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Unconformable and cross-cutting relationships indicate major Precambrian faulting on the Picuris-Pecos Fault System, Southern Sangre de Cristo Mountains, New Mexico

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 New Mexico Geological Society Guidebook, 55th Field Conference, Geology of the Taos Region, 2004, p. 206-219.

UNCONFORMABLE AND CROSS-CUTTING RELATIONSHIPS INDICATE MAJOR PRECAMBRIAN FAULTING ON THE PICURIS-PECOS FAULT SYSTEM, SOUTHERN SANGRE DE CRISTO MOUNTAINS, NEW MEXICO

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Abstract.—What is the age of the Picuris-Pecos fault system? Its 37 km dextral separation of Precambrian lithologic belts makes it the largest well-documented strike-slip system in the southern Rocky Mountains. Numerous studies focusing on regional stratigraphic relationships, basin geometries and structural patterns have variously assigned the major strike slip on the Picuris-Pecos fault system to Precambrian, Ancestral Rocky Mountain, and Laramide orogenies.

New field and petrographic observations were collected from the southern Picuris-Pecos fault system in the southern Sangre de Cristo Mountains. In Deer Creek Canyon, an exceptionally broad and resistant zone of brecciated granitic gneiss is exposed adjacent to folded, but not brecciated, Paleozoic limestones and siliciclastic rocks. The induration of the crush breccias and protocataclasites along with their microcline + chlorite +/- biotite assemblages and lack of void space fillings suggest that brecciation occurred during Precambrian low-grade metamorphic conditions near the brittle-ductile transition. Phanerozoic deformation appears to be dominated by narrow zones of unconsolidated fault gouge cutting the crystalline rocks and associated folding of the Paleozoic strata.

In addition, easily excavated shales and weathered granitic grus showing cataclastic breccia textures are locally exposed between crystalline breccias and overlying, minimally-deformed Mississippian and Pennsylvanian limestones. These apparent erosional nonconformities indicate that major brecciation occurred prior to the late Paleozoic. Furthermore, two northwest-striking bands of Mississippian limestone, 24 and 10 meters in length respectively, crosscut both the brecciated rocks and the overall trend of the Picuris-Pecos fault system. Compositional, faunal and textural similarities between several carbonate bands and the lowermost Mississippian carbonate rocks indicate that they are penecontemporaneous clastic dikes injected from above into coherent Precambrian crystalline breccias.

If the spectacular breccias in Deer Creek Canyon are related to the dextral strike-slip displacements along the Picuris Pecos fault system, then these displacements are Precambrian, not Phanerozoic. This conclusion contradicts hypotheses invoking large dextral strike-slip displacements on north-striking faults during both Laramide and Ancestral Rocky Mountain orogenies and reopens the possibility of major Proterozoic dextral strike-slip faulting in the southern Rocky Mountains.

INTRODUCTION

Over the last 20 years, the tectonic significance of north-striking, dextral strike-slip faulting in New Mexico has been one of the most contentious topics in Rocky Mountain geology. A major 37 km dextral separation on the north-striking Picuris-Pecos fault system has been clearly delineated by surface exposures of offset Precambrian lithologic belts (Montgomery, 1963). This makes the Picuris-Pecos fault system the largest well-documented example of strike-slip deformation in the southern Rockies. Cordell and Keller (1984) extended the zone of dextral strike slip to parallel, less well-exposed faults using truncated aeromagnetic anomalies. Despite these clear dextral separations, studies of the timing and magnitude of strike-slip faulting based on regional stratigraphic relationships (Woodward et al., 1997, 1999; Yin and Ingersoll, 1997; Cather, 1999) and structural patterns (Baltz, 1967; Karlstrom and Daniel, 1993; Baltz and Myers, 1999; Erslev, 2001) have failed to reach a consensus. Part of the problem has been the multi-phase history of Precambrian and Phanerozoic deformation in the Rocky Mountains, with younger structures both reactivating and concealing older structures.

More specifically, separations of Phanerozoic isopach contours have been used to suggest 5 to 20 km (Woodward et al., 1997) and 33 to 110 km (Cather, 1999) of Laramide dextral strike slip. Similarly, Laramide sedimentary basin geometries have been used to suggest both negligible (Yin and Ingersoll, 1997) and 60 to 120 km (Chapin and Cather, 1981; Chapin, 1983) of Laramide dextral strike slip. On the basis of their interpretation of continuous Mesozoic isopachs, Woodward et al. (1999) discounted a Laramide origin for the major dextral offsets of basement rocks and hypothesized that they were generated during the Pennsylvanian Ancestral Rocky Mountain orogeny. Baltz (1999) agreed that the Ancestral Rocky Mountain orogeny was caused by northeast-southwest compression that could have generated dextral strike slip on north-striking faults. He concluded, however, that the total Pennsylvanian dextral slip need not exceed five km.

Regional fault patterns have also been used to propose minimal (Baltz, 1967; Erslev, 2001; Erslev et al., 2004) to greater than 100 km (Karlstrom and Daniels, 1993) of Laramide dextral strike slip within the southern Rocky Mountains. The summed dextral slip amounts of 100 to 170 km (Karlstrom and Daniels, 1993) and 85 to 110 km (Cather, 1999) are largely based on the offsets of magnetic anomalies that have been convincingly linked to dextral separations of Precambrian lithologic belts along the Picuris-Pecos fault system. But the age of these dextral separations has been contested, with Montgomery (1953, 1963), Sutherland (1963) and Baltz and Myers (1999) attributing them to Precambrian deformation and Cather and Chapin (1981), Chapin (1983), Karlstrom and Daniel (1993), Daniel et al. (1995), and Cather (1999) attributing them to the Laramide deformation. Bauer and Ralser (1995) noted the continuity of apparent dextral

drag folding adjacent to the northern Picuris-Pecos fault system and hypothesized that this continuity indicates ductile, and thus probably Precambrian, deformation. In addition, they showed that minimally offset Phanerozoic strata overlie major basement fault zones that parallel the Picuris-Pecos fault system. They suggested that the dextral separations on the Picuris-Pecos fault system might have been caused by the combination of about 26 km of Laramide slip superimposed on about 11 km of Precambrian slip.

This report presents the initial findings of research on the southern Picuris-Pecos fault system, which strikes N20E and can be traced nearly 84 km along the western edge of the southern Sangre de Cristo Mountains in north-central New Mexico (Fig. 1). New field research in an area northeast of Cañoncito along the Deer Creek fault, the uncontested southern extension of the Picuris-Pecos fault system (Sutherland, 1963; Baltz and Myers, 1999), has shown that this portion of the Picuris-Pecos fault system exposes complex contacts between Paleozoic strata, Paleozoic clastic dikes and indurated crush breccias and protocataclasites. These contacts, when combined with petrographic analyses of 26 thin sections, indicate a Precambrian age for the brecciated rocks, consistent with previous interpretations by Montgomery (1953, 1963) and Sutherland (1963) who attributed major dextral strike slip on the Picuris-Pecos fault system to Proterozoic deformation.

GEOLOGIC SETTING AND PREVIOUS WORK

The Picuris-Pecos fault system is exposed in two areas stretching from Taos to Lamy, New Mexico. South of Taos, the Picuris-Pecos fault emerges from the eastern edge of the Rio Grande rift and crosses the Precambrian rocks of the Picuris Mountains. The fault then is covered for approximately 20 km (Bauer and Ralser, 1995) as it crosses the Rio Pueblo, Rio Santa Barbara and Rio Chiquito river valleys before emerging to traverse the eastern flank of the Santa Fe Range, the western spine of the southern Sangre de Cristo Mountains (Fig. 1).

