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CENOZOIC STRUCTURAL DEVELOPMENT OF THE TAOS AREA, NEW MEXICO

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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 deposits younger than about 5 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 throw rate of 35 m/m.y. and a minimum average net slip rate of 130 m/m.y. 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, 5000-m-deep Taos graben. We speculate that this graben may be the sinistrally displaced equivalent of the Miranda and Rio Grande del Rancho grabens. 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 million years ago, well past the 27 Ma onset of extension in the San Luis Basin. During early extension, prior to 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 is indistinct, 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 initial development of the modern 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: 1) Excellent exposures of an active rift boundary (the Sangre de Cristo fault); 2) the best-exposed accommodation zone of the Rio Grande rift (the Embudo fault); 3) good exposures of the most impressive Laramide fault zone in the state (the Picuris-Pecos fault system); 4) a unique and illuminating zone of intersection among these three fault systems, and; 5) 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. Prior to 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 1:24,000 scale geologic maps of the Carson, Taos SW, Ranchos de Taos, Taos, and Los Cordovas 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: 1) 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? 2) What do field relations among the three fault systems suggest about the transition from Laramide shortening to Neogene extension? 3) 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 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 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 to 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, hydrogeology). This approach allowed us to infer subsurface stratigraphy and structure over the region, and then 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 numerous 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 (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 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 towards the edge of the basin.

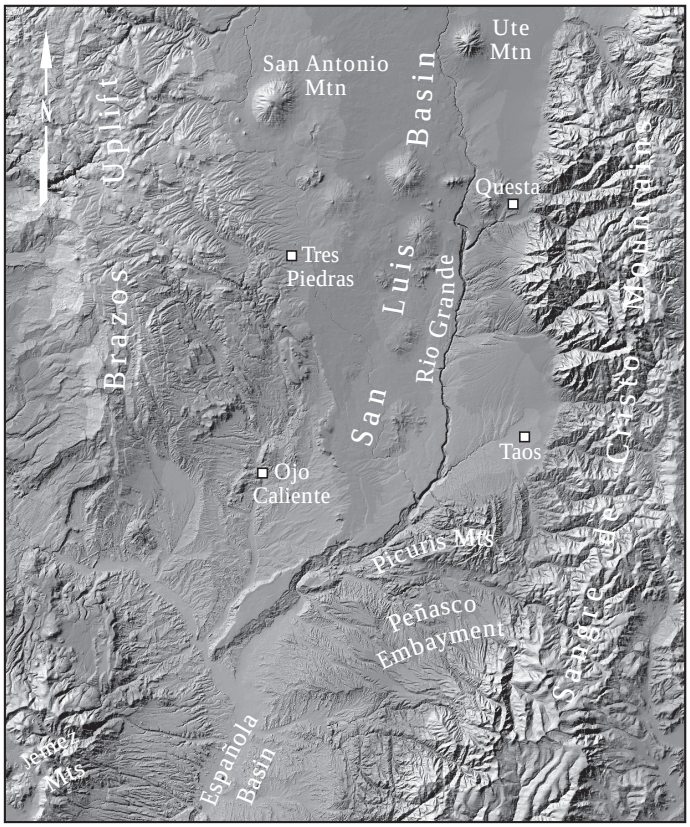


FIGURE 1. Digital shaded-relief index map of the northern Rio Grande rift in New Mexico, showing major tectonic features and the study area.

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 along the eastern basin margin 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 >5km 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., 1996, 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 early-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 are 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 (Fig. 3). 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 rocks, 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 (Fig. 3). 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 portion 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 towards the former Uncompahgre uplift in a simple wedge.

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 study area is the Picuris Formation, a local package 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 believe that some of his correlations are tenuous due to several new, intriguing isotopic ages and the intensity of previously unrecognized faulting of the area (Fig. 4). Although the Llano Quemado breccia is an excellent marker bed, it clearly has limited original lateral extent and it crops out in the Talpa area as a scattering of fault-bounded exposures that complicate straightforward stratigraphic reconstructions. We have retained Rehder's general stratigraphy only along the northern flank of the Picuris Mountains.

