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D. W. McDonald and K. C. Nielsen

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STRUCTURAL AND STRATIGRAPHIC DEVELOPMENT OF THE MIRANDA GRABEN CONSTRAINS THE UPLIFT OF THE PICURIS MOUNTAINS

DAVID W. McDONALD AND KENT C. NIELSEN
Programs in Geosciences, University of Texas at Dallas, P.O. Box 830688, Richardson, Texas, 75083.

Abstract.—The Miranda graben is a complex extension zone located at the junction of the N-striking Picuris-Pecos fault (PPF) and the ENE-striking Embudo fault in the Sangre de Cristo Mountains of northern New Mexico. The PPF is reactivated and segmented into at least 3 segments by the ENE-striking Embudo fault and by several Laramide age NW-striking tear faults. These segments are (from N to S): the Taos, the Picuris, and the Pecos segments. On the east side of the Picuris segment in the Picuris Mountains, the Oligocene-Miocene Miranda graben is formed by the N-striking La Serna fault on the west, the NNE-striking Miranda fault on the east, and the ENE-striking Embudo fault to the north. In the Oligocene, the lower member of the Picuris Formation was deposited east of the PPF. The Bradley conglomerate member was deposited in the north-central Picuris Mountains and is (interpreted to be) laterally equivalent to the lower member. The Proterozoic Ortega Quartzite Formation in the northern Picuris Mountains is inferred to be the main source for these conglomerates, which suggests that the west side of the PPF remained uplifted or was rejuvenated at the end of the late Laramide deformation. By late Oligocene time, subsidence within the graben had begun, as evidenced by the limited deposits of the Llano Quemado breccia. Following deposition of the breccia increased subsidence produced an angular unconformity between the steeply W-dipping breccia and the overlying almost horizontal upper member of the Picuris Formation. In the last 10 m.y. subsidence in the San Luis and Española Basins caused the Picuris Mountains to remain as an uplifted horst block. Based on the significant scarp on the La Serna fault subsidence has continued into the Quaternary.

INTRODUCTION

The Miranda graben developed during the Tertiary at the intersection of the Embudo fault and the Picuris-Pecos fault (PPF) (Fig. 1). The Miranda graben is bounded by the N-striking La Serna fault on the west, the NNE-striking Miranda fault on the east, and the ENE-striking Embudo fault to the north (Fig. 2) (McDonald, 1997 and 1999). This area holds an important record of Proterozoic, Ancestral Rockies, Laramide and Rio Grande rift-related deformation. This paper focuses on the Cenozoic history. Detailed mapping and fracture analysis were conducted in the eastern Picuris Mountains from 1992 to 1997 to evaluate the reactivated nature of the PPF and related faults. This paper presents some of the results of that work.

CENOZOIC STRATIGRAPHY

The flanking uplifts of the Miranda graben expose the Precambrian Alamo Canyon granite on the west, and the Precambrian Fort Burgwin Ridge granite and Mississippian and Pennsylvanian units on the east (Fig. 2). The Tertiary Picuris Formation is the focus of this paper. Cabot (1938) first described the Picuris Formation as being older than the Santa Fe Group and nonconformable on the underlying Pennsylvanian and Precambrian rocks. Galusha and Blick (1971, p. 37) felt that the Picuris Formation developed as a result of the same late Oligocene to early Miocene volcanic activity responsible for the Abiquiu and Espinaso Formations. Rehder (1986) divided the Picuris Formation into three members: the lower member; the resistant middle member, which Rehder named the Llano Quemado breccia; and the upper member. Based on regional correlations, Ingersoll et al. (1990) suggested that the Picuris Formation ranged from the early Oligocene to middle Miocene in age.

Using a compilation of isolated sections of the different members Rehder (1986) estimated that the thickness of the Picuris Formation is 350 m. Montgomery (1953) proposed that the thickness of the Picuris Formation within the Miranda graben is 380-530 m. Miller et al. (1963) suggested that the thickness of the Picuris Formation varied from 60 to 365 m. In this study it is estimated that the Picuris Formation is 500-600 m thick within the Miranda graben.

Lower Member of the Picuris Formation

The lower member of the Picuris Formation is a poorly sorted and poorly lithified conglomerate that is exposed on the footwalls of the La Serna and Miranda normal faults. The conglomerate, which typically dips toward the axis of the graben at a low angle (Fig. 2), contains subangular to subrounded clasts (up to 1 m) of primarily metaquartzite in a sandy matrix. The matrix is composed of quartz-rich sand with minor clay layers and the quartzite clasts often contain sillimanite layers. Red soil layers are exposed at the base of this unit, which are interpreted to be related to hematite and silica rich fluids that annealed the PPF at the close of Laramide deformation (McDonald, 2003). Locally there are isolated, well-lithified outcrops of the lower member that contain calcite cement and are cut by through-going fractures. A significant feature of the lower member is that it contains very little granitic material even though it nonconformably overlies Precambrian granite along the margins of the graben. This suggests that the granites were subdued topographically during deposition.

Rehder (1986) studied the lower member of the Picuris Formation along NM 518 southeast of the Fort Burgwin Ridge (Fig. 2). These outcrops contain quartzite and volcanic clasts in near equal proportion, along with minor clasts of slate and phyllite. The vol-