Just south of Taos, north-south strike-slip faults cut Miocene volcanic and clastic rocks (Bauer et al., 1999; Erslev, 2001),

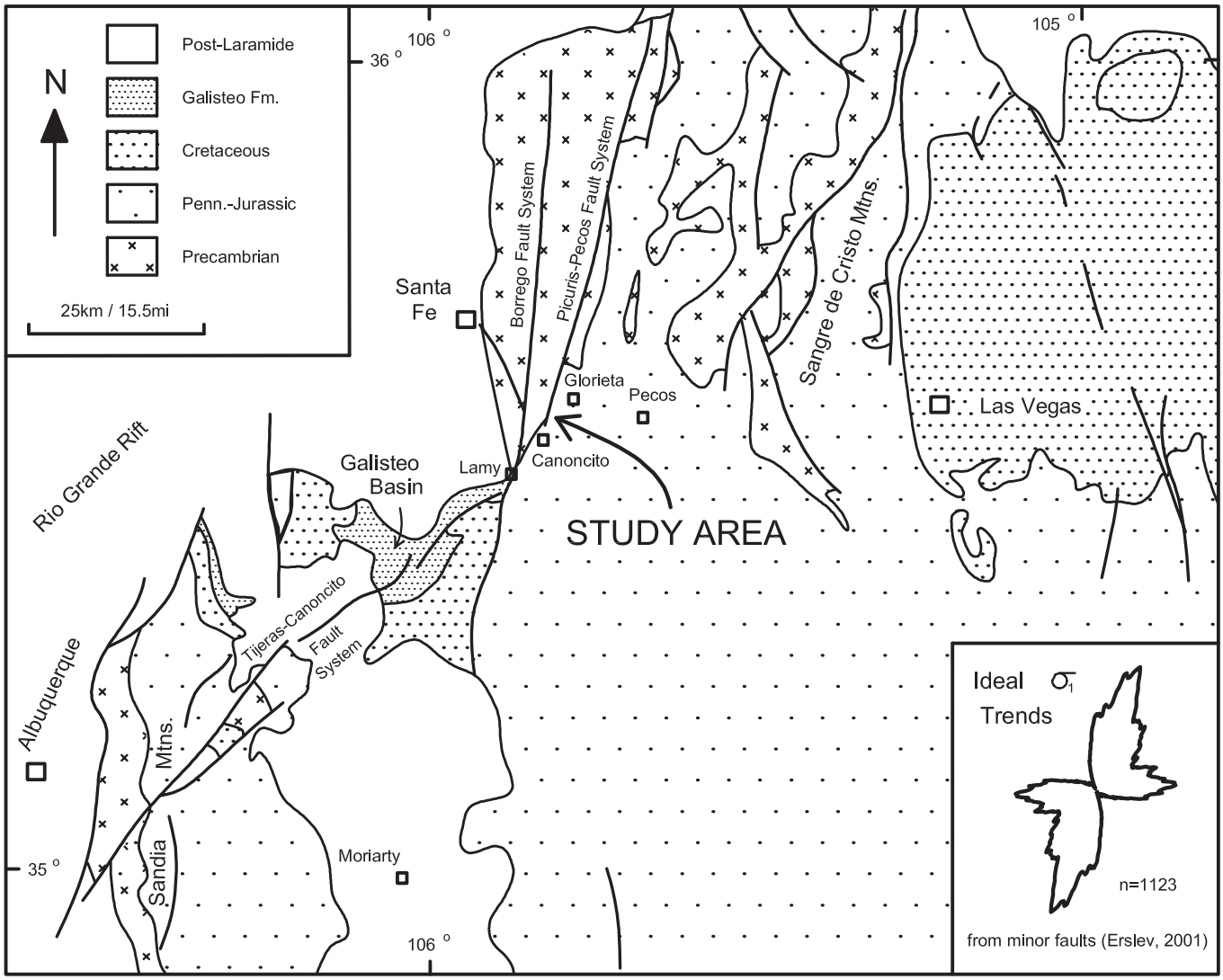


FIGURE 1. Regional map of north-central New Mexico and the southern Sangre de Cristo Mountains with an inset rose diagram of ideal sigma 1 orientations from Erslev (2001).

recording a clear post-Laramide signature. However, a larger pre-rift offset is clearly defined by the 37 km dextral separation between east-west-striking belts of alternating metasedimentary and granitic rocks with distinctive, correlative ductile folds of Proterozoic age (Montgomery, 1963). Grambling et al. (1989) determined relatively uniform metamorphic equilibration conditions of 3.5-4.5 kb and 500°C in Proterozoic rocks from exposures on both sides of the fault, indicating that the Picuris-Pecos fault system was dominated by strike slip, not dip slip. Montgomery (1963) and Bauer (1988) reported continuous folding in the metasedimentary rocks of the Picuris Mountains and inferred that the apparent ductile nature of this folding indicated slip during late Proterozoic metamorphic conditions. Karlstrom and Daniel (1993) contested the nature of this deformation, however, saying that the folding may have been generated by distributed brittle deformation. They attributed the major strike slip to the Laramide orogeny because they inferred that most of the region's brittle deformation occurred during the Laramide.

In the southern exposure of the Picuris-Pecos fault system (Fig. 1), Precambrian granitic and metasedimentary rocks are juxtaposed across the fault or are in fault contact with Paleozoic strata. Montgomery (1963) reported that local zones of indurated brecciation form large, north-striking ribs that stand above the local topography and are located up to a kilometer away from fault contacts between Paleozoic and Precambrian lithologies. At the southern end of Precambrian exposure between Glorieta and Cañoncito just northwest of Interstate I-25 (Fig. 2), north-striking zones of brecciated granitic rocks have been mapped by Budding (1972) and Ilg et al. (1997), who show the contact between Paleozoic sedimentary strata and crystalline rocks as a high-angle, N20E-striking fault.

To the south of I-25, an area also currently being studied for this project but not reported upon here, the Picuris-Pecos fault system is expressed as an area of complicated faulting and folding (Booth, 1976; Ilg et al., 1997). Galisteo Creek covers an area that has been suggested as the location of a large Laramide strike-slip fault. Baltz and Myers (1999) contested this, however, stating the following.

"Booth (1976) showed that, in at least one place, steeply dipping beds of Triassic and Jurassic rocks exposed on terrace margins on opposite sides of Galisteo Creek project into each other along strike. Therefore, it is unlikely that a fault with major strike-slip components exists beneath the valley of Galisteo Creek."

LITHOLOGIES EXPOSED IN DEER CREEK CANYON

Deer Creek Canyon, located a few kilometers northeast of Cañoncito and just northwest of I-25, provides easy access to the Deer Creek fault, which defines the southern-most extension of basement exposures along the Picuris-Pecos fault system (Figs. 2, 3). Excellent exposures of Paleozoic sedimentary strata and ductilely-deformed Precambrian basement rocks are separated by a spectacular cataclastic zone dominated by brecciated Precambrian granitic gneisses (Budding, 1972; Ilg et al., 1997).

Deer Creek intersects I-25 within the Permian Sangre de Cristo Formation, which consists of interbedded, reddish-brown to purplish mudstones, shales, arkosic sandstones and conglomerates. The Sangre de Cristo Formation includes continental non-marine clastic sediments that were deposited in a fluvial-deltaic system (Baltz and Myers, 1999). Bedding dips steepen from 10° to 37° as the Picuris-Pecos fault system is approached from the southeast. Minor thrust and strike-slip faults record two stages of horizontal shortening. Thrust and strike-slip faults indicate an early, probably Laramide, east-west shortening and are cut by strike-slip and normal faults indicating a later, possibly Rio Grande rift-related, transtensional deformation characterized by both east-west extension and north-south shortening (see inset rose diagram of ideal compression directions in Fig. 1 from Erslev, 2001).

The next unit to the northwest in Deer Creek Canyon was mapped as the Pennsylvanian Madera Formation by Budding (1972) and Ilg et al. (1997). However, the stratigraphy of these limestone-dominated strata is more complicated in that they locally include basal Mississippian limestone, which will be discussed later (Ulmer and Laury, 1984; Baltz and Myers, 1999; D. Ulmer-Scholle, personal communication, 3/04). The dominant Pennsylvanian lithologies consist of alternating layers of gray crystalline limestone, gray fossiliferous limestone, yellow to brown, medium- to coarse-grained arkose and quartz arenite, and gray, green, maroon and brown shales. Some fossiliferous limestone and arkose beds near but not at the base of the sequence contain small (1-5 mm) angular grains of brick-red microcline that resemble the microcline in the adjoining crystalline rocks.

The limestone-dominated sequence has highly-variable bedding dips. On average, dips increase to the northwest, following the pattern established by the Sangre de Cristo Formation. Stereonet plots (Fig. 2) of bedding orientations indicate south-plunging fold axes, indicating that deeper structural levels are exposed to the north. Along Deer Creek, an oblique, asymmetric anticline with a northerly trend (Figs. 2, 3, 4) contains nearly flat-lying and even west-dipping upright strata in close proximity to the crystalline rocks. Just north of the area where Deer Creek intersects the breccia-limestone contact, Paleozoic strata immediately adjacent to the crystalline rocks dip as little as 17° to the southeast (Figs. 2, 4).

The crystalline rocks west of the limestone-dominated sequence consist of fully lithified crush breccias and protocataclasites of granitic gneiss (here abbreviated as breccias) with irregular enclaves of mafic rocks, granitic gneiss and attenuated quartz veins. These brittlely-deformed rocks grade into less cataclasized areas of granitic gneiss to the west. Bright brick-red microcline is the dominant feldspar in the granitic units. The Precambrian granitic gneisses have high-angle (>68°), variably-developed foliations with ductile fabrics including microcline augen and quartz commonly displaying S-C fabrics. The gneissic rocks are cross-cut by brittle breccia zones and faults that generally increase in frequency as the Paleozoic strata are approached.

