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THE EMBUDO FAULT BETWEEN PILAR AND ARROYO HONDO, NEW MEXICO: AN ACTIVE INTRACONTINENTAL TRANSFORM FAULT

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INTRODUCTION

The N60E-trending Embudo fault zone is both a hinge zone and a transform fault that transfers the major displacement along this segment of the Rio Grande depression from the Taos fault (Kelley, 1954) along the eastern margin of the San Luis Valley basin to the western margin of the Velarde graben, the Los Alamos fault in the Espanola basin. Reversal of downthrow is shown by Kelley (1978) to be just west of Black Mesa near the confluence of the Chama and Ojo Caliente rivers. The amount of strike slip is unknown because the unknown shapes at depth of the border faults control the amount of horizontal extension. The Jemez caldera lies astride the southwestward projection of the Embudo fault zone.

The Jemez lineament (Chapin and others, 1978; Clark, 1968; Cordell, 1978; Lambert, 1966) (Springerville-Raton line of Lipman, 1979), an alignment of Pliocene-Holocene volcanic centers, extends diagonally across Arizona and New Mexico from near Springerville, Arizona (some include the Pinacate volcanic field of Mexico near the head of the Gulf of California), northeastward from Mt. Taylor and the Jemez caldera to the Raton-Clayton-Capulin volcanic field of northeastern New Mexico. The Embudo fault zone lies astride this lineament where it traverses the Rio Grande depression.

The segment of the fault zone between Pilar and Ranchos de Taos is anomalous in that it has reverse fault displacements that are best displayed in the roadcuts near Arroyo Hondo, about 8 mi (13 km) southwest of Ranchos de Taos. These displacements demonstrate that the Rio Grande depression is not being extended normal to its length (i.e. not extending east-west). If the Embudo fault was a typical transform connecting two rifts, it would be pulling apart and be a zone of active volcanism because of its N60E strike. Instead, it is a zone of active compression in this segment, as shown by the overriding of the Taos Plateau to the north by the Picuris Mountains and its flanking sedimentary blanket.

Kelley (1952, 1977) has argued that longitudinal left slip along the Rio Grande rift is present, that the Laramide ancestry of this zone is significant and that the relationships between the successive deformations should be analyzed carefully. The present motions of the Picuris over the Taos Plateau support a component of left slip along the rift as well as a dominant extension across the rift.

The intersection of northeast-trending faults, such as the Embudo and Tijeras (near Albuquerque, fig. 1), and north-trending faults, such as the Picuris-Pecos and Los Alamos-La Bajada, produce diamond-shaped patterns. The one outlined by the faults named above has opposite corners high (Picuris and Sandia mountains) and low (Velarde graben of Manley (1978) and the Santa Fe embayment (see Kelley, 1978, fig. 2 for additional northeast-elongate diamonds)). Each of these bounding faults reverses throw along its length; for example, the Rio Grande enters and leaves the Espanola basin in reversal zones.

STRATIGRAPHY

Introduction

Displacement history of the Embudo fault zone and progressive uplift of the Picuris Mountains is shown well along the

