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THE PICURIS-PECOS FAULT — REPEATEDLY REACTIVATED, FROM PROTEROZOIC(?) TO NEOGENE

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Abstract—The Picuris-Pecos fault is arguably the largest-displacement, strike-slip fault exposed in the state, yet its kinematic history is poorly constrained. Although it clearly displays 37 km of dextral strike-slip, the slip is determined by offset of Proterozoic-age piercing lines, and therefore only yields a net slip since 1.4 Ga. The original Picuris-Pecos fault mappers concluded that major strike-slip faulting occurred in Proterozoic time and lesser dip-slip movement occurred in Pennsylvanian and Laramide time, but recent investigators have speculated that most or all of the 37 km of strike-slip separation is actually Laramide in age. We conclude that some component of pre-Pennsylvanian (Grenville age?) slip on the Picuris-Pecos fault is a reasonable interpretation based on deflection and attenuation of Proterozoic strata along the fault, geometries and kinematics of Paleozoic and Laramide fault structures, the relative fracturing of Proterozoic versus Paleozoic strata, and the presence of other high-angle, reactivated, pre-Pennsylvanian faults. New field data from faults parallel to the Picuris-Pecos fault indicate that Laramide deformation produced concurrent strike-slip and dip-slip movements, and we speculate that the Picuris-Pecos fault and adjacent sub-parallel structures represent a positive flower structure of Laramide age. Although new apatite fission-track data permit Neogene vertical movement along the southernmost Picuris-Pecos fault, cross-cutting field relationships along the northern fault exposure demonstrate little or no post-26 Ma throw. This along-strike variation may have resulted from different amounts of Neogene extension in the southern and northern parts of the Española Basin.

INTRODUCTION

The Picuris-Pecos fault (Fig. 1) has been described as a *geofracture* (Sutherland in Miller et al., 1963), an antiquated term for a major, long-lived fault zone that has periodically reactivated (Osterwald, 1961). The kinematic history of the Picuris-Pecos fault and nearby faults was presented by Montgomery and Sutherland (in Miller et al., 1963) as: (1) Precambrian(?)—37 km of dextral strike-slip movement; (2) Ancestral Rocky Mountain orogeny (Mississippian and Pennsylvanian)—three episodes of west-up, high-angle faulting; (3) Laramide orogeny (Late Cretaceous-early Tertiary)—dip-slip faulting on reactivated older basement structures, with a minor strike-slip component; (4) Miocene—perhaps renewed west-up movement related to Rio Grande rifting. Research within the last 30 years has moderately expanded our knowledge of the geology of this region of the southern Sangre de Cristo Mountains. Some of the new work supports and some refutes these four conclusions. This paper combines a review of previous work with new observations concerning faulting in an attempt to more precisely characterize the kinematic history of the Picuris-Pecos fault. We emphasize that such models will remain speculative until the completion of detailed studies of fault geometries and kinematics on the Picuris-Pecos fault and nearby structures.