The granitic gneisses grade into indurated crush breccias and cataclasites that follow the trend of the Picuris-Pecos fault system (Ilg et al., 1997) and form rounded, resistant outcrops rising up to 50 m above Deer Creek. The cataclastic zone adjacent to the contact is as wide as 300 m and commonly anastomoses, with subsidiary zones wrapping around domains of less deformed gra-

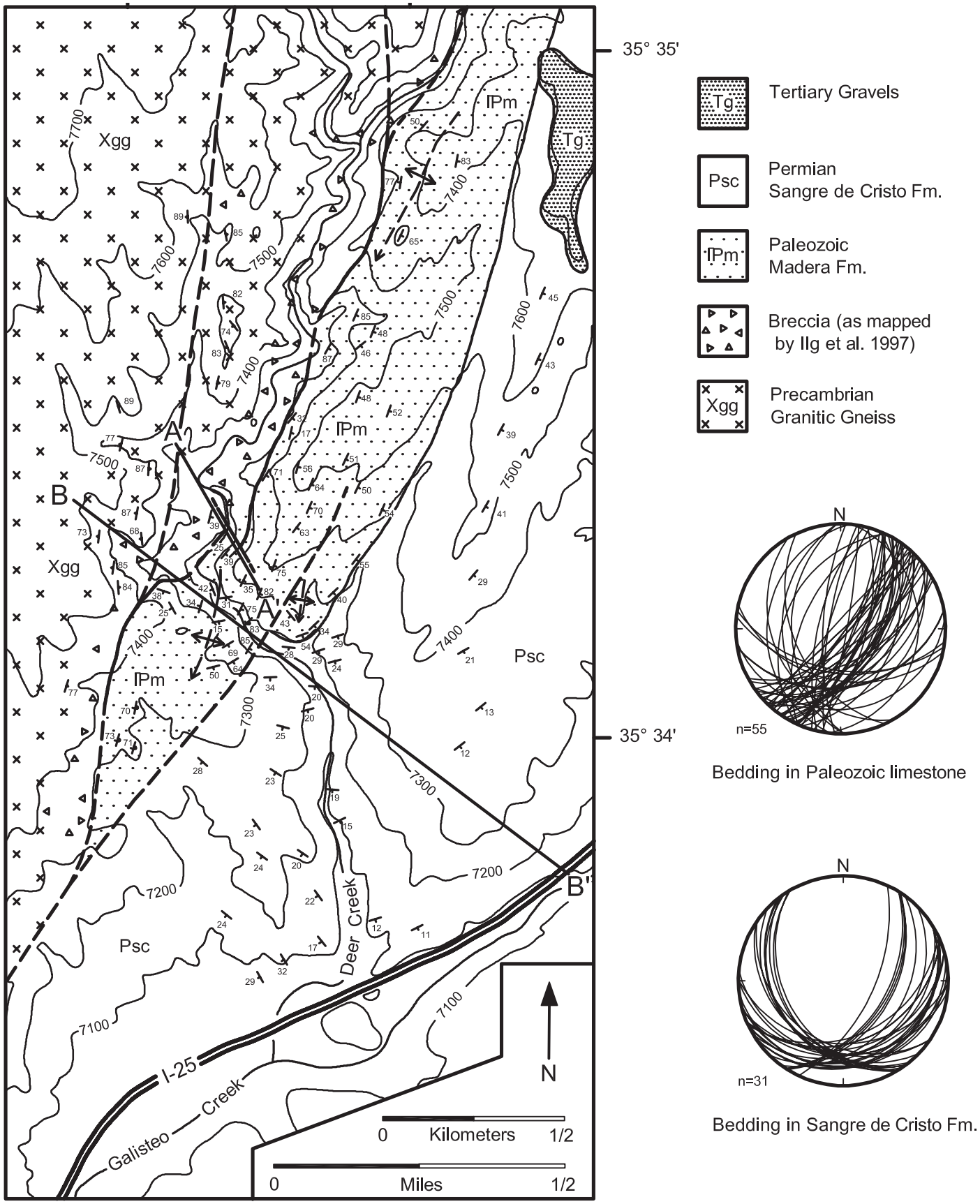


FIGURE 2. Local geologic map of Deer Creek Canyon from the Glorieta 7.5' geologic quadrangle map (Ilg et al. 1997) with slightly modified contacts. New bedding and foliation orientations are plotted on the map and in the inset stereonets.

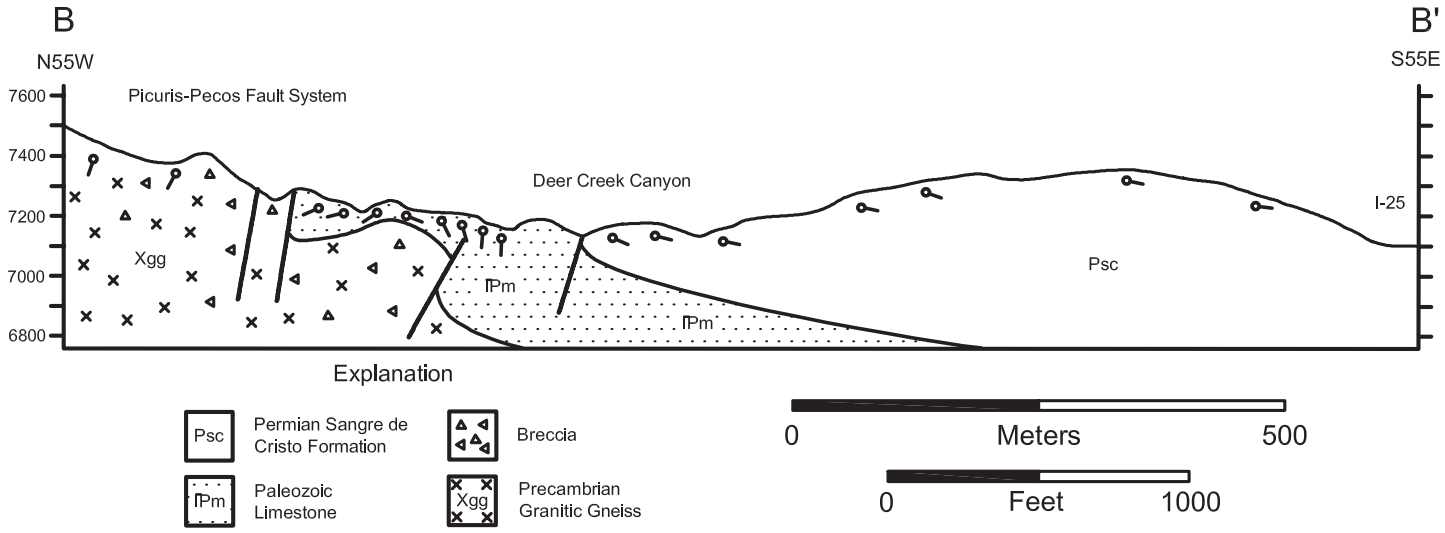


FIGURE 3. Cross-section B-B' paralleling Deer Creek Canyon (see line of section in Fig. 2). Note the more uniformly tilted bedding in the Sangre de Cristo Formation relative to the folded and faulted Pennsylvanian Madera (?) Formation.

nitic gneiss. Fragments of granitic gneiss within breccias can be up to car-sized blocks. Foliation directions in the gneissic clasts are highly variable, with offset clasts commonly showing both sinistral and dextral separations, but no ductile drag on clast margins. Some of these coherent breccia exposures are cut by narrow faults with cm-wide zones of unlithified gouge that clearly were generated by later brittle deformation.

Quartz veins, locally with large, pegmatitic brick-red microcline, form coherent yet attenuated bands within the breccia. Their brecciated textures, both in outcrop and in thin section (Fig. 5a, b), show that the veins have experienced penetrative cataclasis along with the granitic breccias. Mafic enclaves within the breccias locally show a thorough mixing of dark green mafic rock fragments with clasts of brick-red microcline and quartz.

In thin section, granitic breccia clasts generally show the clear ductile fabrics of the granitic gneisses (Fig. 5a). These angular clasts are surrounded by well- recrystallized cataclasite with no evidence of mm-scale vugs or open space fillings. Mineralogically, the granitic breccias are dominated by tartan-twinned microcline, plagioclase, quartz and chlorite or biotite. The mafic minerals in most breccia samples are dominated by relatively clean books of chlorite in apparent equilibrium with cataclasized microcline and strained quartz. Two thin sections contain slightly deformed sheets and smaller, planar laths of brown biotite showing only minor retrogression to chlorite. Thin sections of green, mafic, brecciated rocks show pervasive secondary chlorite overprinting diabasic textures. The felted plagioclase laths appear to be altered to fine-grained white mica aggregates that are commonly surrounded by clear, probably albitic plagioclase. Again, no evidence of mm-scale vugs or open space fillings was seen in the 10 thin sections of breccia that were examined. One thin section from an outcrop several meters from the Paleozoic sedimentary rocks showed younger fractures filled with very fine cataclasite and microcline partially-altered to clay minerals.