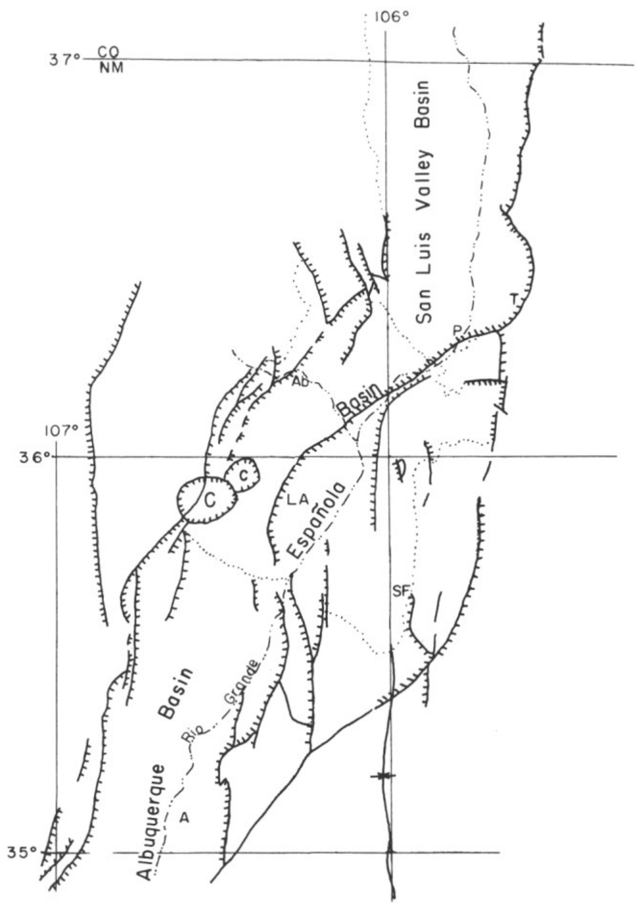

Figure 1. Tectonic map of Rio Grande rift region in northern New Mexico. Downthrown side of faults marked with ticks. Illustrates the prominent northeast-trending transverse faults that step the Rio Grande graben in an en-echelon right pattern. Dotted line marks the boundary of the Española basin. Los Alamos-Embudo-Taos fault extends from LA (Los Alamos) to P (Pilar) to T (Taos). Other cities labeled are A: Albuquerque; Ab: Abiquiu; SF: Santa Fe. Velarde graben occupies the region centered on the word "Española." C: caldera. Modified from Kelley (1978, fig. 2).

Pilar-Arroyo Hondo segment (fig. 2). Only those units exposed in the wedge-shaped segment bounded by the Rio Grande, Arroyo Hondo and New Mexico Highway 68 will be described in this paper, which is an updating of work I reported in Hawley (1978, p. 41-46). The Picuris Tuff, exposed along the base of the Picuris Mountains east of Arroyo Hondo, underlies the units to be described and apparently predates the uplift of the Picuris Mountains. If the Picuris Tuff is a correlative of the Abiquiu Tuff, as is usually presumed, then it is part of the alluvial blanket that marks the initial faulting along the eastern margin of the San Luis Valley basin (Lipman and Mehnert, 1975) about 26 m.y. ago. Virtually no depositional-systems analysis has been attempted for the Picuris Tuff in this region. Its fragmented outcrop pattern presents a challenge to the geologist for interpretation and synthesis. A successful analysis will help delineate the relative displacements between blocks in this complicated structural corner among the Picuris Mountains, Taos Plateau and Sangre de Cristo Mountains.

