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PROTEROZOIC ROCKS OF THE PILAR CLIFFS, PICURIS MOUNTAINS, NEW MEXICO

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Abstract.—The Cenozoic Embudo fault zone has juxtaposed the crystalline rocks of the Picuris Mountains against the Pliocene rocks of the San Luis Basin near the village of Pilar. A combination of north-down faulting and late Cenozoic erosion by the Rio Grande has produced several miles of spectacular exposures of south-dipping Paleoproterozoic rocks along the Pilar cliffs. An impressive ductile shear zone separates the Ortega Formation quartzite from the Glenwoody Formation schist. The Glenwoody Formation is composed of feldspathic quartz-muscovite and quartz-eye schist that probably represents metamorphosed, altered, phenocrystic, felsic volcanic rocks. The Ortega Formation of the Hondo Group is a remarkably clean, 1-km-thick, metamorphosed quartz arenite that is overlain by a metamorphosed siliclastic sequence of interlayered quartzites and pelitic schists of the Rinconada Formation. All supracrustal rocks have undergone a progressive ductile deformational history that involved the formation of pervasive penetrative foliations and lineations, major fold sets, and a variety of ductile shear zones. The Pilar cliffs section forms the north limb of the large, shallowly plunging, east-trending, overturned Hondo syncline. The south-dipping contact (Pilar shear zone) between the Glenwoody Formation and the overlying, upright Ortega Formation in the Pilar cliffs is a ductile shear zone preserving evidence for both early north-vergent shearing and late south-vergent shearing. The Pilar shear zone is probably not a major tectonic break, but instead is one of the south-dipping imbrication structures that are recognized in and around the Ortega Formation in northern New Mexico. In the southern Picuris Mountains, the Hondo Group section is bounded by a second south-dipping ductile shear zone (Plomo fault) along which the overturned Vadito Group has been thrust northward over the Hondo Group. The Ortega and Glenwoody Formations belong to the northeast-trending Yavapai-Mazatzal transition zone, and are part of the 1.70-1.69 Ga rhyolite-quartzite association of the Southwest that is thought to have accumulated in volcanic/sedimentary basins on juvenile, but relatively stable, continental crust. The preferred stratigraphic/structural model states that the Glenwoody Formation is the youngest Vadito Group unit exposed in the range, and was faulted out in the southern Picuris Mountains during the Mazatzal orogeny when the older Yavapai volcanogenic basement and its quartzitic cover were thrust northward at ca. 1.65 Ga as continental crust to the south collided with the Laurentian craton. Later collapse of the mountain belt (or 1.4 Ga intracontinental tectonism) resulted in south-directed movement of the Ortega Formation over the Glenwoody Formation.

GEOLOGIC SETTING OF THE PILAR CLIFFS

The southern margin of the San Luis Basin is defined structurally by the Embudo fault zone, and topographically by the Proterozoic-cored Picuris Mountains (Figs. 1, 2). To the north, west, and south of the Picuris Mountains, basement rocks are bounded by Tertiary sedimentary and volcanic rocks of the Rio Grande rift. To the east, Proterozoic rocks are juxtaposed against the Upper Paleozoic sedimentary strata of the southern Sangre de Cristo Mountains along the Picuris-Pecos fault system.

In the northwestern Picuris Mountains, at the village of Pilar, the Rio Grande bends abruptly southwestward, following the Embudo fault zone along the north flank of the Picuris Mountains into the Española Basin. The Embudo fault zone is an antithetic transfer zone that has Quaternary, northwest-down, left-oblique normal slip along multiple, sub-vertical fault strands (Kelson et al. 2004, this volume). The combination of north-down throw and down-cutting by the Rio Grande has created dramatic topographic relief between mountains and basin along NM-68. The Pilar cliffs are a near-vertical escarpment, several km long, just southwest of the village of Pilar. The 450-m-high cliffs contain a variety of Paleoproterozoic rocks, although access is problematic due to the rugged terrain and unstable scree slopes above the highway.

Due to a combination of excellent exposures, an impressive assortment of rock types, well-preserved sedimentary features, exceptionally well-developed microscopic to macroscopic structures, an extraordinary suite of large silicate porphyroblasts, and relatively easy access, the Precambrian rocks of the Picuris Mountains have long drawn a diverse cast of geologists with a variety of research interests (Just, 1937; Montgomery, 1953; Nielsen, 1972;

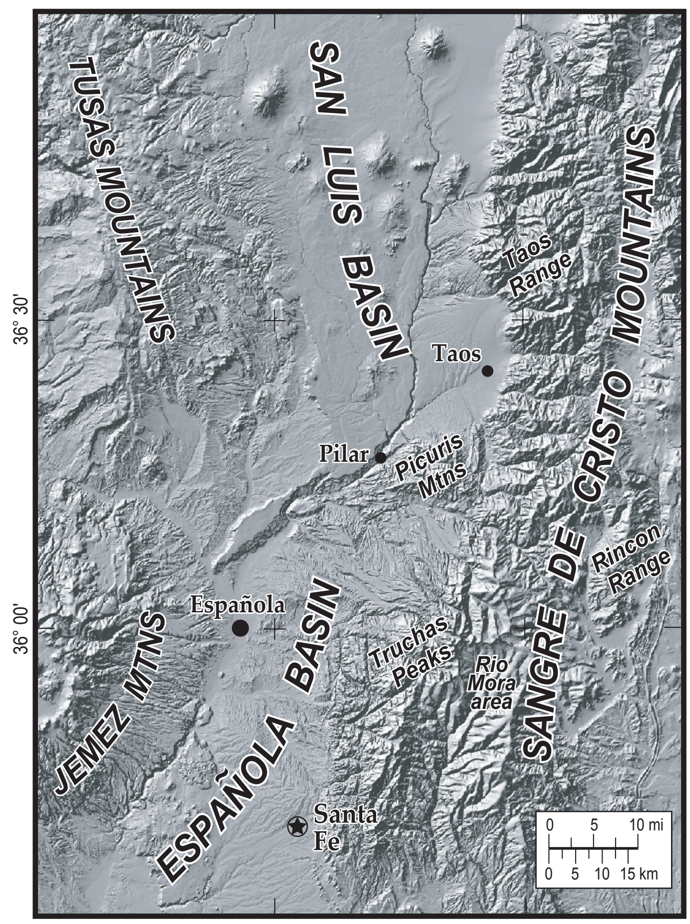

FIGURE 1. Location map of the Picuris Mountains area in north-central New Mexico.