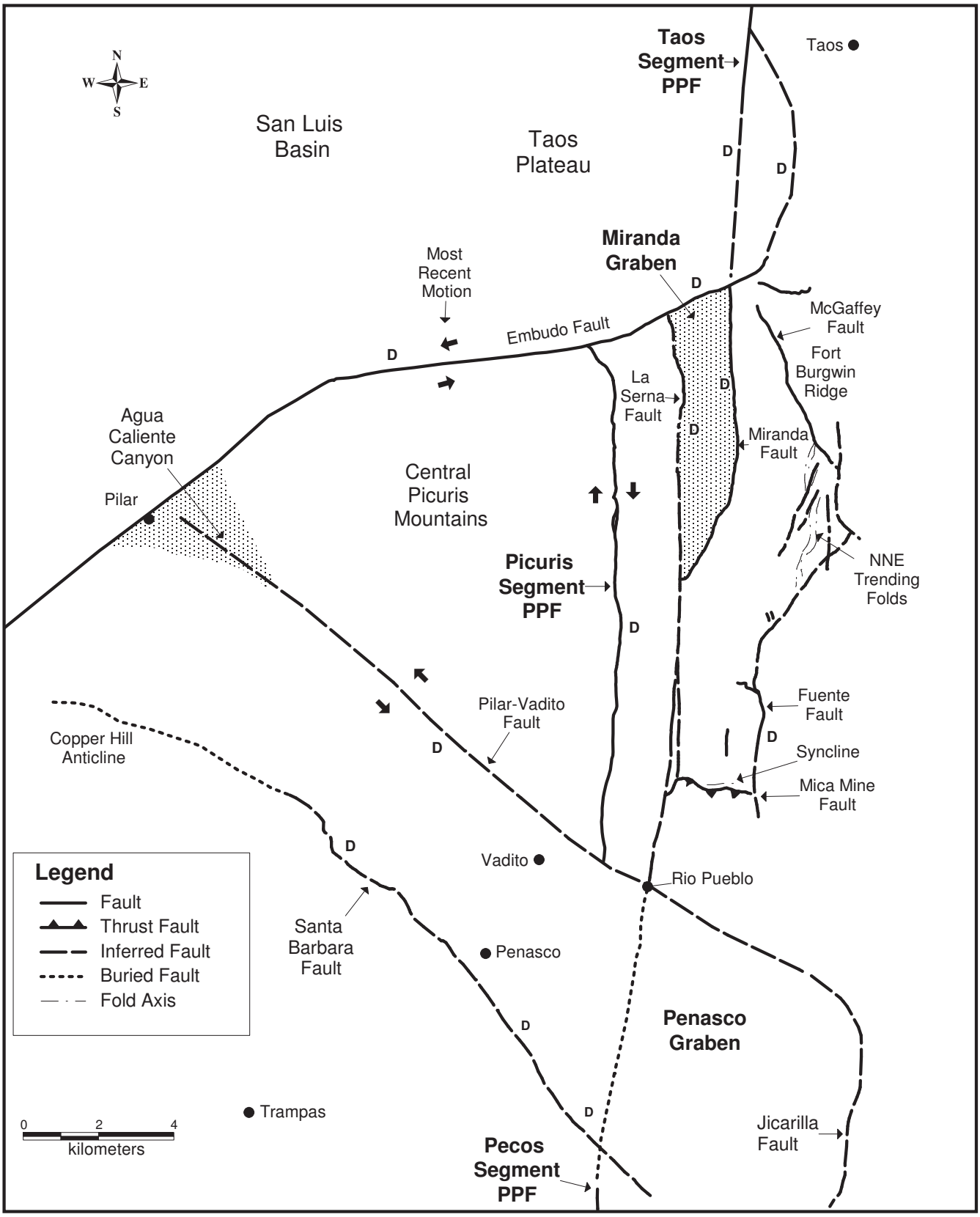


FIGURE 1. Location map of the Miranda graben (pattern). The patterned region in Agua Caliente Canyon is the outcrop distribution of the Bradley conglomerate from Leininger (1982). Map includes the work of McDonald (2003), Miller et al. (1963), and Chapin (1981).

canic clasts range in composition from basaltic to dacitic with andesitic most common (Rehder, 1986). Locally, Rehder (1986) documented that the percentage of volcanic clasts increased from zero at the base to almost 50% near the top of the lower member. Near the Miranda graben, Rehder (1986) found significantly fewer volcanic clasts, and found that the percentage of metasedimentary clasts increases to the south and west with boulder-sized clasts more prominent in the north. Rehder (1986, p. 78) presented paleocurrent measurements based on clast imbrications within the lower member that show south to southwest transport directions. In this study similar relationships were observed, with the largest boulders found on the northern end of the Miranda graben and a gradual decrease in size to the south, suggesting a northern source. The percentage of Precambrian metaquartzite clasts within the Miranda graben is greater than 90%.

The lower member of the Picuris Formation is thicker on the margins of the graben than it is on the southeast side of Fort Burgwin Ridge where it according to Rehder (1986) is ≈ 50 m thick. Based on map patterns and assuming a constant dip for the underlying unconformity, the lower member appears to be ≈ 200-300 m thick on the northwest side of the graben and at least ≈100-200 m thick on the east side of the graben (McDonald, 2003). The age of the lower member is poorly constrained due to its poorly lithified Precambrian clast composition. Bauer et al. (1999) obtained an ^{40}Ar / ^{39}Ar age of 34.6 ± 0.16 Ma for an ash unit from the lower member exposed in the Taos Plateau, north of the Miranda graben (Fig. 1).

Proposed correlation with the Bradley Conglomerate

On the northwest side of the Picuris Mountains, Leininger (1982) mapped the Bradley conglomerate member of the Tesuque Formation. Leininger (1982, p. 13) described the Bradley conglomerate as containing "white to dark-gray quartzite clasts with occasional pink granite fragments… In the best exposure, the conglomerate is very poorly sorted and unstratified…the clasts are rounded to subrounded and range in size from pebbles to boulders (up to 2 m in diameter)," and they decrease in size to the northwest. This suggests that the source was to the southeast. Leininger (1982, p. 13) also stated that good exposures are rare and most clasts occur as float on the hillsides, reflecting the poorly consolidated and lithified nature of the unit. In spite of the ill-defined contacts, using width of map exposure in Agua Caliente Canyon, Leininger (1982, p. 13) estimated the thickness as between 450-600 m. (Fig. 1). Leininger (1982) proposed that the Bradley conglomerate reflects the uplift of the southern Picuris Mountains, which he suggests is also the source for the less common but generally larger granitic clasts.

With the exception of rare granitic clasts, the Bradley conglomerate is very similar to the lower member of the Picuris Formation. In addition to the similarities in lithology and lithification, both units are proximal sediments that have been proposed to originate as debris-flow deposits (Leininger, 1982; Rehder, 1986). As a result we interpret that they are lateral equivalents. How long this depositional cycle continued, or if one unit developed over a more protracted time interval, is unknown.

The age of the Bradley conglomerate has few constraints. It lies nonconformably on Precambrian basement and is covered by the Chama-El Rito Member of the Miocene-age Tesuque Formation. Leininger (1982) assigned the Bradley conglomerate to the lowest member of the Tesuque Formation and proposed its age is 20 Ma, based on Manley's (1979) interpretation that the Chama-El Rito Member was 20-12 Ma. Based on its thickness (600 m) and that it underlies the Chama-El Rito Member, the Bradley conglomerate is likely older than the 20 Ma age proposed by Leininger. Ingersoll et al. (1990) included the Bradley conglomerate in their integration of the Cenozoic geology of northern New Mexico, and proposed that deposition of the Bradley conglomerate was in response to the uplift of the Picuris Mountains. They also stated: "Leininger tentatively correlated this unit (the Bradley conglomerate) with basal Tesuque Formation (Nambe Member) but correlation with Lower and Middle Picuris Formation (Rehder, 1986) seems equally likely" (Ingersoll et al., 1990, p. 1292). Based on its thickness and the correlation with the lower member we suggest that it was deposited in the same 37-28 Ma interval.