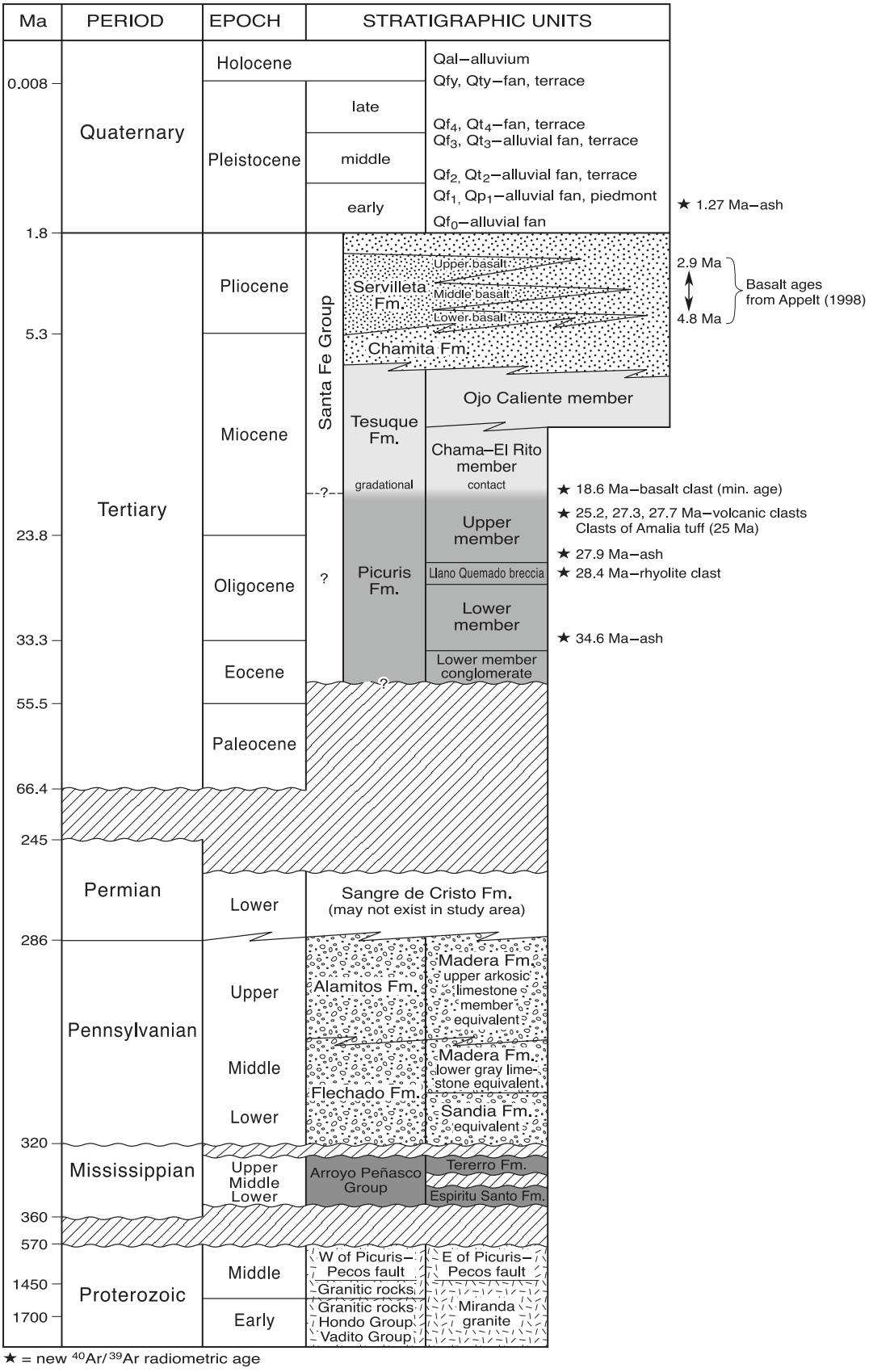


FIGURE 2. Composite stratigraphic section for the Taos/Talpa area, north-central New Mexico. New $^{40}Ar/^{39}Ar$ radiometric ages are listed on right.