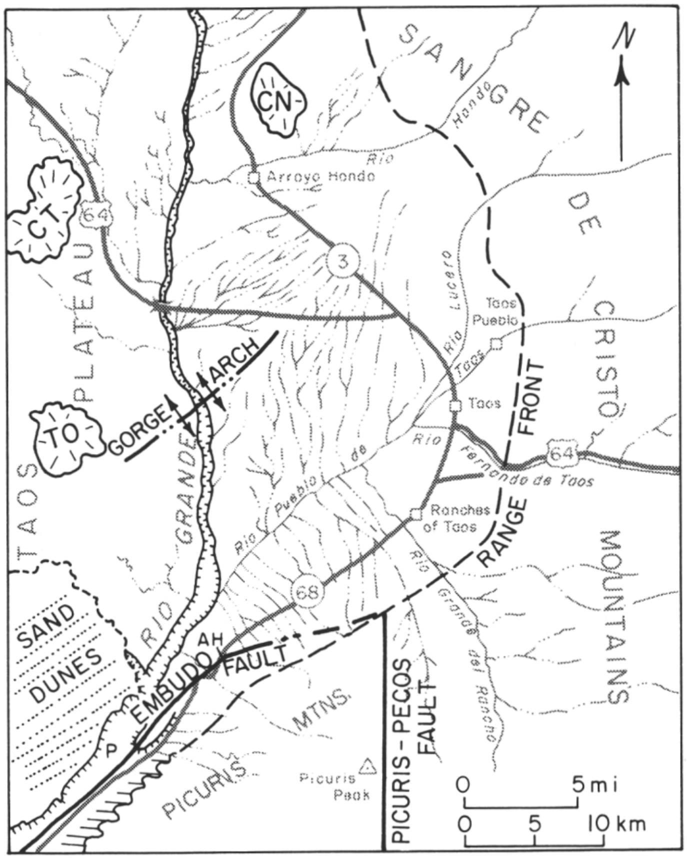

Figure 2. Map of Taos embayment of San Luis Valley basin. Drainage pattern shows divergence of drainage away from Rio Grande Gorge arch. Asymmetry of stream valleys demonstrates homoclinal shifting away from the arch. South of Rio Pueblo de Taos, all side streams show homoclinal shifting to the east. Trellis pattern of streams north of US-64 bridge over the Rio Grande is the result of the down-to-the-east fault and monocline system that (mostly) is just west of and which trends parallel to the Rio Grande. A parallel set of down-to-the-west faults that lies along the northward prolongation of the Picuris-Pecos fault is developed well on the north side of Rio Pueblo de Taos. The lower Rio Hondo and adjacent drainages to the south that drain to the Rio Grande also appear to be structurally controlled (northward-directed homoclinal shifting). The parallelism of the gorge arch, Rio Pueblo de Taos, and the Embudo fault and its continuation down the Rio Grande suggests a common origin for these features. Symbols: CT—Cerros de los Taoses; CN—Cerro Negro; TO—Tres Orejas; AH—Arroyo Hondo; P—Pilar. Heavy dashed line marks boundary between mountain and plateau. Modified from Hawley (1978, fig. N28).

Four distinctive units are mappable in the Pilar-Arroyo Hondo area (fig. 3). These are given letter designations on the illustrations; their correlations are given in the text and figure captions.

All but the oldest contain material derived from the Picuris Mountains. In general, the sequence coarsens upward, suggesting an increase in topographic relief. The coarseness of the youngest bouldery terrace gravels (younger than any of the mapped units), however, is probably the result of climatic changes (glacial epochs according to Miller, in Miller and others, 1963).

Units A and B (Chama-el rito Member (?) of Tesuque Formation)

Best exposure of these units is in roadcut 2 (fig. 4). They consist of fluvial deposits composed of fining-upward sequences of conglomerate, volcanic arenite and mudstone. Sedimentary current features show a generally southerly transport direction. No clasts are derived from the adjacent Picuris Mountains, but instead are dominated by a variety of rounded to subrounded volcanic types, with lesser quantities of granitic rocks, and a minor amount of gray limestone.

Unit A, the older, is finer grained and less cemented than Unit B, and consists of yellowish-buff sandstone layers alter-

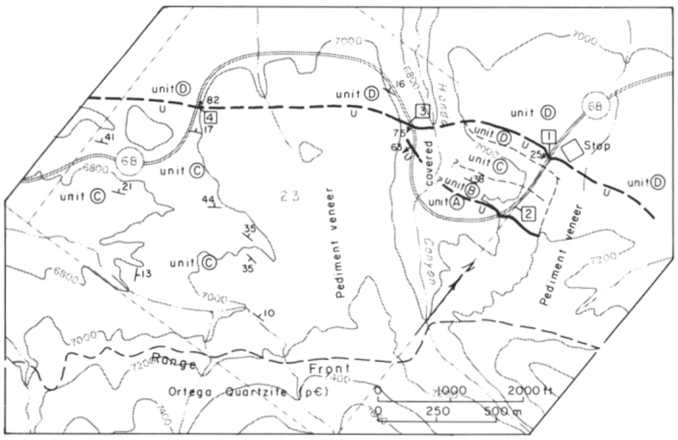

Figure 3. Sketch map of Hondo Canyon segment of Embudo fault. Base adapted from U.S. Geological Survey Taos Southwest quadrangle. Trace of main fault is marked by a topographic scarp across all geologic units. Map units A-D are those described in text; probable formation names: A,B—Chama-el rito Member of Tesuque Formation (Santa Fe Group); C—Ojo Caliente Sandstone of Tesuque Formation (Santa Fe Group); D—upper Servilleta Formation. Roadcut sections of Figure 4 are numbered boxes. Diamond indicates field trip stop, day 1, at roadside park overlook of Rio Grande Gorge. Modified from Hawley (1978, fig. N31).