Llano Quemado Breccia

Lower in the section, the Llano Quemado breccia is a thinly bedded, fine-grained, red sandstone and siltstone. The lower siltstone contains thin layers (<1 m thick total) with small east striking, syn-depositional, mostly extensional faults. Up-section, the unit is a locally coarse angular conglomerate or breccia that is composed of light-gray rhyolite clasts in a dark red sand to silt matrix. The rhyolite clasts are recrystallized and contain biotite, sanidine and quartz phenocrysts (Rehder, 1986, p. 58). The unit is distinguished by the reddish color, coarse-angular clasts, and very resistant nature. The eastern margin of the Llano Quemado breccia is located along the Miranda fault near Arroyo Miranda, and the western margin of the unit corresponds to several minor north trending stream channels. The Llano Quemado breccia is buried to the south by a Quaternary alluvial fan. Rehder (1986) proposed that there were additional exposures of the breccia outside the Miranda graben, but this could not be confirmed. From the Llano Quemado breccia, Rehder (1986, p. 83) used K / Ar dating on phenocrysts of biotite within rhyolite clasts and obtained an age of 28.7 ± 0.4 Ma.

Upper Member of the Picuris Formation

The upper member of the Picuris Formation is composed of mostly well-layered sandstone and tuffaceous beds. The sandstones are immature, light-tan to white in color, fairly uniform in composition, and contain clasts of pumice. Minor conglomeratic layers are composed of subrounded volcanic and metaquartzite clasts. The matrix is 15-20% of the rock, and contains monocrystalline quartz and sanidine, which argue for a volcanic source (Rehder, 1986, p. 68). The upper member contains abundant dark minerals, particularly hornblende, which are prominent in the light-colored sandstones. Basalt clasts occur throughout the upper member. The abundance of basalt clasts increases dramatically toward the north end of Miranda graben suggesting a northern

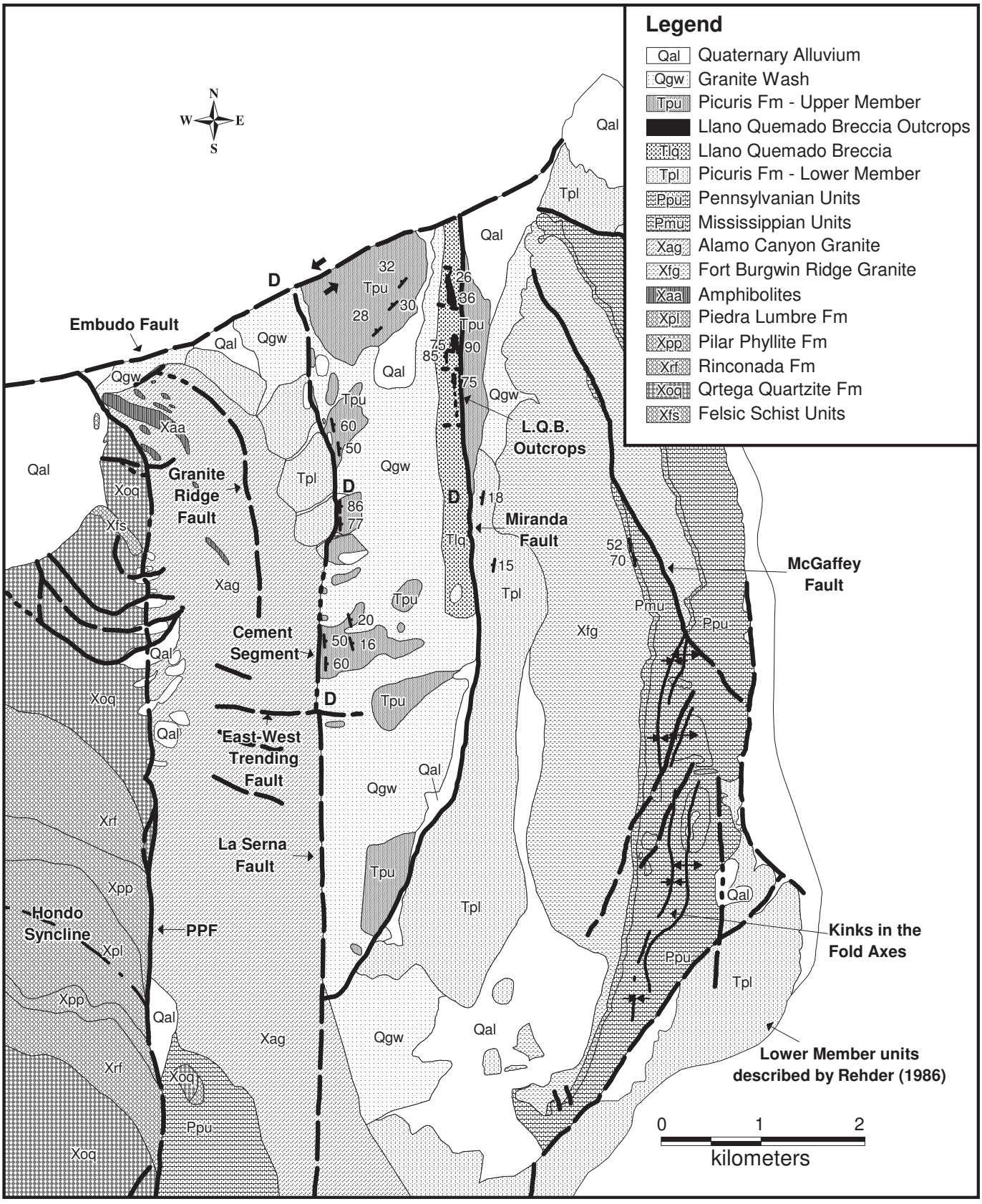


FIGURE 2. Map of the principal features of the Miranda graben, which is formed by the La Serna, Miranda, and Embudo faults (McDonald, 2003). Mapping on the east side of Fort Burgwin Ridge is modified from Chapin (1981).

source. The upper member is poorly exposed and locally weathers into a white powdery surface. There are no complete sections of the upper member within the Miranda graben due to numerous covered intervals and fault contacts. Rehder (1986, measured section F, p. 62) described a composite section within the Miranda graben that is 207 m thick with only 44 m exposed. In the region where the Llano Quemado breccia is exposed, several units of the breccia dip steeply west into the graben and are surrounded by shallowly dipping units of the upper member. This suggests that the breccia units were rotated prior to, or concurrent with, the deposition of the upper member. Ash deposits from near the base of the upper member were dated using ^{40}Ar / ^{39}Ar methodology and obtained an age of 27.9 Ma (Bauer et al., 1999). Within 100 m of the La Serna fault, basalt clasts over 0.3 m in diameter were collected from within the layered sandstones and tuffs of the upper member. The New Mexico Bureau of Mines and Mineral Resources Geochronology Lab dated these basalt clasts using ^{40}Ar / ^{39}Ar methodology and obtained a minimum age of 18.6 ± 0.7 Ma. The age spectrum is disturbed with the early steps indicative of some Ar loss caused by reheating or alteration (P.W. Bauer, personal commun. 1998). As a result the upper member developed over at least an 8 Ma interval.