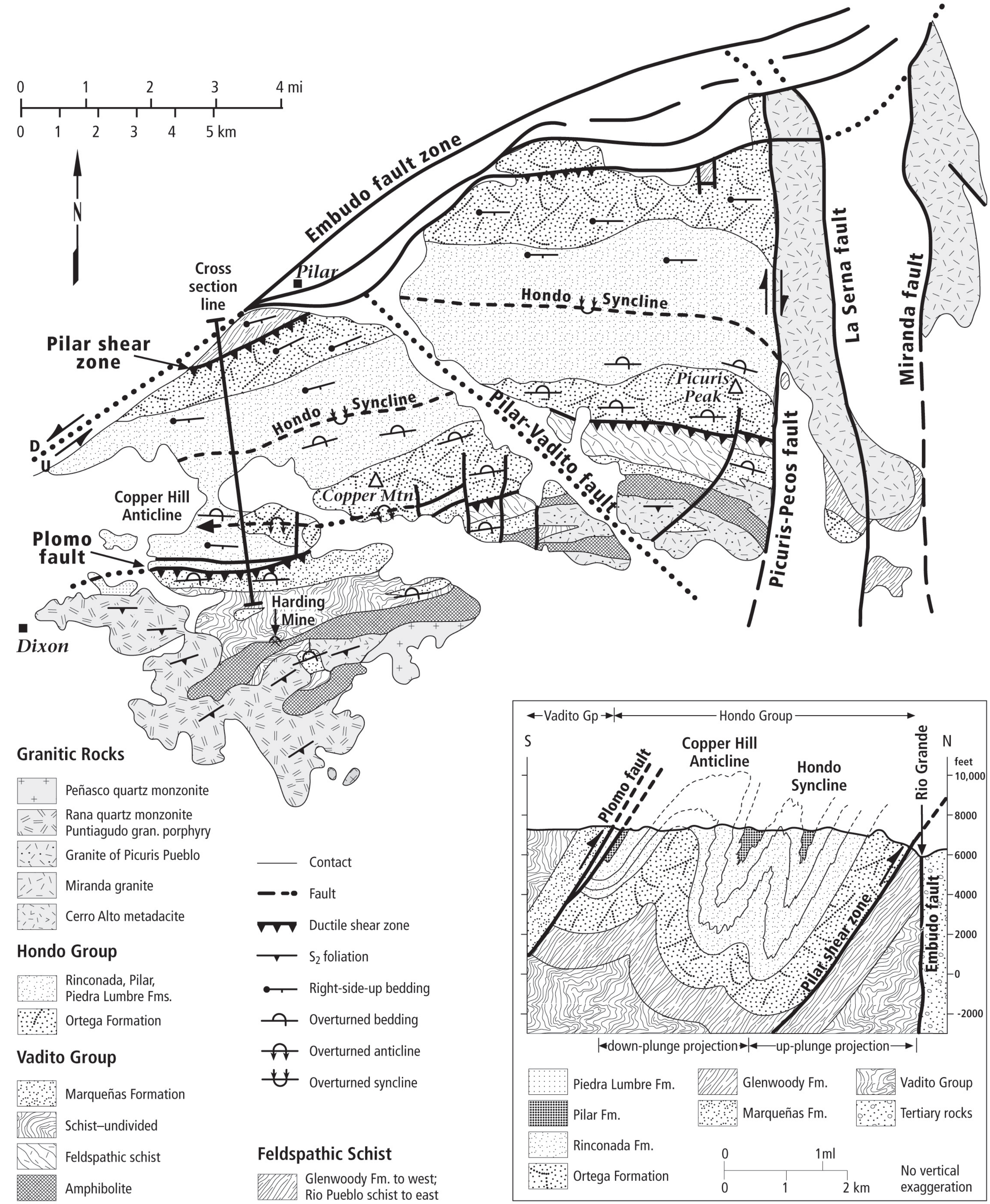

FIGURE 2. Generalized geologic map and cross section of the Proterozoic rocks of the Picuris Mountains, modified from Bauer and Helper (1994).

Gresens and Stensrud, 1974; Long, 1974, 1976; Holdaway, 1978; Nielsen and Scott, 1979; Scott, 1980; Holcombe and Callender, 1982; Hurd, 1982; McCarty, 1983; Grambling and Williams, 1985a, 1985b; Bell, 1985; Soegaard and Eriksson, 1985, 1986; Bauer, 1988, 1993; Mawer et al., 1990; Holdaway and Goodge, 1990; Williams and Bauer, 1993; Bauer and Helper, 1994; Wingsted, 1997). The Picuris Mountains expose supracrustal rocks that have been divided into three major lithostratigraphic packages (Bauer, 1993) using the stratigraphic nomenclature proposed by Bauer and Williams (1989). Most of the northern part of the range is composed of the south-dipping, metasedimentary Hondo Group, which consists mainly of ridge-forming quartzites, pelitic schists, and various phyllites (Figs. 2, 3). To the south and structurally above the Hondo Group, is the heterogeneous, metavolcanic-metavolcaniclastic-metasedimentary Vadito Group and at least four granitoids that range in age from 1680 Ma to 1450 Ma (Bell, 1985). In the northwestern Picuris Mountains and structurally below the Hondo Group, is a homogeneous sequence of quartzofeldspathic schist named the Glenwoody Formation that is best exposed in the Pilar cliffs (Fig. 4). All supracrustal rocks in the area are polydeformed, metamorphosed to amphibolite facies, and are Paleoproterozoic in age.

This paper focuses on the rocks of the Pilar cliffs, their contact relationships, and the structural evolution of the range. Although correlative rocks exist in the Tusas Mountains, Taos Range, Truchas Peaks area, Rio Mora area, and Rincon Range (Fig. 1), the Pilar cliffs provide the best-exposed contact between the Hondo Group and its volcanogenic basement.

