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A SPECTACULAR EXPOSURE OF THE TIJERAS FAULT, WITH EVIDENCE FOR QUATERNARY MOTION

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Abstract—The regionally extensive Tijeras–Cañoncito fault system comprises several northeast-striking, subvertical faults, including the Tijeras fault. Slickensides on minor fault surfaces within the fault zone exhibit a wide range in orientation and record a complex history of strike-slip, oblique-slip and dip-slip motion on the fault system. The oldest documented movement is Laramide (Late Cretaceous–early Tertiary) in age, though the fault system may be older. A recently discovered streamcut provides the best exposure of the Tijeras fault. It reveals a strongly but heterogeneously deformed zone more than 160 m wide, within which Precambrian, Pennsylvanian, Permian and Oligocene(?) rocks are faulted. Quaternary(?) surficial deposits are locally faulted. The streamcut includes a population of minor faults that are interpreted as right-lateral synthetic Riedel shears, which is consistent with Laramide-age deformation. Neogene deformation is indicated by extreme brecciation of an Oligocene(?) porphyritic intrusive rock and by fault slickensides that suggest left-lateral strike-slip motion which is consistent with the development of the Rio Grande rift in the Neogene. Quaternary(?) activity is recorded in the streamcut by a fault that juxtaposes Quaternary(?) surficial deposits against an Oligocene(?) porphyritic intrusive rock; this fault does not offset an overlying Holocene(?) imbricated gravel deposit. The length of the Tijeras–Cañoncito fault system, the width of the fault zone, and the intense deformation within the Tijeras fault zone, all suggest substantial post-Pennsylvanian displacement on the fault system. Slickenside striae indicate that movement within the fault system was dominantly strike-slip.

INTRODUCTION

The Tijeras–Cañoncito fault system

The Tijeras–Cañoncito fault system comprises several northeast-striking, subvertical faults, including the Tijeras, Gutierrez, San Lazarus, Los Angeles and Lamy faults. The system is regionally extensive; it has been mapped for more than 80 km from Kirtland Air Force Base on the southwest (about 16 km southeast of Albuquerque) to the Cañoncito area on the northeast (about 20 km south of Santa Fe). The fault system may continue southwestward into the Rio Grande rift as the Tijeras accommodation zone, one of several places in the rift where the sense of asymmetry of half grabens reverses (Russell and Snelson, 1990, 1994; May and Russell, 1994), or it may link with the north-striking faults that bound the Rio Grande rift on the east. Following Lisenbee et al. (1979), Woodward (1984) and Maynard et al. (1990), we prefer the name "Tijeras–Cañoncito fault system" over "Tijeras fault zone" when referring to the entire group of faults. Both names are entrenched in the literature and are used synonymously. Although somewhat more lengthy, we recommend "Tijeras–Cañoncito fault system" because it approximately locates the structure and distinguishes it from the Tijeras fault, which is only part of the system.

The Tijeras–Cañoncito fault system has a history of recurrent motion. Slickensides on minor fault surfaces record strike-slip, oblique-slip and dip-slip motion. Lisenbee et al. (1979) suggested the fault system was active in the Precambrian and in the Pennsylvanian, but unequivocal evidence of such activity is lacking. The oldest documented movement on the fault system is Laramide (Late Cretaceous–early Tertiary) in age (Abbott et al., this volume). Lisenbee et al. (1979) also documented offset of colluvium of probable Quaternary age, indicating reactivation of the fault system in the Quaternary. All deformation along the Tijeras–Cañoncito fault system has been brittle; there is no evidence of ductile shearing at any time in its history.

The Tijeras–Cañoncito fault system is poorly exposed along much of its length. There are, however, two locations that offer excellent exposure where the internal character of the zone can be directly observed and offset of surficial deposits is apparent. The first locality is a roadcut on westbound Interstate 40 in Tijeras Canyon, where Lisenbee et al. (1979) documented movement of probable Quaternary age: brecciated Precambrian Tijeras greenstone (Kelley and Northrop, 1975) is in fault contact with unconsolidated colluvium. Though no absolute dates have been obtained, the colluvium is probably Pleistocene in age (B. Harrison and D. Love, personal commun., 1994), and thus records Pleistocene and/or Holocene activity. The apparent displacement is northwest-side-down, although there are no constraints on either the magnitude of slip or the true slip direction. The rest of the exposed fault zone in Tijeras Canyon is composed of intensely brecciated Tijeras greenstone and Precambrian Cibola gneiss (Kelley and Northrop, 1975).

The second locality is a recently discovered streamcut, which is the focus of this paper. The exposure lies roughly midway along the Tijeras–Cañoncito fault system near the village of Golden. The arroyo containing the streamcut intersects NM-14 about 6.8 km south of Golden in T12N, R6E (Fig. 1). The exposure is located only tens of meters downstream of the roadside. The stream has incised a channel generally 1–3 m deep, exposing a fault zone more than 160 m wide in a cross-section transverse to the strike of the Tijeras fault. When discovered in late sum-