Quaternary Deposits

Overlying the Picuris Formation within the Miranda graben are recent, unconsolidated sediments that are composed of subangular granite clasts and they are referred to as the granite wash. The granite wash is the result of uplift and erosion of the Alamo Canyon and the Fort Burgwin Ridge Granites along the La Serna and Miranda faults. Alluvial fans on both the western and northeastern margins of the Miranda graben and numerous stream channels characterize granite wash deposition (Fig. 2).

STRUCTURE

The dominant faults of the Miranda graben are the La Serna fault on the west, the Miranda fault and several subparallel faults on Fort Burgwin Ridge on the east, and the Embudo fault to the north (Fig. 2). To the south there are additional faults that are described in McDonald (2003).

La Serna Fault

The most prominent structural feature on the west side of the Miranda graben is the N-striking La Serna fault (McDonald, 1997). The La Serna fault is interpreted as a normal fault with the east side down (Fig. 2). The best-exposed segment of the fault is referred to as the "Cement segment" due to its smooth appearance (Fig. 3). The exposed fault surface is nearly 100 m long and locally has up to 5 m of relief. The fault surface strikes north and dips 85° E, and contains grooves and slickensides that plunge 85° toward 084°. Precambrian granite is exposed west of the fault and the upper member of the Picuris Formation is exposed east of the fault. The upper member dips 50-60° E near the fault. Less than 1 km to the east these same units dip < 20° E. Abundant E- and N-striking fractures cut these clastic units. Thin-sections from rocks along the fault surface showed cataclastic textures and evidence of multiple generations of fault gouge.

North of the Cement segment, the La Serna fault juxtaposes the different members of the Picuris Formation. West of the fault lower member units are exposed, and east of the fault the upper member units dip 50-86° E. Farther north the La Serna fault is covered with Quaternary alluvium. Aerial photograph lineaments suggest that near the Embudo fault, the La Serna fault bends northwest and separates into several splays. The bending may be due to deflection by the Embudo fault as observed along the PPF. However, due to the poorly lithified nature of the sediments it was not possible to verify this in the field.

Less than one kilometer south of the Cement segment, the La Serna fault is offset at least 50 m in a left-lateral sense along an



FIGURE 3. This photograph - looking north - shows the prominent scarp along the Cement segment of the La Serna fault. It trends dips 85° E, and contains slickensides that plunge 85° toward 084°. The scarp is over 50 m long and up to 5 m high. It juxtaposes the Alamo Canyon granite against the upper member of the Picuris Formation. Note clip board and field book for scale.

east striking fault (McDonald, 2003) (Fig. 2). This implies that the La Serna fault is older than the east-west fault. It is inferred that the east striking fault is related to left-lateral motion on the Embudo fault and reflects increased subsidence within the graben to the north. Farther south the La Serna fault is locally buried.

Near the intersection with the Miranda fault, the La Serna fault trend is easier to trace and is characterized by aerial photograph lineament and a consistent zone of fractured basement rocks (Fig. 2). Farther south, the fault splits into two poorly exposed segments approximately 250 m apart (Fig. 1). The western segment places Precambrian quartzite and schist against Pennsylvanian sediments. Along the eastern segment, Precambrian quartzite crops out on both sides of the fault, which is characterized by a poorly exposed breccia zone. Two kilometers farther south, this eastern segment of the La Serna fault forms the western edge of the uplifted Mica Mine fault block (Fig. 1). At the southern edge of the Picuris Mountains the La Serna fault extends through the Picuris Formation and the basalt flow near Vadito. While there is no evidence that the basalt flow is offset by the La Serna fault, there are well-developed fracture sets (typically joints) that follow the trend of the fault. Aerial photograph lineaments are traceable south of NM highway 75.

Kinematic history

The La Serna fault was active during the deposition of the Llano Quemado breccia at 28-25 Ma. Whether it was active in the Laramide or Pennsylvanian is unknown. Since some parts of the fault contain more prominent offsets, I infer that the fault is segmented. Based on the juxtaposition of the upper member against the lower member and on the recent scarp heights, it seems likely that the northern or Cement segment has more vertical and recent offset (≤ 5 m) than the southern segment (< 1 m). Segmentation is also supported by the slickenside data (N > 50), which suggest dominantly, normal dip-slip in the north and subhorizontal oblique-slip in the south. These observations suggest that the northern part of the graben is subsiding at a faster rate. Further evidence of this is shown on the Cement segment of the La Serna fault itself. There are large east-west striking fractures that cut the well-exposed planar fault surface. These fractures are locally listric to the north and indicate recent north-south extension. This represents the interplay of regional bounding faults (the La Serna and Miranda faults) and crosscutting local faults (the east-west striking faults), which helped accommodate the differential motion between the northern and southern parts of the graben. Based on scarp heights and its uneroded nature, the Cement segment is the youngest structure in the region and therefore has been reactivated, which is supported by thin-section evidence of multiple fault gouges.

Miranda Fault

The eastern boundary of the Miranda graben is the Miranda fault (Fig. 1). This fault corresponds to Chapin's (1981) faults #3 and #3A. The Miranda fault separates the Llano Quemado breccia from the upper and lower members of the Picuris Formation on the east. The Llano Quemado breccia west of the fault dip 50-80° W and the lower member of the Picuris Formation units exposed east of the fault dip < 20° W. While there are outcrops of the different units within 50 m of the fault trace, the fault surface is not exposed. The zone where the La Serna and Miranda faults intersect was studied in detail in an effort to establish the relationship between these faults (Fig. 2). The mesoscopic fracture data and the aerial photograph data suggest that the Miranda fault abuts the La Serna fault. It appears that the La Serna fault is the dominant fault at the intersection of the two faults, and that initial motion on the La Serna fault is older. Based on the significant scarp the La Serna has the youngest motion as well.

