



Tijeras-Canoncito fault system--A major zone of recurrent movement in north-central New Mexico

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TIJERAS-CANONCITO FAULT SYSTEM-A MAJOR ZONE OF RECURRENT MOVEMENT IN NORTH-CENTRAL NEW MEXICO

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INTRODUCTION

Recent geologic mapping (Bachman, 1975; Booth, 1977; Johnson, 1973, 1975; Lisenbee, 1976) has shown that the Tijeras fault, which transects the Sandia and Manzanita mountains (Kelley, 1963), and the faults of the Canoncito area of the southern Sangre de Cristo Mountains (Booth, 1977; Budding, 1972) are connected and form a major structural zone that is obliquely transverse to the major uplifts and basins of central New Mexico (fig. 1). The Tijeras-Cationcito fault system extends northeasterly at least 93 km from the vicinity of Albuquerque to about 14 km southeast of Santa Fe. Aeromagnetic and gravity data (Cordell, 1976) suggest that the fault extends southwesterly beneath basin fill of the Rio Grande rift. A continuation northward along the Picuris-Pecos fault was inferred by Miller and others (1963) and is considered probable. If so, the fault system has been active along various segments for a length exceeding 175 km.

Numerous Tertiary intrusive bodies with associated mineral deposits are located along this fault system in the Ortiz (Old Placers), San Pedro (New Placers) and Tijeras Canyon districts (Elston, 1967; Mardirosian, 1977) (locs. 1, 2 and 3, respectively, on fig. 1). Landwehr (1967) suggested that the broad, northeast-trending Bisbee-Morenci belt of major mineralization extends to the southern Sangre de Cristo uplift of New Mexico; the Tijeras-Calioncito fault system and associated mineral deposits are within the Bisbee-Morenci belt, although Landwehr (1967) did not note any of these mineral occurrences.

A large part of the Tijeras-Canoncito fault system follows the strike of foliation and schistosity of Precambrian rocks (fig. 1), and fault movement probably began in the Precambrian. The element of anisotropy that was established in the crust of central New Mexico has been the locus of movement during succeeding episodes of deformation. It seems likely that the direction of slip along any given segment may have been different during different times, being dependent upon the principal and perhaps local stress fields. Also, different segments appear to have undergone different directions of slip during the same deformational event.

DESCRIPTION OF FAULT SYSTEM

The Tijeras-Carioncito fault system mainly consists of north-east-trending, high-angle faults that split and join along strike, and form sigmoidal and en-echelon patterns in map view (fig. 1), with graben and horsts occurring between the major faults.

Although good exposures of fault surfaces are rare, it appears from fairly straight fault traces that most of the faults are nearly vertical. A few high-angle, north-trending, reverse faults splay off the main fault system near the eastern edge of

the Sandia uplift and the southern end of the Sangre de Cristo uplift. The fault system is joined from the north by several late Tertiary normal faults along the east side of the Hagan basin and at the southern end of the Espanola basin.

The faults and associated structures are described beginning at the southwest end of the system and proceeding toward the northeast. On its southwestern end, the Tijeras fault has Precambrian metamorphic rocks juxtaposed with Pennsylvanian strata, with the southeast side down; Quaternary alluvium overlaps the bedrock outcrops to the southwest in the Albuquerque basin. About 1 km to the northeast, the Tijeras fault has Precambrian rocks of contrasting lithologies and metamorphic facies exposed along the trace for nearly 10 km, with low-grade (greenschist facies), regionally metamorphosed greenstone and associated rocks on the southeast (Bruns, 1959), and medium-grade (amphibolite facies), regionally metamorphosed quartzo-feldspathic gneiss on the northwest (Lodewick, 1960). Recent roadcuts along this segment of the fault provide excellent exposures of the fault surface (fig. 2); here, the fault consists of a zone up to 10 m wide with gouge near the center and breccia grading into intensely fractured country rock on both sides. At this exposure, there also is greenstone in fault contact with colluvium, probably of Quaternary age. There is no evidence for the direction or amount of slip or separation on this segment of the fault using Precambrian rocks. The juxtaposed greenstone and colluvium (fig. 2) suggest that the latest movement is normal and downthrown on the northwest side.

The next segment of the fault extends from the eastern base of the Sandia uplift, where Paleozoic rocks are offset, to the northeast end of the Tijeras graben, where rocks ranging in age from Pennsylvanian to Cretaceous are offset. Vertical separation along this segment ranges from zero to 1,000+ m (Kelley and Northrop, 1975), with the southeast side down. The basal Paleozoic strata have right separation, but Kelley and Northrop (1975, p. 87-88) note left separation of 500 to 600 m of fold axes (shown on fig. 1) and left separation of south- and southwest-dipping strata.

The Gutierrez fault connects with the Tijeras fault and extends about 24 km to the northeast, bounding the southeastern margins of the Tijeras graben and Monte Largo horst. Limited exposures indicate that the fault is nearly vertical and consists of a zone of gouge up to 2 m wide. There is a maximum of about 1,100 m of vertical separation where the fault bounds the Tijeras graben, with the north side down (Kelley and Northrop, 1975); Paleozoic and Mesozoic rocks are juxtaposed along this segment of the fault. Farther to the northeast