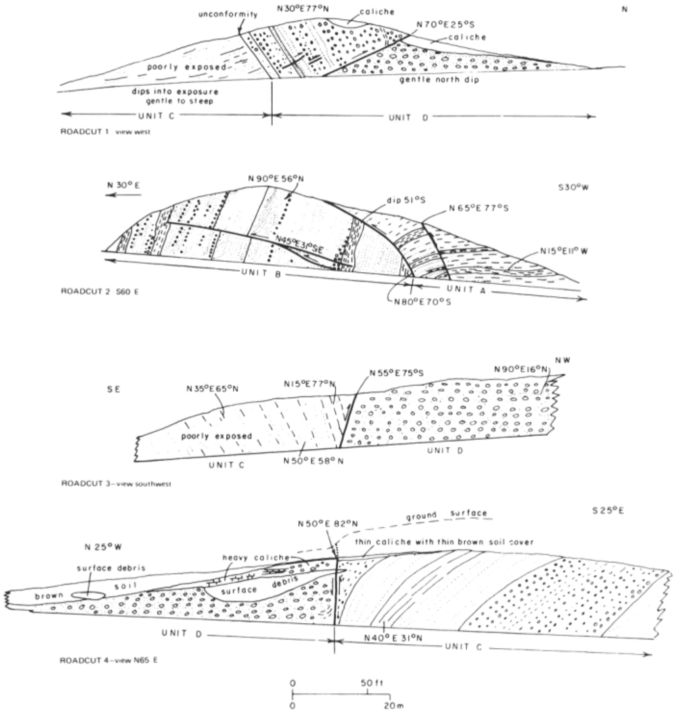

Figure 4. Field sketches of roadcuts located on Figure 3. Roadcuts show transition along Embudo fault from steep normal (roadcut 4) to steep reverse (roadcut 3) to low-angle thrust (roadcut 1). Roadcut 2 shows upthrust relations that may be typical of the poorly exposed Santa Fe beds of Rito Cieneguilla to the southwest. Low-angle fault of roadcut 2 shows oblique motion with upper plate moving into roadcut (northeast). Units A and B: volcanic-rich fluvial deposits of Chama-el rito Member (?) of Tesuque Formation (Santa Fe Group). Unit C—sand-dune, alluvial-fan and lacustrine deposits of Ojo Caliente Sandstone of Tesuque Formation (Santa Fe Group). Unit D—very coarse alluvial-fan debris of upper Servilleta Formation. Figure from Hawley (1978, fig. N32).

nating with bluish-gray pebbly sandstone. Unit B is dominated by gravelly sands that have gray or reddish matrices separated by meter-thick red mudstones. In both units, the gravelly layers are cemented better and tend to hold up low ridges. The generally uncemented, easily eroded nature of these units is shown by the wide amphitheater (fig. 3) that is eroded into these units as compared with the usual narrow V-shaped canyon of Arroyo Hondo. These units have been recognized only in Arroyo Hondo and in the unnamed arroyo immediately to the east.

Unit C (Ojo Caliente Sandstone Member of the Tesuque Formation)

This unit is exposed well on the southward-facing bluffs of Rito Cieneguilla from Pilar northeastward. New Mexico Highway 68 parallels this Rito and its roadcuts provide many convenient exposures until it tops out on the Taos Plateau. The oldest exposed part of Unit C is in the bluffs near Pilar, and because of consistent west to north dips, progressively younger beds are traversed northeastward along Highway 68 until it passes out of Rito Cieneguilla and onto the Taos Plateau.

Unit C consists of three distinctive facies that are interbedded in units 40 to 50 ft (12 to 15 m) thick, and which are interpreted to be sand-dune, playa-type lacustrine and alluvial-fan deposits.

The sand-dune facies consists of buff sand in large cross-bedded units with an easterly paleo-wind direction. These beds are identical to the typical Ojo Caliente Sandstone exposed 15 mi (24 km) to the west along the Ojo Caliente River. The intervening strip is covered by basalts of Black Mesa and its flanking landslide apron so that direct correlation is impossible.

The playa-type lacustrine facies consists of brownish silt and sand that is parallel-bedded (vertically accreted windblown sand) and which contains small carbonate nodules and fossil soil zones.