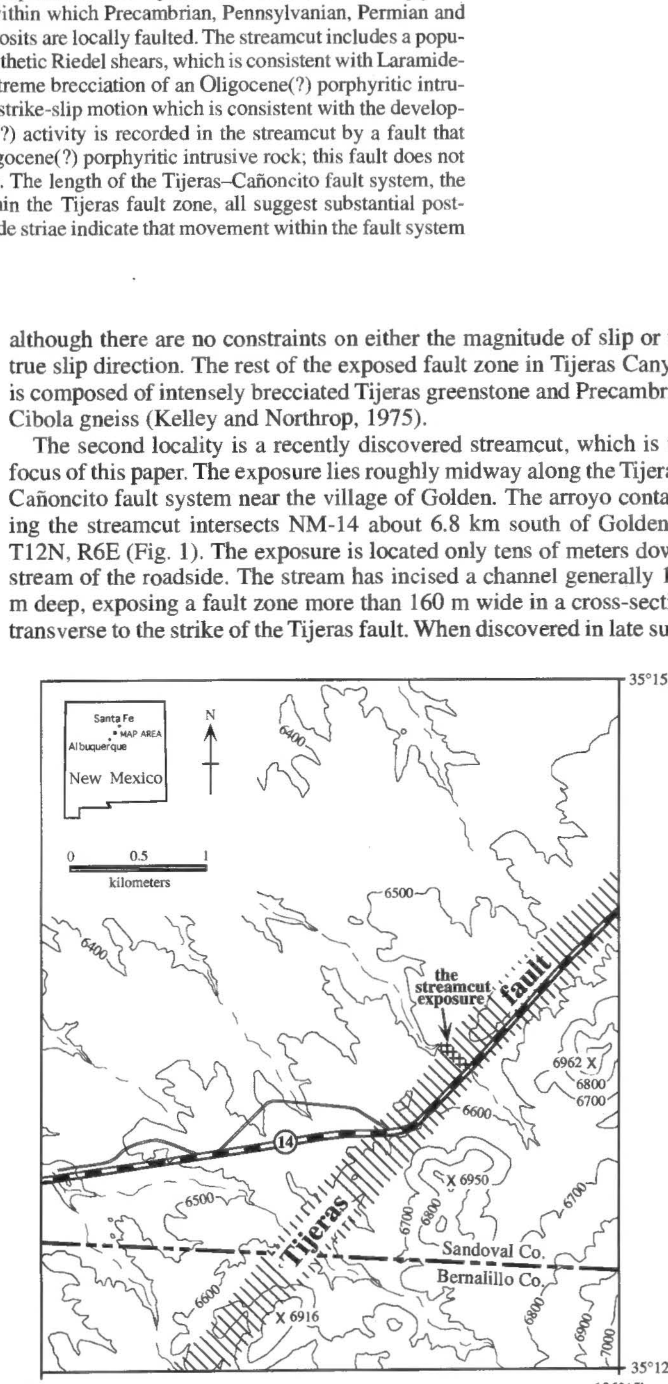

FIGURE 1. Location of streamcut exposure. The area shown is in T12N, R6E on the Sandia Park 7.5' quadrangle.

mer 1994, the exposure appeared very fresh, and it seems likely that it was created or enlarged during that summer. On subsequent visits, it was evident that the modern stream deposits were steadily aggrading and the exposure was beginning to be covered. This streamcut provides the most spectacular and informative known exposure of the Tijeras fault.

Regional geology

Precambrian basement rocks exposed in the vicinity of the Tijeras–Cañoncito fault system are coarsely crystalline plutonic rocks and greenschist- to amphibolite-grade metamorphic rocks (Lambert 1961; Huzarski, 1971; Kelley and Northrop, 1975; Connolly, 1982; Vernon, 1986). The basement rocks are overlain by up to several thousand meters of late Paleozoic and Mesozoic sedimentary strata (Kelley and Northrop, 1975). These beds record a Late Pennsylvanian–Early Permian orogenic event associated with formation of the ancestral Rocky Mountains (Baars, 1982; Beck and Chapin, 1991), followed by multiple Mesozoic transgressions and regressions (Molenaar, 1977; 1983). Renewed tectonic activity during the Late Cretaceous–early Tertiary Laramide orogeny resulted in high-angle faulting, and the formation of basement-cored uplifts and associated intermontane basins in north-central New Mexico (Chapin and Cather, 1981; Chapin and Nelson, 1986; Martinez, 1989; Cabezas, 1991; Cather, 1992). A significant component of right-lateral strike-slip movement occurred on north-striking faults during the Laramide orogeny (Chapin and Cather, 1981; Hamilton, 1981; Cather, 1992; Karlstrom and Daniel, 1993). A period of relative tectonic quiescence marked by widespread volcanic and igneous activity followed Laramide deformation (Stearns, 1953; Cather, 1989). A shallow intrusive center, the San Pedro–Ortiz porphyry belt, was emplaced in and around the Tijeras–Cañoncito fault system in the Oligocene (Bachman and Mehnert, 1978; Woodward, 1984; Maynard et al., 1991). From the Miocene through the Holocene, the region accommodated significant east-west extension with formation of the north-trending Rio Grande rift (Keller and Cather, 1994). The rift appears to have developed with a small component of left-lateral motion (Kelley, 1982; Lewis and Baldridge, 1994; Salyards et al., 1994).

Terminology of fault rocks and minor faults

The Tijeras fault, as exposed by the streamcut, is a zone more than 160 m wide of brittlely deformed bedrock. We follow Sibson (1977) in subdividing incohesive cataclastic rocks into fault breccia and fault gouge. In fault breccia, visible fragments of the parent rock comprise at least 30% of the rock mass, whereas fault gouge contains less than 30% visible fragments. Both breccia and gouge locally exhibit a strong fabric. In keeping with Chester et al. (1985), we refer to this fabric as a cataclastic foliation.

Minor faults referred to herein are mesoscopic surfaces marked by a discernible clay fault gouge, fault slickenside surface, and/or lithologic discontinuity. Fault gouge is abundant in the most intensely deformed part of the fault zone (units 1–19 of Appendix). The gouge typically is considerably lighter in color than the wall rocks from which it presumably was derived. It generally occurs in planar to curviplanar zones less than a few centimeters wide. In the strongly deformed units, gouge zones anastomose around lens-shaped pods of somewhat less deformed material. Fault slickensides are present only in less deformed bedrock near the margin of the fault zone. We follow Fleuty (1975) in defining a fault slickenside as a polished and commonly, though not invariably, striated brittle shear surface. Slickenside striae are linear structures on a slickenside that form by friction parallel to the direction of movement. In a few instances, the sense of movement can be deduced from structures developed on the fault slickenside. The criteria we used to determine the sense of shear on a fault slickenside were described by Petit (1987).

STREAMCUT EXPOSURE OF TIJERAS FAULT NEAR GOLDEN

Bedrock geology

The geology of the streamcut is described in a detailed log measured from southeast to northwest (see Appendix). Thicknesses given in the log reflect the true thicknesses of each unit measured transverse to the strike of the Tijeras fault (taken to be 045°, Emerick, 1950), not the apparent thickness in the streamcut. The exposure can be subdivided into three parts based on the intensity of deformation.

The first 92.9 m of the log (upstream, southeastern end) covers the most extensively deformed section (units 1–19), wherein rocks of many different ages and lithologies have been juxtaposed and locally mixed (Fig. 2). Lithologies in this section include Precambrian Cibola gneiss, probable late Paleozoic interbedded shale and thin limestone beds, limestone of the Pennsylvanian Madera Group, carbonate-rich sandstone, probably the San Ysidro Member of the Permian Yeso Formation, and an Oligocene(?) porphyritic intrusive rock. By association with other porphyritic intrusive rocks in the nearby San Pedro–Ortiz porphyry belt (Bachman and Mehnert, 1978; Maynard et al., 1990), the porphyritic intrusive rock in the fault zone is probably Oligocene in age. The rocks in this section are so intensely brecciated that field identification of the parent material is locally impossible (e.g., units 4, 10 and 17, Appendix). Unidentifiable units may be zones in which different rocks have been tectonically mixed. Mixing is clearly evident in unit 8 (Figs. 2B, 3) where a block of limestone of the Pennsylvanian Madera Group is set in a matrix of strongly brecciated Precambrian Cibola gneiss. Also in unit 8, faulting mixed Pennsylvanian(?) black shales with Cibola gneiss. The strongly brecciated units in the first section of the fault zone typically exhibit a foliation defined by innumerable slip surfaces and anastomosing zones of fault gouge. The foliation is subvertical and strikes northeast, subparallel to the trend of the Tijeras–Cañoncito fault system. Sedimentary bedding and relict gneissic foliations are generally not discernible in the first section, except in places where the breccia contains relatively intact blocks a meter or more in diameter. These blocks are fractured, and shatter easily under the blow of a hammer. No fault slickensides were identified in this section of the fault zone.