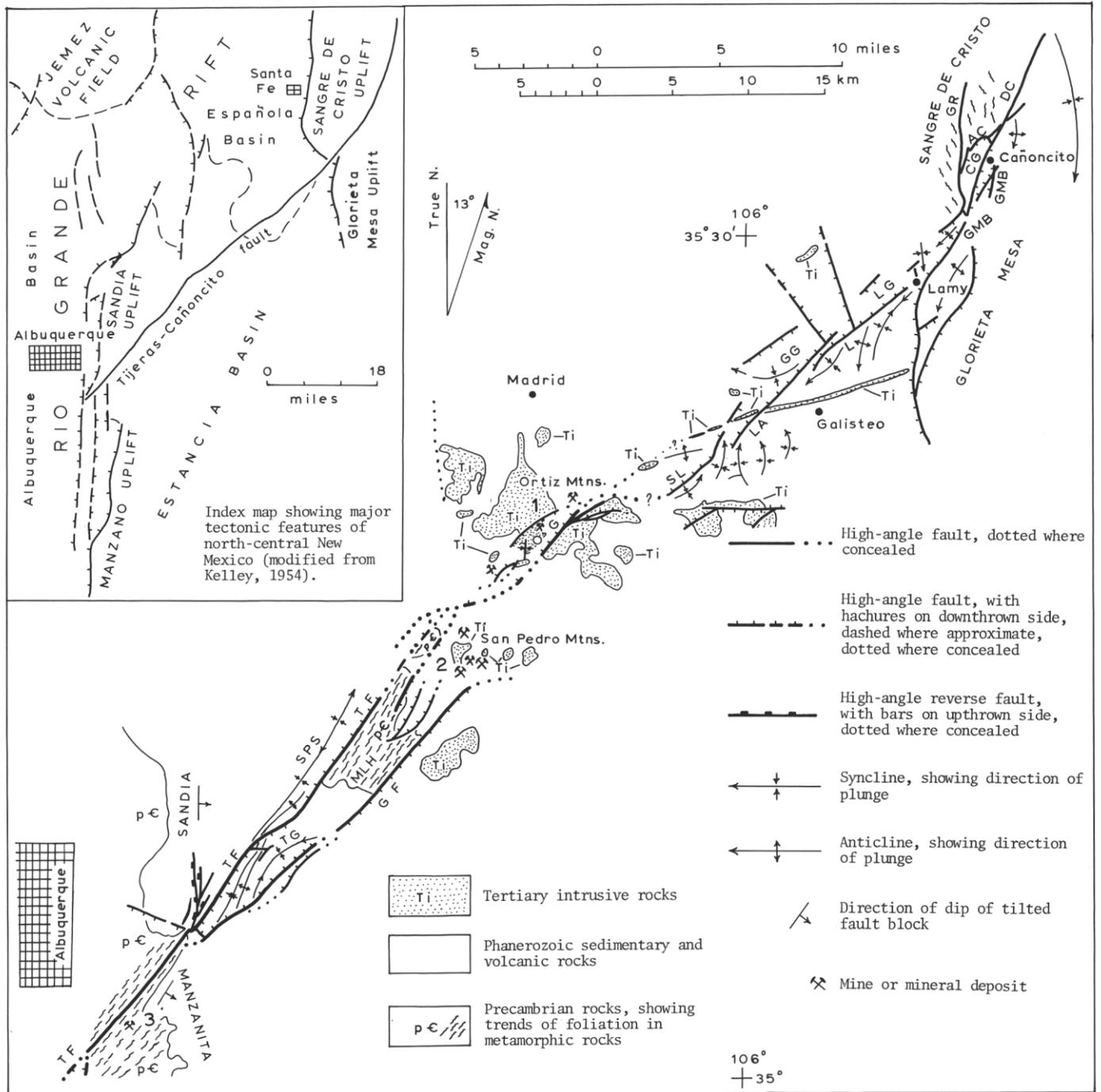


Figure 1. Generalized tectonic map showing Tijeras-Cañoncito fault system and related features. Major structural features are, from southwest to northeast: TF, Tijeras fault; TG, Tijeras graben; SPS, San Pedro syncline; MLH, Monte Largo horst; GF, Gutierrez fault; OG, Ortiz graben; SL, San Lazarus fault; LA, Los Angeles fault; GG, Galisteo graben; L, Lamy fault; LG, Lamy graben; AC, Apache Creek fault; GMB, Glorieta Mesa boundary fault; DC, Deer Creek fault; GR, Garcia ranch fault; CG, Cañoncito graben. Numbers near mines are localities discussed in text.



Figure 2. View northeast along Tijeras fault. Sheared Precambrian quartzo-feldspathic gneiss (gn) and Quaternary(?) colluvium (co) in contact with sheared Precambrian greenstone (gs) to right.

where the fault bounds the Monte Largo horst, the southeast side is down with Pennsylvanian strata against Precambrian metamorphic rocks, with about 500 m of vertical separation. To the northeast, the fault splays toward the east and apparently dies out beneath alluvium.

The northwestern boundary of the Monte Largo horst is the continuation of the Tijeras fault which has Pennsylvanian strata against Precambrian metamorphic rocks, with about 1,000+ m of vertical separation (Kelley and Northrop, 1975). The northern continuation of Monte Largo horst consists of a smaller horst block cored with Precambrian metamorphic rocks. A small graben occurs along the crest of the horst at its northeastern end. Bachman (1975) infers that the Tijeras fault continues to the northeast beneath upper Cenozoic gravel and curves eastward, making a sigmoidal bend.

In the Ortiz Mountains, a small graben is present where the bounding faults displace Cretaceous sedimentary strata and Tertiary intrusive rocks. The graben is confined to the northeast-trending part of the sigmoidal bend. Vertical separations here appear to be no more than a few hundred meters.

From the Ortiz Mountains northeastward almost to Lamy, a distance of 26 km, the fault system lies at the south end of the Espaliola basin. Jurassic, Cretaceous and Tertiary strata are deformed by a series of en-echelon faults and associated graben, folds and shale diapirs. These en-echelon faults average 10 km in length (fig. 1) and probably reach a maximum dis-

placement of 600 m. The individual members of the en-echelon group from south to north are the San Lazarus, Los Angeles and Lamy faults.

In the Ortiz Mountains, faults of the Ortiz graben pass northeast beneath the younger Tuerto Gravels which are equivalent to the Ancha Formation. Bachman (1975) infers a sigmoidal bend in the east boundary fault of the graben so that it would continue beneath the gravel cap and connect with the San Lazarus fault to the east. Although he shows the western boundary fault as turning eastward, stratigraphic relations in the Eocene Galisteo Formation suggest that this fault, or another parallel to it, continues northeastward beneath the gravel. If so, the Ortiz graben narrows at the sigmoidal bend of the east boundary fault, but widens again northward. An east-trending normal fault cuts the Galisteo syncline axis east of the sigmoidal bend (fig. 1), but does not appear to connect with the San Lazarus fault.

The San Lazarus fault is exposed for 5 km along a curving trace which emerges from beneath the Tuerto Gravels on the southwest. It separates lower from middle units of the Galisteo Formation for most of that distance. Just south of Galisteo Creek, it overlaps Los Angeles fault. As both faults are down to the northwest and offset increases noticeably along strike, the area of overlap is structurally high. This produces an anticline (figs. 1, 3) which extends west for at least 5 km to a small Tertiary (Oligocene?) igneous body, probably a laccolithic tongue from the Ortiz intrusive center. The anticline may end just to the west, beneath the Tuerto Gravels, at the west boundary fault of the Ortiz graben.

Cretaceous shale crops out at both ends of the exposed anticline. On the west, it lies along the south flank of the small igneous body. On the east, it is exposed in a complex domal area on both sides of San Lazarus fault. In addition, three elongate domes or anticlines with exposed cores of Cretaceous shale and one dome in the Galisteo Formation lie east of the area of overlap of the two faults. Individual structures show a northerly elongation. They are bordered by peripheral synclines and cut by radial, diagonal and concentric faults. A sixth exposed shale mass lies along San Lazarus fault south of the other bodies. Due to the discordant bedding relations between the shale and enclosing Tertiary units, the folding, distortion and extreme dip of bedding and contained fossils in the shale, and the juxtaposition of Cretaceous shale against various units in the basal Galisteo Formation, these shale-cored structures were interpreted by Stearns (1953) and Lisenbee (1976) as diapiric intrusions.

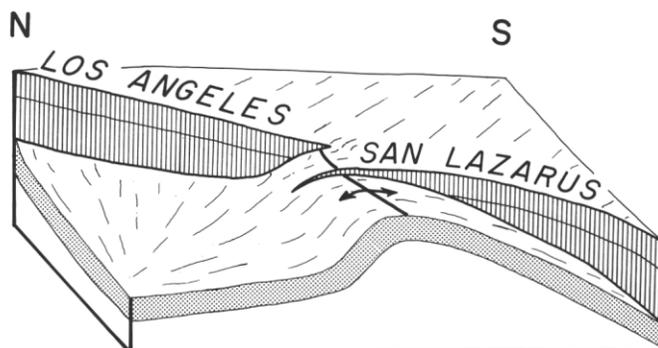


Figure 3. Block diagram viewed southeast illustrating relationship of anticline to Los Angeles and San Lazarus faults.