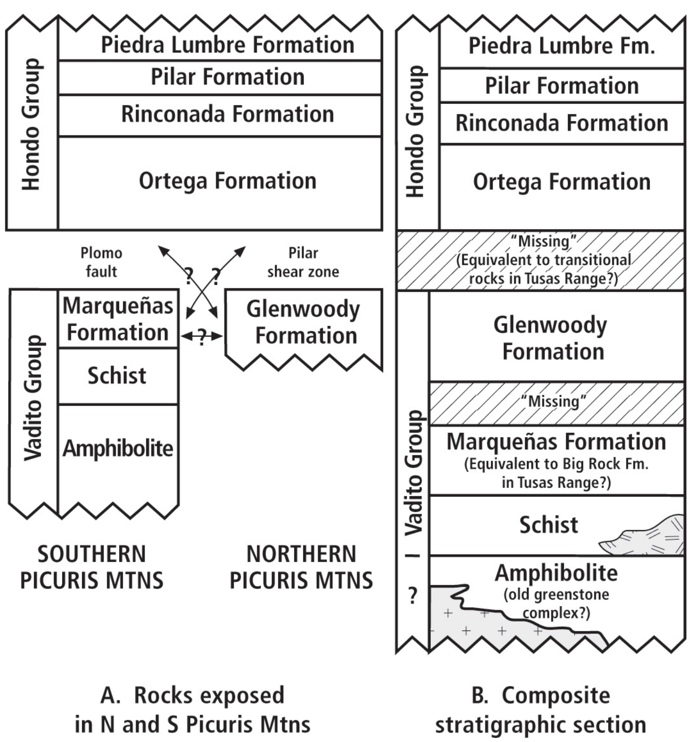

FIGURE 3. Generalized stratigraphy of Proterozoic rocks in the Picuris Mountains, modified from Bauer (1993). A) Column depicting the possible stratigraphic relationships among the Hondo Group, Vadito Group, and the Glenwoody Formation. B) Preferred stratigraphic model.

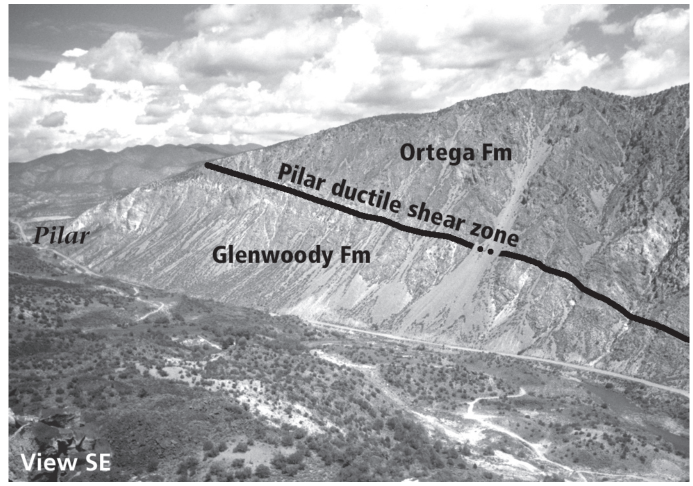

FIGURE 4. View southeast of the Pilar cliffs from the Taos Plateau. The contact between the Glenwoody Formation and Ortega Formation is sharp and well-exposed in the cliffs. The upper section of the Glenwoody Formation is pink due to high concentrations of manganese.

PRECAMBRIAN ROCKS

The Vadito Group was redefined by Bauer and Williams (1989) to include the regionally exposed, felsic-dominated, metavolcanic-metasedimentary sequence that stratigraphically underlies the Ortega Formation. A Vadito Group principal reference section was chosen south of Kiowa Mountain in the Tusas Mountains. Several distinctive units are designated as formations, including the Glenwoody Formation exposed in the Pilar cliffs. The Vadito Group of the southern Picuris Mountains is a heterogeneous succession of complexly interlayered metamorphosed volcanic, volcaniclastic, and clastic sedimentary rocks. Rock types range considerably along strike, pinch out and reappear, and probably represent deformed felsic and mafic volcanic rocks interlayered with volcaniclastic and epiclastic sediments (Bauer, 1988). Crossbeds in Vadito Group quartzites generally young to the north, indicating that the section is overturned (Bauer, 1988)

The metasedimentary sequence originally called the Ortega Group was renamed the Hondo Group by Bauer and Williams (1989), and a principal reference section was designated in the Hondo Canyon area of the northern Picuris Mountains. The Hondo Group is a several-km-thick sequence of mature terrigeneous metasedimentary rocks that crop out in most of the major Precambrian-cored uplifts of northern New Mexico. The Hondo Group consists of a thick basal quartzite (Ortega Formation) overlain by interlayered pelitic schists and quartzites (Rinconada Formation), black graphitic phyllite (Pilar Formation), and laminated pelitic phyllites and schists (Piedra Lumbre Formation). Ubiquitous primary sedimentary structures confirm a sedimentary origin for these rocks and provide reliable stratigraphic younging information.

Glenwoody Formation (Vadito Group)

Montgomery (1963) defined the Rio Pueblo Schist as the basal "migmatitic quartzite" of the lower quartzite of the Ortega

Formation in the southeastern Picuris Mountains, near the town of Rio Pueblo. He considered this feldspathic unit to consist of granitic rock intruded and intermixed with quartzite, and noted that a similar micaceous quartzite crops out below the Ortega Formation in a 300-m-thick section on the steep slopes near the town of Pilar. Gresens and Stensrud (1974) suggested that due to alteration, several metavolcanic units in the Picuris Mountains had been misinterpreted as metasediments. They cited the rocks in the lower Pilar cliffs as a prime example, and proposed that the sequence is hydrothermally altered, locally reworked, felsic volcanic tuffs and flows. Subsequent studies have confirmed their hypothesis, and the unit was formally named the Glenwoody Formation by Bauer and Williams (1989) for an early 1900s mining camp that stood at the base of the cliffs. The base of the unit is not exposed.

The Glenwoody Formation is composed of a sequence of light-colored, pink to white to green, feldspathic, quartz-muscovite and quartz-eye schists (Fig. 5). Modal mineralogy averages approximately 50-75% quartz plus 25-50% muscovite. Thin sections show anhedral to euhedral, rounded and flattened, quartz megacrysts in a fine-grained matrix of quartz, muscovite, and feldspar (Fig. 6a,b).

The rocks are well-layered on a range of scales. On a mesoscopic scale, thick sections of pink schist are interlayered with light green schist and white schist. On a finer scale, individual layers differ in the shade of pink or green or white, in the proportion of white megacrysts, and the relative proportions of quartz and muscovite. Compositional layering in schists is parallel to the Ortega-Glenwoody contact. No primary sedimentary structures have been recognized. The contact with the overlying Ortega Formation is sharp, mylonitic, and transitional rocks are absent.