The next 46.1 m (units 20–26) are characterized by moderate to locally strong deformation of late Paleozoic sedimentary rocks. Exposed bedrock units include limestone of the Madera Group and sandstone and mudstone of the Permian Abo Formation. Two small exposures (units 20 and 24) are not readily identifiable, but probably are also late Paleozoic in age. Bedding in mudstones and siltstones is completely overprinted by a cataclastic foliation, but bedding is locally preserved in sandstones and invariably preserved in limestones. Unit 25 is a good example of this, and provides clear evidence that deformation is localized in finer-grained rocks. Two exposures of the Madera Group (units 21 and 23), separated by only 14 m, have considerably different bedding orientations, which likely is a consequence of differential rotation of blocks within the fault zone. Although gouge-filled fault zones are numerous in the sandstones, fault slickensides are uncommon.

The last 23.0 m of the streamcut (units 27–29) is characterized by significantly less deformation than in the previous two sections. The Permian Abo Formation is the only bedrock unit exposed. Bedding is evident in all sandstones and in some mudstones. Bedding orientations are fairly consistent in this section, and are considerably less steep than elsewhere upstream. In unit 27, conjugate sets of north-striking, high-angle faults show apparent normal separations, resulting in a series of horsts and grabens. Several gouge zones are present, though the gouge is more silty and less clayey than upstream. The sandstone beds preserve abundant fault slickensides. Major slip surfaces are less abundant downstream. This style of deformation continues downstream for at least another 100 m, but is not included in the descriptive log.

In summary, the bedrock is heterogeneously deformed in a zone more than 160 m wide. Rocks of various ages and lithologies have been juxtaposed, including Precambrian Cibola gneiss, late Paleozoic(?) black shales, limestone of the Pennsylvanian Madera Group, Permian Abo and Yeso(?) Formations, and an Oligocene(?) porphyritic intrusive rock. Cibola gneiss, late Paleozoic(?) black shales, and limestone of the Madera Group have been mixed locally by faulting. Brittle faulting locally has destroyed sedimentary bedding and original gneissic foliations. Where preserved, bedding is generally steep and subparallel to the Tijeras fault, but dips shallowly at the margin and outside of the fault zone. A cataclastic foliation is developed in much of the zone, and its orientation is consistently subparallel to the Tijeras fault. Fault slickensides are abundant near the margin of the fault zone.

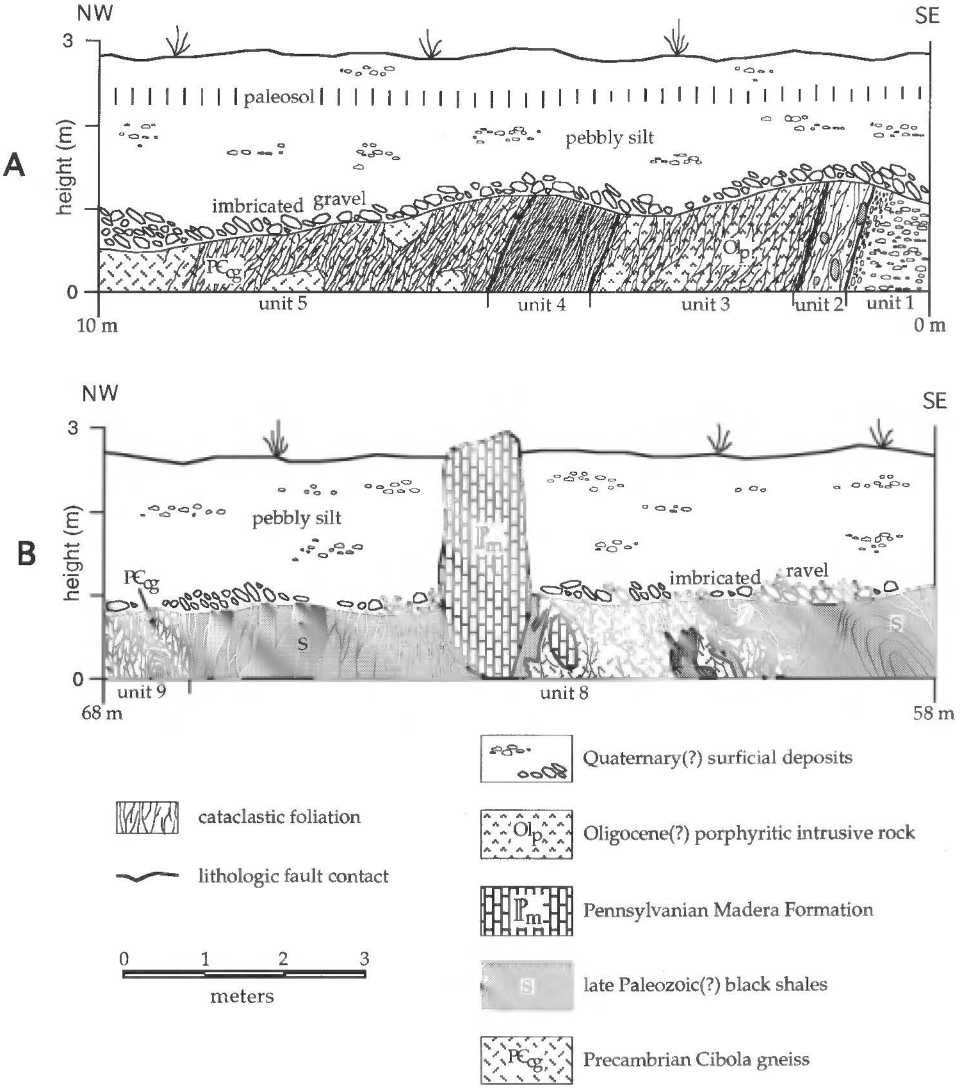

FIGURE 2. Illustrations of selected areas of the streamcut exposure. Views are to the northeast. Detailed descriptions of each unit are provided in the Appendix. A, Southeast end of the streamcut exposure. Note Quaternary(?) fault between units 1 and 3, which places Quaternary sandy gravel and carbonate-rich mottled clay against Oligocene(?) porphyry (see Fig. 4). This view shows apparent dip; the true dip of the faults and cataclastic foliation is subvertical. Holocene(?) imbricated gravel overlies the faults and foliated domains, and is not itself deformed. B, Zone of tectonic mixing. Unit 8 is a dramatic example of tectonic mixing, wherein a limestone knocker of the Pennsylvanian Madera Group is set in a matrix of strongly brecciated Precambrian Cibola gneiss. Black shales are locally mixed with Cibola gneiss.