UPRIGHT, LOW-ANGLE CONTACTS BETWEEN THE PALEOZOIC SEDIMENTARY SEQUENCE AND THE CRYSTALLINE ROCKS

Montgomery (1963) and Sutherland (1963) indicated that the linear trace of the southern Picuris-Pecos fault system was due to the near-vertical dip of the Phanerozoic faults separating the crystalline rocks from the Paleozoic strata. As a result, we expected the linear contact between the crystalline and Paleozoic rocks in Deer Creek Canyon to be a high-angle fault, with the Paleozoic beds increasing in dip toward the fault. This relationship is visible in several areas along the contact, but in several places, carbonate strata overly crystalline rocks with shallow eastward dips (32°, 39°, and 25° at localities T1, T2 and IV in Fig. 4). In these areas, the basal limestone is separated from indurated breccias by a zone of shale, grus and/or green-grey altered (?) basement rocks.

Two of these poorly indurated intervals were excavated at locations T1 and T2 (Fig. 4), which are summarized in detail by Figs. 6 and 7. At locality T1 (Fig. 6), the overlying limestone contains clastic detritus (including pink microcline) and fossils (including fenestrate bryozoans and crinoids) indicating a Pennsylvanian age (D. Ulmer-Scholle, personal commun., 3/04). The limited diversity of the fauna and the lack of brachiopods and coarser clastic material suggest a middle Pennsylvanian age for the basal limestone (D. Ulmer-Scholle, personal commun., 3/04). Underlying black and green shales contain nodules cemented by carbonate. A thin section of a nodule in the shale of locality T1 revealed a chloritic matrix surrounding thoroughly altered fragments of metamorphic rock with aligned, lensoidal quartz grains and no remaining altered microcline. A sharp, moderately discordant contact separates nodule-rich shales and granitic grus, which then grades into indurated breccia. The feldspathic grus itself shows excellent cataclastic and brecciated fabrics, indicating that

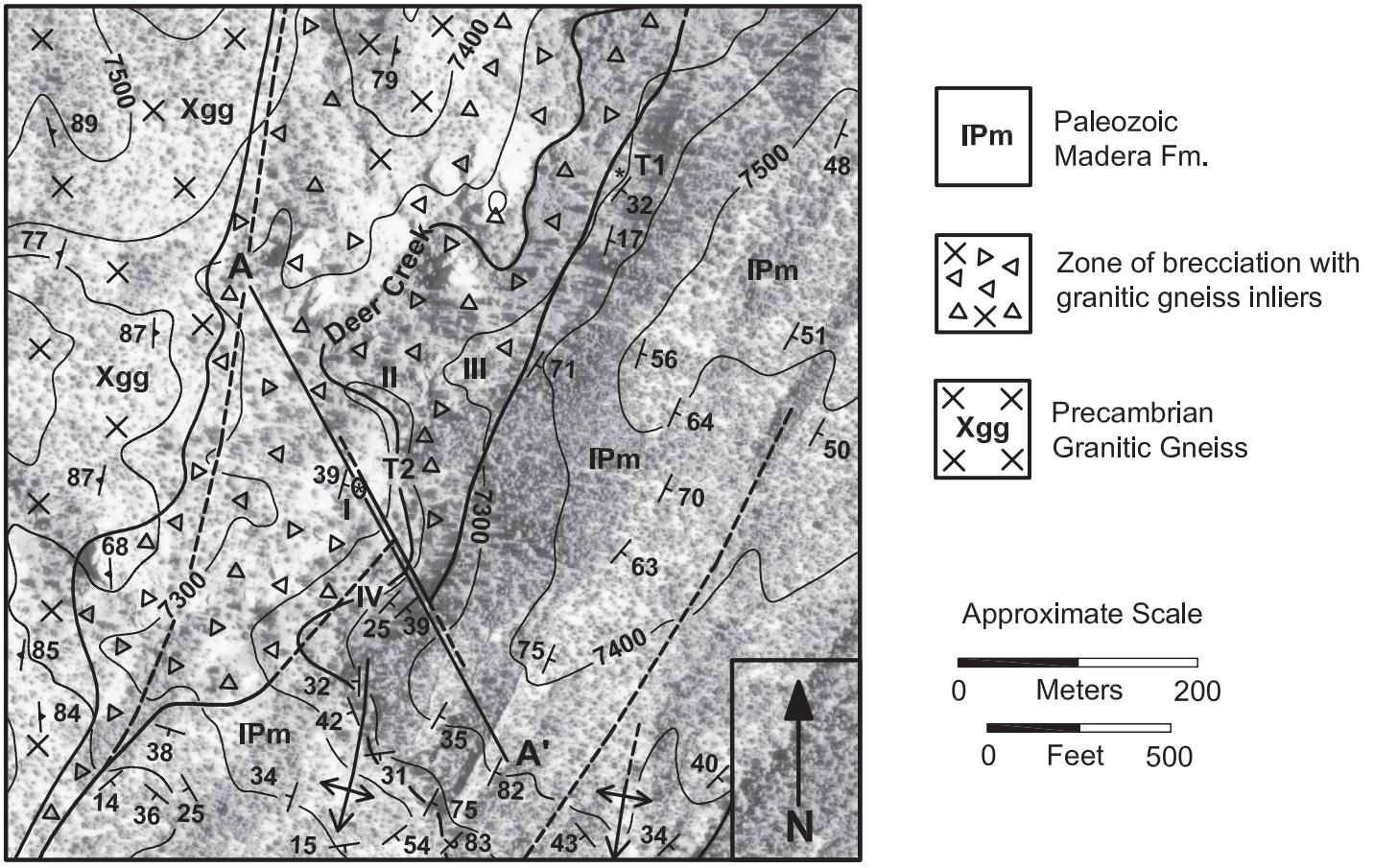


FIGURE 4. Aerial photo of a section of Deer Creek Canyon (location indicated as the inset box in Fig. 2) showing the Paleozoic and crystalline rock contacts. The photo is not rectified so the locations of the topographic contours are approximate. Location T1 is the keel-like limestone inlier on breccia; locations I, II and III are areas containing tabular clastic carbonate dikes; location IV is the bedded limestone southeast and across the canyon from the limestone keel. T1 and T2 refer to the trenches excavated for stratigraphic profiles of the contact between the Paleozoic and Precambrian rocks (see Figs. 6, 7).

grus formation post-dated the brittle deformation responsible for the brecciated rocks.

At locality T2 on a ridge crest just west of Deer Creek, an isolated keel-like slab of limestone overlies crystalline breccia (Figs. 4, 7, 8). The limestone contains relict patches of brown-weathering dolomite, de-dolomite textures including pervasive matrix recrystallization to microspar calcite, brachiopod spines, thick-walled ostracod fragments (locally replaced by chert) and possible replacements of evaporite minerals. In combination, these are highly diagnostic of the Mississippian section of the Sangre de Cristo Mountains, most probably the Espiritu Santo Formation or Macho member of the Tererro Formation (Scholle and Ulmer-Scholle, 2003; D. Ulmer-Scholle, personal communication, 3/04). Bedding-parallel stylolites, abundant calcite twins, and calcite veins cut the basal limestone but do not, in the samples that have been thin sectioned, brecciate the rocks into disjointed clasts.

On the southern, eastern and western sides of this sedimentary inlier at locality T2, the stylolitic limestone bedding is separated from the underlying breccia by a thin zone of poorly indurated grus on top of grey-green, feldspar-poor rock (Fig. 7). At 40 cm depth below the limestone, traces of pink feldspar are first seen, and by 67 cm depth, the brick-red microcline of the indurated, brecciated rocks is visible.

Along the northern side of the outcrop, the bedding is folded into a monoclinal syncline that is bounded by an unconsolidated gouge zone cutting the underlying crystalline breccia (Fig. 4). If the bedding orientation (N15E-39SE) is extended to the southeast across Deer Creek parallel to this bounding fault, it intersects below Pennsylvanian limestone outcrops of the same general attitude on the eastern side of the stream valley (Fig. 8). Unfortunately, nowhere across Deer Creek at this locality are the contacts between the Pennsylvanian, Mississippian and crystalline rocks exposed due to alluvial sediments and talus in the creek canyon.