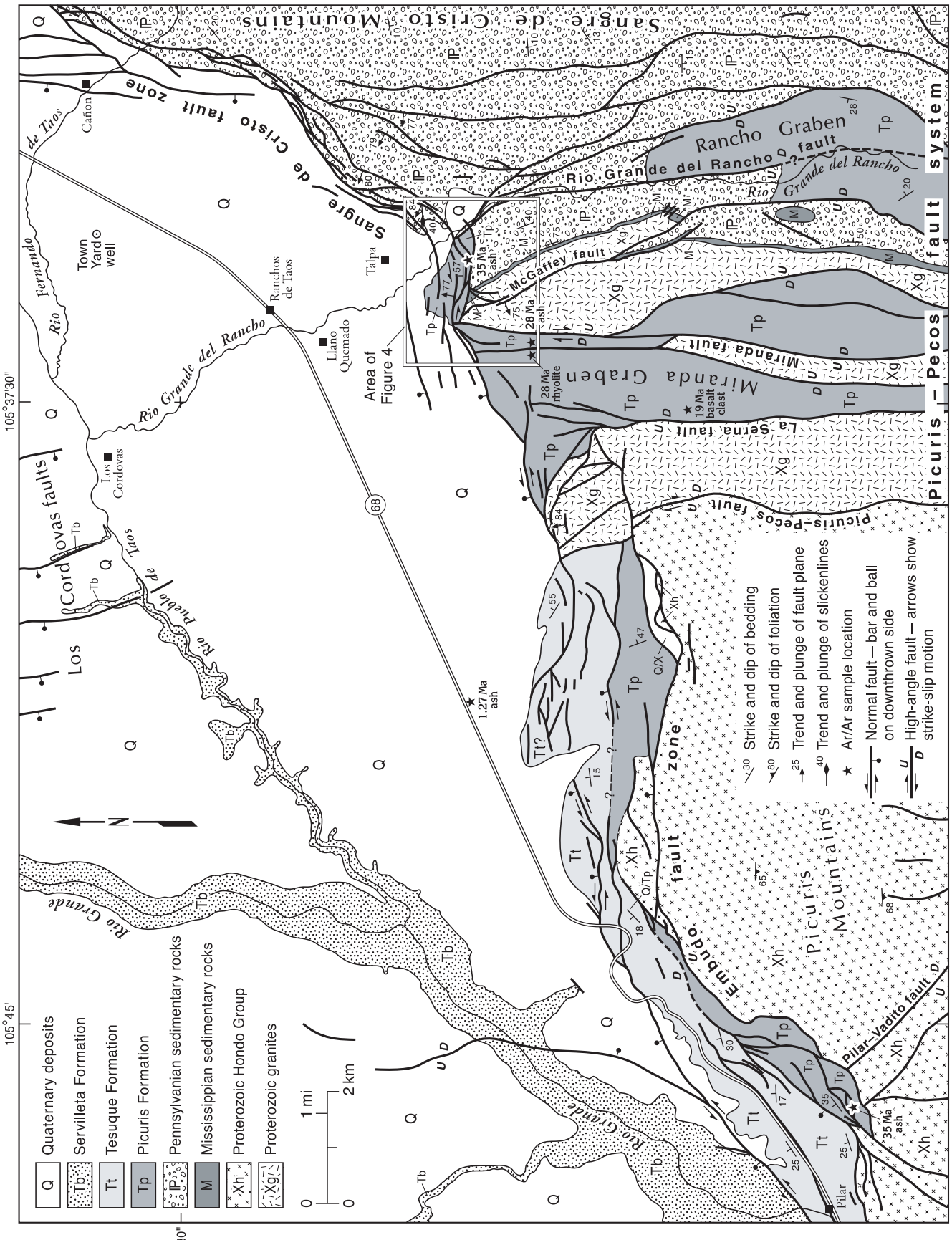


FIGURE 3. Generalized geologic map of the southern Taos Valley, New Mexico. This compilation is based on 1:12,000 scale maps of the Ranchos de Taos quad (Bauer and Kelson, 1999), Taos SW quad (Bauer and Kelson, 1997), Carson quad (Kelson and Bauer, 1999), Taos quad (Bauer and Kelson, 2000), and Los Cordovas quad (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.

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 (34.64±0.16 Ma $^{40}Ar/^{39}Ar$ age) 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 Questa/Latir volcanic field to the north and northeast (Rehder, 1986). However, the deposit (34-28 Ma, based on dates of ash layers in the study area) cannot be older than the source (ca. 26 Ma for the Questa/Latir field), and therefore, the volcanic component of the unit was probably derived from the older San Juan volcanic field to the north and northwest.

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. A rhyolite clast has yielded an 40Ar/39Ar eruptive age of 28.35±0.11 Ma. The unit 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 cross-bedding 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, polylithologic, ash-rich, conglomeratic sandstone that crops out in the western map area, in the Miranda graben. 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 up to 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). A new ca. 18 Ma radiometric age of a basalt clast in this unit suggests that the upper member likely accumulated until at least 18 m.y.a. 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.

Santa Fe Group

Because the Santa Fe Group is not exposed in the study area, the nature of the unit here is unknown. Borehole data in the San Luis Basin indicate that relatively thin Quaternary deposits are underlain by thick Tertiary sands and gravels. Cuttings from deep exploration boreholes in the Taos area suggest the presence of Tesuque-like deposits, such as the Chamita, Ojo Caliente, and Chama-El Rito members, in the subsurface (P. Drakos, personal commun., 2000). At present, due to 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 (1570 ft) (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, 1999). 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, 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 (Fig. 3) penetrated what appears to be a 650-ft interval of primarily Ojo Caliente sands (Drakos and Lazarus, 1998).

In late Miocene time, high-angle rift faulting produced deep, narrow, fault-bounded basins that filled with kilometers of clastic sediments and volcanic rocks. In the Taos/Pilar area, the clastic sediments are named the Chamita Member of the Tesuque Formation, and the volcanic unit is named the Servilleta Formation. However, based on recent mapping to the west, D. Koning (personal commun., 2003) believes that the Chamita name should be abandoned in both the San Luis and Española Basins. The thickness of this basin fill 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 formation contacts based solely on well cuttings. The thickness has been estimated to range from 100 to 230 m (330 to 750 ft) 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" below the lower Servilleta basalt was estimated to be 284 m (930 ft) (Drakos and Lazarus, 1998).

Low-relief 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 up to 12 m thick, are grouped into packages 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 package consists of two sets of flows totaling 51 m, that locally are separated by up to 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 packages, 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 basalt flows from 4.81+/-0.04 to 3.12±0.13 Ma at the Gorge Bridge where US-64 crosses the gorge, and from 4.33±0.02 to 2.93±0.14 Ma at the Dunn Bridge near Arroyo Hondo (Appelt, 1998). Based on our field mapping and a single problematic $^{40}Ar/^{39}Ar$ age of 2.7±0.79 Ma for a basalt near the Taos airport, we suspect that there exist both younger basalt flows and additional vents east of the Rio Grande gorge.

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 late Pliocene(?) to Holocene. In the southwestern part of the study area, high alluvial fans derived from the Picuris Mountains interfinger with alluvial terrace deposits along the Rio Grande del Rancho north of Talpa (Fig. 3). 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 smaller, 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 down-valley 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.

Between the Rio Pueblo de Taos and Arroyo Hondo, the Servilleta basalt is overlain unconformably by fine-grained deposits (the Blueberry Hill deposits of Kelson and Bauer, 2003) 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 sediments are probably early to middle Pleistocene in age, and appear to have been extensively saturated by a high water table throughout much of the eastern Taos Plateau. These deposits most likely were deposited prior to the development of the Rio Grande gorge (Wells et al., 1987), and reflect alluviation on the plateau prior to regional incision and the resulting drop of the water table.

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:

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 was likely;

3) During the Laramide orogeny, at least 26(?) km of right-slip occurred on the Picuris-Pecos fault (Miller et al., 1963), 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 appear to have developed contemporaneously on different fault strands (Bauer and Ralser, 1995);

4) During the Neogene, rift-related faulting occurred in the Santa Fe Range, rather than the Picuris Mountains, perhaps due to 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.

5) In addition, based on our mapping in the Peñasco quadrangle, we would add that at least part of the Picuris-Pecos fault system was active into the Pliocene. This is based on the offset of 5.6 Ma basalt and an overlying gravel deposit north of the Village of Vadito.