Surficial deposits

Quaternary(?) surficial deposits overlie the bedrock and are locally disrupted by the Tijeras fault. The surficial deposits are described in some detail as they record Quaternary(?) faulting. Determining the relative ages of all surficial units is not unambiguous in the main streamcut because faulting has disrupted the section. However, relative ages are confirmed by correlation with undisturbed exposures on the southeast side of the highway.

The oldest surficial deposit is a carbonate-rich mottled clay (unit 2, Appendix). It is clearly faulted and has been dragged along the fault (Figs. 2A, 4). It is 0.5 m wide, and contains a strong, northeast-striking, subvertical foliation defined by anastomosing white gouge zones and elongate cobbles oriented parallel to the foliation. The unit is mostly clay and silt, and was probably derived largely from a carbonate paleosol horizon exposed on the southeast side of the highway. It also contains several outsized clasts up to 30 cm in maximum diameter, which may have been incorporated from another surficial deposit. The deposit is probably not older than Quaternary (B. Harrison and D. Love, personal commun., 1994). A 5–10-cm-wide zone of white gouge and strongly brecciated porphyritic intrusive rock separates the carbonate-rich mottled clay unit from adjacent bedrock. The apparent displacement along this

FIGURE 3. Unit 8, wherein tectonic mixing is illustrated by a knocker of limestone from the Pennsylvanian Madera Group (m) set in a matrix of brecciated Precambrian Cibola gneiss (cg). Late Paleozoic(?) black shales (s) are mixed with Cibola gneiss. All bedrock units are unconformably overlain by a Holocene(?) pebbly silt (ps) surficial deposit. View is to the southwest; Jacob staff increments are 10 cm.

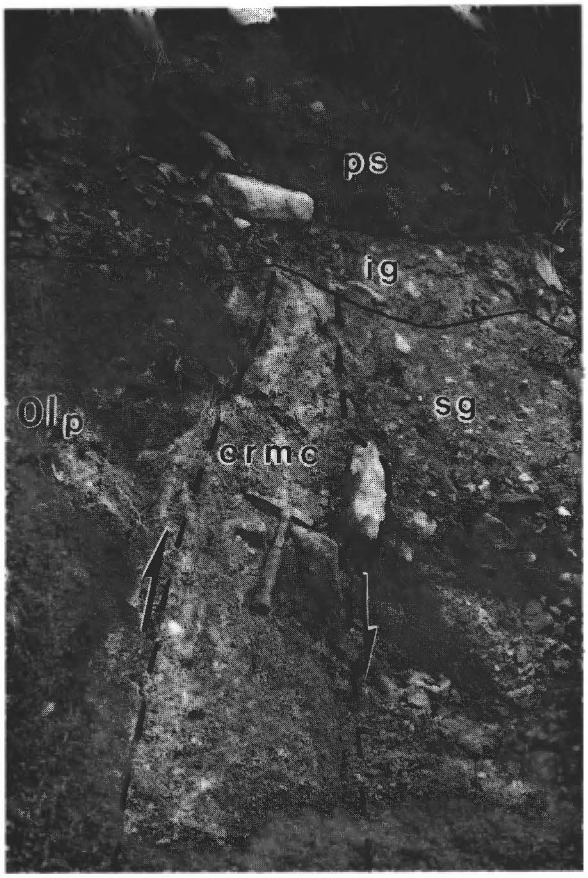

FIGURE 4. Quaternary(?) fault. The Quaternary(?) sandy gravel (sg, unit 1, Appendix) is in fault contact with the Quaternary(?) carbonate-rich mottled clay (crmc, unit 2). Unit 2 is in fault contact with a brecciated Oligocene(?) porphyry (Olp, unit 3). All are overlain by Holocene(?) imbricated gravel (ig) and pebbly silt (ps) deposits.

FIGURE 5. Apparent Holocene(?) faults. The Holocene(?) imbricated gravel (ig) surficial deposit appears to be offset in two places. At bottom right, a large, elongate cobble of the imbricated gravel surficial deposit lies in the plane of a fault in the Precambrian Cibola gneiss (cg). At bottom left, a fault appears to juxtapose Cibola gneiss (cg) against the imbricated gravel surficial deposit, but the gravel was deposited in a channel that truncated the fault. The overlying pebbly silt (ps) and paleosol (A) do not appear to be offset.

fault is southwest-side-down, which is opposite that of the previously documented Quaternary(?) fault in Tijeras Canyon (Lisenbee et al., 1979). No attempt has been made to determine the relative timing of Quaternary(?) faulting in the streamcut area with that in Tijeras Canyon.

A Quaternary(?) sandy gravel surficial deposit (unit 1) unconformably overlies the carbonate paleosol horizon on the southeast side of the highway, but is in fault contact with the carbonate-rich mottled clay (unit 2) in the streamcut exposure (Fig. 4). The sandy gravel is at least 1 m thick and is very poorly consolidated, with clast-supported pebbles 1–4 cm in diameter. Flat-lying elongate pebbles define a well developed horizontal stratification. A strong subvertical foliation defined by vertically oriented elongate pebbles overprints the original stratification close to the fault contact with unit 2. An imbricated gravel surficial deposit unconformably overlies both the sandy gravel and the carbonate-rich mottled clay (Figs. 2A, 4). Clasts in this deposit are imbricated cobbles and pebbles, recording paleotransport similar to that of the modern stream. It is typically 10–25 cm thick, but is up to 1 m thick in places. The imbricated gravel is easily traced along the streamcut for 80 m, though locally it is absent. This deposit appears to be offset in two places in unit 5 (Fig. 5). In one place, a large, elongate cobble in the surficial deposit lies in the plane of a fault in the Precambrian Cibola gneiss. This cobble may have rotated by faulting. In a second place, about 1.5 m downstream (Fig. 5), a fault appears to juxtapose Cibola gneiss against the imbricated gravel surficial deposit. Excavation, however, demonstrates that this fault is truncated by a channel deposit, and therefore is older than the deposit. The imbricated gravel is probably Holocene in age (B. Harrison and D. Love, personal commun., 1994).

A 3-m-thick pebbly silt conformably overlies the imbricated gravel surficial deposit (Figs. 2A, 5), and is the youngest surficial deposit in the area. It contains abundant charcoal, fossil gastropods, and a 10–20-cm-thick A horizon of a paleosol, which is probably Holocene in age (B. Harrison and D. Love, personal commun., 1994). Above the paleosol, the deposit locally contains objects of historic age, such as cans and slag. The pebbly silt is not noticeably offset by faulting.