The only major variation in mineralogy in the Pilar cliffs section is due to manganese and rare earth element enrichment in the uppermost 30 m of the section (Codding et al., 1983; Grambling et al., 1983, Grambling, 1984, Grambling and Williams, 1985). From the highway, this enriched zone is clearly visible as a pink horizon below the massive, gray Ortega Formation quartzite. The pink coloration is due to abundant pink muscovite (containing up to 6% ferric iron and traces of manganese) and the local appearance of piemontite, a deep red, prismatic, manganese epidote (Grambling, 1984). Below the contact with the Ortega Fm quartzite is a green, 1-m-thick, andalusite-muscovite-quartz schist. The green color is from Mn-andalusite ($(Al,Mn^{3+})_2SiO_5$, formerly known as viridine) a bright-green variety of andalusite (Grambling, 1984). Tourmaline (from Mg-rich dravite to Fe-rich schorl) is common throughout the Glenwoody Formation and in the lowermost Ortega Formation (Modreski and Klein, 1999). A diverse suite of accessory minerals is associated with the tourmaline-rich zones including fuchsite (green muscovite), purple muscovite, epidote, clinozoisite, zoisite, thulite (pink zoisite), tremolite, sillimanite, kyanite, cyprine (blue idocrase), allanite, and stibiotantalite (Modreski and Klein, 1999).

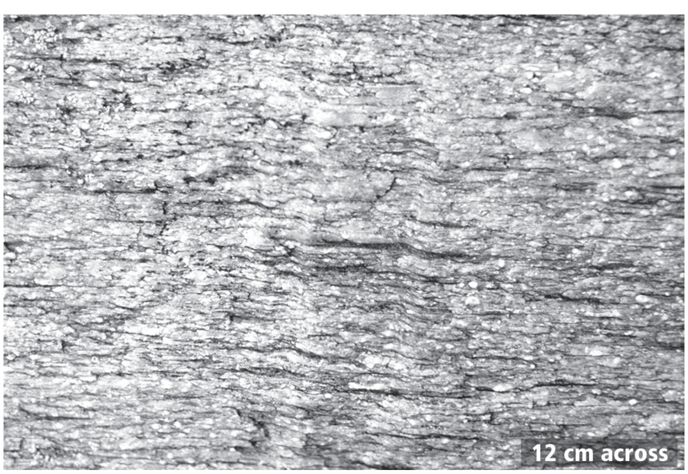

FIGURE 5. Field photograph of well-foliated quartzofeldspathic schist with megacrysts of light-colored feldspar and quartz from the Pilar cliffs.

Lateral extent of the Glenwoody Formation

Although the Pilar cliffs contain the best-known exposure of the Glenwoody Formation, it has been identified elsewhere in the Picuris Mountains and in nearby mountain ranges. Several small, fault-bounded exposures have been mapped along the northern flank of the Picuris Mountains near the base of the Ortega Formation (Fig. 2; Bauer and Kelson, 1997). Several more isolated exposures of similar schist were mapped as Rio Pueblo Schist by Montgomery (1963). The best exposures are in open-pit mica mines on an isolated hill in the southeast Picuris Mountains, where the rock is composed of up to 60% coarse white muscovite flakes in a matrix of granular quartz and feldspar. Quartz eyes are abundant and are flattened in the foliation plane.

North of the mines, similar schists that contain impressive crenulation cleavages (Fig. 7) are in contact with granitic rock and massive gray quartzite (Bauer, 1988). Granitic rock intrudes and crosscuts layering in the schist. A Mn-rich horizon is stratigraphically below the quartzite, and piemontite and altered porphyroblasts that might be pseudomorphs after Mn-andalusite exist along the contact. This contact is interpreted as correlative with the Pilar cliffs contact.

The Glenwoody Formation and Vadito Group are nowhere in contact in the Picuris Mountains, and therefore stratigraphic relationships between the two are uncertain (Bauer, 1993). However, the Vadito Group type-section of the Tusas Mountains (Bauer and Williams, 1989) contains similar feldspathic, quartz-eye, muscovite schists near a transitional zone of uppermost Vadito Group just beneath the Hondo Group (Williams, 1991). The Glenwoody Formation is interpreted as a similar stratigraphic unit that was originally deposited near the top of the Vadito Group (Fig. 3).

The Mn-rich marker layer, which occurs near the Glenwoody (Vadito)-Hondo contact, aids in correlating Vadito-Hondo units across the Proterozoic highlands of northern New Mexico (Grambling and Williams, 1985a; Williams, 1987). The layer is up to 100 m thick and can be traced almost continuously across individual uplifts, although the exact stratigraphic position of the zone varies somewhat from range to range. The layer is exposed in every range in northern New Mexico in which the Vadito Group-Hondo Group contact is exposed and may correlate with