The alluvial-fan facies forms ribbed outcrops and consists of gray pebbly gravel that is subangular to subrounded. All clasts are schist and quartzite derived from the Precambrian rocks exposed immediately to the south in the Picuris Mountains. The gray color is due to the abundance of sand and small pebble-sized fragments of black slate and phyllite. Placers of garnet crystals also are present. The average size of the conglomerate clasts is slightly larger in the higher exposed layers.

Total exposed section is estimated to be about 1500 ft (460 m) thick. The base is not exposed and the top is an angular unconformity under the Servilleta Formation (Unit D).

Unit **D** (Servilleta Formation)

This unit will be described in three segments, in stratigraphic order from oldest to youngest: the conglomerates north of the Embudo fault scarp along the Rio Grande, their overlying basalts, and the single basalt and associated conglomerates south of the Embudo fault scarp.

The canyon of the Rio Grande north of Pilar is carved into the Servilleta Formation. Near Pilar, extensive landslide cover masks the underlying sedimentary rocks except for those beds immediately underlying the capping basalts and exposures in canyons on the east wall 2.5 mi (4 km) north of Pilar. Here, about 500 ft (150 m) of gray pebble-cobble conglomerate that is subrounded to subangular and which coarsens upward are exposed in a steep-walled arroyo. All clasts are of rock types exposed in the Picuris Mountains to the southeast. Pebble imbrication and crossbed transport directions lie in the northwest quadrant. None of the units is of mudflow origin, but instead is characteristic of braided-stream alluvial-fan types. Presumably, these lie on the Santa Fe Group, but if present above river level, they are covered. The widening of the canyon in this reach might be a result of erosion through the lightly cemented Servilleta sedimentary rocks into the eolian sand facies of the Ojo Caliente Member of the Tesuque Formation. These beds dip only a few degrees north and west (initial dip?) and appear to underlie conformably the capping basalts of the Rio Grande Canyon.

The basalts exposed along the Rio Grande Gorge are in distinct packages of 3-5 flows each separated by sedimentary interbeds of varying thickness. The lowest exposed basalt package terminates a few kilometers north of the confluence of the Rio Pueblo de Taos and the Rio Grande; the visible result is the change in shape of the gorge from a steep V-shaped canyon southward to the wider slump-block-coated U-shaped canyon. Continuing southward, successively higher basalt packages step farther southward over the northwardbuilding Servilleta alluvial fans until, from Pilar onward, only the top package continues the length of Black Mesa nearly to Espanola. The lowest basalt of each package from Rio Pueblo de Taos south nearly to Pilar is commonly partially altered to a greenish color. (Kono and others (1967) ascribed this to a montmorillonite clay from their samples in the Rio Pueblo de Taos.) This consistent relationship and the presence locally of soft-sediment deformation suggest that a playa or alluvial flat developed between the northward-prograding alluvial fans from the rising Picuris Mountains and the southward-moving basalt flows.

These olivine-tholeiites (Aoki, 1967) range in age from 4.5 to 3.62 m.y. (Ozima and others, 1967). Manley (1976) reported an age of 2.8 m.y. for the basalt capping Black Mesa near Espanola. This latter basalt appears to overlie the youngest package of the Rio Grande Gorge basalt and does not carry along the mesa cap to Pilar. Instead, it appears to stay on the west side of the mesa and continue north toward Cerro Mojino. Lipman (1978, p. 40) located the largest exposed sources of Servilleta basalts as two very-low-angle shield volcanoes a few kilometers east of Tres Piedras (30 mi (48 km) northwest of Taos, near the western edge of the Taos Plateau).

South of the Embudo fault, a single discontinuous basalt caps the mesa northeast of Pilar. A thin conglomerate at its base rests with angular unconformity across the Ojo Caliente Member of the Tesuque Formation. The basalt and underlying conglomerate are thickest in the bluffs above Pilar where each is nearly 40 ft (12 m) thick. Farther northeast, the basalt and/or the underlying conglomerate together are 20 ft (6 m) or less in thickness and are locally absent. Bent pipe vesicles do not give consistent flow directions (west near Pilar and southeast a mile farther east). Whether this flow correlates with the top basalt or any of the four basalts that are exposed north of the Embudo fault along the mesa northeast of Pilar is unknown. There are no identifiable differences in hand specimen. (Aoki (1967) remarked on the uniformity of these basalts along the Rio Grande Gorge to the north.)