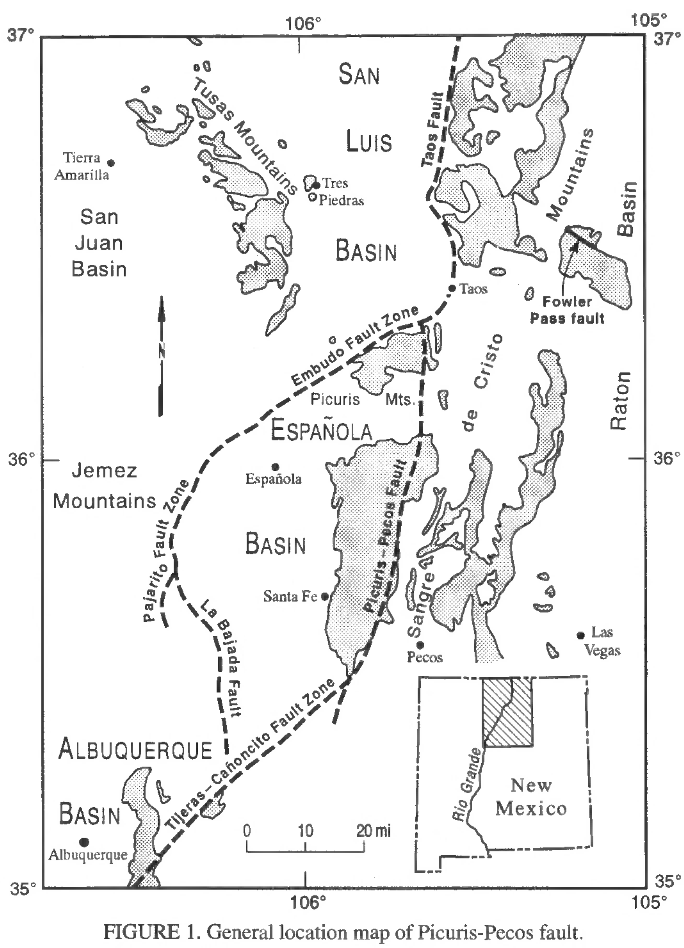


FIGURE 1. General location map of Picuris-Pecos fault.

FAULT GEOMETRY

The Picuris-Pecos fault (originally named the Alamo Canyon tear fault) was first recognized by Montgomery (1953) in the Picuris Mountains. He later mapped its southward continuation in the southernmost Sangre de Cristo Mountains (Miller et al., 1963) as a N- to NNE-striking, vertical to near-vertical structure that appears to consist of a single large-displacement fault over much of its length. Subsidiary map-scale, sub-parallel faults such as the Cow Creek, Bull Creek, Jicarilla and Garcia Ranch-Borrego faults exist along its southern exposure (Fig. 2).

The Picuris-Pecos fault can be traced for at least 84 km, from the northern Picuris Mountains south of Taos to 24 km south of the village of Cañoncito. Less well documented continuations southward include a 32-km-long fault that cuts Mesozoic rocks from the Lamy area southward (Read and Andrews, 1944), and surface and subsurface structures that bound the eastern side of the Estancia Basin (J. Hawley, personal commun., 1995) and the Tularosa Basin to near El Paso (S. Cather, personal commun., 1995). Sutherland (in Miller et al., 1963) also noted that the fault projects northward into the trace of the Taos fault, the main range-bounding normal fault that separates the Taos Range from the San Luis Basin (Fig. 1).

PROTEROZOIC ANCESTRY

Montgomery (1953) reported that in the Picuris Mountains, Precambrian strata along the western block of the Picuris-Pecos fault was apparently ductilely dragged southward along the fault (Fig. 3). He also later noted that similar strata in the Truchas Peaks area, on the eastern block of the fault, were deflected northward, and that the two sequences, although once continuous, had been separated by 37 km of dextral strike-slip movement (in Miller et al., 1963; Fig. 4). Montgomery reasoned that