Alternatively, it has been suggested that a major fault in the stream valley offsets the limestones, juxtaposing the Mississippian limestone at the keel with the Pennsylvanian limestone on the southeast side of the valley near the location of the "?" in Fig. 8. The lack of exposure in the valley suggests that this is a viable explanation but two observations make us question this interpretation. Firstly, the northwest-striking fault bounding the northeastern side of the keel (Fig. 4) is well exposed on both sides

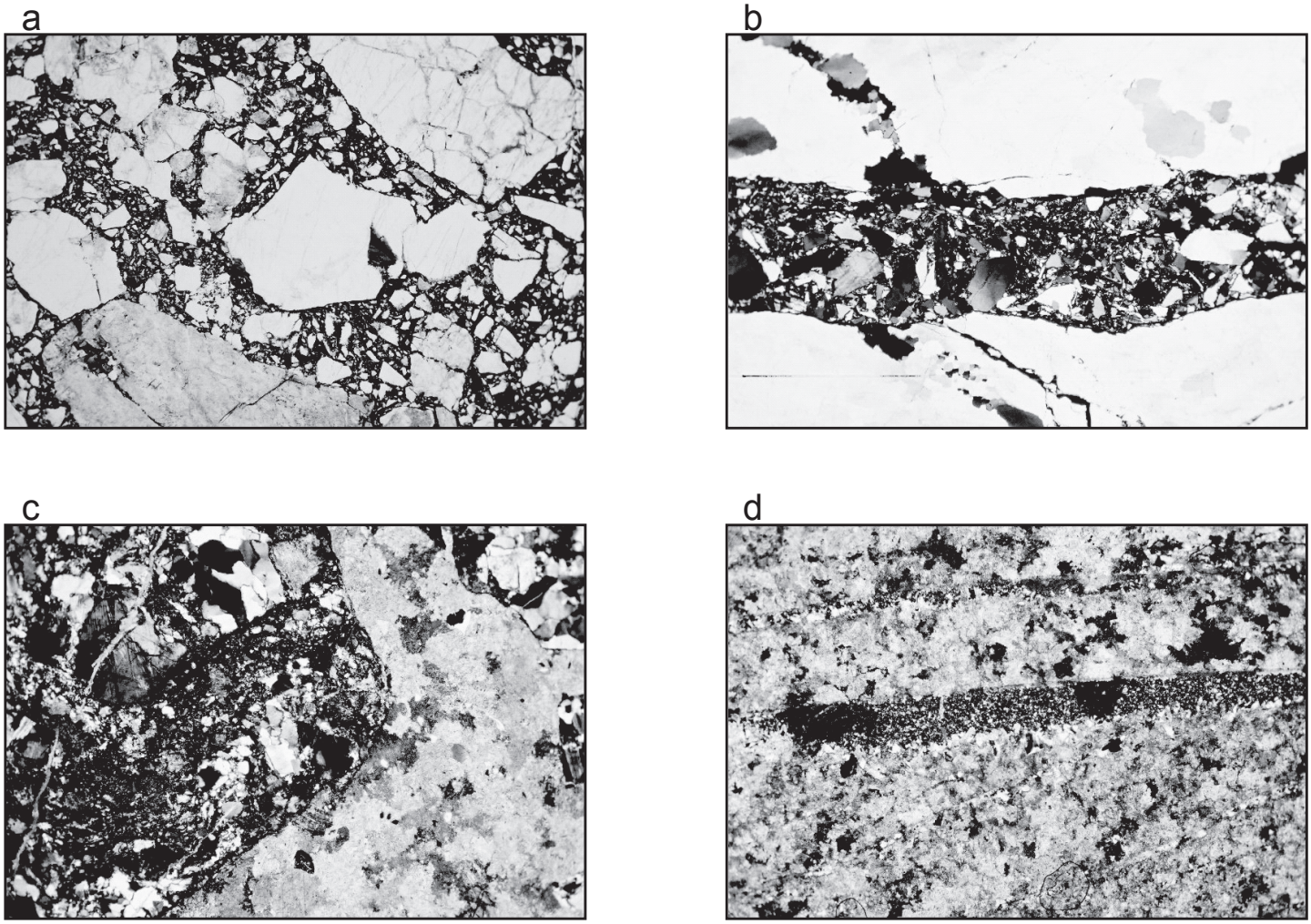


FIGURE 5. Cross-polarized photomicrographs of a) granitic breccia with biotite in the fine grained cataclastic matrix (field of view = 4.4 mm), b) brecciated quartz vein (field of view = 10.9 mm), c) granitic breccia with domains of gneiss and cataclasite cross-cut by a clastic carbonate dike (field of view = 4.4 mm), and d) blades of chert partially replaced by calcite from within a clastic carbonate dike (field of view = 1.75 mm).

of the Deer Creek valley. Secondly, if there was a major Phanerozoic fault in the valley, it should be well exposed in the breccia on strike to the NNE where the stream valley arcs sharply northwest. More detailed mapping is underway to resolve this question.

These moderate-angle, limestone-over-breccia contacts can be explained as either faults or nonconformities between the Paleozoic carbonate sequence and brecciated Precambrian granitic gneiss (e.g., Fig. 8). The younger-over-older stratigraphic relationships and the low dip angles indicate that if the contacts are faults, they must be normal faults. The lack of fault gouge, slickensides and the apparent truncation of the Mississippian limestone keel by the NW-striking fault suggests that any faulting might need to have been when the rocks were unconsolidated, prior to current Rio Grande rifting. But the lack of other examples of older low-angle normal faulting in the area makes this interpretation somewhat suspect in our eyes.

Alternatively, the contacts at T1 and T2 can be interpreted as nonconformities where sedimentary rocks were laid down on Precambrian basement. This interpretation explains the younger-over-older relationships and the pervasive alteration and grus formation at the contacts. Similar nonconformable contacts between brecciated basement rocks and Paleozoic limestone have been mapped in the western Santa Fe Range by Adam Read (personal communication, 3/04). Minor discordances within the trenched sections can be attributed to original topography on the basement surface and subsequent shear related to tilting during the Laramide orogeny. The fact that the basal units in the keel are Mississippian in age indicates a pre-Ancestral Rocky Mountain age for this nonconformity, which in turn indicates that the major brecciation of the crystalline rocks is most likely Precambrian in age.

The different age of the overlying section at localities T1 (Pennsylvanian) and T2 (Mississippian) provides an added complexity that needs to be addressed as well as the thickness of the carbonate strata. Ten km to the NNE and one km east of the Picuris-Pecos fault, Moench and Robertson (1980) mapped major lateral changes in the Paleozoic rocks nonconformably overlying the Precambrian basement. South of a NNW-striking cross fault, Pennsylvanian undifferentiated strata overlie the basement. North of this fault, the Pennsylvanian undifferentiated strata wedge out

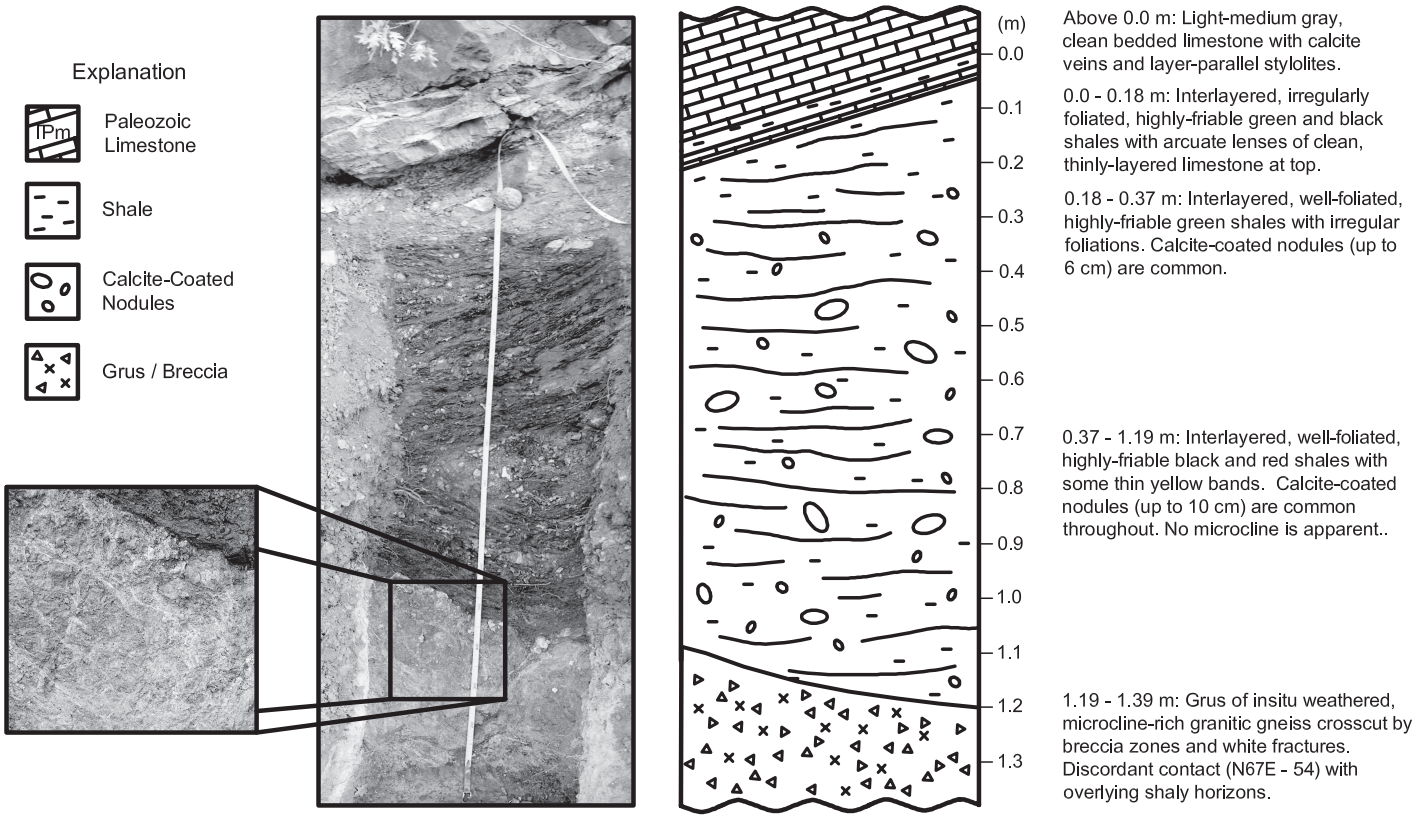


FIGURE 6. Stratigraphic column of trench T1 (see Fig. 4 for location). The stratigraphic profile in the photograph is inclined 44° and trends N55W. Grus formed by weathering of brecciated granitic gneiss lies discordantly below ~1 meter of shales which grade upward into limestone.