Los Angeles fault begins on the south in an anticline plunging northeastward from one of the elongate shale-cored folds. The fault extends northeastward for 10 km, and for much of its length, places middle units of the Galisteo Formation on the northwest against lower units of the Galisteo on the southeast. The throw on the fault is at least 600 m for part of this distance. Beds may be rotated to steeper dips, as much as 70° NW, for a few tens of meters away from the fault. One exposure shows a distinct fault plane dipping 81°W.

North of Galisteo Creek, near the intersection of the Santa Fe Railroad tracks and the Galisteo-to-Cerrillos road, the fault crosses an easterly trending Oligocene dike, causing left separation of 60 m. In addition, a short segment of the dike trends northeast parallel to Los Angeles fault. This segment is inferred to predate the exposed fault, but to reflect a zone of weakness in pre-Eocene rocks below. A similar dike segment parallels the southern end of the San Lazarus fault for at least 545 m.

Along Los Angeles Creek, north of the Galisteo-Cerrillos road, the Lamy and Los Angeles faults overlap (fig. 3). The Lamy fault begins in Cretaceous shale beneath a cover of alluvium. The shale and overlying basal Galisteo Formation comprise a southerly plunging anticline here (fig. 4), but the general character of the fold is destroyed to the north as throw along the Lamy fault increases and beds of the Jurassic Morrison (too small to show on fig. 4) and Cretaceous Dakota formations are exposed along the upthrown southeast side. At that point, Cretaceous shale lies between the two faults for approximately 1 km (fig. 4). The subvertical shale beds may have moved, in part, diapirically.

The Lamy fault extends at least to the village of Lamy. Cretaceous formations are dominant along the upthrown southeast side, and various units of the Galisteo Formation and, near Lamy, Cretaceous shale about the fault on the northwest. In one exposure in Los Angeles Creek, the fault surface dips 84°NW placing Cretaceous shale in the footwall against middle units of the Galisteo Formation. Slickensides on the fault surface are nearly horizontal. Beds in both hanging wall and footwall are rotated and sheared for a few meters from the fault surface.

Many folds displaying an en-echelon pattern (figs. 1, 4) are present along the upthrown southeast side of the fault. Small south-plunging folds at the south end of the fault are outlined by the contact of the Mancos Shale and Galisteo Formation. Two synclines separated by a south-plunging anticline roughly parallel the fault for much of its length. Cretaceous shale exposed in the limbs of these larger folds was interpreted by Lisenbee (1976) as similar to shale-cored diapiric structures south of Galisteo Creek. They appear, however, to reflect only folding and not piercement.

The Lamy and Los Angeles faults are paralleled at a distance of 2 to 3 km on the northwest by shorter normal faults. In the two locations where the fault planes are visible, they are well defined surfaces dipping 49° and 65°SE. Displacement on these normal faults is a maximum of 450 m. The resulting structures are referred to here as the Galisteo and Lamy graben (fig. 1). In the larger Galisteo graben, west of Los Angeles fault, beds of the Galisteo Formation are rotated due to increased throw on the fault along strike to form a curving syncline plunging away from the fault to the west.

A northwesterly trending graben, parallel to the axis of the Esparmila basin, abuts the Lamy fault. The Eocene Galisteo and Oligocene Espinaso formations are affected (fig. 4), but

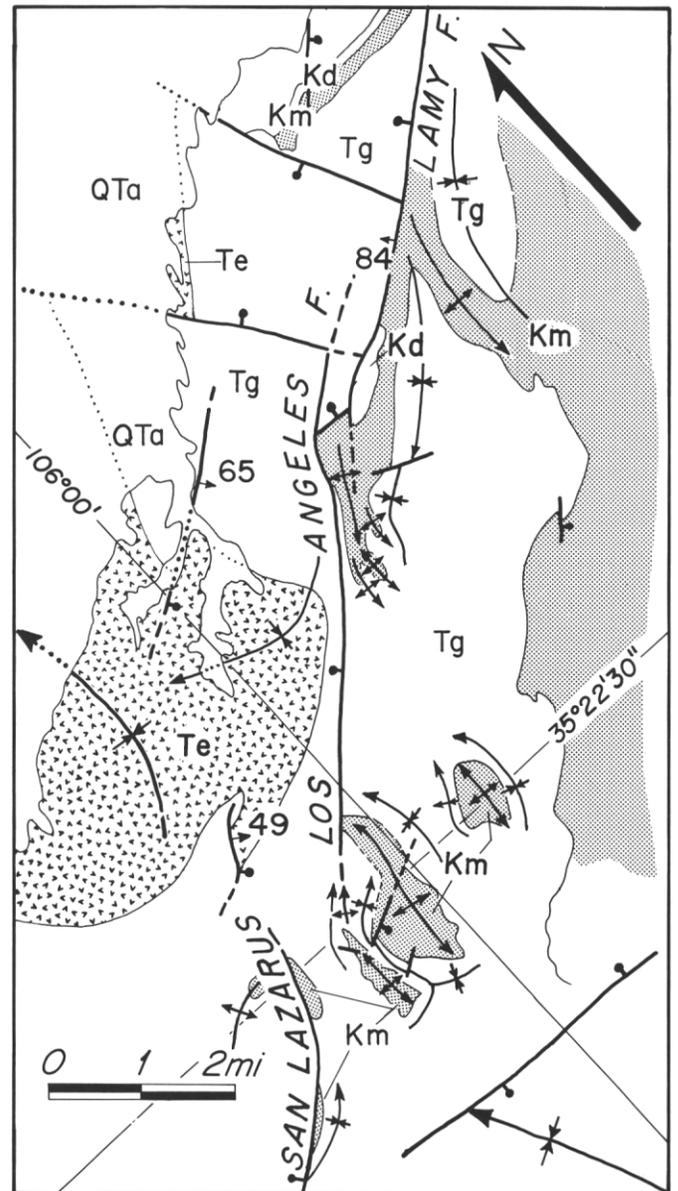


Figure 4. Generalized bedrock geologic map of southernmost end of Española basin. Dakota Sandstone (Kd), Mancos Shale (Km), Galisteo Formation (Tg), Espinaso Volcanics (Te) and Ancha Formation (QTa).

the faults are covered to the northwest by basal conglomerate of the (Pliocene to Quaternary) Ancha Formation. Stratigraphic offset increases toward the northwest and is at least 600 m on the northeast fault.

At Lamy, faults of the Tijeras-Carioncito group join those forming the west boundary of the Glorieta Mesa uplift. The general N50E trend followed from Tijeras to Lamy changes to N30E. This is the local trend of the recurrently active Picuris-Pecos fault as defined by Miller and others (1963), and the Lamy to Cafioncito area lies along the extension of this structure.

From Lamy to north of Carloncito, the Sangre de Cristo uplift is separated from the structurally lower Glorieta Mesa

uplift by a complexly faulted and folded graben. In plan view (fig. 1), the graben is approximately 2.5 km wide in the north but narrows to 0.8 km at the southwest end. It contains rotated beds of Pennsylvanian to Jurassic age which show a faulted synclinal pattern plunging to the southwest. As explained in a subsequent section, this fold is the product of successive periods of deformation, and the faults have recurrent movement.