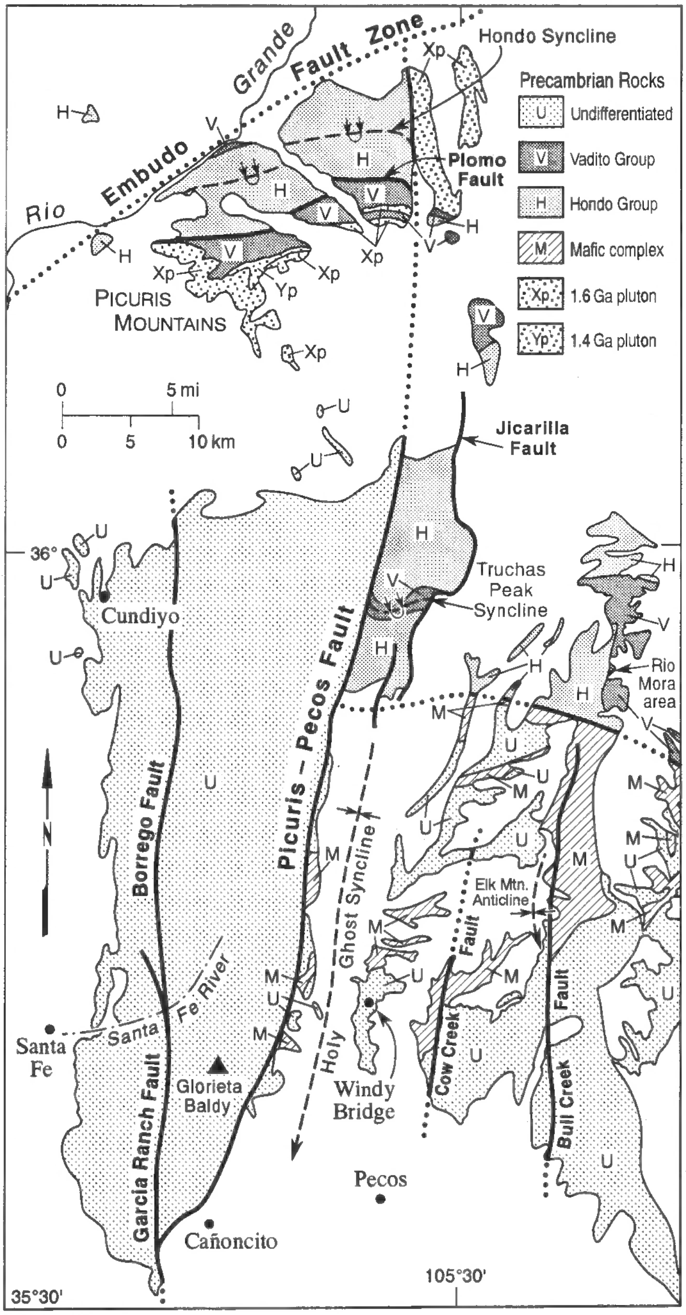


FIGURE 2. Geologic map showing generalized Proterozoic geology and major high-angle faults of the Picuris Mountains and southernmost Sangre de Cristo Mountains. Offset rock units and structures in the Picuris Mountains and Truchas Peaks area represent 37 km of right-lateral separation on the Picuris-Pecos fault.

the lack of fracturing and veining in the hinge areas of the folds pointed to elevated P-T conditions that were characteristic of Proterozoic, rather than Phanerozoic, deformation. Bauer (1988) confirmed this observation, and also mapped attenuation of interlayered quartzite and schist members of the Hondo Group as they approached the fault (Fig. 3).

Geophysical data compatible with Montgomery's idea were presented by Cordell and Keller (1984), who interpreted 38 km of right-slip offset of a gravity low along the Picuris-Pecos fault from the aeromagnetic map of New Mexico. They also noted a magnetization boundary that coincides with the mapped fault, and a NE-trending magnetic low west of the fault on the north flank of the Picuris Mountains that is similarly offset 38 km to match with a NE-trending anomaly east of the fault.

Both Montgomery and Bauer found localized areas of brecciation and silicification along the fault, including a conspicuous 6-km-long zone of