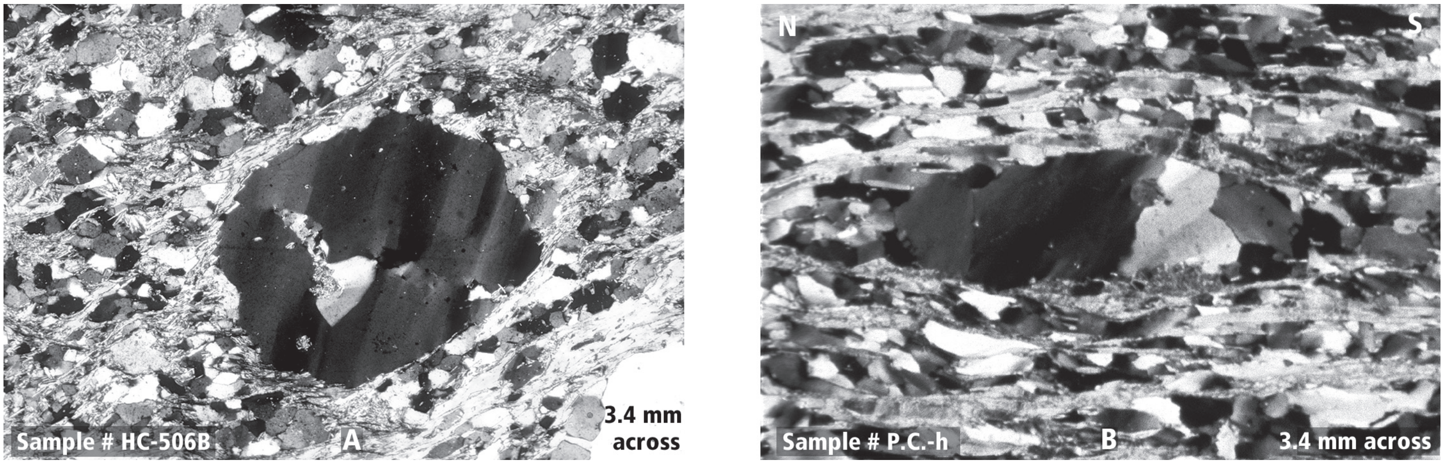

FIGURE 6. Photomicrographs of quartz megacrysts in quartz-muscovite schists from the Glenwoody Formation in the northern Picuris Mountains. A) Round, internally strained quartz megacryst in a mildly deformed schist. B) Flattened, internally strained quartz eye with core and mantle structure in strongly foliated, mylonitic schist from 35 m below the Pilar shear zone.

similar Mn-rich rocks in Colorado and Arizona (Williams, 1987). Williams (1987) concluded that most observations are consistent with a model involving syngenetic deposition from hydrothermal solutions or from a widespread manganese enrichment of basin waters at the end of Vadito Group volcanism. Alternatively, manganese and associated elements may have been concentrated during weathering of Vadito Group schists. If either of these models is correct, the Mn-rich layer represents a time marker in the Proterozoic section.

Origin and age of the Glenwoody Formation

Textures throughout the Glenwoody Formation are consistent with a volcanic protolith such as rhyolitic ash-flow tuff (Bauer, 1988; Vernon, 1986). Rounded quartz eyes and feldspar megacrysts probably represent relict phenocrysts. The Glenwoody Formation is interpreted as strained, metamorphosed, and altered rhyolitic flows and tuffs. If the exposed thickness of the section (a minimum of 300 m) is representative of the thickness of a pile of rhyolites and rhyolitic tuffs, these rocks accumulated in or near a major Paleoproterozoic volcano.

Rocks of the Vadito Group are lithologically, texturally, and geochemically similar to modern incipient rift assemblages (Condie, 1986; Grambling and Ward, 1987; Williams, 1987). Although the base of the Glenwoody Formation is not exposed, basement to the Glenwoody Formation/Vadito Group was probably a 1.80-1.75 Ga arc or backarc assemblage such as the Moppin or Gold Hill successions in the Tusas and Taos Ranges (Karlstrom et al., 2004). The absence of clastic sediments and mafic volcanics, and the lack of identifiable structures such as growth faults in the Glenwoody Formation suggest that it formed after the most active phases of rifting.

Rocks similar to the Glenwoody Formation lie stratigraphically beneath the Hondo Group in most of the major Precambrian-cored uplifts of northern New Mexico. It is possible that these voluminous felsic volcanic rocks represent the final stage of stabilization of continental crust prior to Hondo Group deposition, and may also have provided one component of source material for the enormous thickness of quartz sand that blanketed the region at about 1700 Ma. Karlstrom et al. (2004) interpreted the rhyolite-quartzite successions of New Mexico, Colorado, and Arizona as having developed in syntectonic basins that evolved on newly cratonized crust.

A preliminary, unpublished U-Pb zircon age of about 1700 Ma was reported by L.T. Silver for feldspathic quartz-muscovite schist of the Glenwoody Formation (Bauer, 1993). This date probably represents the crystallization age of the felsic volcanic protolith. Rb-Sr and K-Ar ages ranged from 1708 Ma to 1316 Ma (Bauer and Pollock, 1993). L.T. Silver (personal commun. in Grambling and Williams, 1985a) also reported a U-Pb zircon age of about 1700 Ma for felsic metavolcanic rocks in the Tusas Mountains, and Grambling and Williams (1985a) suggested that those rocks could be correlative with the Glenwoody Forma-

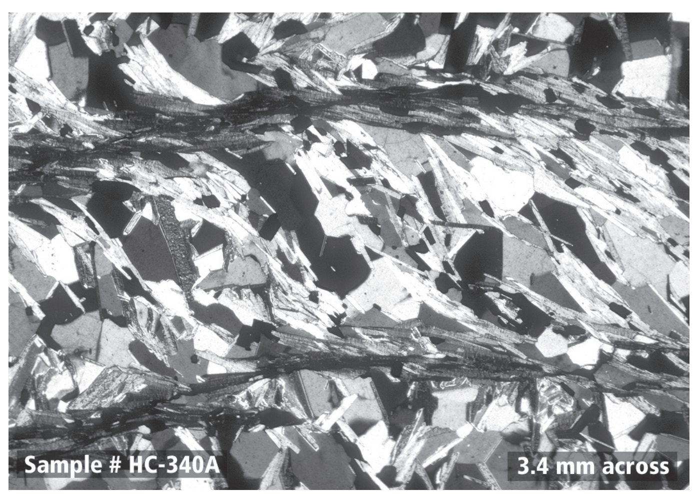

FIGURE 7. Photomicrograph of Rio Pueblo schist from the southeastern Picuris Mountains. An early cleavage defined by quartz/muscovite segregations and aligned muscovite grains is overprinted by a coarse, horizontal crenulation cleavage. Note annealed texture of both micas that form polygonal arcs and quartz that is strain free.

tion. A felsic schist from the upper Vadito Group in the southern Picuris Mountains yielded a preliminary U/Pb zircon age of 1693 Ma (Bauer and Helper, 1994).

Ortega Formation (Hondo Group)

The basal unit of the Hondo Group is the km-thick Ortega Formation quartzite. The Ortega Formation is overlain by a sequence of interlayered pelitic schists and crossbedded quartzites (Rinconada Formation), a black slate or fine-grained phyllite (Pilar Formation), and laminated pelitic schist and phyllite with minor micaceous quartzite and calc-silicate rock (Piedra Lumbre Formation). Although there is some variation of lithology along strike, nearly all formations and members are readily distinguishable throughout the Picuris Mountains and contain abundant sedimentological younging indicators.