Near its northern end, south of Taos, the Picuris-Pecos fault consists of five major, 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 due to 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 packages. West of the fault is the Hondo Group, a metasedimentary terrain of quartzite and schist. East of the fault is a distinctive medium-grained, orange-yellow 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 upper Picuris Formation is cut by high-angle faults with sub-horizontal slickenlines within the Miranda and La Serna fault zones, suggesting that strike-slip faulting occurred during the Neogene, a time that 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 that involves 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 (Fig. 1). 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., 1996, 1997, 2004a). 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 (1999). 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 its Laramide grabens. The northern Embudo fault is characterized by left-lateral slip (Muehlberger, 1979; Steinpress, 1980; Leininger, 1982; Hillman, 1986; Hall, 1988; Bradford, 1992; Kelson et al., 1997, 2004a). 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

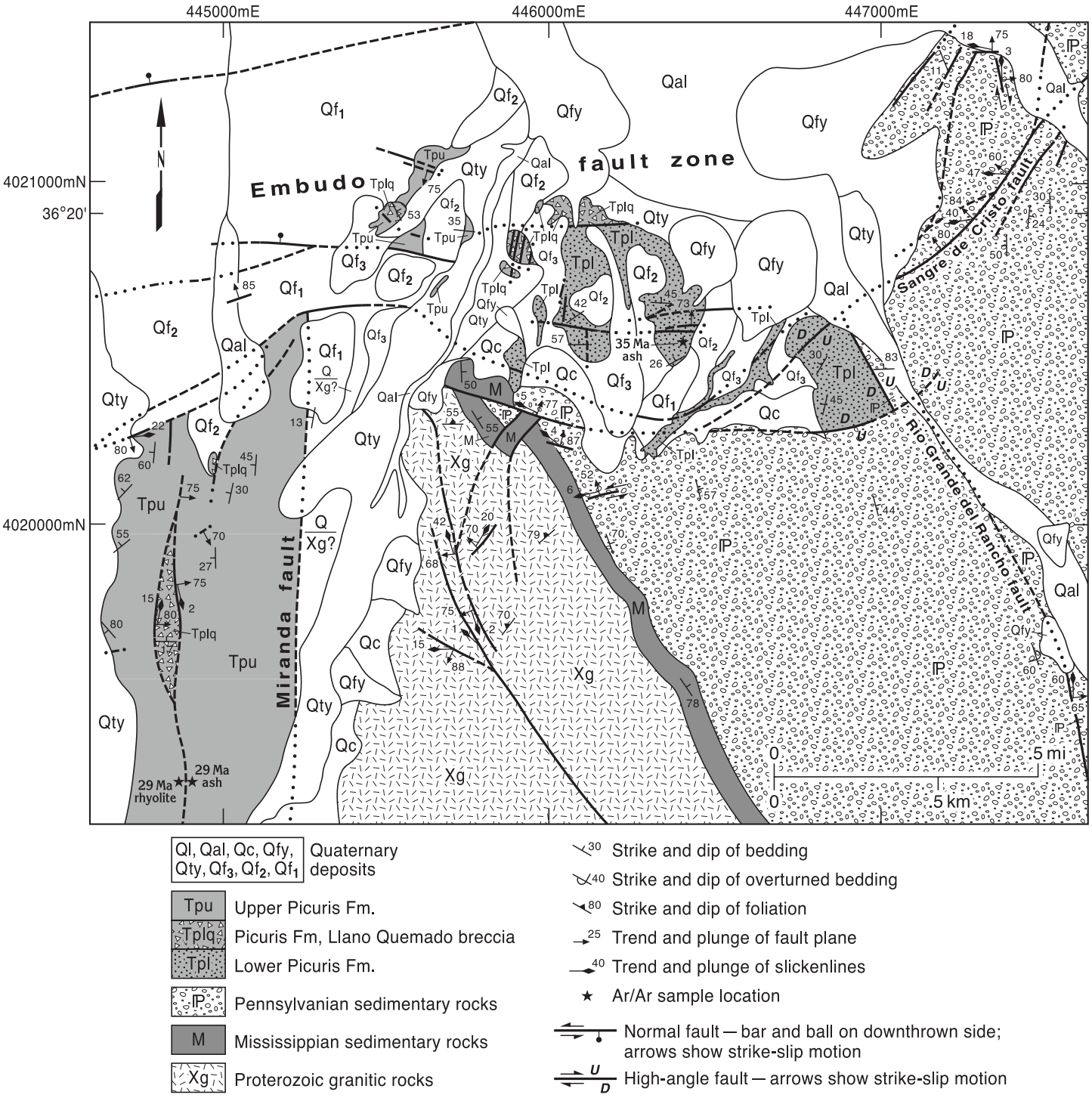


FIGURE 4. Detailed geologic map of the Talpa area, where the Embudo, Picuris-Pecos, and Sangre de Cristo fault systems intersect. The zone of intersection consists of highly faulted blocks of Proterozoic through Tertiary rocks. The transition zone from the Embudo fault system to the Sangre de Cristo 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 1:6000 mapping in the Ranchos de Taos quadrangle conducted in 1999.

3050 m (10,000 ft).

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 thoroughgoing 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.