The youngest part of the Servilleta Formation in this area is extremely coarse and overlies the basalts of the Rio Grande Gorge. The formation includes the alluvial-fan deposits of Arroyo Hondo deposited prior to the entrenching of Arroyo Hondo in response to the active downcutting of the Rio Grande. Angular cobble- to boulder-sized clasts of phyllite, schist and quartzite litter the surface of the fan deposit. Remnants of fan deposits overlie the basalt member of the Servilleta Formation, and in places, beheaded channels are present on the mesa extending northeast from Pilar.

The headward growth of Rito Cieneguilla and its major tributaries (Agua Caliente and Piedra Lumbre) gradually abstracted and diverted all drainages from the Picuris Mountains that crossed the Embudo fault; as a result, these drainages became parallel to it to join the Rio Grande at Pilar. The numerous gravel deposits of this dissection have not been studied yet to determine whether they have structural as well as climatic controls.

EMBUDO FAULT

The stratigraphic data presented in the previous section show that erosion of Precambrian rocks from the Picuris Mountains had begun already in late Santa Fe time (Ojo Caliente Sandstone Member) or over 7 m.y. ago during the late Miocene (using Manley's (1978) correlation chart). Thus, the Embudo fault was in existence by this time. Whether it was active earlier is not known, although the presence of Picuris Tuff and its northward correlative, the Los Pinos Formation, which Lipman and Mehnert (1975) state marks the inception of Rio Grande rifting in southern Colorado, suggests that this region was subsiding, and that the Embudo fault was not active or is at least unrecognized.

The coarsening upward of Picuris-derived clasts indicates that the topographic relief between the San Luis Valley basin and the Picuris Mountains across the Embudo fault has been increasing. Using gravity data, Cordell (1976) postulates that Precambrian basement is at sea level a few kilometers north of Pilar. In contrast, the Picuris Mountains reach upward to 10,810 ft (3,300 m) a few kilometers east of Pilar. Thus, structural relief across the fault zone is at least 10,000 ft (3,000 m), depending on the amount of eastward dip of the basement to Taos.

The Embudo fault, as used here, is that fault which has a mappable surface trace from Pilar northeast to Hondo Canyon. It also is visible for several kilometers southwest of Pilar as a linear groove that cuts the feet of the massive landslides that flank the Rio Grande. East of Hondo Canyon, the fault scarp loses its sharp definition as it turns eastward so that only discontinuous segments can be found and elsewhere it appears to be masked by landsliding.

Microfaulted sand-dune facies of Unit D is displayed well in the roadcuts for one-half mile (.8 km) southwest of where the road reaches the Taos Plateau. Contradictory fault slip solutions have been obtained using observed separations on bed set and crossbed set boundaries. Assuming that they formed after the beds had been rotated to their present attitudes, most faults striking north to west and dipping southwest (averaging 45°) show reverse-slip solutions, and steeply dipping faults that strike northeast show left strike-slip. Why some faults do not fit these patterns has yet to be resolved but may relate to the timing of this microfaulting, and the uplift and tilting of the entire unit.

The linearity of Rio Pueblo Taos suggests fault control, although it may be only a synclinal downwarp parallel to the gorge arch (fig. 2). The streams draining into the Rio Pueblo de Taos have asymmetrical shapes with the steep slope on the east, suggesting an eastward-tilting of this region as far as Taos. The northeastward projection of the gorge arch across New Mexico Highway 3 to the mouth of the Rio Hondo marks the prominent drainage divide of streams draining west to the Rio Grande from streams draining south to the Rio Pueblo de Taos. The western boundary of this warped block appears to be the down-to-the-east faults and monoclines that parallel the Rio Grande from west of the village of Arroyo Hondo (trellis drainage west of Arroyo Hondo (fig. 2)) south nearly to Pilar. The eastern boundary is marked by prominent piedmont scarps along the Sangre de Cristo range front. The range front turns southwest to join the Embudo fault zone. The north-trending faulting between the Picuris-Pecos fault and that across Rio Grande del Rancho includes a variety of motions, most of which have yet to be sorted out. This area currently is being studied in detail as part of our program to unravel the depositional and structural history of this region.