Fault slickenside data

The orientations of 62 minor faults from bedrock exposures throughout the streamcut (Fig. 6) vary widely, but the vast majority are steeply dipping (>60°). Three populations of minor faults are identified, none of which parallel the trend of the Tijeras fault (045°, 90°). The most pronounced population is subvertical, strikes about 060°, and is present throughout the fault zone. Kinematic data from this population along other segments of the Tijeras–Cañoncito fault system indicate right-lateral strike-slip motion. Five minor faults in the Oligocene(?) porphyritic intrusive rock contribute to this population. A second population of faults is subvertical and strikes north-northeast. Three minor faults in the Oligocene(?) porphyritic intrusive rock contribute to this population. A third population is composed of subvertical, northwest-striking faults oriented roughly perpendicular to the general trend of the fault zone. These faults account for about one-fifth of the entire sample of faults. Shear fractures (R criteria of Petit, 1987) on two slickensides that contribute to this population of faults record a dominant component of right-lateral strike-slip motion on the slickenside surface. Twenty of the 62 minor faults contain fault slickensides with well developed striae (Fig. 7). Eighteen of these are from unit 28, near the margin of the fault zone. The rake (pitch) of striae is generally small (<45°). The striae record a large component of strike-slip (rake <30°) and oblique-slip (30°< rake <60°) motion, with a subordinate amount of dip-slip (rake >60°) motion (Fig. 8).

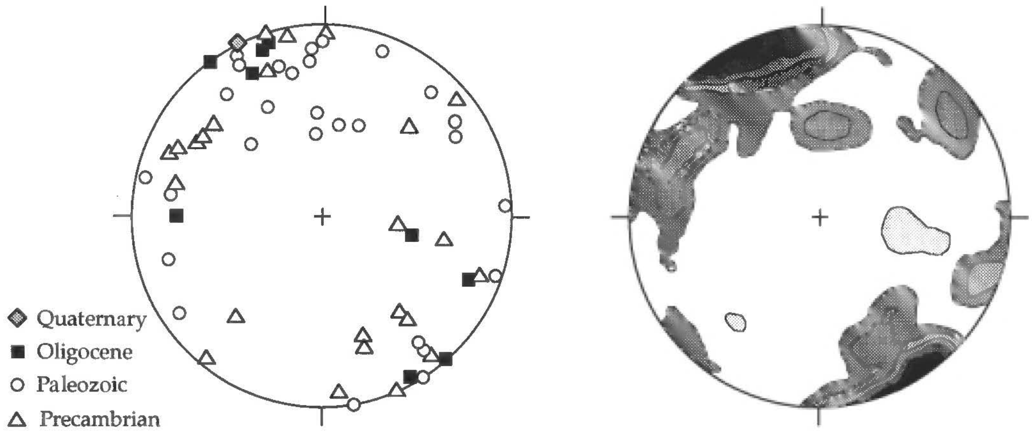

FIGURE 6. Equal area, lower hemisphere projection of poles to 62 minor faults. Most faults dip steeply. Three populations of faults are identified: ENE-striking, NNE-striking, and NW-striking. The symbols represent faults that cut Precambrian, late Paleozoic, and Oligocene(?) rocks, and Quaternary(?) fault in unit 2. Contoured in multiples of random distribution (mrd). White is less than 1 mrd, each subsequent contour represents an increase in one mrd. The data are plotted and contoured using the program and method of Starkey (1977).

DISCUSSION

The magnitude of the net displacement accommodated by the Tijeras–Cañoncito fault system has not been determined because no piercing points have been identified. Vertical separations of late Paleozoic and Mesozoic stratigraphy are generally less than a few hundred meters. Several lines of evidence, however, suggest significant post-Pennsylvanian displacement along the fault system. First, the fault system is extensive, having been mapped for about 80 km through late Paleozoic and Mesozoic rocks. Though not impossible, it is energetically unfavorable to create such a long structure without accommodating a substantial amount of slip. Second, the fault zone is very wide, which also suggests the possibility of substantial displacement. The Tijeras fault alone is a zone more than 160 m wide of brecciated Precambrian and late Paleozoic rocks. The Gutierrez fault, which parallels the Tijeras fault to the southeast, is also a major fault and may have accommodated as much or more slip than the Tijeras fault. Third, the intensity of deformation within the fault zone also suggests significant slip. Precambrian, Pennsylvanian and Oligocene(?) rocks are strongly brecciated within the fault zone. Locally, Precambrian and late Paleozoic rocks are tectonically mixed (Figs. 2B, 3). These observations suggest substantial post-Pennsylvanian and/or post-Oligocene(?) displacement on the Tijeras–Cañoncito fault system.

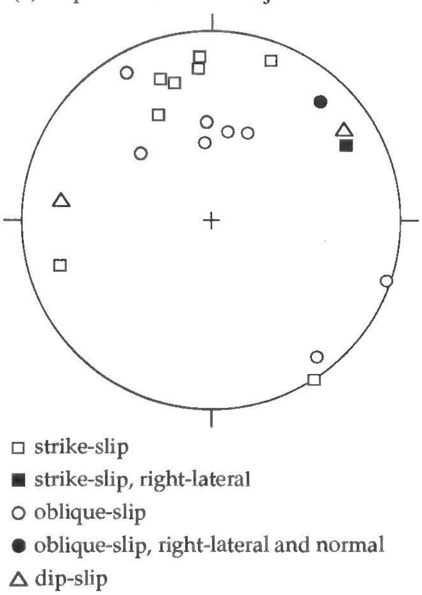

FIGURE 7. Equal area, lower hemisphere projection of poles to 20 fault slickensides. Indicated symbols represent strike-slip (rake of striation <30°); oblique-slip (30°<rake<60°); dip-slip (rake>60°); and faults with a component of right-lateral slip.

The orientations of minor faults and slickenside striae help constrain the sense of motion and timing of deformation in the fault zone. Several populations of minor faults that are distinctly oblique to the trend of the Tijeras fault have been identified. We interpret these populations in terms of Riedel shear geometries. The orientation of each population of minor faults suggests a certain sense of movement on the Tijeras–Cañoncito fault system. The timing of deformation is constrained by comparing the sense of movement recorded by rocks of different ages with our current understanding of the tectonic history of north-central New Mexico.

The most pronounced population of minor faults is subvertical and trends about 60°. This population is properly oriented for slip as synthetic right-lateral Riedel shears during right-lateral motion on the Tijeras–Cañoncito fault system (Fig. 9A). Their orientations are inconsistent with Riedel shears developed during left-lateral motion. East-west to northeast-southwest shortening during the Laramide orogeny would have favored right-lateral transtensional motion on the Tijeras–Cañoncito fault system (Cather, 1992). These faults are therefore interpreted to be Laramide in age. One bit of evidence that seems to contradict this interpretation is the fact that this population of faults is also found in the Oligocene(?) porphyritic intrusive rock (Fig. 6). Since the porphyritic intrusive rock is almost certainly post-Laramide in age, it might appear that this is evidence for post-Laramide right-lateral motion. This, however, is inconsistent with the Cenozoic tectonic history of north-central New Mexico. We therefore suggest that these faults are extensions of reactivated Laramide faults that propagated into the porphyritic intrusive rock during the Neogene and/or Quaternary.