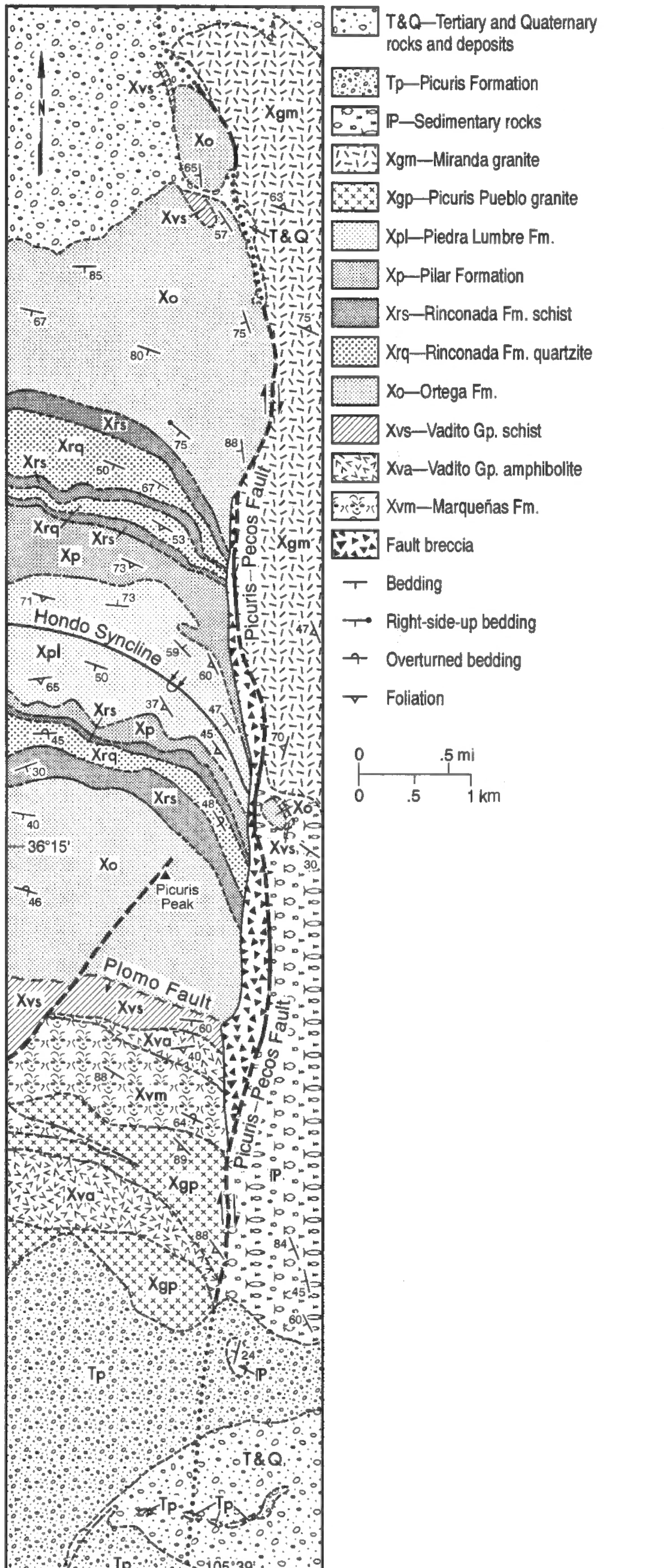
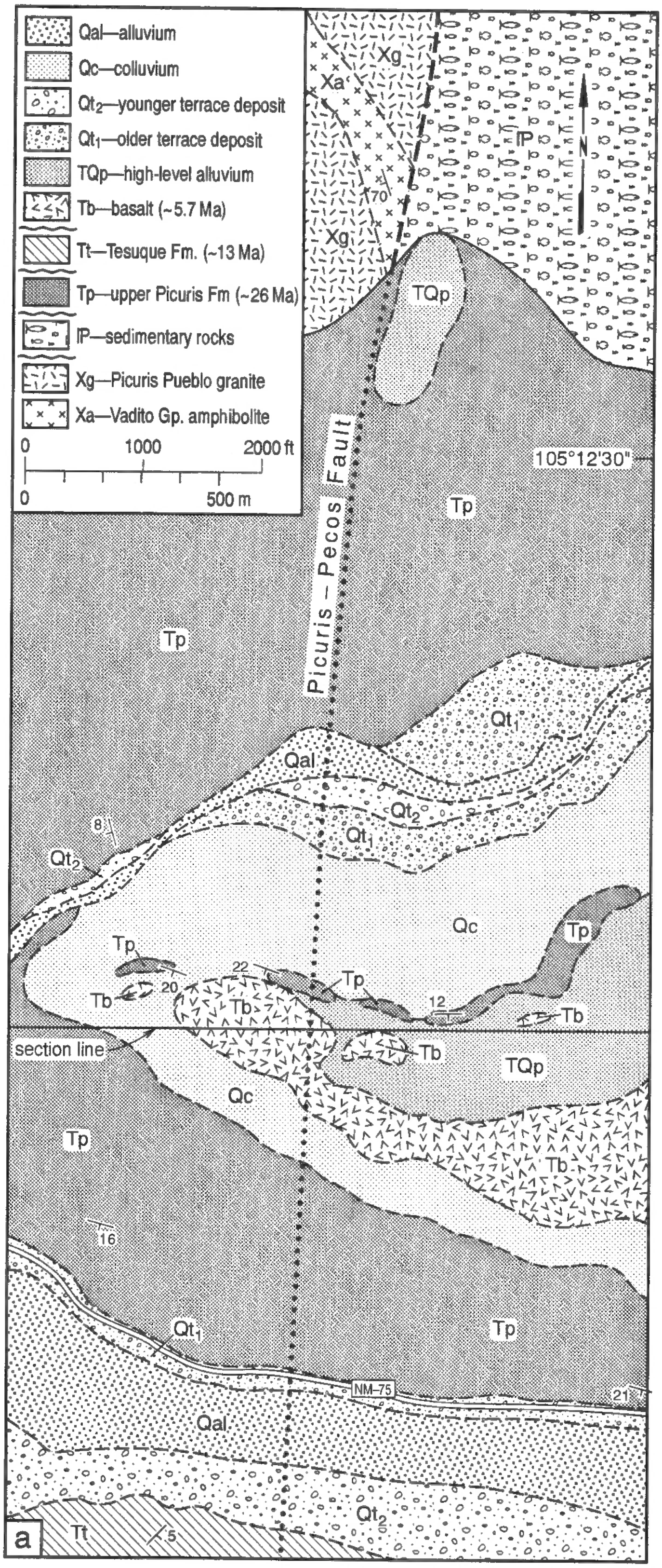