over a distance of one km, at which point Permian Sangre de Cristo strata overlies the basement. Two more kilometers to the northeast, Mississippian Terrero and Espiritu Santo Formations overlie the basement, and are themselves overlain by the Permian Sangre de Cristo Formation. While it has been argued that this mapping may be in error, such radical misidentification of units seems improbable, especially considering the lithologic contrasts between the Sangre de Cristo and older formations. Alternatively, the age differences between the units immediately overlying basement may be due to local uplift resulting from Ancestral Rocky Mountain tectonism analogous to the relationships documented by Beck and Chapin (1994) in the Joyita Hills.

In Deer Creek Canyon, an excellent candidate for a fault to uplift the northern area (T1) and downwarp the southern area (T2 at the keel) is the northwest-striking fault zone bounding the northern side of the keel (Fig. 4). Interestingly enough, this fault is at a high angle to the bedding in the Phanerozoic section and displaces the basement-cover contact markedly yet appears to be truncated by resistant ridges of limestone just below the Sangre de Cristo Formation (Fig. 4). These observations suggest that this is an Ancestral Rocky Mountain fault analogous to that mapped by Beck and Chapin (1994). In addition, if this tentative hypothesis is correct, the NW-striking fault's continuity across the breccia-Paleozoic limestone contact provides a pin line that doesn't allow major Laramide strike slip on this contact. The sequence of deformation required by this hypothesis is shown diagrammatically in Fig. 9.

LIMESTONE PODS AND BANDS WITHIN THE BRECCIAS: CLASTIC DIKES?

Breccia outcrops were examined carefully for Paleozoic rock fragments as a means of determining whether they contained Phanerozoic lithologies and thus were Phanerozoic in age. On either side of Deer Creek, narrow (up to 30 cm), tabular and irregular calcite-rich bands were observed at localities I, II and III in Fig. 4. Their contacts with the crystalline breccias are sharp; the largest carbonate band, 25 meters long, strikes NW-SE with a high-angle dip. Cross-cutting relationships with the crystalline rock fragments, which commonly contain individual cataclastic zones, indicate that these carbonate bands are younger features, as does the microcline alteration to clay minerals on some contacts.

Three lenticular pods of carbonate approximately 10 to 20 cm in length were exposed in the trail next to Deer Creek at locality II (Fig. 4). These pods macroscopically resemble clasts in a fault breccia. Adjoining outcrops, however, reveal complex networks of thin, commonly tabular bands of fine grained carbonate cut by carbonate veins. A thin section of one of the pods revealed apparent injection features, including clasts of granitic breccia surrounded by recrystallized microspar limestone, and no evidence of bedding. Clear de-dolomite textures strongly suggest a Mis-

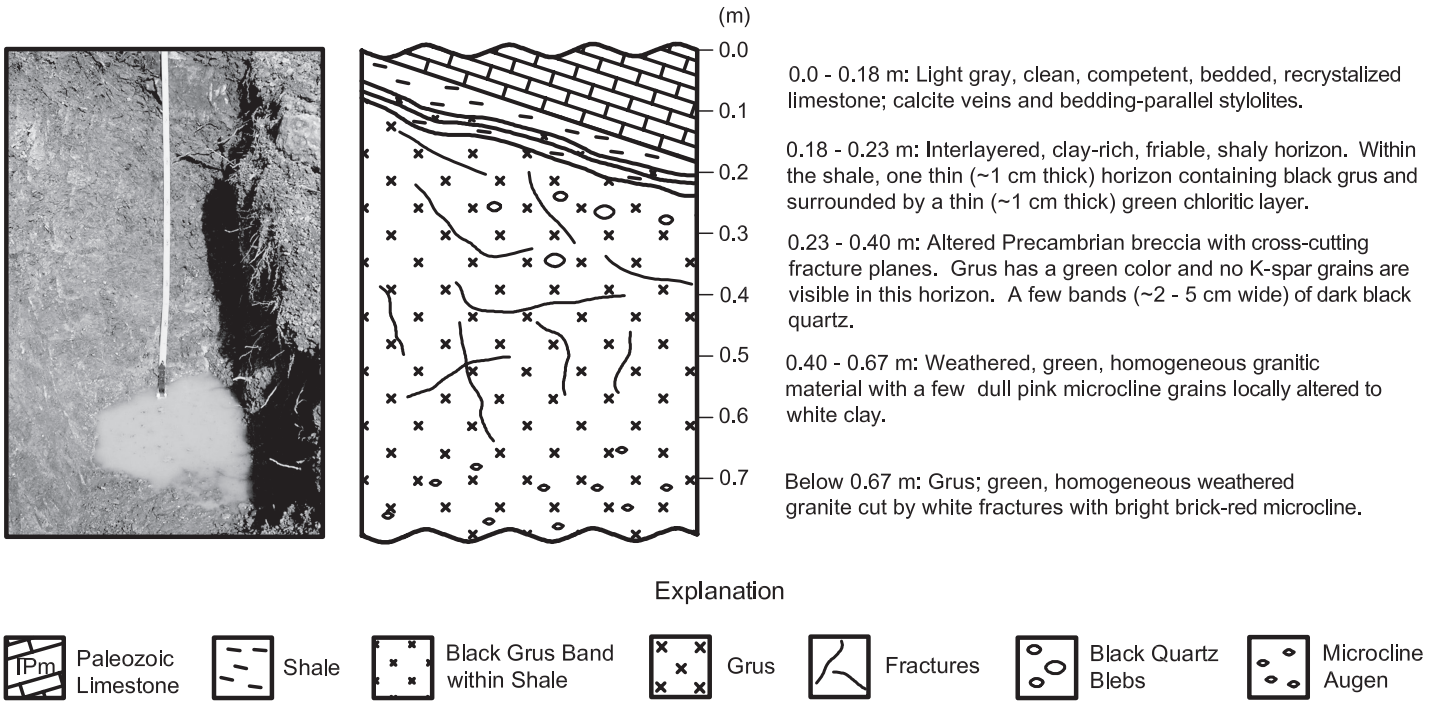


FIGURE 7. Stratigraphic column of trench T2 (see Fig. 4 for location) immediately northwest of the limestone keel. The stratigraphic profile in the photograph is inclined 48° and trends approximately S40W. The contact between limestone and weathered crystalline rocks is sharp, with a thin (~12 - 15 cm) shaly horizon. The fractured grus layer only shows brick-red microcline near the base of the trench.

issippian age for the microspar limestone pods, which strongly resemble the Mississippian rocks at the keel (D. Ulmer-Scholle, personal commun., 3/04).

Thin sections of the carbonate pods and bands show fragments of crystalline rock, which are commonly composites of Precambrian gneiss cut by cataclastic bands (Fig. 5c). These breccia clasts are truncated by recrystallized microspar carbonate similar in texture to that seen in the basal carbonate units. Regionally, this recrystallization occurred in the mid-Mississippian due to the influx of fresh water into a hypersaline carbonate sequence (D. Ulmer-Scholle, personal communication, 3/04). The lack of brecciated limestone fragments in the carbonate bands and the stringers of sand- to silt-sized silicic clasts suggest that the carbonate bands were injected as fine-grained sediment. Brachiopod and ostracod shell fragments confirm a Mississippian age for the material in the pods and bands (D. Ulmer-Scholle, personal commun., 3/04). Cross-cutting stylolites, chert-replaced brachiopod shell fragments and calcite veins indicate limited post-