A second population of minor faults is subvertical and strikes north-northeast. These faults are properly oriented for slip as synthetic left-lateral Riedel shears during left-lateral strike-slip motion on the Tijeras–Cañoncito fault system (Fig. 9B). Their orientation is inconsistent with Riedel shears formed in a right-lateral strike-slip regime. The Tijeras–

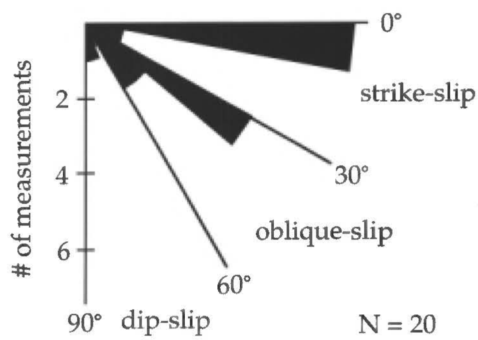

FIGURE 8. Rakes of 20 fault striae from slickenside surfaces near the margin of the fault zone. Each petal is 10°. Most faults record strike-slip or oblique-slip motion. Only two slickenside surfaces record dip-slip motion.

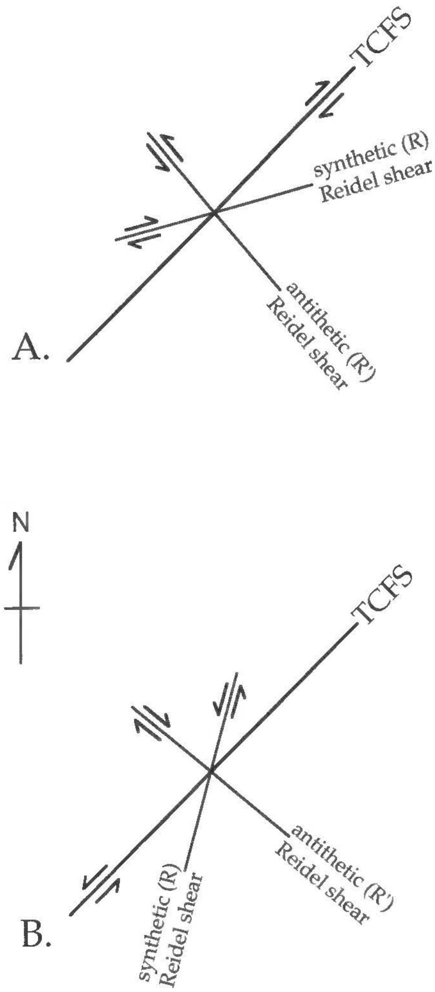

FIGURE 9. Anticipated Riedel shear geometries. A, right-lateral motion on the Tijeras–Cañoncito fault system. B, left-lateral motion on the Tijeras–Cañoncito fault system.

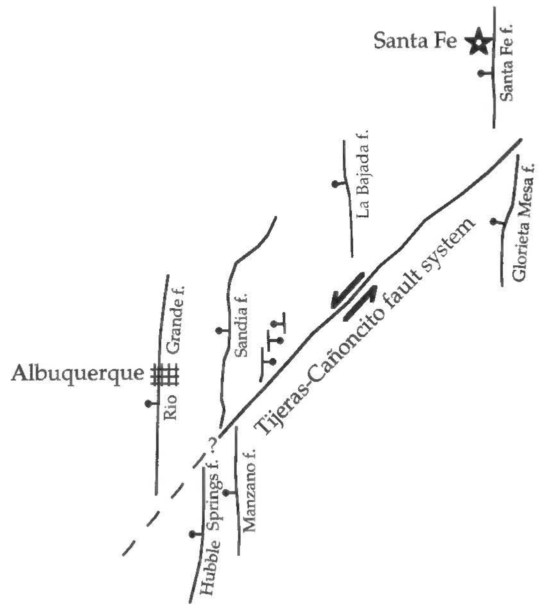

FIGURE 10. Schematic diagram of Neogene rifting. Left-lateral transtensional motion on the northeast-trending Tijeras–Cañoncito fault system, coupled with extension on north-striking faults, may have accommodated E–W extension during the Neogene and Quaternary.

Cañoncito fault system could have accommodated rifting through left-lateral transtension in the Neogene and Quaternary (Fig. 10). These north-northeast striking faults are therefore interpreted to be related to rifting in the Neogene and/or Quaternary. In an exposure of Permian Abo Formation near the margin of the fault zone (unit 27), conjugate sets of north to northeast-striking, high-angle minor faults have apparent normal separations that created a series of horsts and grabens. This geometry of faults is consistent with the development of the Rio Grande rift. There is firm evidence for mid- to late-Cenozoic deformation on the Tijeras fault in the intense deformation of the Oligocene(?) porphyritic intrusive rock and in offset of Quaternary(?) surficial deposits.

The third population is composed of subvertical, northwest-striking minor faults oriented roughly perpendicular to the Tijeras–Cañoncito fault system. They account for about one-fifth of all the minor faults. We interpret these to be antithetic Riedel shears, though their orientation does not suggest a particular sense of shear (see Fig. 9). However, two slickenside surfaces in this population exhibit synthetic and antithetic shears (R criteria of Petit, 1987) that record right-lateral motion. This is consistent with left-lateral motion on the Tijeras fault (Fig. 9B), and thus is probably related to the Tijeras fault accommodating the development of the Rio Grande rift in the Neogene.

CONCLUSION

A recently discovered streamcut across the Tijeras fault near Golden, New Mexico, is a spectacular window into the internal structure of the Tijeras–Cañoncito fault system. The fault zone is more than 160 meters wide. Faulting locally mixed lithologies of diverse origins and geologic ages. Precambrian, Pennsylvanian, Permian and Oligocene(?) rocks in the fault zone are generally intensely brecciated, locally to the extent where field identification of the parent rock is impossible. In many areas of the fault zone, sedimentary bedding and gneissic foliations have been completely overprinted by a cataclastic foliation that is consistently subparallel to the Tijeras–Cañoncito fault system. Where preserved, bedding is subvertical within the fault zone, but is shallowly dipping at the margin and outside of the fault zone.