FIGURE 3. Geologic map of the Picuris-Pecos fault exposures in the eastern Picuris Mountains. Note dextral deflection and attenuation of Hondo Group (Ortega Fm, Rinconada Fm, Pilar Fm, Piedra Lumbre Fm) strata and ductile structures into the fault. A 6-km-long breccia zone along the fault overprints deflections. Figure 4 is close-up portrayal of southern map area. Mapping by Bauer.



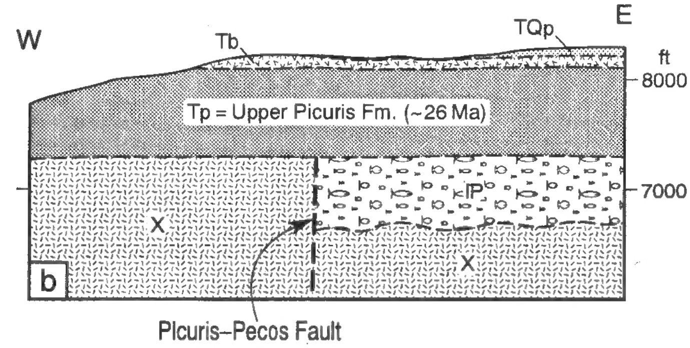


FIGURE 4. Map (a) and cross section (b) of southern part of Figure 3 in southeastern Picuris Mountains. Picuris-Pecos fault, which juxtaposes Proterozoic against Pennsylvanian in north is covered by 26 Ma Picuris Formation in south. Mapping by Bauer.

brecciated rock adjacent to the Picuris-Pecos fault in the Picuris Mountains (Fig. 3). Montgomery found a similar breccia zone west of Pecos Baldy, and concluded that the age of these breccia zones was unknown. In the Picuris Mountains, the extreme brecciation along the Picuris-Pecos fault overprints the deflected and attenuated Proterozoic strata. If the brecciation is Laramide in age, then the deflection is earlier. Sedimentological studies of the Mississippian-Pennsylvanian strata along the Picuris-Pecos fault show that only low to moderate amounts of Pennsylvanian stratigraphic (dip) separation occurred (Miller et al., 1963; Casey, 1980; Soegaard and Caldwell, 1990). If, in addition, Pennsylvanian strike-slip movement was minor, then the strike-slip deflections along the fault in the Picuris and Truchas areas are pre-Pennsylvanian. Little is known of the early Paleozoic tectonic history of north-central New Mexico, probably because tectonism was minor. In addition, if the deflections are truly ductile, it is unlikely that Phanerozoic P-T conditions were suitable for their development. We are therefore left with a possible pre-Pennsylvanian age for some strike-slip faulting on the Picuris-Pecos fault.

Chapin and Cather's (1981) model for Laramide tectonism and sedimentation in the southern Rocky Mountain area included major right-lateral slip along the Picuris-Pecos fault. They noted that an important question is how much of the 37 km of right shift is pre-Pennsylvanian, and how much is Laramide. By reinterpreting Sutherland's (in Miller et al., 1963) sedimentological data, Chapin and Cather (1981) theorized that 26 km could be a rough estimate for Laramide movement on the Picuris-Pecos fault. If so, the unaccounted 11 km may be a measure of pre-Laramide strike-slip displacement.

Karlstrom and Daniel (1993) noted that net slip on the Picuris-Pecos fault could represent multiple movements whose timing was uncertain. However, they favored a Laramide timing based on the brittle fault character and compatibility with the Chapin and Cather (1981) right slip model. They observed that the Picuris-Pecos and Borrego faults abruptly truncate Proterozoic foliations in the southernmost Sangre de Cristo Mountains, implying that the faults have no Proterozoic ancestry. We agree that the Picuris-Pecos fault truncates Proterozoic foliations (as well as strata and folds), but that need not preclude pre-Pennsylvanian movement. In fact, in a reactivated fault zone, one would expect to see Phanerozoic brittle faults cutting older structures. Proterozoic ancestry on the Picuris-Pecos fault does not necessarily contradict the Laramide strike-slip model of Karlstrom and Daniel (1993) but we find no compelling reason to dismiss Montgomery's original field-based hypothesis of Proterozoic displacement. The following field observations from several nearby areas support the concept of Proterozoic faulting.