The presence of basalt inliers at the surface of the piedmont slope from Hondo Canyon (fig. 5) east suggests that unidentified faults underlie this surface and may aid in controlling the course of the Rio Pueblo de Taos immediately to the north.

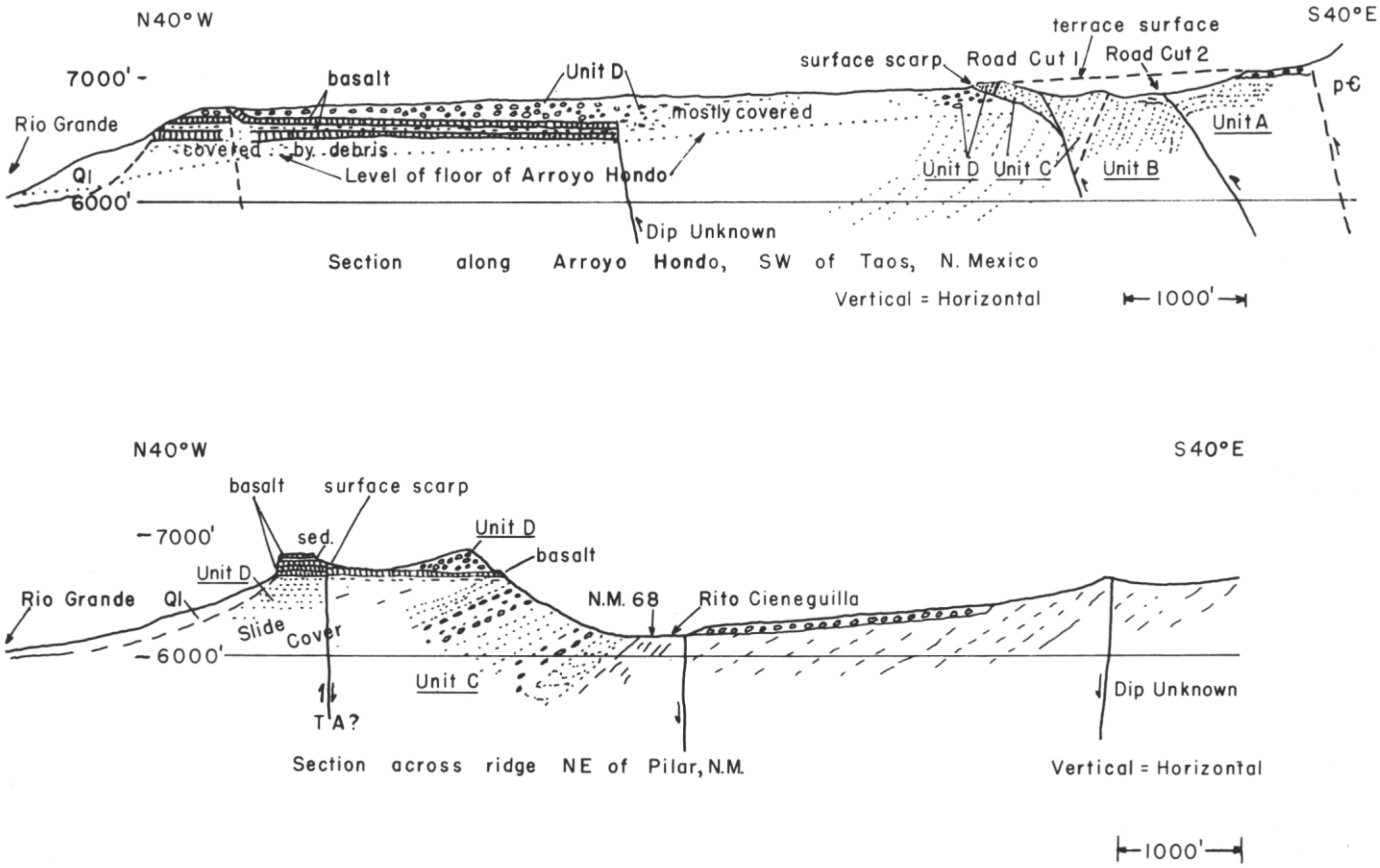

Figure 5. Cross sections across Embudo fault (surface scarp) at Hondo Canyon and Pilar. Units and roadcuts on Hondo Canyon section are those of Figure 4. Basalts are part of Servilleta Formation. Lower Servilleta Formation underlies basalt. Dips of beds east of Rito Cieneguilla show approximate structure pending detailed study. Dip of Embudo fault at Pilar is unknown because of landslide cover and pipeline debris. Surface scarp is down to south in the section and reverses to north side down about 1000 ft (300 m) northeast along strike.

Lambert (1966) first described the north-trending set of down-to-the-west faults that traverse Rio Pueblo de Taos west of Taos. He pointed out that they are in line with the northern projection of the Pecos-Picuris fault, the major regional fault on which several periods of slip can be demonstrated (Miller and others, 1963).

The fact that the Embudo fault shows reverse motions along its roadcut exposures in Hondo Canyon suggests that it may have upthrust geometry throughout the segment east of Pilar. The reversal of throw southwest of Pilar shows its scissor motion that appears to have its pivot on the Precambrian high that separates the Espanola from the San Luis Valley basins (marked by Cerro Azul) (Cordell, 1976; Kelley, 1978). Because this fault acts like a transform fault (it connects two rift segments), there must be a significant but as yet undemonstrated strike-slip component. The size of the strike-slip component is a function of the three-dimensional shape of the rift basin, a shape that is known poorly (at best). Whether the faults are planar or listric also makes significant differences in estimates of extension. The consistent tilt of the basin-filling units toward the Sangre de Cristo Mountains implies a listric shape to the border fault.

The reverse component has major regional significance because, if rifting was extending perpendicularly to the length of the rift, then this fault would be an oblique pull-apart fault, a leaky transform. Instead, it is the opposite, which suggests that the diamond-shaped block that has the Picuris and Sandia mountains at the opposite narrow ends is being shortened across this long diagonal (rotated counterclockwise). This supports Kelley's (1977) feeling that there must be a left-slip component parallel to the rift. The Embudo fault data support a left-slip component along the rift.