The name Ortega was first used to describe a thick quartzite, quartzose schist, metaconglomerate, feldspathic schist, and metarhyolite exposed in the Tusas and Picuris Mountains (Just, 1937). Montgomery (1953) later used Ortega Formation to include the entire section of metaclastic rocks in the Picuris Mountains, and called the thick basal quartzite the Lower Quartzite. Nielsen (1972) renamed the Lower Quartzite the Ortega Formation. Long (1976) proposed the name Ortega Group for a sequence of metasediments in the Picuris Range that included a thick orthoquartzite (Ortega Formation) and the overlying schists and quartzites of the Rinconada Formation. Bauer and Williams (1989) substituted Hondo Group for Ortega Group.

The Ortega Formation is typically a remarkably mature (generally 98% modal quartz), massive, cliff-forming, gray to grayish-white, medium- to coarse-grained crossbedded quartzite. Crossbeds are defined by concentrations of black iron-oxide minerals (Fig. 8). Aluminum silicate minerals (kyanite and sillimanite) are concentrated in thin muscovite schist horizons. Common accessory minerals are ilmenite, hematite, tourmaline, epidote, muscovite, and zircon. The 800-1200 m thickness of the Ortega Formation is remarkably consistent from range to range in northern New Mexico despite widespread polyphase ductile deformation.

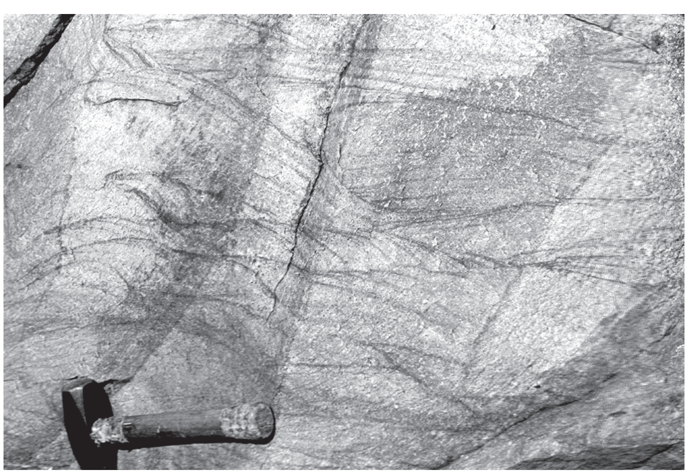

FIGURE 8. Field photograph of overturned crossbeds in Ortega Formation quartzite from the northwestern Picuris Mountains. Cross laminations are defined by concentrations of dark-colored heavy minerals.

Lateral extent of the Ortega Formation

The Ortega Formation is the principal ridge-former in the Picuris Mountains, and forms northern and southern, south-dipping strike ridges across the range (Fig. 2). The Copper Hill anticline is defined by the top of the Ortega Formation, and several small exposures of aluminous quartzite exist east of the Picuris-Pecos fault. The Ortega Formation crops out in most of the basement-cored uplifts of northern New Mexico, including the Tusas Mountains, Taos Range, Rincon Range, Truchas Peaks area, and Rio Mora area (Fig. 1). Comparable quartzites are located in Arizona (Mazatzal Group) and southern Colorado (Uncompahgre Quartzite, quartzites in the Front Range, and quartzites in the Sangre de Cristo Mountains).

Origin and age of the Ortega Formation

Of the three supracrustal sequences in the Picuris Mountains, the sedimentology of the Hondo Group is the most studied, and its depositional setting was well documented by Soegaard and Eriksson (1985, 1986). They deduced that the Hondo Group is transgressive, was deposited on a broad, continental, shallow marine shelf that sloped gently to the south and southeast, and received a continuous influx of sediment from the north and northeast during prolonged subsidence. They concluded that the Ortega Formation accumulated subsequent to rifting on a stable continental shelf in a stable tectonic environment, but noted that depositional models for accumulation of thick quartz arenites such as the Ortega Formation are poorly constrained because no modern analogs exist. However, new research indicates that the apparent maturity of such quartzites may be due to Proterozoic deep weathering of a sandstone protolith rather than original deposition of an extremely pure quartz sandstone (Medaris et al., 2003). Karlstrom et al. (2004) noted that Paleoproterozoic quartzite-rhyolite successions are not anorogenic in a regional sense, as they were accumulating while tectonism and plutonism were ongoing in the northern New Mexico region. Instead, they viewed the Hondo Group as forming in syntectonic basins on the newly stabilized craton.

No radiometric dates that constrain the time of deposition have been reported for the Hondo Group in the Picuris Mountains. If the Ortega Formation did rest in primary stratigraphic contact on the Glenwoody Formation prior to faulting, then the Hondo Group probably accumulated shortly after 1700 Ma. Consistent with this interpretation, Grambling et al. (1988) reported an age of ca. 1691 Ma for a felsic stock that appears to intrude the Hondo Group near Pecos Baldy Peak in the southern Sangre de Cristo Mountains.

Regionally, detrital zircons from the Ortega Formation range in age from about 1850 to 1700 Ma (Maxon, 1976; Aleinikoff et al., 1985; S.A. Bowring, personal commun. in Williams, 1987). This range of ages implies that although one source component of the Ortega Formation could have been derived from underlying felsic rocks, another component was apparently derived from unknown distal sources (Williams, 1987).

STRUCTURAL GEOLOGY

The overall structural geometry of the Picuris Mountains is that of a mountain-scale, overturned syncline of the Hondo Group bounded by south-dipping ductile shear zones and older rocks of the Glenwoody Formation on the north and Vadito Group on the south (Fig. 2). The syncline is defined by thick, mechanically stiff limbs of massive Ortega Formation quartzite surrounding a less competent core of thinly interlayered Rinconada Formation schist and quartzite.

Porphyroblasts of biotite, garnet, and staurolite have experienced multiple stages of growth during the polyphase metamorphic and strain history of Hondo Group rocks. The supracrustal rocks of the Pilar cliffs area have experienced peak metamorphic conditions of lower to middle amphibolite facies metamorphism (Bauer, 1993). In the Hondo syncline area, an aluminosilicate triple point equilibrium (?) assemblage of kyanite/andalusite/sillimanite exists in the Hondo Group.

The following sections summarize the character, geometry, and kinematics of all scales of Proterozoic structures in the northwestern Picuris Mountains. More detailed analyses can be found in the original studies (Montgomery, 1953; Nielsen, 1972; Long, 1976; Scott, 1980; Holcombe and Callender, 1982; Hurd, 1982; McCarty, 1983; Bell, 1985; Bauer, 1988, 1993; Bauer and Helper, 1994; Wingstead, 1997).

