angle faults on the plateau did not cause thickening or thinning of volcanic flows across the faults, evidence exists for active rift faulting during the time that the Servilleta basalts were erupted and the interlayered Chamita sediments were accumulating (Peterson 1981; Dungan et al. 1984). A notable example is found at the Dunn Bridge fault where the thickness of the sedimentary interval between the middle and upper basalts varies 17 m across the fault.

Discussion and speculations

Collectively, available geologic and geophysical data provide a basis for interpreting the kinematic histories of the major faults in the southeastern San Luis Basin and for speculating on the transition from Laramide deformation to Neogene rifting in the Taos area and on the evolution of accommodation zones within this major rift basin. First, available data suggest that the Picuris–Pecos fault system is present on the northern side of the Embudo fault and has been reactivated by later episodes of rift-related deformation. The five north-south faults within the Picuris–Pecos fault system in the southern map area form a 8-km-wide zone of high brittle strain in rocks that range in age from Early Proterozoic to less than about 18 Ma. This concentrated zone of high-angle faulting probably has had a long history of reactivation as both strike-slip and dip-slip/oblique-slip systems (Bauer and Ralser 1995). Thus because these faults are cut by the Embudo fault, they pre-date the Embudo system and, importantly, most likely exist in the subsurface north of the active Embudo fault. Because the older members of the Picuris Formation are restricted to the structurally low areas within the fault system, we suggest