Three dominant faults and many subsidiary ones affect the graben. From west to east, these are the Apache Canyon, Galisteo Creek and Glorieta Mesa boundary faults of Booth (1976, 1977). The following descriptions are based on his work unless otherwise noted.

In plan view, the Apache Canyon fault curves in an elongate S pattern. At the base of the S, the fault trends southwesterly and is covered by the Ancha Formation; on the north near Carioncito, it joins the Deer Creek and Galisteo Creek faults. Throw is at least 515 m locally, but the actual amount cannot be determined due to removal of the Paleozoic section from the uplifted blocks. Booth (1976) states that a thick gouge zone is developed between the Precambrian and Pennsylvanian units, and his map shows several zones of brecciated granite gneiss.

Budding (1972) mapped the Garcia ranch fault as splitting from the Apache Canyon fault along the west flank of the graben and extending northward for several kilometers. He interprets this as a reverse fault. The cross sections of Booth (1976) show normal movement along the Apache Canyon fault, although no attitudes are given on the geologic map. The dip on this recurrently active structure is probably nearly vertical.

Contacts and foliation of Precambrian granitic and amphibolitic gneisses in the Sangre de Cristo uplift abut the fault at roughly 40°. Northeasterly trending sedimentary units in the graben also abut the fault obliquely so that a progressive change from Pennsylvanian to Triassic is seen from northeast to southwest. These units dip southeasterly at 30° to 70°.

The Galisteo Creek fault (fig. 1) separates easterly and westerly dipping Paleozoic and Mesozoic units in the graben. It overlaps slightly with one segment of the Glorieta Mesa boundary fault on the southwest, and joins with the Deer Creek fault about 6 km to the northeast. The linear trace suggests a sub-vertical dip. It is down on the southeast approximately 1,000 m at the intersection with the Apache Canyon fault, but offset decreases to about 60 m at the southwest end. Booth (1976) describes a puzzling occurrence of brecciated fragments of Precambrian gneiss in a pseudotachylyte matrix along a 2.7 km stretch of the fault near Carioncito. The zone, which is up to 12 m wide, separates Paleozoic and Mesozoic units.

The east boundary of the Carioncito graben is defined by several faults which together were called the Glorieta Mesa boundary fault by Booth (1976). Although the application of one name to several faults is awkward, it is used here in the context outlined by Booth for those faults which limit the Glorieta Mesa uplift on the west. Johnson (1975) referred to one of these faults as the "South Fork Carioncito fault."

The longest segment of the Glorieta Mesa boundary fault group extends southwest from the Galisteo Creek fault to Lamy, thence south for 20 km. Other segments of the group lie approximately 1 km east of the Galisteo Creek fault and parallel to it for 5 km. Individual members of this group are slightly sinuous in plan view, and two faults cross in an X

pattern. An en-echelon pattern is present in several small faults at the northeast, but all are downdropped to the west. The Triassic units of Glorieta Mesa are rotated to strikes which parallel the faults and show westerly dips up to 50°, so that the boundary of the graben is essentially a faulted monocline. Structural relief is as much as 180 m. At the area of overlap of the two major divisions of the fault, the terminations are joined by a monocline which faces north into the graben.

Northeastward from the Carioncito graben, deformation is expressed along the Deer Creek fault (fig. 1). It extends N15° to 20°E from the area of join of the Apache Creek and Galisteo Creek faults, separating Precambrian Embudo Granite on the west from Pennsylvanian sedimentary units on the east. The Pennsylvanian rocks are overturned locally near the fault (Budding, 1972), and are crossed by smaller faults and south-plunging folds in the west limb of the Glorieta syncline.

Miller and others (1963) state that the Picuris-Pecos fault (not shown in fig. 1), which they mapped along the crest of the Sangre de Cristo Range for a distance of 60 km, continues intermittently through the 24 km separating it and the Deer Creek fault north of Carioncito.

TIMING AND NATURE OF FAULT MOVEMENT

The Tijeras-Cañoncito fault system has undergone at least four episodes of movement, ranging in age from Precambrian to Quaternary, with various segments of the system appearing to have moved semi-independently of other segments.

Precambrian

In southwestern Tijeras Canyon where low-grade greenstones south of the Tijeras fault are juxtaposed with higher-grade granitic gneisses on the north (fig. 5), field evidence

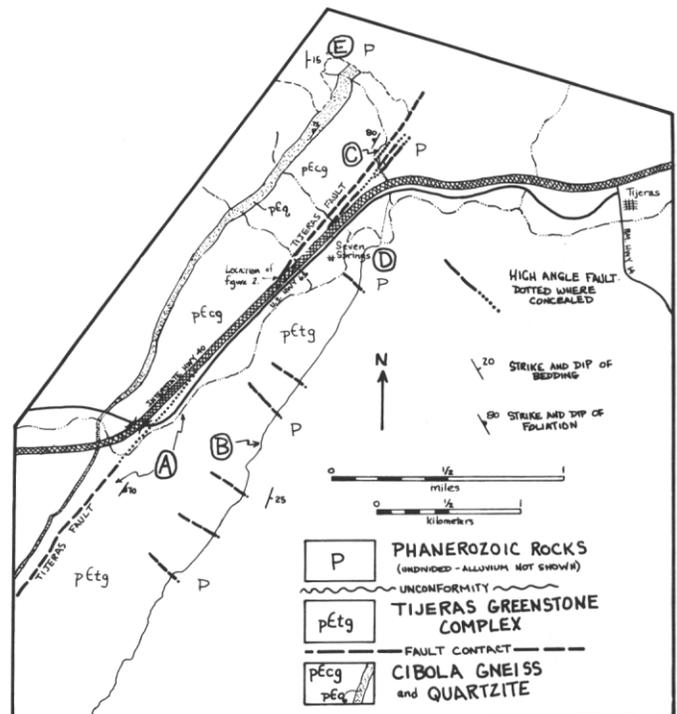


Figure 5. Generalized geologic map of Tijeras Canyon area, Bernalillo County, New Mexico. Circled letters refer to areas mentioned in text.

suggests that a major component of Precambrian movement was left slip, perhaps several kilometers, and that this movement was coincident with middle Proterozoic granitic plutonism. A major line of evidence is the presence of numerous quartz veins, simple pegmatites and minor aplites arranged en echelon in the greenstone adjacent to the Tijeras fault (fig. 5, loc. A). Although synmetamorphic quartz veins are common within the greenstone terrane, intrusive bodies adjacent to the fault are discordant to foliation and clearly post-metamorphic. These lensoid bodies are generally subvertical or dip steeply southeast with a strike slightly more northerly than the Tijeras fault and display a pinnate geometry suggestive of left slip (fig. 6). The aplites and pegmatites suggest a genetic relationship to granitic plutonism which is dated radiometrically at 1.4 to 1.8 b.y. (Brookins, 1974; Condie, 1978).