Glenwoody Formation

The predominant tectonite fabric in the Glenwoody Formation is a well-developed, somewhat anastomosing foliation (S1) that is parallel to compositional layering in the overlying Hondo Group (Fig. 9). This is the earliest fabric recognized in these rocks, and in many areas is the only visible foliation. A south-dipping extension lineation (L1) defined by elongate quartz, muscovite, and tourmaline grains is ubiquitous on S1 surfaces. Although S1 has the appearance of a mylonitic fabric in outcrop, thin sections show recrystallized quartz and muscovite.

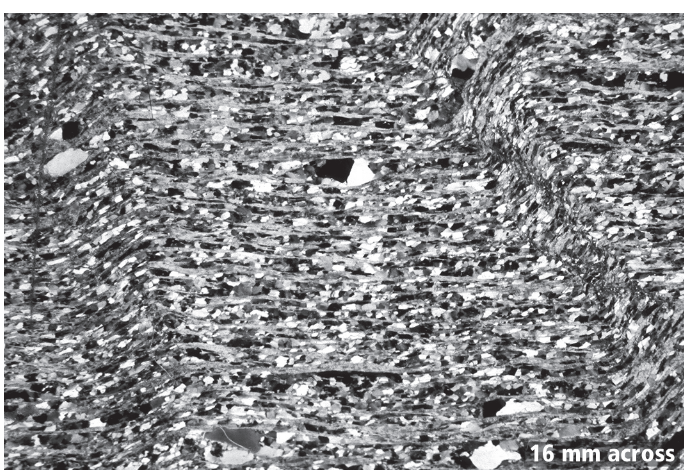

FIGURE 9. Photomicrograph of kink folds overprinting a well-developed S1 schistosity in a green, quartz-eye schist from the Glenwoody Formation, Pilar cliffs.

Megacrysts of quartz and rare feldspar in the schist are interpreted as relict, metamorphosed phenocrysts. Although locally these grains may appear relatively euhedral, all show some evidence of internal strain. Typically, the grains are flattened in the foliation plane, and elongate in the extension direction. In extreme cases, quartz megacrysts are highly flattened with distinct asymmetric tails of dynamically recrystallized quartz grains. Such quartz porphyroclasts lie isolated in a relatively homogeneous matrix of fine-grained quartz and muscovite.

No unequivocal F1 folds have been found in the Glenwoody Formation, although elsewhere F1 folds are rootless intrafolial isoclinal folds. In one locality on the Pilar cliffs, dark, thin interlayers of tourmaline-rich rock pinch out parallel to S1. It is not known if they represent early isoclinal folds, original depositional pinch-outs, or local hydrothermal alteration.

Locally, S1 is overprinted by an S2 crenulation cleavage (Fig. 9). Intensities of S2 range from gentle warpings of S1 to a strong, penetrative crenulation. No mesoscopic F2 folds have been recognized in the Glenwoody Formation.

Hondo Group

The structural and metamorphic geology of the Hondo Group in the northwestern Picuris Mountains has most recently been investigated by Bauer (1988, 1993), Bauer and Helper (1994), and Kelson and Bauer (1998). They reported that supracrustal rocks have undergone a progressive deformational history that resulted in the formation of three major generations of structures, D1, D2, and D3. A summary of their findings is presented below.

D1 is characterized by a relict schistosity (S1) and localized zones of high simple shear strain, rather than by large fold structures. On both limbs of the Hondo syncline, the Ortega Formation contains up to l-m-thick, bedding-parallel zones of deformed vein quartz surrounded by an anastomosing aluminous schist matrix (Fig. 10). The zones contain highly contorted vein quartz layers, aligned vein quartz pods, sheath folds, well-developed mineral stretching lineations (Fig. 11) and contorted crossbeds. Locally, the shear zones are folded by upright, mesoscopic F2 folds.

On the northern limb of the Hondo syncline, in the north-central part of the range, the Ortega Formation is nearly 2 km thick, whereas elsewhere in the range the quartzite is approximately 1 km thick (Fig. 2). Because the Ortega Formation is remarkably consistent in thickness from range to range in northern New Mexico, the northern limb of the syncline is probably thickened tectonically rather than stratigraphically, perhaps during D1/D2 ductile thrusting. Similar imbrications have been described by Williams (1987) in the Tusas Range, Grambling (1988) in the Rio Mora and Guadalupita areas, and Read et al. (1999) in the Rincon Range.

The principal structures in the Hondo Group are second-generation folds (F2) that can be stratigraphically defined by crossbeds in quartzites and graded beds in some schists and phyllites. Most F2 folds are inclined, tight to isoclinal, and shallowly east-

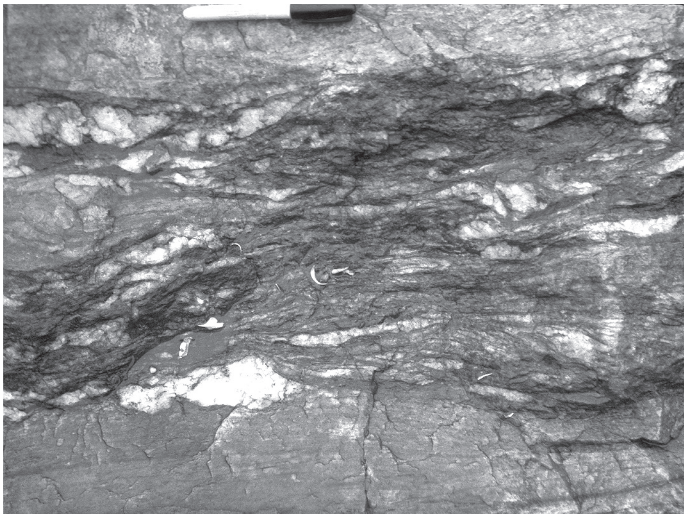

FIGURE 10. Field photograph of bedding-parallel shear zone containing deformed pods of vein quartz in a schistose layer in Ortega Formation quartzite. The anastomosing schist zones are rich in aluminosilicate minerals. Such shear zones are common near the base of the quartzite in the northern Picuris Mountains. Marking pen at top of photo for scale.