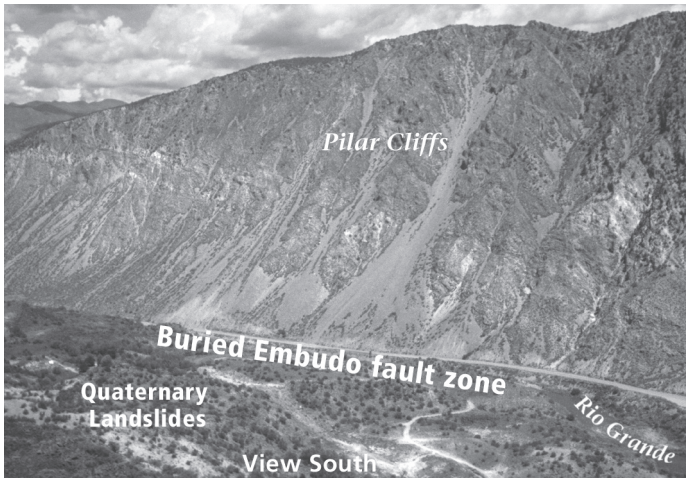


FIGURE 5. View southeast from the Taos Plateau volcanic field, across the Embudo fault zone and Rio Grande, to the Proterozoic rocks of the Pilar cliffs that are highly faulted and fractured. The faults typically display gently west-plunging slickenlines that document north-down, sinistral strike-slip movement on the Embudo fault system. The principle faults are buried beneath the Rio Grande alluvium, scree slopes, and Quaternary landslides such as those in the foreground.



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 wide, and consists of clay-rich fault gouge and tectonically imbricated clasts. The 3-m-wide gouge zone, characterized by extensive shearing and rotated clasts, grades into relatively undeformed Picuris Formation siltstone past the right edge of the photo.

New estimates of an average slip rate on the Embudo fault zone and an average, east-west, extension rate across the southern San Luis Basin of the Rio Grande rift for the last 3 Ma produce values of 96 m/m.y. and 88 m/m.y., respectively. The estimates were made by measuring the vertical offset of ca. 3 Ma Servilleta Formation basalt flows across the Embudo fault zone southwest of the Village of Pilar, and determining an average slip vector for that stretch of the fault zone. The value compares favorably with a previous estimate of 0.13 mm/yr of Quaternary slip on the southern San Luis Basin that was made by adding slip rates on the Sangre de Cristo and Los Cordovas faults (Kelson and Olig, 1995).

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 numerous 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., 1998). The northern three of these sections (i.e., the San Pedro Mesa, Urraca, and Questa sections)

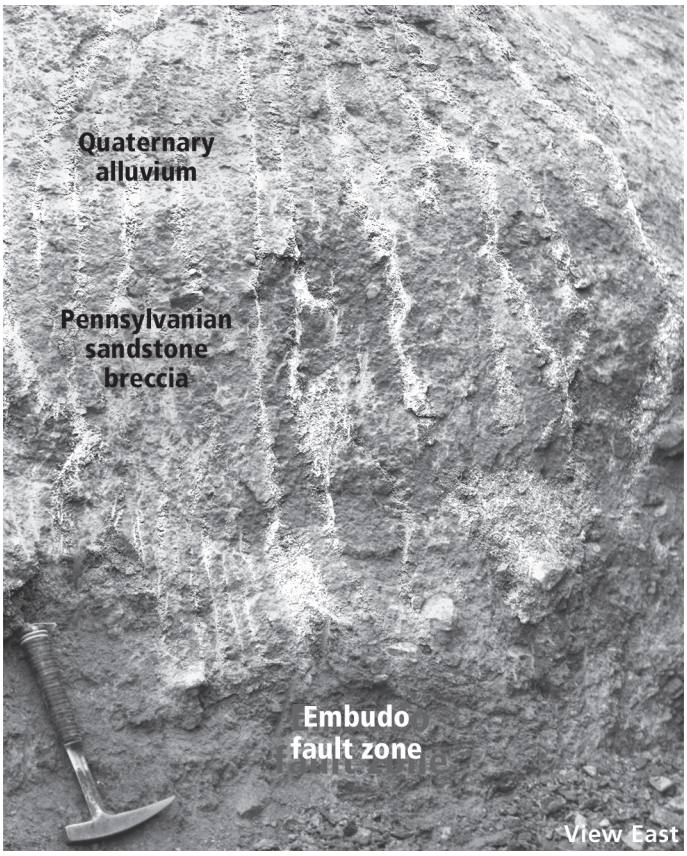


FIGURE 7. View east showing the style of deformation associated with the Embudo fault in middle(?) Pleistocene alluvial-fan deposits, south of the village of Llano Quemado. The deformation consists of vertical, calcite-filled anastomozing fractures and small-displacement faults. The dark rock at bottom is highly deformed and altered Pennsylvanian sandstone.

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.

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 suggested 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. Progressively greater amounts of displacement of older alluvial fan surfaces suggest that the fault has produced multiple surface ruptures within the past several tens of thousands of years or more. In addition, a distinct bevel in the scarp profile near Taos Pueblo suggests the occurrence of two late Pleistocene surface ruptures, each with about 1.5 m of vertical displacement. These displacements are consistent with large earthquakes having magnitudes in the range of **M**6.5 to **M**7.5 (Kelson et al., 2003, 2004b). A trench exposure across a primary fault strand near Taos Pueblo suggests that the most-recent surface rupture along the southern Sangre de Cristo fault occurred about 10,000 to 30,000 years ago (Kelson et al., 2003, 2004b). Based on scarp morphology data, Menges (1988, 1990) estimated a recurrence interval of about 10 to 50 ka, and Quaternary slip rates ranging from 30 to 260 m/m.y.