The streamcut exposure provides valuable insight into the deformational history of the Tijeras fault. Strongly deformed Precambrian, late Paleozoic and Oligocene(?) bedrock units are overlain by Quaternary(?) surficial deposits throughout most of the exposure. A population of minor faults that fits the orientation for right-lateral synthetic Riedel shears are interpreted to have formed by right-lateral motion on the Tijeras–Cañoncito fault system, consistent with deformation during the Laramide orogeny. In addition, three lines of evidence support Neogene activity. First, a porphyritic intrusive rock is intensely brecciated. By association with other porphyritic intrusive rocks in the nearby San Pedro–Ortiz porphyry belt, the brecciated porphyritic intrusive rock is probably Oligocene in age. The porphyritic intrusive rock is the only post-Laramide bedrock lithology present, and its intense deformation demonstrates that there has been significant post-Laramide movement on the Tijeras fault. The strongly deformed porphyritic intrusive rock is locally overlain by Quaternary(?) surficial deposits, suggesting that the deformation is bracketed between the Oligocene(?) and the Quaternary(?). Second, a population of minor faults fits the orientation for left-lateral synthetic Riedel shears in a left-lateral strike-slip regime. Given our understanding of the tectonics of the Rio Grande rift, it is expected that the Tijeras fault would have accommodated left-lateral motion in the Neogene, and therefore this population of minor faults is interpreted to record Neogene activity. Third, two northwest-striking slickensides record right-lateral strike-slip motion. These are interpreted to be antithetic Riedel shears in a left-lateral strike-slip regime, which is consistent with the development of the Rio Grande rift in the Neogene.

Surficial deposits exposed by the streamcut provide clear evidence for Quaternary activity. Two Quaternary(?) surficial deposits were cut by and dragged along a fault, but are overlain by a Holocene(?) imbricated gravel. The apparent displacement on this fault is opposite that of the previously described Quaternary(?) fault in Tijeras Canyon (Lisenbee et al., 1979), but the relative timing of faulting in the streamcut and in Tijeras Canyon has not been determined.

The magnitude of displacement accommodated by the Tijeras–Cañoncito fault system has not been determined because no piercing points have been identified. The length of the fault system, and the width and intense deformation within the fault zone, however, all suggest substantial displacement on the fault system.

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APPENDIX—LOG OF STREAMCUT EXPOSURE

1. Quaternary(?) pebbly gravel surficial deposit. Largely clast supported, with typical clasts ranging from 1–4 cm in diameter. The unit has a moderately well developed horizontal stratification defined by flat-lying tabular pebbles. In a zone 10–15 cm wide immediately adjacent to unit 2, horizontal stratification has been completely overprinted by a strong vertical fabric defined by vertically oriented elongate pebbles. The fabric is interpreted to be created by reorientation of pebbles along a fault contact with unit 2 (Fig. 4). >1 m

2. Quaternary(?) carbonate-rich mottled clay. This unit is predominantly clay, but also contains several outsized cobbles up to 30 cm in maximum diameter. The unit has a strong, northeast-trending, subvertical fabric defined by anastomosing white fault gouge zones and vertically oriented elongate cobbles. The contact with unit 3 is a vertical zone 5–10 cm wide of anastomosing gouge-filled faults trending 062°, 90° (Fig. 4). 0.5 m

3. Oligocene(?) porphyritic intrusive rock. Most of the unit is strongly brecciated, though lens-shaped pods of somewhat less fractured rock are locally present. This unit contains several zones 5–30 cm wide of anastomosing gouge-filled faults. The contact with unit 4 is a zone of anastomosing faults 5 cm wide. 2.5 m

4. Dark brown breccia zone. Identification of the parent rock(s) was not possible due to very strong brecciation, though the presence of some quartz grains suggests that it may have been derived in part from the Precambrian Cibola gneiss. There is a very strong cataclastic fabric oriented 050°, 90°. The contact with unit 5 is a gradational zone of anastomosing faults 5 cm wide, oriented 072°, 62° NW. 1.2 m

5. Precambrian Cibola gneiss. This unit is composed of roughly equal amounts of relatively intact blocks of gneiss and a matrix of strongly brecciated gneiss. The blocks are typically 1–2 m in diameter, and preserve the original gneissic foliation. The strongly brecciated gneiss has a well developed cataclastic fabric, which generally strikes ENE and dips 40°–70° NNW. The fabric locally wraps around the intact blocks. Iron staining is common. Gouge filled fault zones 1–40 cm wide are common throughout. The gneiss is overlain by a Holocene(?) imbricated gravel surficial deposit, which appears to be faulted in two places (Fig. 5). In one place, a large, elongate cobble in the surficial deposit lies in the plane of a fault in the Precambrian Cibola gneiss. This cobble may have rotated by faulting. In a second place, about 1.5 m downstream, a fault appears to juxtapose Cibola gneiss against the imbricated gravel surficial deposit. Excavation, however, demonstrates that the fault is truncated by a channel deposit, and therefore is older than the surficial deposit. 17.7 m

6. Precambrian Cibola gneiss. The unit is largely intact Cibola gneiss, though locally it is punctuated by brecciated rock. A steeply southeast-dipping gneissic foliation is clearly visible in most of the unit, though 1–20-cm-wide zones of fault gouge and breccia are locally evident. A fault oriented 130°, 60° NE separates this unit from unit 7. 11.0 m

7. Precambrian Cibola gneiss. Most of the unit is strongly brecciated and altered. A 1-m-wide block of relatively intact Cibola gneiss retains a gneissic foliation, though the block itself is highly fractured and shatters easily under the blow of a hammer. Numerous 1–4-cm-wide fault gouge zones are present; many of these ɔnes are contorted and may be traced for only a few centimeters. An older fault oriented 129°, 86°N is cut by a younger fault oriented 078°, 85°S with an apparent left-lateral offset of a few centimeters. The contact with unit 8 is a contorted fault gouge zone 1–5 cm wide. 3.8 m

8. Late Paleozoic(?) black shales, Precambrian Cibola gneiss, and limestone of the Pennsylvanian Madera Group. This unit is a zone in which faulting has mixed rocks of different lithologies and ages. Most of this unit is black, brown and tan shales interbedded with numerous 1–2-cm-thick beds of limestone and a 10-cm-wide tan sandstone bed. This is probably part of the Pennsylvanian Sandia Formation or Madera Group. Bedding is complexly folded, and is unrecognizable in the shales. The limestone beds are generally discontinuous over 10–30 cm, but a few may be traced across the 1 m height of the outcrop. Individual limestone beds are clearly folded, but many folds appear to involve only one limestone bed, with adjacent beds having a different fold pattern. Two larger folds involve several beds. Both are tight and steeply plunging with fold hinges oriented 100°, 62° and 171°, 66°. The late Paleozoic(?) black shales locally contain pods of very strongly brecciated Precambrian Cibola gneiss. Near the center of the unit, Precambrian Cibola gneiss and Madera limestones are mixed into the black shales. The Cibola gneiss is very strongly brecciated and contains numerous zones of fault gouge. The gneiss resembles grus in hand sample. There is a well developed, subvertical, cataclastic fabric in the gneiss, but no evidence of the original gneissic foliation. The Cibola gneiss contains several pods of black shale that also contain a subvertical fabric. Some shale pods are at least 80 cm long and 30 cm wide. A knocker of gray limestone of the Madera Group is set in a matrix of very strongly brecciated Cibola gneiss (Fig. 3). The block is oriented subvertically, parallel to the cataclastic fabric in the gneiss. Another block of gray fossiliferous Madera limestone trends northeast and stands subvertically about 2.5 m high. It is set in black shales. The block is teardrop-shaped in cross-section; the top is about 1.3 m thick, and it pinches out at the streambed. It also appears to pinch out along strike. A sharp fault contact separates this unit from unit 9. 17.6 m