Fort Burgwin Ridge Faults

Chapin (1981) mapped several faults along Fort Burgwin Ridge, which he interpreted as Laramide-age reverse faults. These faults generally follow the main trend of the ridge and in places juxtapose Proterozoic granite against Pennsylvanian sediments (Fig. 2). The most significant of these faults is his fault #1, which Bauer et al. (1999) named the McGaffey fault. Along the NW-striking McGaffey fault, Chapin (1981, p. 130) described a crushed zone (0.6 m wide) of granite that was characterized by epidote and calcite alteration. The zone has vertical walls with subhorizontal slickensides that plunge 0-10° N (Chapin, 1981, p. 130). Chapin estimated that along the fault there is up to 900 m of throw in the north and less than 150 m to the south. Slickenside data (multiple measurements) collected in this study along the northern end of the McGaffey fault (160°/85°W) plunge 44° toward 340°, and suggest a significant dip-slip component. The increased displacement to the north is similar to the displacement pattern on the La Serna fault and Miranda faults. Chapin (1981) proposed that the fault dies out to the south into a series of NNE-striking folds (Fig. 2). The folds are formed in Pennsylvanian and Mississippian units, are *en echelon* in nature, and trend 010-030°. The orientations of the folds suggest left-lateral offset on the McGaffey fault, while up to 2 km of right-lateral separation is observed in the Mississippian – Precambrian contact. It is inferred that the McGaffey fault is a Laramide-age reverse fault that was reactivated in the Miocene.

Embudo Fault

The Embudo fault bounds the northern end of the Miranda graben and the Picuris Mountains (Fig. 2). It has been associated with a Precambrian fabric (the Jemez lineament) that extends from the Jemez Mountains in the southeast to the Taos Range in the northeast (Nielsen, 1986; Karlstrom and Humphreys, 1998). It has been proposed to be a transform fault linking the southern boundary of the San Luis Basin and the northern boundary of the Española Basin (Kelley, 1979). The style of deformation varies along strike, suggesting that it is not a continuous, through-going fault (Muehlberger, 1979; Hall, 1988; Kelson et al; 1997). In the Picuris Mountains, the fault trace corresponds with a prominent

lineament documented in the aerial photographs and defined in the field typically as an erosional fault-line scarp and by changes in the alluvium composition. The fault strikes 060-080° across the northern end of the Miranda graben. The complex nature of the fault zone is apparent in related faults in the granite exposures along the north end of the graben. They consist of a N-dipping normal fault that truncates an older series of S-dipping reverse faults that may be related to the Granite Ridge fault (Fig. 2). This interpretation is similar to the work of Kelson et al. (1997, p. 32) who found that a broad zone, with low scarps, and anastomosing fault strands that show both north-down and south-down displacements characterizes the segment of the Embudo fault that extends across the northern Miranda graben. Overall this suggests that the Embudo fault is actually a zone of several subparallel faults and that the main trace is probably farther north that the generally mapped trace (McDonald, 2003; Montgomery, 1953; Kelson et al; 1997). Since recent alluvium covers this zone, it is unknown how far north the main fault trace is, possibly several kilometers.

Deflection of the PPF by the Embudo fault

One of the most prominent trends observable in aerial photographs is the linear trend of the PPF. The north-south trend is deflected to the northwest near the intersection with the Embudo fault as originally observed by Montgomery (1953) and Chapin (1981). This deflection is seen in the ridges on both sides of Alamo Canyon and on Fort Burgwin Ridge (Fig. 2). The deflection is developed in both Precambrian and Tertiary units, and is interpreted to be the result of left-lateral motion on the Embudo fault. The deflection can be observed in outcrop patterns and the foliation trends in the Precambrian units. Within the Ortega Formation foliations remain subparallel to the PPF, but near the intersection with the Embudo fault they change from 000-010°/50-70° W to 120-140°/70° W. This 60° counterclockwise rotation of the foliation is difficult to evaluate due to the extremely brecciated nature of the quartzite near the trace of the PPF, as first described by Montgomery (1953). Several W-NW striking zones of increased brecciation are associated with small changes in the orientation of the foliation. In between there are areas where the quartzites are not as intensely fractured. This pattern suggests that the change in foliation trend near the junction of the PPF and Embudo fault was dominantly a brittle process that is accommodated by a series of minor offsets on several faults. Farther south there are several faults with both left-lateral and normal displacements that offset the PPF (Fig. 2).

The Alamo Canyon granite is strongly affected by the Embudo fault. There are numerous slickensides that plunge shallowly SW to W along the Granite Ridge fault (Fig. 2) and along the north end of the ridgeline. These SW-W plunging slickensides on the north end of Alamo Canyon granite are interpreted as evidence of NE-oriented shortening in the late Laramide (McDonald, 2003). Farther south along the main ridge of the Alamo Canyon granite there are numerous E- to ESE-striking fractures and high-angle faults that cut the ridge crest. These faults are often located in narrow canyons and have slickensides that show both strike-slip and dip-slip motion. The frequency of these faults and fractures diminishes to the south.

At the northwest edge of the Miranda graben, the lower member of the Picuris Formation rests nonconformably on the Alamo Canyon granite. This nonconformity is deflected to the northwest and truncated by the Embudo fault (Fig. 2). The dip of this nonconformity changes from 35-60° E to almost 90° at the junction of the PPF and Embudo fault. It seems reasonable that the dip of this unconformity was originally ≤ 20°, as it is today farther south along both sides of the graben, however it is also possible that the contact was originally undulating. The extreme change in dip is locally enhanced by significant uplift along the Embudo fault. Further evidence of this uplift is the change in dip of the upper member units on the southeast side of the fault.

In summary, the deflection of the PPF by the Embudo fault took place in several stages characterized by different styles of deformation. The initial stage was the result of NE-oriented shortening during the late Laramide deformation (latest Paleocene to late Eocene) that resulted in the convergence between the PPF and the Embudo fault. The later stage of deflection was the result of the uplift and continued left-lateral motion on the Embudo fault. Since the significant deflection is not observed in the Llano Quemado breccia then most of this deflection took place prior to 28 Ma.

EVOLUTION OF THE MIRANDA GRABEN

Early Laramide Deformation

In the Sangre de Cristo Mountains, east-west shortening associated with early Laramide deformation (late Cretaceous to late Paleocene) resulted in the development of N-striking folds and thrust faults including the Jicarilla fault, which is located south of the graben (Fig. 1). Associated with these thrust faults were several tear (strike-slip) faults including the NW-striking Pilar-Vadito (Montgomery, 1953; McDonald, 2003) and Santa Barbara faults (Kelley, 1979; McDonald, 2003) and the ENE-striking Embudo fault. Inferred strike-slip motion on these NW-striking faults and probably on the ENE-striking Embudo fault in early Laramide time segmented the PPF into at least 3 segments (Fig. 1). The Taos segment extends from the Embudo fault north and is interpreted to be main boundary fault on the east side of the San Luis Basin. The Picuris segment extends from the Embudo fault to the Pilar-Vadito fault. The Pecos segment extends from the Peñasco graben south possibly to the Tijeras – Canoncito fault.