An area within the gneiss terrane just north of the Tijeras fault approximately 1.9 km west of the village of Tijeras (fig. 5, loc. C) shows a well developed fracture and minor fault pattern dominated by northwest-striking right-lateral shears offsetting north-northwest-trending pinnate quartz veins (fig. 6B). Pervasive shearing of northeasterly strike related to the Tijeras fault has occurred within the greenstone, tending to rotate the en-echelon structures into parallelism with the Tijeras fault; structures within the stronger, more brittle gneiss appear to have been rotated counter-clockwise to their present orientations. The shear fractures and pinnate quartz veins in the gneiss, the Tijeras fault, and the aplites and pegmatites in the greenstone, when taken together, form a conjugate shear system suggesting an origin for this part of the Tijeras fault during a period of approximately north-south compression in Proterozoic time (fig. 6).

Direct evidence of Precambrian movement is lacking in the Canoncito area. Booth (1976), however, noted extensive brecciation of the granodiorite along the Apache Canyon and Deer Creek faults. Large, angular blocks are set in a finely ground matrix and cemented with silica. In that the breccia does not

contain fragments of the Pennsylvanian or Permian rocks of the presently downthrown block, and does not appear to have been broken by the subsequent movements in the area, he concluded that it was cemented Precambrian-age breccia which subsequently behaved as competent, crystalline rock.

Precambrian movement is documented along the Picuris-Pecos fault, the probable northward continuation of the Tijeras-Carioncito fault system. Miller and others (1963) show right separation of 37 km based on offset of fold axes, and of metasedimentary and metaigneous rocks. They suggest that the fault should continue to the Carioncito area. Reconnaissance mapping by Booth and Elmer Baltz north and east of Carioncito "... did not fully substantiate ..." the claim (Booth, 1976). Although they found a probable fault (the Deer Creek fault?), they believe that the volume and type of gouge and the degree of deformation of adjacent rocks are not of the type to be expected along a fault showing many kilometers of lateral movement. Such movement may have been distributed across several faults, some of which may lie beneath the Paleozoic rocks east of the Deer Creek fault. If the Picuris-Pecos fault continues southward to Calioncito and Lamy, its further extension is a matter of conjecture. It might continue southward, essentially along the present west flank of the Glorieta Mesa uplift and the zone inferred by Read and others (1944) to mark the east flank of the San Luis highland. Alternatively, it might follow the present line of the Tijeras-Carioncito fault system as suggested by Miller and others (1963). In either case, it could serve as a zone of crustal weakness in subsequent periods of deformation.

Paleozoic

Evidence of late Paleozoic deformation, as recognized in stratigraphic relations of thickness and/or facies, is developed well along the Tijeras-Carioncito fault zone and northward along the Picuris-Pecos fault. Basal deposits of the Sandia Formation (Pennsylvanian) are markedly different across the Tijeras fault. Southeast of the fault (fig. 5, loc. D), the basal beds consist of about 1 m of small-pebble, quartzose conglomerate overlain by shale and sandstone; northwest of the fault (fig. 5, 1. E), there are about 20 to 25 m of quartzose boulder conglomerate and coarse-grained sandstone. This suggests the presence of a low scarp facing north along the face of the fault during deposition of the basal Sandia Formation. This scarp probably was due directly to Pennsylvanian fault movement as the Precambrian rocks to the northwest of the fault are more resistant. The direction of slip is not known, but the facies contrast could be explained by either dip slip or strike slip.

In Tijeras Canyon (fig. 5, loc. B), northwest-striking, high-angle faults cut the Arroyo Periasco and Log Springs formations (Mississippian) and the Sandia Formation (Pennsylvanian). The faults do not offset the overlying Madera Limestone (Pennsylvanian), but juxtapose distinctly different sections of Mississippian strata (fig. 7). These faults are indicative of late Mississippian to early Pennsylvanian tectonism not previously reported in the Sandia or Manzano mountains. Their proximity to the Tijeras fault suggests a genetic relationship.

Detailed stratigraphic studies by Booth (1976) in the Lamy to Cailoncito area document activity on the Apache Canyon, Deer Creek and Glorieta Mesa boundary faults during much of the Pennsylvanian and into Early Permian. Formations west of the Apache Canyon fault are exposed north of Lamy. They are thin or absent relative to those which crop out east of the

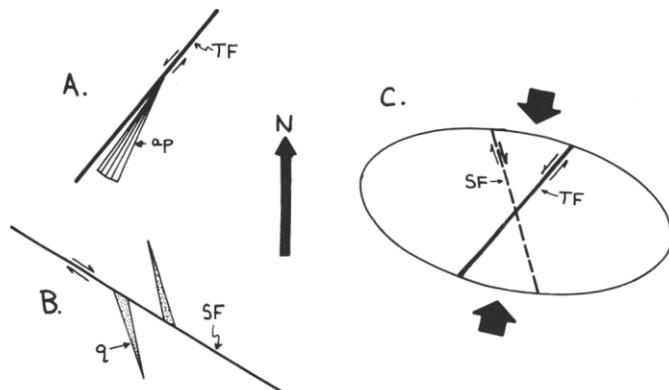


Figure 6. Synoptic structural diagrams of Tijeras fault zone in Tijeras Canyon. TF, Tijeras fault; ap, quartz veins, aplites and pegmatites in greenstone. Range of orientations shown; SF, shear fractures in Cibola Gneiss; q, pinnate quartz vein. (A) Generalized map view of structures at loc. A of Figure 5. Arrows show inferred movement directions. (B) Generalized map view of structures at loc. C of Figure 5. Arrows show inferred movement directions. (C) Generalized strain ellipse. Inferred orientation of greatest principal compressive stress during inception of the Tijeras fault is shown with large arrows.