The Cow Creek fault, Bull Creek fault (Fig. 2), and other smaller faults have been mapped across the Proterozoic Pecos complex east of the Pecos River (unpub. mapping by D.C. Mathewson, 1975, 1976). Many of these faults juxtapose dramatically distinct Proterozoic rock packages, such that the net slips must be large (kilometers?). Although many faults also cut the overlying, shallowly dipping Paleozoic sedimentary strata, the Paleozoic rocks show only minor stratigraphic separation. In several cases, this minor separation is due to minor dip-slip faulting rather than strike-slip offset. The most likely interpretation is that major pre-Pennsylvanian faults were later reactivated as small displacement dip-slip faults.

Another line of evidence for pre-Pennsylvanian faulting exists in the Santa Fe area, where numerous north-striking breccia zones cut Proterozoic granite. Such a brecciated granite is exposed where Hyde Park Road enters the canyon of Little Tesuque Creek. Overlying the granite are nearly horizontal Pennsylvanian sedimentary rocks that are neither faulted nor brecciated (Spiegel and Baldwin, 1963, p. 70). Therefore, the brittle deformation is most likely pre-Pennsylvanian.

We can also make a qualitative observation concerning the intensity of faulting and fracturing. In several areas of the southern Sangre de Cristo Mountains in which Proterozoic and Paleozoic strata both crop out, Proterozoic rocks consistently are more intensely faulted and fractured than Paleozoic rocks. Although this could be attributed to differences in rheology, in some areas where massive carbonates directly overlie Proterozoic granites, the fracture densities are dramatically different. We tentatively interpret this to indicate that a component of brittle deformation occurred between approximately 1400 Ma (the age of the youngest granite) and 325 Ma (the age of the carbonates).

The Picuris-Pecos fault is not the only large, high-angle, right-lateral shear zone in the southern Sangre de Cristo Mountains that may have a Proterozoic ancestry. Grambling and Dallmeyer (1993) used changes in rock types, deformational history, metamorphic grade and argon cooling ages to constrain the age of the Fowler Pass shear zone in the Cimarron Mountains. They concluded that the NW-striking, high-angle, right-slip shear zone was active at ca 1150–1100 Ma, perhaps as an intracratonic response to the Grenville orogeny.

ANCESTRAL ROCKY MOUNTAIN DEFORMATION

Excellent sedimentological evidence exists for an active Picuris-Pecos fault in Paleozoic time. The Mississippian Del Padre Sandstone is abnormally thick at several locations along the Picuris-Pecos fault, and Sutherland (in Miller et al., 1963) concluded that it accumulated along a high-angle Picuris-Pecos fault scarp. Additionally, Sutherland described two later episodes of west-up faulting along the northern exposure of the fault, in the early Pennsylvanian (Morrowan), and in the middle Pennsylvanian (late Desmoinesian). He also stated that the Picuris-Pecos fault has remained vertical throughout its history. By placing the Pennsylvanian history in a dynamic model of plate interactions, Soegaard and Caldwell (1990) implied that the fault had not remained vertical during Pennsylvanian time. They concluded that during deposition of the Sandia Formation (between Morrowan and early Desmoinesian time, ca 310 Ma), westward compression in the Ouachita foldbelt caused eastward thrusting along the Picuris-Pecos fault. When the Sangre de Cristo Formation was deposited in late Desmoinesian to Wolfcampian time (ca 290–300 Ma), the active convergent boundary had shifted southwestward to the Marathon region, and the Picuris-Pecos fault had become a high-angle fault. It is unclear whether they were suggesting that the fault dip actually changed through time, or that the fault was steeply west-dipping and changed from dip-slip to oblique-slip.

No Paleozoic strike-slip displacement has been reported on the Picuris-Pecos fault or nearby high-angle faults. No data preclude such displacement, and in fact, Pennsylvanian left-oblique slip on north-striking faults has been documented in the Joyita Hills near Socorro (Beck and Chapin, 1994), and has been inferred in the Estancia Basin (Barrow and Keller, 1994).