Within the eastern Picuris Mountains early Laramide deformation is found in the geological relationships on Fort Burgwin Ridge (Fig. 2). The nonconformity between the Precambrian granite and the overlying Paleozoic strata dips steeply to the east (up to 80°) and the Carboniferous strata are folded along a north-south axis (Chapin, 1981). Due to subsequent erosion the amount of throw is unconstrained, but it is > 300 m (Chapin, 1981).

Outcrop scale fracture data within the Precambrian and Pennsylvanian units consistently show an older set of N-striking, 60-

70° W-dipping fractures and faults characterized by gouge zones. Several have reverse separation and suggest a west-plunging east-west oriented σ_1. Based on their orientation and since they are not developed in the Picuris Formation, they are inferred to be the result of early Laramide deformation.

Late Laramide Deformation

Erslev, (2001) proposed that late Laramide deformation (latest Paleocene to late Eocene) was characterized by NE-oriented shortening . In a study of slickenlines from Laramide-age minor faults from northern New Mexico, Erslev (2001) found that some N-striking faults contained evidence of strike-slip motion that cut units as young as Eocene, but not the 27 Ma Galisteo dike. Erslev (2001) argued that σ_1 was NE-trending, and σ_2 was vertical. Within the fracture data there is abundant evidence of NE-oriented shortening throughout the eastern Picuris Mountains (McDonald, 2003). This evidence includes numerous low-angle SW-dipping faults on both sides of the PPF, many with slickensides that suggest NE-oriented shortening. One of the most prominent structures is the Mica Mine fault and its associated ESE-striking syncline (Fig. 1). In this study the orientation of early Tertiary σ_1 is similar to that of Erslev (2001) but based on the thrust geometries, σ_3 is interpreted to be vertical. On Fort Burgwin Ridge several faults, including the McGaffey fault, contain more than one set of slickensides suggesting a multi-phase history. The first phase was characterized by uplift and reverse faulting on Fort Burgwin Ridge described previously (Chapin, 1981). Along the nearly vertical McGaffey fault the Mississippian / Precambrian unconformity is offset in a right-lateral sense almost 2 km. Based on the NE-oriented shortening during the late Laramide deformation, it seems likely that the second phase of motion included some right-lateral strike-slip motion. There is no evidence of the NE-oriented shortening within the 28 Ma Llano Quemado breccia or the upper member of the Picuris Formation, which fits the pre-27 Ma age suggested by Erslev (2001).

Deposition of the Lower Member in the Latest Eocene to Middle Oligocene

The lower member is preserved in the area of the Miranda graben, the area southeast of the Picuris Mountains and along the Pilar-Vadito fault. This suggests that these areas were subdued during the Oligocene. The lower member is up to 300 m thick near the PPF and thins to the south and east. Paleocurrent measurements from Rehder (1986, p. 78) show generally southerly transport in the eastern Picuris Mountains and clast imbrications along the Pilar-Vadito fault trend subparallel to the fault trace. Rehder proposed that the source was the Taos Range, 15 km to the northeast and topographically high in the Oligocene (Kelley, 1990). However the correlation with the Bradley conglomerate suggests that there was a source within the Picuris Mountains (Fig. 4A). Based on the presence the Ortega Formation west of the PPF and that the lower member reaches its maximum thickness near the fault, suggests that it was the source for the lower member units within the graben (Fig. 2). The lower member units east of Fort Burgwin Ridge indicate an additional volcanic source that was partially blocked by the ridge.

In addition to their lithologic similarities, both the Bradley conglomerate and the lower member of the Picuris Formation have a close spatial association with the Pilar-Vadito and Embudo faults. Montgomery (1953) mapped the Pilar-Vadito fault from Agua Caliente Canyon near Pilar to Vadito and documented that the trace of the Pilar-Vadito fault is covered by coarse conglomerate deposits (0.8 km wide) of the Picuris Formation (Montgomery, 1953, p. 52). Based on the coarseness and the composition these conglomerates are interpreted to be the lower member. Since these sediments form a linear outcrop belt along the Pilar-Vadito fault, the fault zone must have been a low during deposition. Also since the Bradley conglomerate reaches its maximum thickness in Agua Caliente Canyon at the intersection of the northwest terminus of the Pilar-Vadito fault and the Embudo fault (Leininger, 1982), it implies that the Embudo fault was down to the north (Fig. 1).

Correlation of the Bradley conglomerate and the Picuris Formation has several tectonic implications. First, to expose the Ortega Formation, it is interpreted that at the end of the late Laramide deformation in the late Eocene, the west side of the PPF remained high or it was rejuvenated. Second, the east side of the PPF (including the Alamo Canyon and Fort Burgwin Ridge Granites) was subdued or possibly buried by younger sediments, accounting for the scarcity of granite clasts. Third, the uplift was not topographically prominent because few of the other metasedimentary units occur as clasts. Fourth, since the PPF was no longer active, erosion of the Ortega Quartzite eventually ceased. This occurred at the end of the deposition of the lower member ($\approx$ 28 Ma), based on the lack of quartzite clasts in the Llano Quemado breccia.

Deposition of the Llano Quemado Breccia in the Middle to Late Oligocene

The distribution of the 28 Ma Llano Quemado breccia (Rehder, 1986) indicates subsidence was localized between the N-striking La Serna and Miranda faults (Fig. 4B). We infer that the Miranda fault originated at this time as a southward propagating extension of the Taos segment of the PPF. The coarse and immature nature of the sediments indicates a proximal source, and the distribution of the unit suggests that the source was probably a volcanic vent north of the graben, within the Taos Plateau (Ingersoll, et al., 1990; Rehder, 1986). This also suggests that the Embudo fault was no longer undergoing strong subsidence to the north. While coeval units may have been deposited outside the graben, they do not have the resistant, proximal character that typifies the breccia preserved within the Miranda graben. The lack of Precambrian clasts within this unit suggests that their source terranes were no longer exposed.