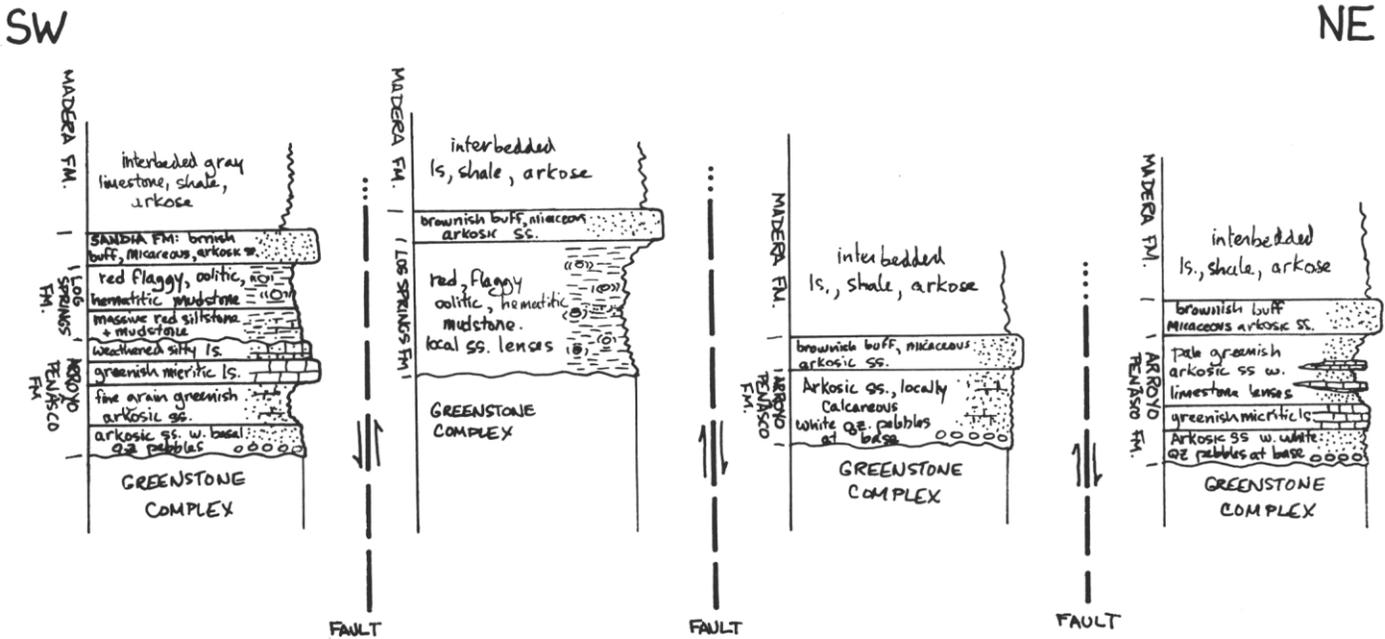


Figure 7. Generalized southwest-northeast structural-stratigraphic diagram showing juxtaposed facies along unconformity on south side of Tijeras Canyon (loc. B on fig. 5). Maximum pre-Sandia Formation thickness is approximately 10 m. Arrows show sense of vertical separation of unconformity by faults. Faults do not continue into upper part of Madera Formation.

Apache Canyon and Deer Creek faults northeast of Carioncito. In a series of diagrammatic cross sections, Booth (1976) shows unequal amounts of movement on the Galisteo Creek, Apache Canyon and Glorieta Mesa boundary faults (fig. 8). A horst and a graben result, with the block between the Galisteo Creek and Glorieta Mesa boundary faults being relatively elevated.

The "lower gray member" of the Madera Formation is 45 m thick north of Lamy. To the northeast, it is as much as 235 m thick in the Rowe-Mora basin (Booth, 1976, p. 82). Nondeposition or subsequent uplift and erosion west of Apache Canyon fault are indicated.

Booth (1976) found the "upper arkosic member" of the Madera Formation to be absent north of Lamy. Northeast of Cationcito (east of the Apache Canyon fault), an incomplete section 248 m thick is exposed. These stratigraphic relations indicate uplift of the western block during Atokan-Morrowan time. He interpreted deposition to have occurred in en-echelon, fault-bounded basins.

In Early Permian (Wolfcampian) time, rapid uplift occurred west of the Apache Canyon fault (fig. 8). North of Lamy, 90 m of Sangre de Cristo Formation are present west of Apache Canyon fault (Booth, 1976). In an incomplete section east of the fault near Carioncito, 900 m of mudstone, coarse-grained, angular sandstone and fresh-water limestone are exposed. Orange, bedded gypsum and purple shale near the top of the formation suggest deposition in a restricted evaporite basin (Booth, 1976). Deposition in a local, rapidly subsiding basin bounded by the Apache Canyon and Deer Creek faults is indicated.

Miller and others (1963) also recognized early Pennsylvanian (Morrowan to mid-Desmoinesian) uplift along the Picuris-Pecos fault. Clastic sediments were shed eastward to form the Flechado Formation and southward to form the La Pasada Formation, equivalent to the lower gray member of the Madera Formation and the older Sandia Formation. They also found

evidence of movement into Virgilian time along the Picuris-Pecos fault as the Uncompahgre highland continued to be uplifted and eroded to give the sediments of the Alamos Formation (Upper Pennsylvanian).

Tertiary

Post-Cretaceous movement is responsible for most of the structure observed along the fault system. Along the northeastern part of the system, both early and late Tertiary movements

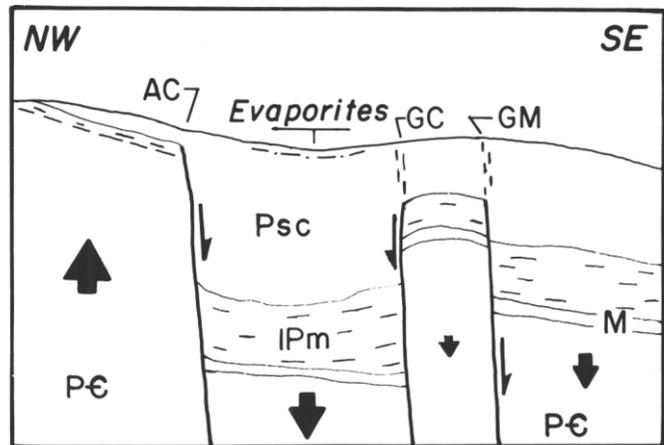


Figure 8. Diagrammatic illustration of relationship between faulting and deposition in the Cañoncito area. The Apache Canyon (AC), Galisteo Creek (GC) and Glorieta Mesa boundary (GM) faults were active to varying degrees during deposition of the Madera (IPm) and Sangre de Cristo (Psc) formations. The faults separate blocks for which arrowheads show the direction and relative amounts of movement. Units are thin or absent west of the Apache Canyon fault. After Booth (1976).

are demonstrable. To the southwest, the time of movement cannot be determined precisely because rocks younger than Cretaceous are not present. It seems likely, however, that the main segment of the Tijeras-Cañoncito fault system and adjacent structures underwent deformation in the late Cenozoic in response to uplift and eastward tilting of the Sandia fault block and regional extension across the Rio Grande rift. During this time, there was rejuvenated movement along the Tijeras-Cañoncito system because it was a major anisotropic element in the crust. Dip slip appears to be the dominant component of movement, with subordinate left slip.

High-angle, reverse faults that join the Tijeras fault near its southwestern end have been suggested to be of Laramide (Late Cretaceous-early Tertiary) age by Kelley and Northrop (1975), although they note that there is no stratigraphic evidence to pin down such an age and the faults could be middle or late Tertiary. It seems more likely to us that these faults formed in response to a local compressive stress field in the hinge or synclinal bend of the eastward-tilted Sandia fault block in the late Cenozoic.

Minor left slip (400 to 600 m), demonstrated by offset fold axes in the Tijeras graben (Kelley and Northrop, 1975), may be responsible for dilation near change in strike of the faults to east-northeast. This may be the origin of the Galisteo graben, the Ortiz graben and the San Pedro syncline. Rise of the Monte Largo horst is difficult to explain, but it may be noteworthy that the horst is not enclosed totally by strands of the fault system, but rather, is bounded on the southeast by the Gutierrez fault that splays to the east and dies out.

The amount of dip slip is largest on the southwest part of the Tijeras-Cañoncito fault system near the Monte Largo horst and Tijeras graben; this probably is due to deformation having been greatest where the Tijeras fault transects the Sandia uplift and to the compression at the synclinal bend east of the Sandia uplift. Northeast of Monte Largo horst, there are only graben along the Tijeras-Cañoncito system, probably because the left slip tended to dilate any bifurcations along the fault system in the absence of the crowding action of the Sandia uplift.

Early Tertiary (Laramide) structural activity in the Lamy-Cañoncito area resulted in a large, faulted, east-facing monocline. An early stage of rotation of the beds, down to the east, formed a southwest-plunging asymmetric anticline (Booth, 1976; Read and others, 1944). The entire stratigraphic section from Mississippian to Upper Cretaceous (Mesaverde Formation) was affected. The structure is believed to have formed as a drape-fold (monocline). This is characteristic of Laramide structures of the Rocky Mountain region in which Phanerozoic strata are rotated (draped) over the edges of basement blocks. Figure 9 shows cross sections illustrating development of the structure across the present Cañoncito graben and the Lamy area.