LARAMIDE DIP-SLIP VERSUS STRIKE-SLIP

The evidence for post-Pennsylvanian faulting is unequivocal along much of the Picuris-Pecos fault, where Precambrian rocks are juxtaposed against brecciated and drag-folded Pennsylvanian strata. During its long history, the fault has included components of both strike-slip and dip-slip movement, but assigning these components to absolute times is surprisingly difficult. Sutherland (in Miller et al., 1963) proposed that Laramide faulting occurred as vertical, west-side-up, dip-slip movement on the Picuris-Pecos fault with no rotation of the fault plane from the Paleozoic vertical orientation. Along the upper Pecos River, west of Cowles, the present configuration of Proterozoic against Pennsylvanian Alamitos Formation requires a minimum throw of 500 m. Such throw is minor compared with 26+ km of Laramide right-lateral displacement (Chapin and Cather, 1981).

A major fault called the Jicarilla fault, which is a high-angle branch of the Picuris-Pecos fault system (Sutherland, in Miller et al., 1963), is located in the northern Pecos area (Fig. 2). The arcuate, 20-km-long fault separates Proterozoic from Pennsylvanian strata. Sutherland described it as a 60°-70° west-dipping reverse fault with a minimum throw of 90–150 m. The attitude of Pennsylvanian footwall strata range from horizontal 2 km east of the fault, to overturned adjacent to the fault. The map of Moench et al. (1988) contains a 70° west-dipping reverse fault on a small splay of the Jicarilla fault. Most likely, movement on the Jicarilla fault occurred during Laramide deformation, contemporaneous with west-up movement on the Picuris-Pecos fault (Sutherland, in Miller et al., 1963) and the possible 26+ km of right slip (Chapin and Cather, 1981).

Sutherland (in Miller et al., 1963) also mapped a major south-plunging syncline-anticline pair (Holy Ghost syncline, Elk Mountain anticline) east of the Picuris-Pecos fault. Both folds affect Paleozoic rocks and were interpreted as Laramide in age.

Based on measurements of fault striations on slickensides, there is abundant evidence for extensive strike-slip faulting in the southern Sangre de Cristo Mountains. Bauer (1988) measured sub-horizontal fault striae on high-angle faults of the Picuris-Pecos fault in the northern Picuris Mountains south of Taos. The reconnaissance map of Moench et al. (1988) contains two fault striae measurements on the Picuris-Pecos fault, one in the Truchas Peaks area, and one in the Glorieta Baldy area. Both striae are horizontal on steeply W-dipping fault planes. Their map also shows two fault striae measurements on the Borrego fault, near the Santa Fe Ski Area. One plunges 30°NE on a 50° W-dipping fault, whereas the other plunges 55°SW on a 60° WNW-dipping fault. In the southern Sangre de Cristo Mountains, we have examined several areas adjacent to the Picuris-Pecos fault, including the Precambrian exposures west of Cañoncito (C.G. Daniel, personal commun., 1995), the I-25 roadcut exposures of Permian-Triassic strata just east of Cañoncito, Proterozoic and Paleozoic rocks near Windy Bridge on the Pecos River, and Precambrian rocks along the Santa Fe River and near the village of Cundiyo (Fig. 2). In each area, shallowly plunging fault striations dominate. Because many of these measurements were in Paleozoic and Mesozoic rocks, we suspect that they represent Laramide deformation. If so, they support the Chapin and Cather (1981) model of Laramide lateral slip.

At least parts of the Picuris-Pecos fault are clearly Paleozoic structures that were reactivated during the Laramide and again during Neogene rifting. In contrast, Abbott et al. (this volume) concluded that the Tijeras-Cañoncito fault system has a complex history of recurrent movement, but found no evidence for pre-Laramide displacement. Cather (1992) linked the Picuris-Pecos fault and Tijeras-Cañoncito fault during Laramide time, both as right-lateral wrench faults. His model also suggested west-down normal faulting on the Tijeras-Cañoncito fault, whereas Sutherland (in Miller et al., 1963) and Cather (1992) characterized the Picuris-Pecos fault as west-up reverse.

NEOGENE FAULTING

Mapping near the southernmost exposure of the Picuris-Pecos fault in the Picuris Mountains yields a minimum age for local faulting. As the fault is traced southward, it passes from bedrock exposures to Cenozoic cover (Fig. 4). The oldest Cenozoic unit in the area is the 26 Ma Picuris Formation (Rehder, 1986), a pre-rift alluvial unit that underlies the Tesuque Formation in the eastern Picuris Mountains. The Picuris Formation overlies the fault, indicating that no measurable displacement has occurred on this part of the Picuris-Pecos fault for at least 26 Ma.