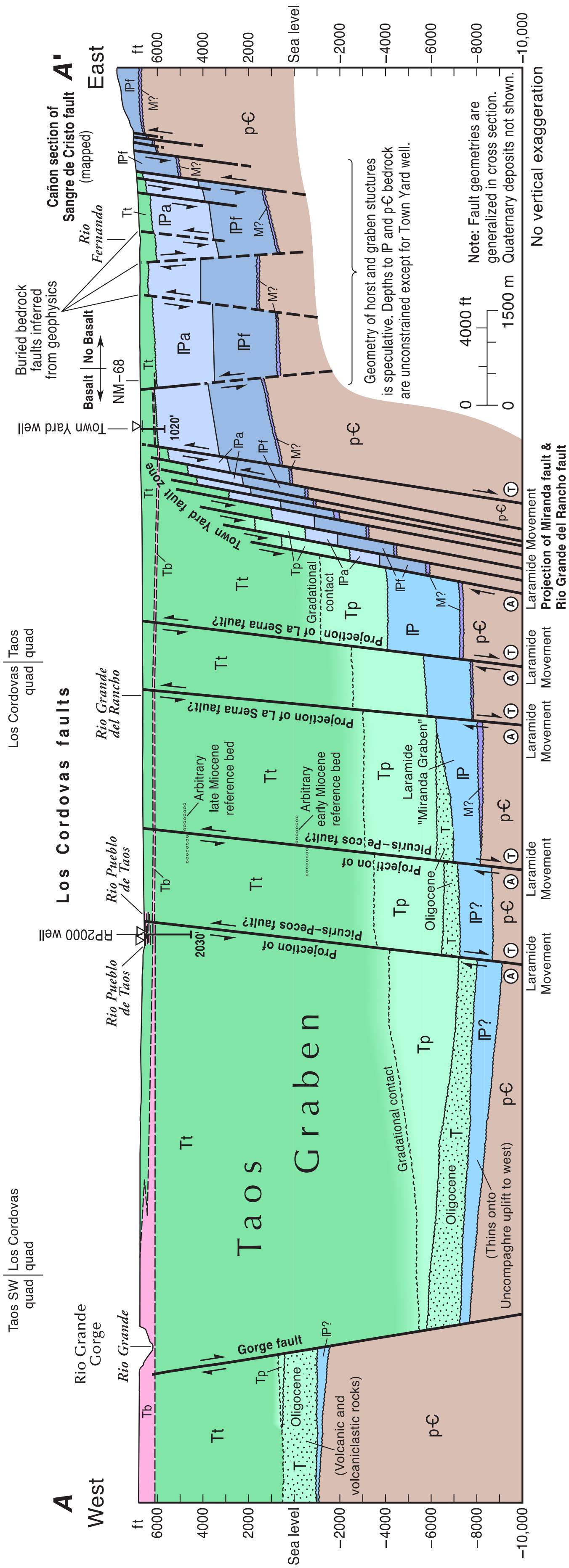


FIGURE 12—Speculative west-east cross section **A-A′** across Figure 10. The section shows a prominent Taos graben with a strongly fault dissected eastern shoulder (the Taos embayment), and a speculative faulted western shoulder across the Gorge fault. The thickness of Tertiary basin fill and depth to bedrock is based on geophysically derived estimates by Keller et al. (1984). The Los Cordovas faults are interpreted as reactivated structures that were primarily strike-slip faults during Laramide time and normal growth faults during rifting. **p€**= Proterozoic rocks; **M** = Mississippian rocks; **IP**= Pennsylvanian rocks; **IPf** = Pennsylvanian Flechado Fm; **IPa** = Pennsylvanian Alamitos Fm; **T** Oligocene = Oligocene volcaniclastic rocks; **Tp** = Upper Picuris Fm; **Tt** = Tesuque Fm and younger units; **Tb** = Servilleta Formation basalt.

that the Picuris–Pecos fault zone defined the Eocene(?) to early Miocene Miranda graben, which served as a locus of deposition for volcaniclastic sediments transported southward into the graben. At least parts of the graben remained low during the Neogene, preserving rocks of the Picuris Formation. Thus because the faults bordering the Miranda graben are older than the Embudo fault system, the graben most likely extends northward into the basin. If so, the Picuris Formation may exist in a buried part of the Miranda graben on the northern side of the Embudo fault, beneath late Tertiary and younger sediments in the Taos embayment.

Within the Picuris–Pecos fault system, faults that cut the youngest part of the Picuris Formation exhibit prominent kinematic evidence of dextral strike-slip movement. Because the rocks deformed by this strike slip are younger than the initiation of rift extension (about 27 Ma, Brister and Gries 1994), early rifting in this area included some component of dextral slip. Thus because the Embudo fault cuts these faults, we speculate that the north-striking faults represent pre-Embudo fault rift activity. Furthermore, preliminary mapping 20 km to the south has found that the Picuris–Pecos fault system displaces both Picuris Formation and a small Pliocene (5.4 Ma) basalt flow, indicating that Neogene slip on the Picuris–Pecos fault is not restricted to the area of the Embudo fault.

We highlight the similarity between the number and spacing of faults within the Picuris–Pecos fault system and those of the Los Cordovas fault zone. As noted above both fault zones contain multiple north-striking, near-vertical faults that are spaced at fairly regular intervals of approximately 1–1.5 km (Fig. 1). In addition the north-striking Los Cordovas faults coincide with the central, deepest part of the Taos graben, just as the Miranda and La Serna faults border the Miranda graben. It seems likely that, if the Picuris–Pecos fault system extends north of the Embudo fault and is buried beneath young sediments in the southern San Luis Basin, east-west extension during early phases of rifting would have capitalized on the existing weak fault zones of the Picuris–Pecos fault system. Thus we speculate that the Picuris–Pecos, La Serna, Miranda, McGaffey, and Rio Grande del Rancho faults likely project into the southern Taos embayment on the northern side of the Embudo fault. In addition we propose that the faults within the Los Cordovas fault zone may reflect reactivation of the faults within the Picuris–Pecos fault system. In this scenario faults within the Picuris–Pecos fault system may have controlled the geometry of the Taos graben during rifting. West-down movement on the Los Cordovas faults probably was related to late Cenozoic rifting with the extensional strain occurring along pre-existing zones of crustal weakness formed during Laramide (and earlier?) deformation. In Figure 12 we show the major strands of the Picuris–Pecos fault system as major Laramide rift-reactivated growth faults that shallow into the Pleistocene Los Cordovas faults.