Rotation of the Llano Quemado breccia

The linear, steeply dipping outcrop of the Llano Quemado breccia is parallel to the Miranda fault to the east. Chapin (1981)

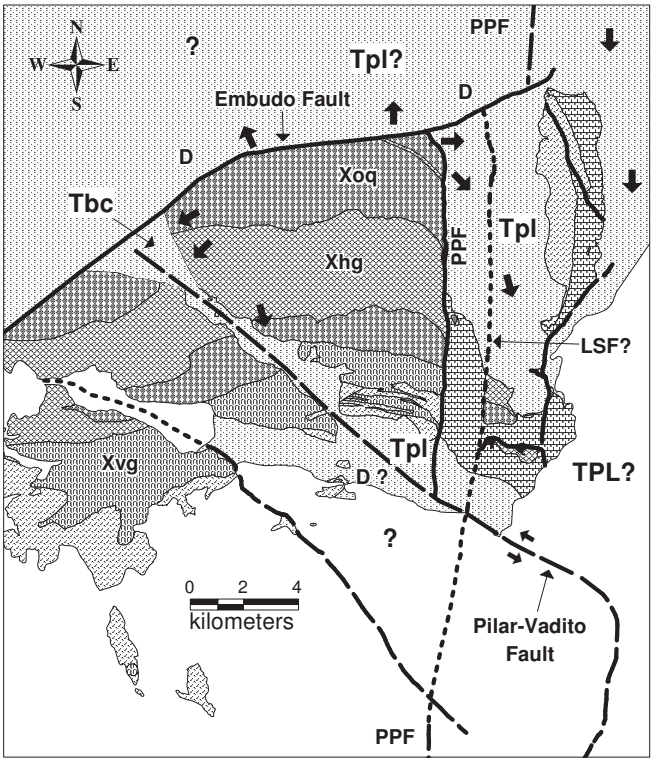


Fig. 4A. Early Oligocene model for the Picuris Mountains.

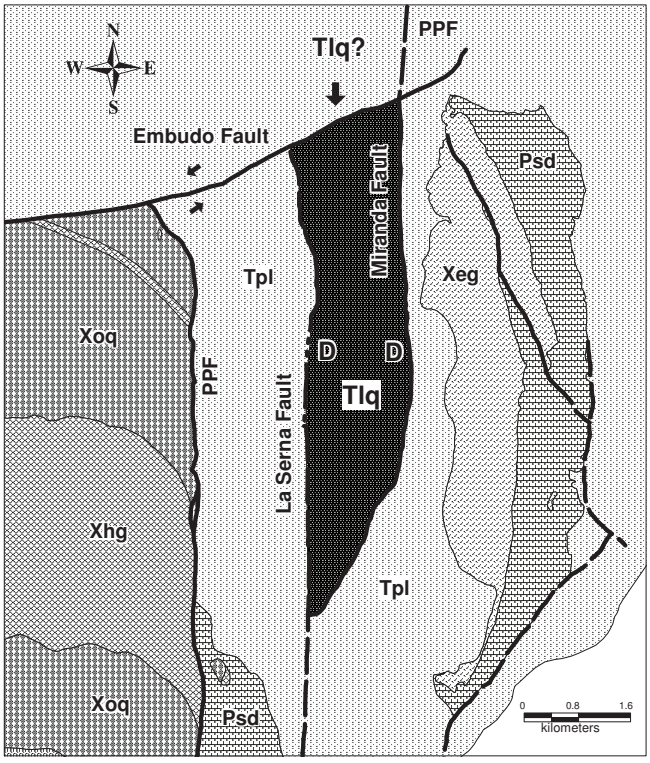


Fig. 4 B. Late Oligocene model for the Miranda graben.

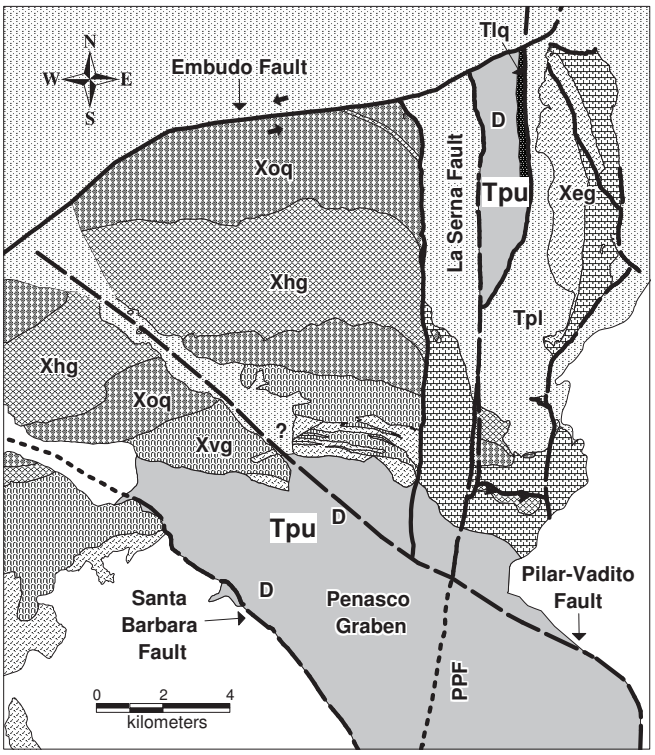


Fig. 4C. Early Miocene model for the Picuris Mountains.

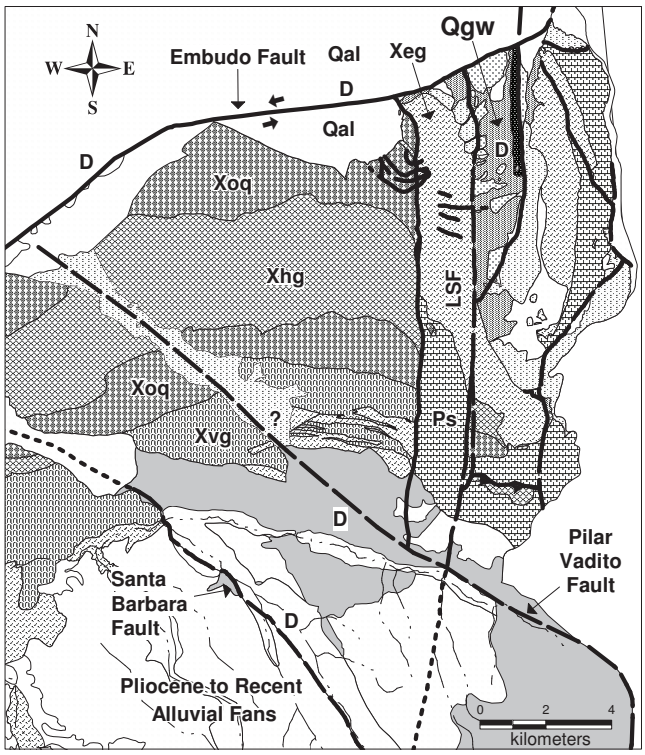


Fig. 4D. Late Miocene to Recent model.