This finding contrasts with recent apatite fission-track work for the southernmost exposures of the fault near Glorieta Baldy (Kelley, this volume). Kelley concluded that throw of approximately 400 m has occurred on the Picuris-Pecos fault in the middle to late Cenozoic. She noted that the displacement may vary along the fault and that other nearby faults such as the Garcia Ranch-Borrego could have also been active in the Neogene.

SPECULATION AND KINEMATIC MODEL

At the latitude of Santa Fe, north-striking, right-lateral faults of late Laramide age are distributed across a 320-km-wide zone from the San Juan Basin to the Raton Basin (Cather, 1992). The Picuris-Pecos fault was located in the center of an enormous transpressional highland, such that the entire 320-km-wide belt had the geometry of a positive flower structure (Cather, 1992). We propose that, in Laramide time, the southern Picuris-Pecos fault system itself represents a similar flower geom-

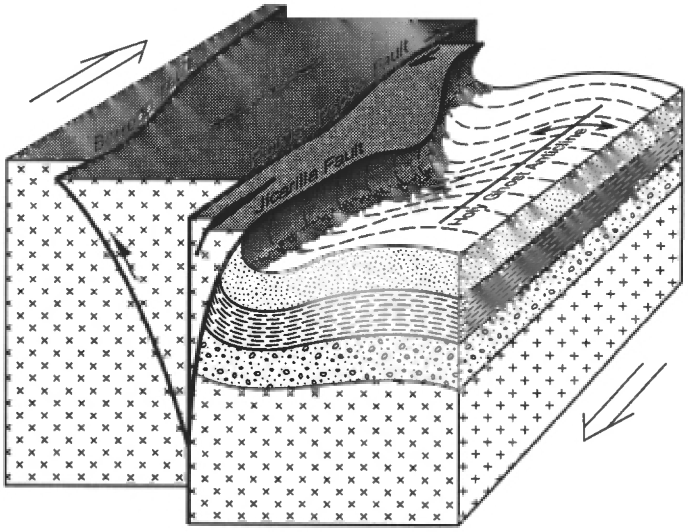


FIGURE 5. Schematic block diagram of the major faults in the southern Sangre de Cristo Mountains illustrating the speculative Laramide positive flower structure.

etry on a smaller scale (Fig. 5). Both the geometry and kinematic data support this idea. The Picuris-Pecos fault is vertical, with a cumulative displacement history that is dominantly strike-slip. The smaller Jicarilla fault to the east displays dip-slip movement and dips steeply toward the Picuris-Pecos fault. The Garcia Ranch/Borrego fault to the west is steeply dipping with oblique-slip movement. Other unstudied or unrecognized faults may have similar characteristics. This model also provides a mechanism for producing folds such as the Holy Ghost anticline and Elk Mountain syncline, which parallel the fault.

Any defendable kinematic history of the Picuris-Pecos fault system must explain the map-scale deflections and associated layer attenuations in the Picuris and Truchas Ranges, as well as the apparent pre-Pennsylvanian ancestry of nearby faults. We propose the following speculative history for the Picuris-Pecos fault system:

1. Pre-Pennsylvanian (Grenville age?) right slip on the Picuris-Pecos fault (perhaps 11 km?) may have caused the deflection and attenuation of Proterozoic supracrustal rocks and older ductile structures.

2. As per Sutherland (in Miller et al., 1963), a triad of Mississippian and Pennsylvanian west-up motions on the Picuris-Pecos fault resulted in sedimentation along the northern segment of the fault. Although no strike-slip component of movement is documented, some is permissible.

3. During the Laramide orogeny, at least 26 km of right slip occurred on the Picuris-Pecos fault. Displacement also occurred on north-striking, high-angle faults to the east and west. The overall geometry of the fault system was a positive flower structure, with dip-slip displacement dominating some subsidiary faults such as the Jicarilla. Strike-slip, oblique-slip, and dip-slip fault striae all developed contemporaneously on different fault strands, perhaps corresponding with the Eocene opening of the transtensional Galisteo basin (Cather, 1992) to the south.

4. During Neogene time, rift-related faulting was concentrated 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.

ACKNOWLEDGMENTS

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