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, 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 60-80° northwest with moderately west-plunging slickenlines (Fig. 9). North of the Rio Fernando, faults dip between 70-89° westward with generally downdip

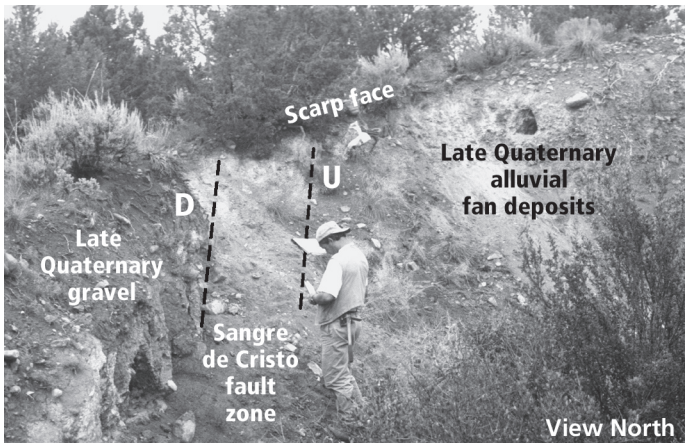


FIGURE 8. View north (along strike) of a rare exposure of the Sangre de Cristo fault located about 2.5 km northeast of Taos. Late Quaternary coarse gravel exposed on left (west) has well-developed soil structure and carbonate morphology, and is in fault contact with bedded alluvial-fan deposits on the right (east). The fault dips steeply to the northwest (80˚ towards azimuth 310˚). Topographic profiling of an adjacent fault scarp indicates at least 6 m of net vertical surface displacement, and the presence of scarp bevel suggests recurrent late Quaternary movement.

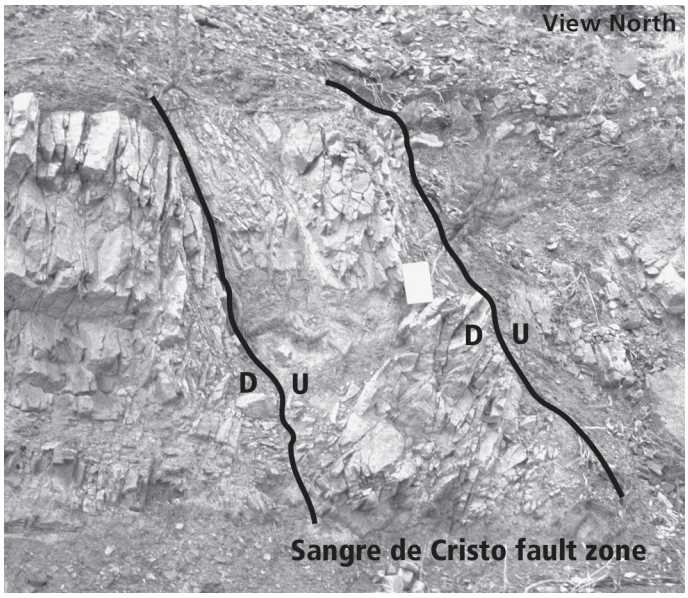


FIGURE 9. View north of a roadcut exposure of Sangre de Cristo fault deformation along US-64, 1 km southeast of the village of Cañon. Pennsylvanian sandstone and shale are highly fractured and contorted, with brecciation and gouge formed along anastomozing fault planes. Field book for scale.

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 10 or more individual fault strands that generally are about 10 km long and have fairly regular spacings of 1.0 to 1.5 km (Fig. 1). 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 (Fig. 11). Machette and Personius (1984) reported that the fault offset is greater than the 15- to 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. 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. In addition, there is some suggestion that the newly released high-resolution aeromagnetic map of the study area shows a buried structural link between the Picuris-Pecos fault system and the Los Cordovas faults (T. Grauch, personal commun., 2003).

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 Holocene colluvial gravels are not faulted. A distinctive red to yellow faulted clay horizon that rests on the basalt. Laboratory analysis has shown that the material is very fine grained, sticky but not bentonitic, well-crystalline, very clean with minor quartz, and composed mainly of illite and smectite (G. Austin, personal commun., 2001). It probably represents a lake deposit that was derived from altered volcanic rocks.

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 the southern San Luis Basin. At the latitude of Taos, the north-south graben is approximately 13 km wide, and filled with over 5000 m of basin fill (16,400 ft) (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. 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 Ma (Dungan et al., 1984). An unnamed east-down fault mapped by Kelson and Bauer (1999) 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 E-W to NE-SW (Kelson et al., 1996, 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 291 m (720 ft) to the bottom of the hole at 311 m (1020 ft). Prior to this well, no control points existed for the location of the Paleozoic section in the Taos valley. Because the well is located nearly two miles 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 feet deeper, because the Alamitos Formation can be over 1220 m (4000 ft) thick. Based on this information, we speculate that there