FIGURE 4. Model figures for the eastern Picuris Mountains for the intervals shown. Maps are based on the work of McDonald (2003), Miller et al (1963), Bauer (1988), and Chapin (1981). Units include Precambrian metavolcanics (Xvg), quartzite (Xoq), metasediments (Xhg), and granites (Xeg); Paleozoic sediments (Psd); Tertiary Picuris Formation (Tpl, Tlq, Tpu) and Bradley conglomerate (Tbc); and Quaternary sediments (Qgw and Qal).

proposed that normal drag along the Miranda fault caused the steep dips. Erslev (personal commun., 1999) reported several horizontal dextral slickensides along outcrops of the unit and proposed that strike-slip faulting caused the rotation. Similar slickensides were observed in this study as well. Mapping in this study also revealed that the Llano Quemado breccia is bound by the Embudo fault to the north and the SW-trending ridge of the Fort Burgwin granite to the south. In this study no evidence was found that those features are offset. In a detailed analysis of the Embudo fault, Kelson et al. (1997) do not show any north-south offsets along the northern margin of the Miranda graben. Due to the ability to create slickensides with minor offsets, we infer that the strike-slip motion on the Miranda fault was very limited, and reflects the increased subsidence at the north end of the graben. An alternative mechanism is counterclockwise domino-block rotations associated with the sinistral motion on the Embudo fault to the north.

Slickenside data (44° toward 340°) collected along the McGaffey fault (160°/85°W) suggest that the fault was characterized by oblique-slip motion. We infer that this slip occurred in Miocene time when σ1 was ~ vertical (Erslev, 2001). Further support for this interpretation is the increased throw to the north along the McGaffey fault recorded by Chapin (1981). Since the Miranda fault is not exposed there are no similar slickensides observed, but as the throw increases to the north along the McGaffey fault, there is a similar increase in dip (from 50° to 80° W) of the breccia unit to the north along the Miranda fault. There is a similar increase in dip to the north within the units of the upper member exposed along the La Serna fault (from 50 to 80° E). Therefore we infer that the oblique-slip subsidence was responsible for the rotation of the Llano Quemado breccia. As the graben subsided the rheological differences between the rigid Llano Quemado breccia and the poorly consolidated lower member caused the breccia units to be rotated and broken into smaller rigid blocks. Eventually, the breccia units protruded into and were filled around by the upper member.

Deposition of the Upper Member in the Early to Middle Miocene

Subsidence must have continued in the graben between the La Serna and Miranda faults, as the upper member of the Picuris Formation is generally limited to the Miranda graben and the Peñasco graben (Fig. 4C). However, the upper member of the Picuris Formation extends over a much larger area than the Llano Quemado breccia, suggesting that subsidence area had broadened. Based on the age of the Llano Quemado breccia (28 Ma), and the age of the basalt clasts (18 Ma) contained in the upper member, deposition extended for approximately 10 Ma. Due to the unconformable nature of these units it is unknown whether there were significant hiatuses involved. After the deposition of the upper member (~18-15 Ma), there was a period of non-deposition as inferred from the lack of middle to late Miocene units preserved in the graben.

EXHUMATION OF THE PICURIS MOUNTAINS

The results of this study indicate that the exhumation of the Picuris Mountains was in two stages. The first stage was the result of NE-oriented shortening during the late Laramide. Evidence for the first stage is the development of the lower member of the Picuris Formation and the Bradley conglomerate that are interpreted in this study to have been sourced mainly by the Ortega Formation. The second stage occurred during the middle to late Miocene. By the middle Miocene σ_1 was vertical, which caused increased extension in the Rio Grande rift (Chapin and Cather, 1994). In the Picuris Mountains rifting was reflected in the increased subsidence of the San Luis Basin to the north and the Española Basin to the south. We interpret that the extreme subsidence within these basins caused the Picuris Mountains to remain as a relatively elevated horst block (Fig. 1). The differential uplift was enhanced by the fact that the Picuris Mountains are located within the triangle-shaped accommodation zone between the San Luis and Española Basins. One of the consequences of the development of the Picuris Mountains was the subsidence to the south in the Española Basin. The differential subsidence at the northeast end of the basin resulted in the development of the Peñasco graben (McDonald, 2003). The Peñasco graben is formed between the NW-striking Pilar-Vadito and Santa Barbara faults (Fig. 4C and 4D). The Pilar-Vadito fault originally developed as a left-lateral tear fault in the early Laramide deformation. It was reactivated as a normal fault in the Tertiary (Montgomery, 1953).

The late Miocene (10 Ma) timing of the exhumation of the Picuris Mountains is based on the development of the late Miocene to Pliocene age Chamita Formation (Galusha and Blick, 1971; Muehlberger, 1979; Leininger, 1982; Dungan et al., 1984). The lower Chamita Formation contains abundant volcanic clasts that were likely derived from the Chama-El Rito Formation. The middle and upper Chamita Formation is composed of clasts of Precambrian basement (Dungan et al., 1984). The clasts coarsen upwards, which implies increasing uplift in the source terrane. As a result, Muehlberger (1979) concluded that the uplift of the mountains took place during the deposition of the Chamita Formation.

Erosion of the Picuris Mountains and subsidence within the Miranda graben continues today as evidenced by the prominent uneroded scarp associated with the La Serna fault (Fig. 3). The Pliocene (?) to Holocene granite wash is being deposited on both sides of the graben and to the north of the Embudo fault. Recent fractures cut through the soil horizons and the prominent scarp associated with the La Serna fault. Motion on the Embudo fault continues as evidenced by the presence of recent fault scarps, offset sediments, and paleo-earthquakes indicating Quaternary motion (Muehlberger, 1979; Kelson et al., 1997; Bauer et al., 1999).

Erslev (2001) suggested that extension took place along an ENE-WSW axis but the fracture and fault data from this study suggests that extension took place on several axes and that σ_2 and

σ_3 must have been essentially equal, since most steeply dipping faults were reactivated. Unfavorably oriented faults were not reactivated. Age relationships varied by region, but at all scales investigated, faults and fractures form a roughly orthogonal pattern: typically NNW- to NNE-striking and ENE- to ESE-striking. Kinematic indicators reveal normal and left-lateral offset related to subsidence at the north end of the Miranda graben and the left-lateral motion on the Embudo fault. Good examples of these faults include the east-striking fault that offsets the La Serna fault and the faults within the Precambrian units that offset the PPF (Fig. 2). Collectively they imply oblique-slip, left-lateral, northwest-down motion on the north end of the eastern Picuris Mountains in the Late Miocene to Quaternary.

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