The Apache Canyon and Galisteo Creek faults were reactivated (fig. 9A and B), and cut rotated Paleozoic and Mesozoic units as the Sangre de Cristo block was uplifted (Booth, 1976). Budding (1972) also assigned a Laramide age to the Garcia ranch fault and associated tightly compressed syncline. Cross sections by Booth (1976) indicate a minimum structural relief of 770 m. This movement, up to the northwest, reverses that of Pennsylvanian time on the Galisteo Creek fault. Booth (1976, p. 98) proposed that the Precambrian breccia along the fault was scraped from the Precambrian block and attached to rising Permian rocks of the northwest block. At the end of

tectonic activity, the breccia was bounded by sedimentary strata. Subsequent erosion beveled the Sangre de Cristo block, stripping the sedimentary layers, perhaps as much as 1,800 m, and an unknown amount of Precambrian rock.

The monocline extended southwest along the present area of Galisteo Creek. At the level of the Cretaceous, as seen in exposures south of Lamy, it was uplifted approximately 450 m on the northwest (fig. 9C). Along the east side of Cerro Colorado, basal units of the Mesaverde Formation are present above a complete section of Mancos Shale. The total thickness of Cretaceous rocks here is approximately 630 m. In a distance of less than 1 km to the northwest, vertical beds of the middle (?) Mancos Shale are overlain by the basal Galisteo Formation. Immediately across Galisteo Creek to the northwest, 270 m of Cretaceous remain, but the thickness decreases to the northwest. It is not clear if faulting or only folding was involved, but rotation of almost 90° occurred.

Southwest from Lamy, the Tijeras-Cañoncito fault system was active as either a fault group, up to the northwest, or as a southeast-facing monocline. Mesozoic units were beveled southeast of the present San Lazarus, Los Angeles and Lamy faults, but the extreme angular relation to the basal Galisteo Formation seen at Lamy is lacking. Faulting of the section is considered more likely.

Southward from Lamy, movement on the Glorieta Mesa boundary fault may have occurred during the Laramide. The timing of deformation along this segment of the fault is unclear, however, as no units younger than Late Cretaceous are cut at the present erosional level.

The Picuris-Pecos fault also was active. Miller and others (1963) document a minimum of 450 m of vertical movement, up on the west. The Jicarilla fault parallels the Picuris-Pecos fault east of the Truchas Peaks area. It is a reverse fault, with a minimum throw of 150 m, which cuts rotated beds of Pennsylvanian age. The vertical Picuris-Pecos fault probably reflects the dip of the ancient fault zone. The reverse Jicarilla fault may be a truer reflection of the Laramide stress field. If so, horizontal compression and lateral shortening are indicated. Budding (1972) interpreted the Garcia ranch, Apache Creek and Deer Creek faults as having had reverse movement in the Laramide. If the Tijeras-Cañoncito fault system acted as an integrated unit during the Laramide, reverse faults or possibly some component of right slip may have affected the Tijeras and Monte Largo areas as well as the Lamy-Cañoncito-Truchas areas.

Following erosion of the Mesozoic section south and west of Lamy, deposition of the continental Galisteo (Eocene) and overlying Espinazo (Oligocene) formations covered the area to a thickness of perhaps 1500 m. The erosion surface locally controlled deposition of at least the basal Galisteo Formation.

Late Tertiary (Rio Grande rift) deformation profoundly affected the Tijeras-Cañoncito fault system along the south end of the Espanola basin. The sense of movement was reversed along the entire distance as the formerly uplifted northwest side subsided.

The time of initiation of late Tertiary deformation is not defined well in the Galisteo region. The 37 m.y. old Espinazo Formation (Weber, 1971) was folded and preserved in the core of a north-northwest-plunging syncline, the first phase of formation of the Santa Fe embayment. Movement in the area is, therefore, younger than Oligocene. Folding was succeeded by