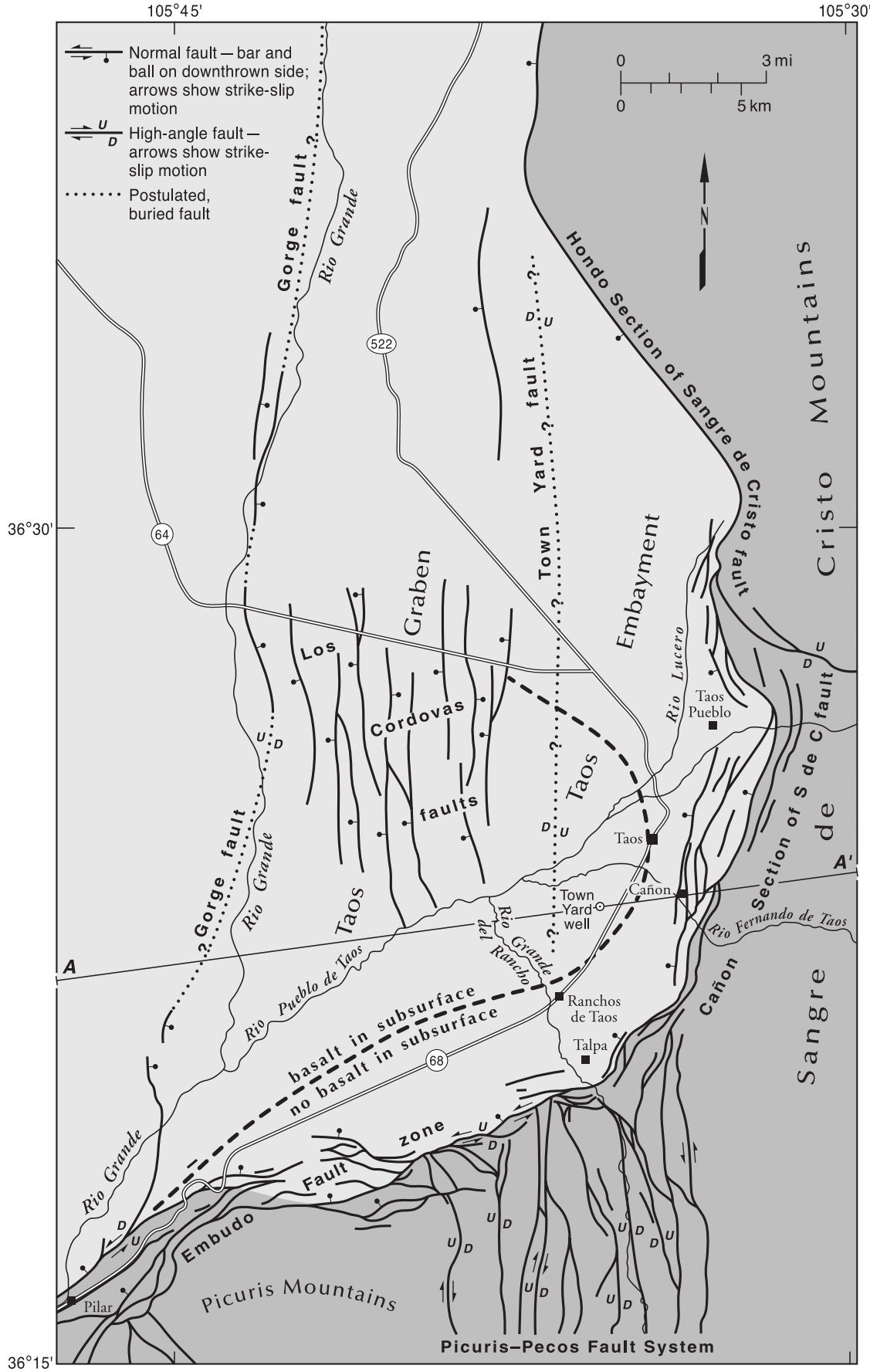


FIGURE 10. Tectonic map of the southeastern San Luis Basin showing mapped structures and subsurface inferred structures related to Laramide and rift deformation. The inferred Gorge fault connects known Pliocene/Pleistocene-age faults along the Rio Grande gorge, and corresponds with the western geophysical expression of the Taos graben. The Town Yard fault corresponds with the 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 map of Machette and Personius (1984).

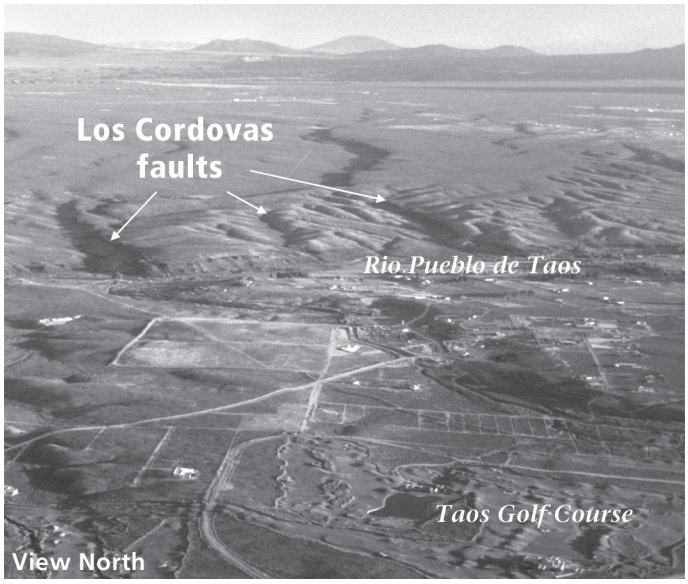


FIGURE 11. Early morning, low-altitude, oblique aerial view (looking north) of the surface expression of Los Cordovas faults on the Taos plateau. The Rio Pueblo de Taos flows from right to left across the center of the photo, with agricultural lands situated on young river terraces. The several, north-trending west-facing scarps (in shadow) represent Servilleta Formation basalt and old alluvial-fan deposits 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.

is NNE-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).

The Taos graben was mostly formed by the time the lower Servilleta basalt erupted, about 4.5 million years 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 approximately 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 basalt flows 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 (56 ft) across the fault.