9. Precambrian Cibola gneiss. The gneiss is very strongly brecciated, and the original gneissic foliation has been destroyed. The gneiss has the appearance of grus, and is easily dug out of the streamcut with a pick. Numerous subvertical faults strike 072°. A vertical fault striking 066° marks the contact with unit 10. 4.8 m

10. Zone of extreme shearing. Identification of the parent rock is not possible in the field. Several fault gouge zones are present. There are a few quartz-rich clasts 2–5 cm in diameter, which suggests that at least part of the unit may be derived from the Cibola gneiss. A fault oriented 052°, 82°W separates this unit from unit 11. 1.2 m

11. Precambrian Cibola gneiss. This unit is similar to unit 9. A few brecciated quartz-rich clasts 1–3 cm in diameter are present in this very strongly brecciated unit. The contact with unit 12 is a fault oriented 053°, 90°. 0.8 m

12. Oligocene(?) porphyritic intrusive rock. The porphyritic intrusive rock is light tan, intensely brecciated, and easily excavated with a pick. No intact, unfractured blocks are present. The contact with unit 13 is abrupt. 2.2 m

13. Fault gouge. This unit consists of dark gray to black clay containing several clasts of porphyritic intrusive rock 4–8 cm in diameter, and was probably derived from the porphyritic intrusive rock. The clay unit is oriented 060°, 85°NW, and varies from 10–20 cm in thickness. The contact with unit 14 is abrupt. 0.2 m

14. Precambrian Cibola gneiss. This unit is very similar to unit 9. The rock is strongly brecciated; no evidence of the original gneissic foliation exists, and there are no intact blocks of gneiss. A few intensely brecciated quartz-rich clasts are present, as well as numerous 1–2 cm thick fault gouge zones. The contact with unit 15 is abrupt. 1.7 m

15. Fault gouge. This unit is similar to unit 13. The contact with unit 16 is abrupt. 0.2 m

16. Oligocene(?) porphyritic intrusive rock. Most of this unit is intensely brecciated in the same manner as unit 12, though more intact blocks are locally present. These blocks are fractured and shatter easily under the blow of a hammer. In hand sample, light-colored rectangular grains 1–5 mm in diameter are visible, and are interpreted to be plagioclase crystals that have since altered to clays. Also visible in hand sample are black, lathe-shaped crystals generally 5 mm long, which are probably hornblende. There are numerous high-angle fault gouge zones 1–2 cm in width. A fault oriented 062°, 71°SE separates this unit from unit 17. 6.2 m

17. Rock flour. Identification of the parent material is impossible in the field. The unit is tan in color, and does not exhibit a cataclastic fabric. A fault oriented 049°, 90° separates unit 17 from unit 18. 0.5 m

18. Oligocene(?) porphyritic intrusive rock. This unit is similar in character to unit 16. Most of the unit is intensely brecciated, though several intact blocks are present. In this unit an older fault oriented 000°, 66°E is cut by a younger fault oriented 071°, 82°SE. A fault oriented 072°, 84°SE separates this unit from unit 19. 2.5 m

19. Permian(?) sandstones. Sandstones are yellowish-brown and tan and are cemented with carbonate. This unit may be derived from the San Ysidro Member of the Permian Yeso Formation. The unit was brecciated into clasts 2–4 cm in diameter and subsequently cemented. 4.4 m

Bedrock not exposed 12.9 m

20. Permian(?) sandstone. Coarse, red sandstone locally brecciated. Sand grains are 1–5 mm in diameter. This unit is probably from the Permian Abo Formation. 0.4 m

Bedrock not exposed 0.8 m

21. Pennsylvanian Madera Group. Gray, fossiliferous limestone with numerous chert nodules. Bedding is oriented 046°, 65°SE. A single fault slickenside oriented 019°, 87°W has fault striae with a rake of 38°N, recording oblique-slip motion. 4.3 m

Bedrock not exposed 3.7 m

22. Thick, gray, fossiliferous limestone beds of the Madera Group. 3.9 m

Bedrock not exposed 6.4 m

23. Thick, gray, fossiliferous limestone beds of the Madera Group oriented 160°, 57° NE. 5.1 m

Bedrock not exposed 2.7

24. Fault gouge. The gouge is yellowish-brown and gray and exhibits a steeply dipping cataclastic foliation. Smaller gouge zones cross-cut the cataclastic foliation. This unit is in fault contact with unit 25. 1.2 m

25. Permian Abo Formation, approximately 75% maroon mudstone and 25% sandstone. Bedding in all mudstones is destroyed and replaced by a cataclastic foliation oriented 025°, 90°. Sandstone beds are generally only slightly fractured. Two bed orientations are: 000°, 90° and 026°, 65°W. The latter has a slickenside surface oriented 008°, 70°E with fault striae having a rake of 82°N, recording dip-slip motion on a high-angle fault. 6.9 m

Bedrock not exposed 5.7 m

26. Permian Abo red sandstones and mudstones cut by several gouge zones 1–10 cm thick. Two of these zones are oriented 145°, 80°NE and 080°, 90°. 3.8 m

Bedrock not exposed 1.2 m

27. Permian Abo Formation, approximately 80% red sandstone and 20% red mudstone. Bedding dips approximately 40°NE, which is considerably less steep than elsewhere upstream in the main part of the fault zone. The sandstone is locally intensely brecciated with a well developed cataclastic foliation. The foliation wraps around a series of fault-bounded blocks about 0.5 m across. The faults that bound the blocks are high-angle, dipping >72°. The resulting geometry of blocks resembles a series of horsts and grabens. A few meters downstream, reduction spots have been offset by a number of small, high-angle faults with apparent offsets of 1–5 cm. This creates a similar geometry of horsts and grabens on a smaller scale. Many fault gouge zones are present, though the fault gouge is less clayey and more silty than upstream. All bedding in mudstones has been destroyed. 11.1 m

Bedrock not exposed 5.7 m

28. Permian Abo Formation, beds of red sandstone oriented 165°, 37°E. It is essentially intact, but includes abundant slickenside surfaces. 3.3 m

29. Permian Abo Formation. Bedding in red mudstone is locally preserved. 2.9 m

Total width = 162 m