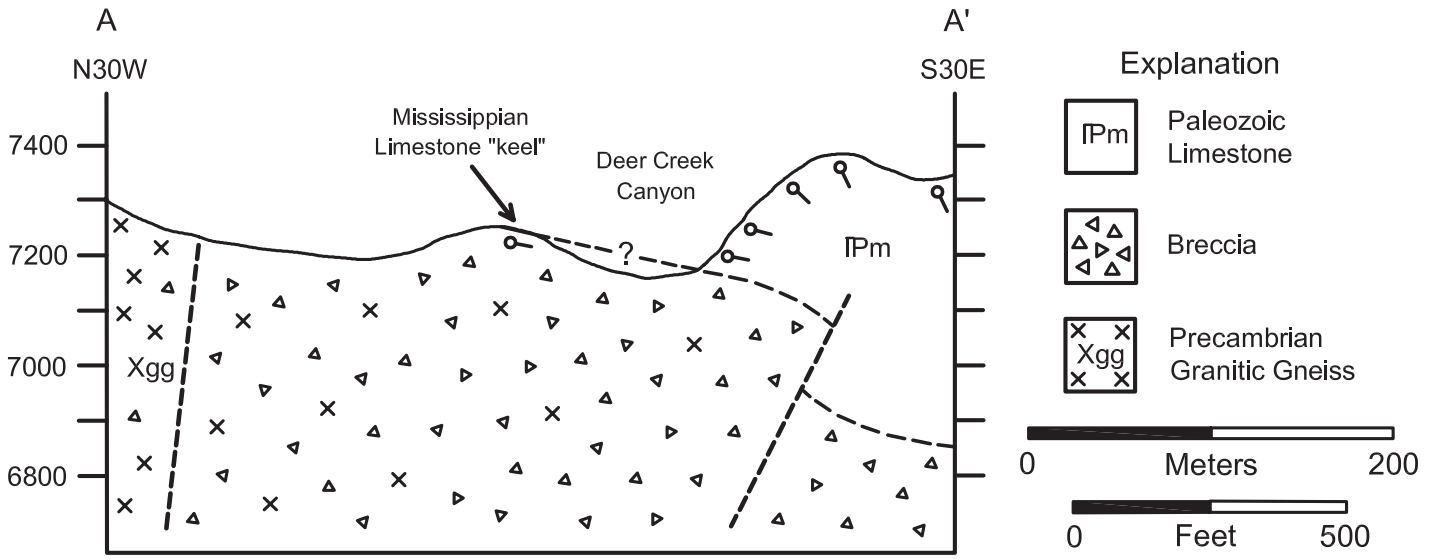


FIGURE 8. Section A-A' crossing Deer Creek Canyon through the limestone keel. Note how the dip of bedding in the keel can be extrapolated across the canyon to limestone exposures immediately to the southeast.

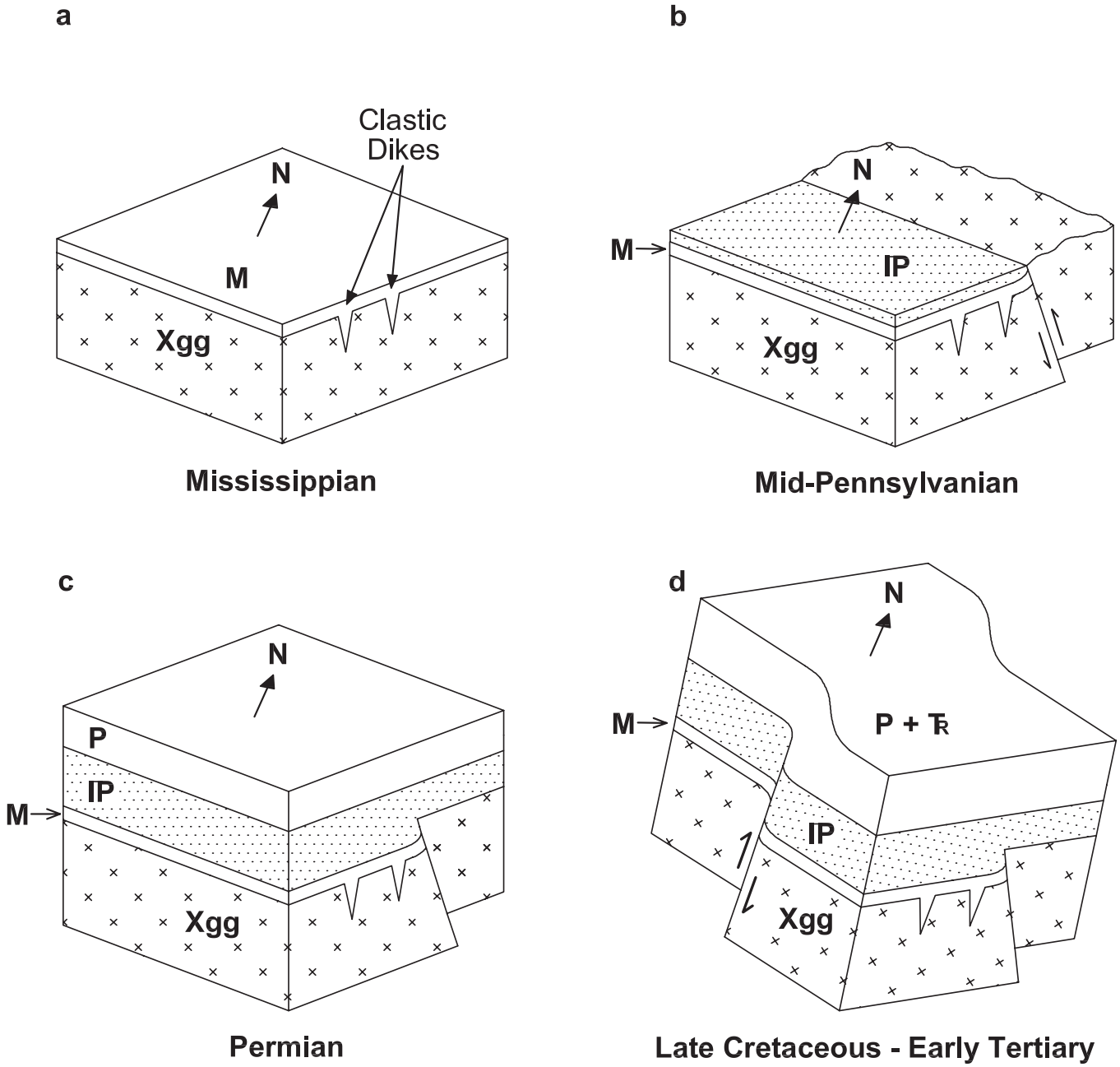


FIGURE 9. Schematic geologic hypothesis for contact relationships in Deer Creek Canyon. a) Deposition of Mississippian sediments on Precambrian gneisses and breccias and intrusion of clastic dikes. b) Early Pennsylvanian syndepositional faulting on northwest-striking faults with erosion of the hanging wall. c) Permian Sangre de Cristo deposition across the Pennsylvanian fault. d) Laramide faulting, folding and regional tilting to the east about a N20E axis.

recrystallization deformation. The carbonate pods and bands, while deformed, have not been disjointed to the same degree as the surrounding crystalline breccias and gneisses.

These carbonate pods and bands can be interpreted as fault fragments or as clastic dikes. While the aspect ratio of the fragments at locality II is suggestive of a fault origin, the 25 X 1 meter aspect ratio of the major carbonate band at locality I and its NW-SE strike makes it difficult to imagine it to be a breccia clast in a N20E-striking fault. In addition, despite careful searching in both outcrop and thin section, clear breccia fragments of limestone within limestone were not seen despite the abundance of crystalline breccia fragments. This, along with the preservation of Mississippian recrystallization fabrics and fossils, suggests that the limestone was injected as limey sediment into open fissures during the Mississippian. The proximity of the bands to the basal Mississippian carbonate layers, which are upright and dipping away from the exposures, indicates that these bands probably represent "Neptunian" clastic dikes injected downward from above. The pods of

carbonate at locality II that resemble fault breccia fragments may have been injected as a clastic dike and then were shaped into fault lozenges by subsequent Phanerozoic faulting.

DISCUSSION AND IMPLICATIONS FOR THE AGE OF THE PICURIS-PECOS FAULT

The field and petrographic relationships from Deer Creek Canyon provide strong evidence for major Precambrian faulting along the Picuris-Pecos fault system. The unusual induration and the apparent low-grade metamorphic mineral assemblages of the breccias combined with nonconformable relationships and cross-cutting clastic dikes all indicate a pre-Mississippian age for brecciation.

The crush breccias and protocataclasites in Deer Creek Canyon are remarkably thick and resistant to erosion. This conclusion is further supported by the unusually indurated, nearly void-free nature of the brecciated rocks, which suggests that elevated pressures during brittle deformation allowed the collapse of void spaces that formed during high strain rate brecciation before they were filled. An origin during low-grade metamorphism is further indicated by the coexistence of relatively clean books of chlorite and biotite with unaltered microcline in the breccias.