DISCUSSION AND SPECULATIONS

Available geologic and geophysical data provide a basis for interpreting the kinematic histories of the major faults in the southeastern San Luis Basin, for speculating on the transition from Laramide deformation to Neogene rifting in the Taos area, and for discussing the evolution of the Embudo accommodation zone. First, available data suggest that the Picuris-Pecos fault system is present on the northern side of the Embudo fault, and has been re-activated by later episodes of rift-related deformation. The five major, north-south faults within the Picuris-Pecos fault system in the study area form a 8-km-wide zone of high brittle strain in rocks that range in age from Early Proterozoic to less than ca. 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 that the Picuris-Pecos fault zone defined the Eocene(?) to early Miocene Laramide-style grabens, which served as loci of deposition for volcaniclastic sediments shed southward from volcanic highlands. At least parts of the Miranda and Rio Grande del Rancho grabens have 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 (ca. 27 Ma, Brister and Gries, 1994; ca. 25 Ma, Miggins et al., 2002), 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 about 1 to 1.5 km (Fig. 10). In addition, the north-striking Los Cordovas faults coincide with the central, deepest part of the Taos graben, just as the La Serna and Rio Grande del Rancho faults border the Laramide-style grabens. 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

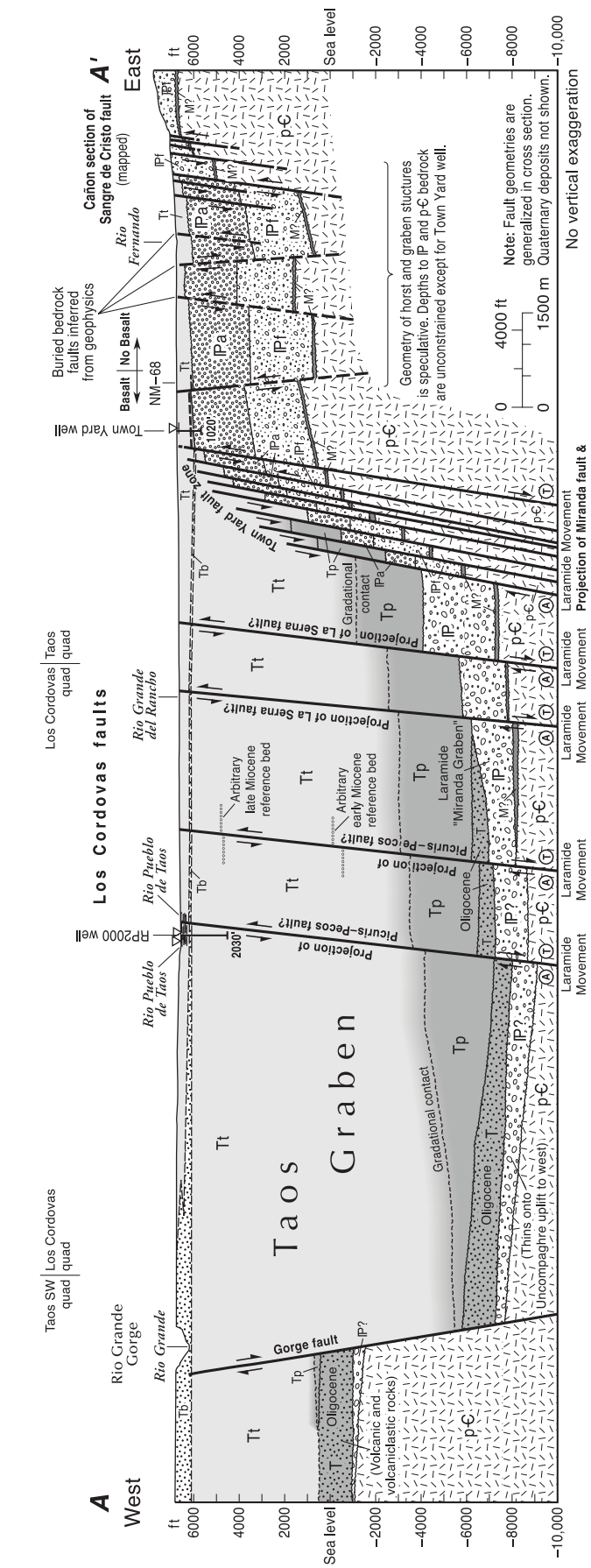


FIGURE 12. Speculative west-east cross section A-A' across Figure 10. The section shows a prominent Taos graben with a strongly fault-dissected eastern shoulder (the Taos embayment), and a speculative faulted western shoulder across the Gorge fault. The thickness of Tertiary basin fill and depth to bedrock 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.

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. On Figure 12, we show the principle elements 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. 10). 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 migrated eastward approximately 10 km, to its present location at the base of the Sangre de Cristo Mountains, forming the Taos embayment and the Town Yard structural bench (Figs. 10, 12). Minor west-down movement has continued along the Los Cordovas fault zone, as a result of distributed extension within the southern San Luis Basin.

Previous workers have suggested that the Embudo fault is probably a relatively young rift feature that corresponds with the initial uplift of the Picuris Mountains in the late Miocene (Manley, 1978; Muehlberger, 1979; 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, and Miggins et al. (2002) stated that eruption of the 25 Ma Amalia Tuff represents a good estimate of the onset of rifting. 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 at least until about 18 million years 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, and Miggins et al. (2002) concluded that the central San Luis Basin experienced a major period of uplift and block faulting at ca. 15 Ma. 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 modern style of the Embudo accommodation zone, and, consequently, 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 volcaniclastic sediments from about 35 Ma (Picuris Formation) to 18 Ma (Tesuque Formation), 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, growth-fault 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, prior to 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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