We also note that the Questa section of the Sangre de Cristo fault, which is located north of the Taos embayment, projects southward toward the Picuris–Pecos fault system (Fig. 1). Based on this observation, we suggest that the eastern edge of the San Luis Basin during the early phases of rifting occurred along the San Pedro Mesa, Urraca, and Questa sections of the Sangre de Cristo fault along the (now-buried) sections of the Picuris–Pecos fault system presently buried beneath young sediments near Taos and along the Picuris–Pecos fault presently exposed south of the Embudo fault. At some time (possibly the middle Miocene?) the Embudo fault zone and the Cañon and Hondo sections of the Sangre de Cristo fault developed, and the faults of the Picuris–Pecos fault system north of the Embudo fault foundered and became less active. In this scenario the eastern margin of the Rio Grande rift essentially migrated eastward approximately 10 km to its present location at the base of the Sangre de Cristo mountain range forming the Taos embayment. Minor west-down movement has continued along the Los Cordovas fault zone as a result of distributed extension within the San Luis Basin block.

Previous workers have suggested that the Embudo fault is a relatively young rift feature that corresponds with the initial uplift of the Picuris Mountains in the late Miocene (Manley 1978; Ingersoll et al. 1990). Our mapping shows that there is not a distinct boundary between the Embudo fault zone and the Cañon section of the Sangre de Cristo fault with both faults merging gradually in the Talpa area. Both of these faults exhibit evidence of repeated Pleistocene movement and possible Holocene activity (Kelson et al. 1997) and appear to be kinematically linked. Our current working hypothesis is that the crescent-shaped Taos embayment, defined by the Cañon and Hondo sections on the east and the eastern edge of the Taos graben on the west, formed in partnership with the Embudo transfer zone during early Miocene time. If so the pre-early Miocene eastern edge of the rift was defined, from north to south, by the Sangre de Cristo fault zone north of the Rio Hondo, the buried eastern edge of the Taos graben (i.e., Town Yard fault) and the Picuris–Pecos fault system.

Lipman and Mehnert (1979) placed the beginning of rifting at 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. In a regional study of Cenozoic faulting, Erslev (1999) concluded that the latest phase of north-south strike-slip faulting is post-25 Ma in central and northern New Mexico. Kinematic indicators along the Picuris–Pecos fault system where it cuts the Miocene Picuris Formation show that appreciable strike-slip faulting was occurring in the Taos area less than 18 m.y. ago. The evidence of strike-slip on these faults is indistinguishable from strain formed during the Laramide deformation in the region and appears to be concentrated on older, reactivated north-south faults. We therefore propose that in the southeastern San Luis Basin, the transition from Laramide shortening to rift extension is indistinct, and that at least some Laramide strike-slip faults evolved into rift-related normal faults. The contemporaneous occurrence of strike-slip and normal faulting may suggest that either the initiation of rift extension began earlier in the northern San Luis Basin, or that the region may have experienced overall transtension perhaps with lateral slip partitioned onto some faults and extension partitioned onto other faults. Lastly Chapin and Cather (1994) stated that rates of extensional strain in the rift increased in the middle Miocene. Perhaps that change—due to some fundamental change in lithospheric processes—corresponded with the last gasp of Laramide-style tectonics and allowed normal faulting to dominate the regional deformation. We speculate that this change might have also triggered the development of the Embudo fault as a transfer zone within the rift and, as another consequence, development of the Hondo and Cañon sections of the Sangre de Cristo fault along the present-day range front.

In summary, the three major fault systems in the Taos area are more geometrically complex than described in previous literature. The Picuris–Pecos fault is actually only the western strand of an 8-km-wide (brittle deformational zone herein named the Picuris–Pecos fault system. The fault system is a repeatedly reactivated crustal flaw that was a locus for south-transported Laramide sediments (Picuris Formation) from about 35 Ma to 18 Ma, and possibly later. The faults most likely exist in the basement of the basin west of Taos. The Pleistocene Los Cordovas faults may be westward-transported remnants of the Picuris–Pecos fault system. The Picuris–Pecos faults may also define the structural boundaries of the Taos graben. The Picuris–Pecos fault system is truncated by the Embudo transfer fault, which merges into the Sangre de Cristo fault. During early extension, before development of the Embudo fault, the Picuris–Pecos fault system and its now-buried northward extension may have represented the eastern rift margin along with the Questa section of the Sangre de Cristo fault and the Town Yard fault. At some later time (mid-Miocene?) as the Embudo transfer fault developed, the Sangre de Cristo fault jumped eastward to the Cañon and Hondo sections forming the Taos embayment and the Town Yard structural bench that underlies Taos.

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