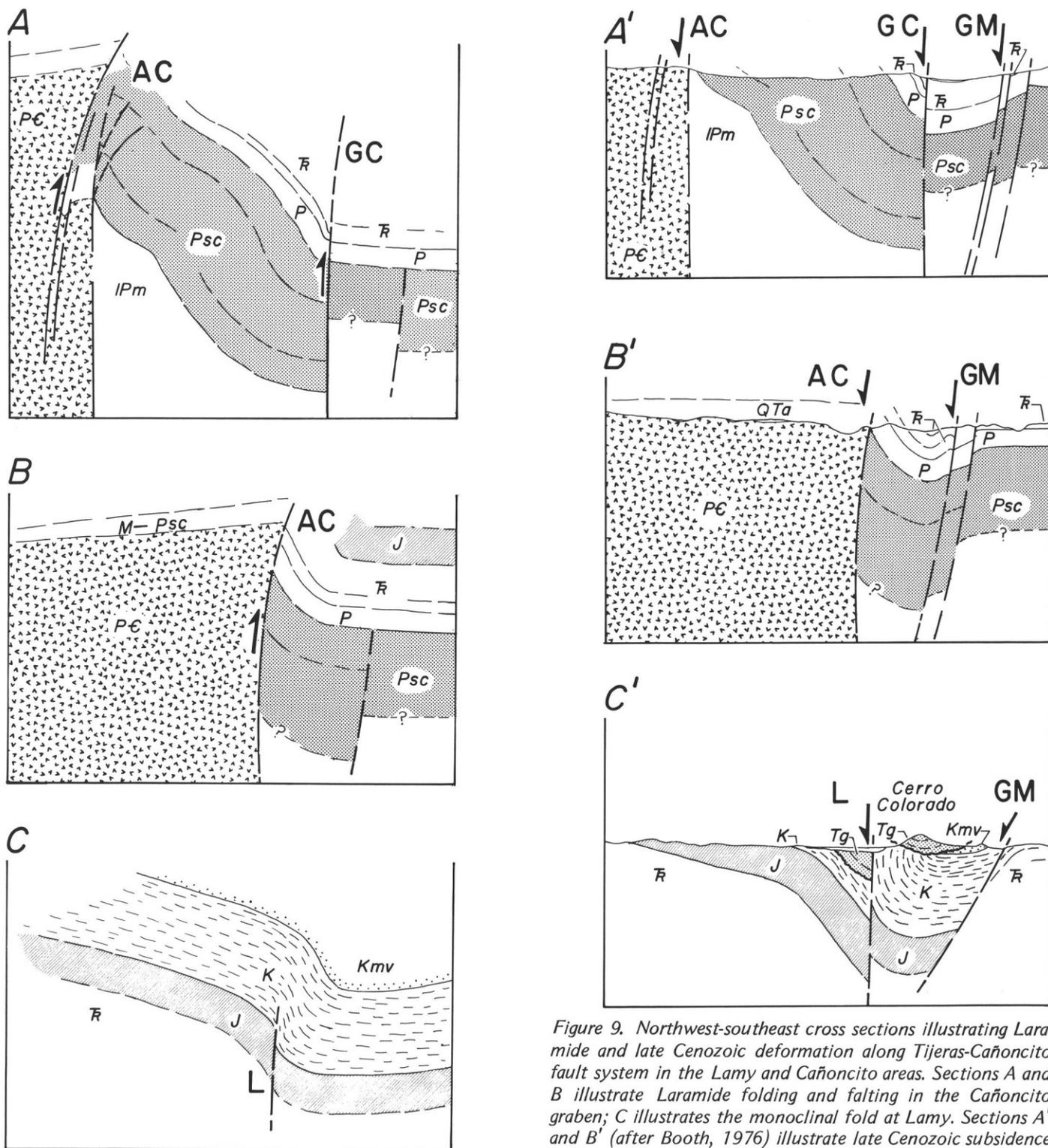


Figure 9. Northwest-southeast cross sections illustrating Laramide and late Cenozoic deformation along Tijeras-Cañoncito fault system in the Lamy and Cañoncito areas. Sections A and B illustrate Laramide folding and faulting in the Cañoncito graben; C illustrates the monoclinial fold at Lamy. Sections A' and B' (after Booth, 1976) illustrate late Cenozoic subsidence across the Cañoncito graben by folding and reactivation of the Apache Canyon (AC), Galisteo Creek (GC) and Glorieta Mesa boundary (GM) faults. Section C' shows the effects of late Cenozoic deformation along the Lamy fault (L) just southwest of the village of Lamy. Note erosionally thinned Cretaceous beneath Galisteo Formation on the downthrown northwest block. PC, Precambrian gneiss; IPm, Madera; Psc, Sangre de Cristo; P, Permian-undifferentiated; R, Triassic-undifferentiated; J, Jurassic undifferentiated; K, Dakota and Mancos; Kmv, Mesaverde; Tg, Galisteo; QTa, Ancha.

fracture on both the northeast-trending Tijeras-Cationcito fault system, and on northerly and northwesterly-trending normal faults. Subsidence and deformation were more pronounced north of the Tijeras-Lamy system where a major graben formed parallel to the fold axis but in its east limb (figs. 1, 4). The axis of the basin shifted eastward with change in tectonic style from folding to faulting. The boundary faults of the graben, as well as some of the smaller faults of the Tijeras-Cationcito system, are covered by the Ancha Formation.

Dominantly vertical movement affected the San Lazarus, Los Angeles and Lamy faults. As shown by slickensides and offset of a dike, and as implied by the en-echelon pattern of associated folds and fault segments (fig. 4), some horizontal movement also occurred. Conflicting evidence as to the nature of strike-slip movement is present. The offset of the dike by the Los Angeles fault illustrates left slip; the en-echelon pattern of overlap of the three major faults also suggests left slip. The en-echelon orientation of subsidiary folds on the up-thrown block, however, suggests formation related to some component of right slip. This appears to reflect a complicated history of development as sagging was combined with crustal extension north of the fault system. The presence of only horizontal slickensides on the surface of major faults implies that at least the later development was strike slip.

The east margin of the Espanola basin crosses the Tijeras-Canoncito fault system in the Lamy area. South of Lamy, the Glorieta Mesa boundary fault represents the eastern limit of this basin. To the northwest, the basin seems to lack basin margin faults, or to have faults of limited displacement (Kelley, 1978; Manley, 1979). The margin appears rotated, down to the west, so that sedimentary units of the basin fill onlap the Precambrian surface. The Lamy-to-Cationcito segments of the Tijeras-Canoncito fault system are at the join between a rotated margin to the northwest and a faulted margin to the south. Drill-hole data from the area of U.S. Highway 285 just southwest of Lamy show the base of the Galisteo Formation to be downdropped approximately 550 m to the northwest across the Lamy fault.

In the Lamy-to-Canoncito area, the Sangre de Cristo uplift subsided relative to the Glorieta Mesa uplift. Movement was reactivated along the Galisteo Creek and Glorieta Mesa boundary faults, and accompanied by rotation of the strata on the southeast block, produced the east boundary of the Canoncito graben (Booth, 1976). Booth notes a local example of "reverse drag" along the Galisteo Creek fault. He interprets this to represent a remnant of the original east dip of the monocline caught on the upthrown side of the Galisteo Creek fault. Similar reverse drag along the Lamy fault (fig. 9C') in overturned beds of Mancos Shale also reflects earlier Laramide deformation.

Quaternary

Roadcuts in Tijeras Canyon show Precambrian greenstone in fault contact with colluvium (fig. 2) of probable Quaternary age. Kelley and Northrop (1975, p. 93) report that an earthquake occurred in the Tijeras graben in 1947, indicating Holocene tectonic activity. The latest episode on the southwestern part of the Tijeras fault is normal separation with the northwest side down (fig. 2). This possibly is due to crustal extension associated with the Rio Grande rift (Woodward, 1977). Sanford and others (1979) reported several epicenters for earthquakes of magnitudes ranging from less than one to greater than 1.5 for the Tijeras-to-Lamy area. They are not

restricted to the major northeast-trending zone of crustal weakness, but several appear to lie along it.

In the area northeast of Lamy, Booth (1976) reported both Tesuque (Miocene) and Ancha (Pliocene-Quaternary) formations on both sides of the Glorieta Mesa boundary fault. Although the presence of Tesuque Formation is questionable (V. C. Kelley, personal commun., 1978), Ancha Formation appears to rest on a cut surface which is about 90 m lower to the northwest of the fault. Nowhere are the gravels seen to be cut directly by the fault, but Booth (1976) interpreted the difference in elevation of the erosional surface to indicate "... uplift along the Glorieta Mesa boundary Fault." A similar geometry would result with continued subsidence to the northwest in post-Ancha time.

CONCLUSIONS

The Tijeras-Canoncito fault system trends northeasterly, obliquely transverse to the major uplifts and basins of central New Mexico, and has undergone recurrent movement since Precambrian time. This system of high-angle faults cuts rocks ranging in age from Precambrian to late Tertiary, and there is local offset of colluvium of probable Quaternary age. This major zone of anisotropy probably extends as deep as does brittle deformation, and has localized late Paleozoic to Quaternary deformation.

Earliest movement (Precambrian) on the southwestern end of the system was probably several kilometers of left slip. If the system connected with the Picuris-Pecos fault, right slip of many kilometers would have occurred on the northeast end during the Precambrian. The timing and connection between the Tijeras Canyon and the Picuris segments are not known and the problem is not resolved. Pennsylvanian movement may have had a dip-slip component with the northwest side down-thrown near Tijeras, but up in the Canoncito-Lamy area.

Two periods of Cenozoic deformation, Paleocene and Miocene to Recent are known to have affected the northeast end of the system. Paleocene deformation resulted in a southeast-facing monocline near Lamy connecting to an uplifted fault block, the Sangre de Cristo uplift, to the northeast.

Late Cenozoic displacement was very complex with a large component of dip-slip movement and subordinate strike slip. The strike-slip component locally appears to display both left and right movement. Such complexity results from the character of the fault system during crustal extension associated with the Rio Grande rift. This transcurrent shear zone separated regimes of strong extension to the northwest from less deformed crust to the southeast.

Historic earthquake activity and offset of Quaternary colluvium along the Tijeras fault suggest that future tectonic activity along this part of the fault system is likely.

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