ADDENDUM

I received the volume by Riecker (1979) as this manuscript was being typed. In it are summaries by Kelley (tectonics, middle Rio Grande rift), Lipman and Mehnert (Taos Plateau volcanic field) and Manley (Espanola basin) that represent the most recent statements by these workers. Kelley shows that the right en-echelon offset of basins involves ramping down-to-the-north of uplifts arranged in relay and that this process requires a left-slip component along the north-trending faults. Lipman and Mehnert redefine the Servilleta Formation (this paper adopted the usage of Lambert (1966)) to be only the tholeiitic basalts. They state that the interbedded sedimentary rocks have the same names as laterally equivalent units such as the Ancha Formation to the south (Manley, 1978), and that overlying sedimentary rocks are of an unrelated lithology and genesis, being mainly Pleistocene glacial outwash fans. Manley renames several of Kelley's (1952) faults and defines the

Velarde graben. The graben extends southwest from near Pilar (my interpretation), where the Rio Grande enters the structure, to where the river turns south; here, the graben widens and the border faults also turn south. The western border is the Pajarito fault zone (Los Alamos fault of Kelley) and the eastern border is an unnamed zone trending through Pojoaque.

The narrow northeast-trending segment of the graben is the Embudo fault of Kelley. The northeastern segment of the southern border fault, the Velarde fault of Manley, is the fault discussed in this paper that I have called the Embudo fault. The Velarde graben is a sub-basin of the Espanola basin that is the currently active down-dropping segment of the basin. The Velarde (Embudo) fault is part of the transform zone between the Velarde graben and the San Luis Valley basin. The rotation and hinge action of this fault is shown by the change from a long narrow northeast-trending graben northeastward to a reverse and upthrust style of faulting where it bounds the southern end of the currently active subsiding block of the Taos reentrant.

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