The only comparable thickness of brecciated rocks attributed to Laramide deformation that we have seen in the Rocky Mountains is in the hanging wall of the Laramide Williams Range Thrust along the western flank of the Front Range in central Colorado (Kellogg, 1999). In contrast to the breccias along Deer Creek, these breccias are not resistant to erosion as they typically underlie grassy meadows and are highly susceptible to Holocene landsliding (Kellogg, 1999). Other Laramide basement fault zones in the Front Range, Teton Range, Owl Creek Mountains, Wind River Range, Bighorn Mountains, Beartooth Mountains, Madison Range and San Juan Mountains are characterized by extensive alteration of feldspars to clay (Erslev et al., 1988; Yonkee and Mitra, 1993; Erslev and Rogers, 1993). This alteration results in the fault zones forming topographic lows and allows them to be readily excavated with hand tools. While it is possible that Laramide breccias were locally indurated by Tertiary mineralizing fluids, one would expect those same fluids to indurate the immediately adjacent grus and shaly layers at the base of the Paleozoic limestones at Deer Creek Canyon. If these are late Paleozoic nonconformities, it is doubtful they would remain so poorly lithified during an Ancestral Rocky Mountain or Laramide brecciation event that generated fully-lithified breccias. Thus, it is with confidence that we interpret the indurated crush breccias and protocataclasites to be Precambrian in age.

These observations are reinforced by what we interpret to be nonconformable relationships between overlying Paleozoic limestones and the breccias in Deer Creek Canyon. The existence of lower angle, knife-sharp contacts between grus containing beautifully preserved brecciated fabrics and overlying limestone and shaly rocks indicates that the Paleozoic strata was laid down unconformably over pre-existing, brecciated basement.

The existence of clastic dikes composed of Mississippian limestone nearly identical in texture to that in basal Mississippian limestones provides yet another argument for a Precambrian age for the breccias. The fact that they locally crosscut the overall trend of the breccia zone provides additional insights into the age of deformation. Since the clastic dikes and the lowest Paleozoic unit exposed are Mississippian in age, then the dikes, and the breccias that they cut, predate the Ancestral Rocky Mountain orogeny as well as the Laramide orogeny.

It can be argued that the crush breccias and cataclasites in Deer Creek Canyon are unrelated to the major dextral slip along the Picuris-Pecos fault. The possibility that the major dextral strike slip occurred east or west of the Deer Creek breccias is not supported by the continuous Paleozoic strata on Glorieta Mesa to the east and the minimal separations of Precambrian rocks along basement faults (e.g., Borrego Fault) immediately to the west (Moench and Robertson, 1980). The breccias could be construed as representing a separate Precambrian event, perhaps one related to the overall east-west structural grain of the Precambrian rocks. We find this possibility unlikely considering that the breccias parallel the Picuris-Pecos system both locally (Fig. 4; Budding, 1972; Ilg et al., 1997) and regionally (Montgomery, 1963). We prefer to correlate the largest strike-slip fault in the southern Rocky Mountains with the thickest, most profoundly brecciated fault zone that we have seen in the Rockies. We do not doubt that Phanerozoic slip has occurred on the gouge-filled faults that cut both the breccias and the overlying sedimentary rocks, but their width is minimal relative to both the thickness of the indurated breccias in Deer Creek Canyon and the thickness of Laramide basement fault zones with only a few kilometers of slip (Erslev et al., 1988).

In conclusion, numerous field and petrographic relationships in Deer Creek Canyon appear to confirm the Precambrian age assigned to the major dextral slip on the Picuris-Pecos fault system by Montgomery (1953, 1963) and Baltz and Myers (1999). Relatively high temperatures of cataclasis are indicated by the breccias' mineral assemblages and lack of void space fillings. This suggests that the apparently ductile drag on the northern part of the Picuris-Pecos fault system is consistent with the brittle features and the lack of ductile drag in the southern part of the fault system if slip along the Picuris-Pecos fault system at the current level of exposure occurred near the brittle-ductile transition. Slightly higher temperatures or more ductile (e.g., quartz-rich) lithologies to the north can explain the greater amount of ductile deformation in that area. Differences in strain rate can explain both the combination of brittle fabrics with negligible open space fillings in the Deer Creek breccias and the mixture of ductile and brittle deformation along the northern Picuris-Pecos fault system (Bauer, 1988). Between high-strain-rate seismic events that generated the brecciated rocks, slower strain rates may have collapsed the voids between breccia fragments, indurating the breccias of Deer Creek Canyon and allowing ductile folding adjacent to the northern Picuris-Pecos fault system.

This conclusion has major implications to Phanerozoic and Precambrian tectonic models for the Rocky Mountains. A Precambrian age for dextral strike slip along the Picuris-Pecos fault system suggests that the parallel dextral separations indicated by aeromagnetic anomalies also occurred in the Precambrian.

This greatly restricts the amount of allowable dextral slip on north-striking faults in both the Laramide and Ancestral Rocky Mountain orogens. In many ways, this makes the reconstruction of these orogens easier because it eliminates the problem posed by the lack of evidence for major Phanerozoic dextral strike-slip faults in central Colorado (Erslev et al., 2004). The likelihood of large dextral strike slip of Proterozoic age in New Mexico raises the intriguing question of how this Proterozoic deformation was accommodated along strike as well as its age and tectonic origin. In fact, many details remain to be addressed, such as the kinematic and tectonic significance of the NW-striking Paleozoic clastic dikes and faults that appear to crosscut the Picuris-Pecos fault system. Regardless of the details yet to be defined, this research shows that the rugged exposures of the Rockies can still offer new insights into long-standing geological controversies.

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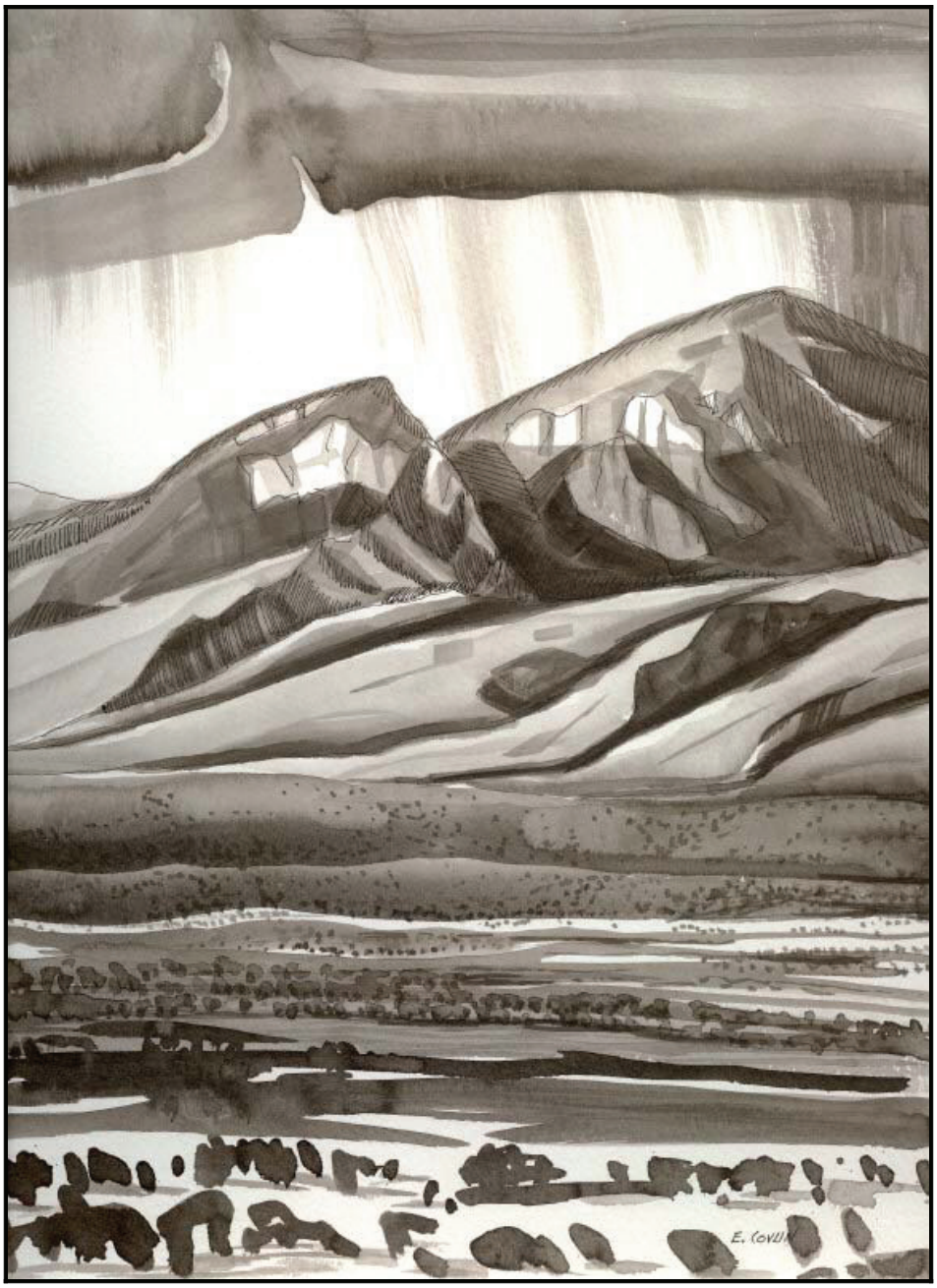
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El Salto *by Elise Covlin* *Courtesy Brian and Julie Brister*