FIGURE 12. Field photograph of F2 folds in the Hondo Group showing the S1 foliation and the slightly divergent S2 defined by F2 fold hinges. Hammer for scale at bottom of frame.

or west-plunging. Macroscopic F2 folds are common (Fig. 12). Axial surfaces dip 40-80°S. The map-scale fold geometry of the thick, mechanically stiff Ortega Formation is simple, and on a macroscopic scale is best illustrated by the Hondo syncline and Copper Hill anticline (Fig. 2). The Hondo syncline is mountain range-scale structure that is a tight, north-verging, shallowly west-plunging fold with an axial surface that dips approximately 65°S. Dips of bedding range from an average of 60°S on the northern limb to 66°S (overturned) on the southern limb. In detail, however, thinly interlayered units of the Rinconada, Pilar, and Piedra Lumbre Formations with differing competencies have been folded disharmonically and noncylindrically (Fig. 13). Minor folds and near-bedding-parallel ductile faults are concentrated on the overturned, tectonically thinned, southern limb of the Hondo syncline in the Rinconada and Pilar Formations. Coaxially refolded folds with geometries of antiformal synclines and synformal anticlines exist locally. Wavelengths of these minor folds range from meters to tens of meters. Although small-scale F2 folds show a significant range of hinge orientations, hinges generally lie within a great circle that coincides with the orientation of compositional layering and S2 (figure 6 in Bauer, 1993).

A minimum estimate of F2 shortening within the Hondo Group, made by comparing the fold profile of the Ortega Formation with an unfolded reconstruction, yielded values of about 65% (Bauer, 1993). This estimate neglects the unknown contribution of tectonic imbrication and bedding-parallel shear zones.

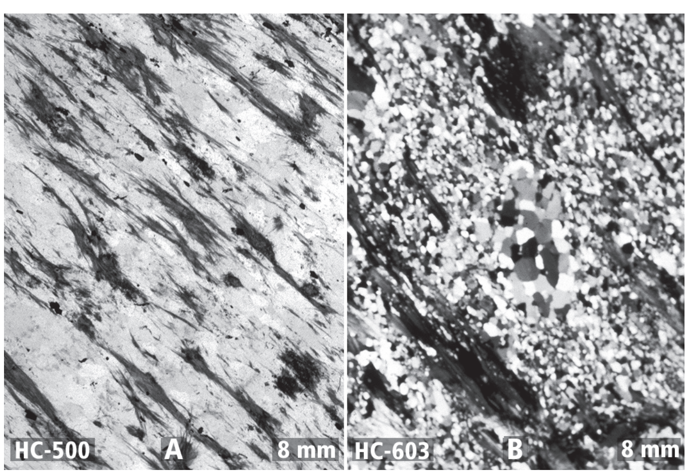

FIGURE 11. Photomicrograph of well-developed mineral lineations in Ortega Formation quartzite from the northwest Picuris Mountains. Both samples are cut parallel to mineral lineation and perpendicular to foliation. A) Fibrolitic sillimanite lineation. B) Kyanite lineation.

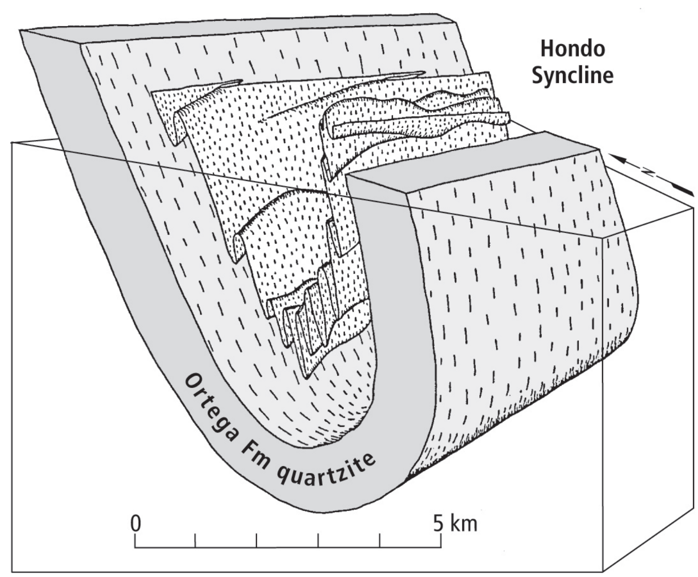

FIGURE 13. Conceptual block model sketch of the Hondo syncline in the Picuris Mountains, viewed to the northeast, modified from Bauer (1993). The kilometer-thick Ortega Formation quartzite forms simple, relatively cylindrical F2 folds, whereas overlying thinly bedded quartzites and metapelites form complex non-cylindrical folds. Vadito Group rocks and intrusions are not shown.

The latest pervasive ductile deformation (D3) in the area was characterized by formation of a strong cleavage (S3) that slightly transects Hondo Group F2 folds, and is now the dominant cleavage in most schistose rocks of the Ortega Group. S3 reactivated and obscured preexisting foliations. In addition, in several locations in the northwest Picuris Mountains, quartzite quartz ribbon mylonites exhibit dramatic pristine (not annealed, Fig. 14) quartz microstructures indicative of dynamic recrystallization. The mylonites appear to post-date D1 and D2 deformational and metamorphic fabrics, which are characteristically annealed.

Contacts Between Supracrustal Sequences

The three supracrustal sequences in the Picuris Mountains are separated by two south-dipping ductile shear zones that bracket the Hondo Group (Fig. 2). The Pilar shear zone separates the Ortega and Glenwoody Formations in the Pilar cliffs, and the Plomo fault separates Hondo Group from Vadito Group to the south. Even though the Plomo fault lies well south of the Pilar cliffs, an understanding of its geometry and kinematics is useful for interpreting the nature of the stratigraphy and structure of the Pilar cliffs area.

Pilar shear zone

The bedding-parallel Pilar shear zone is well exposed in the Pilar cliffs. Although the schist/quartzite contact is sharp, in places, small blocks of quartzite are entrained in the schist (Fig. 15). Ortega Formation quartzite contains small shear zones near the contact, and thicker schistose shear zones throughout the basal quartzite. In general, the intensity of shear strain in the Glenwoody Formation schist decreases with distance downward from the quartzite. Notably, it appears that the Pilar shear zone contains two kinematically distinct sets of mylonites; north-verging, schistose mylonites and south-verging, fine-grained, quartz mylonites.

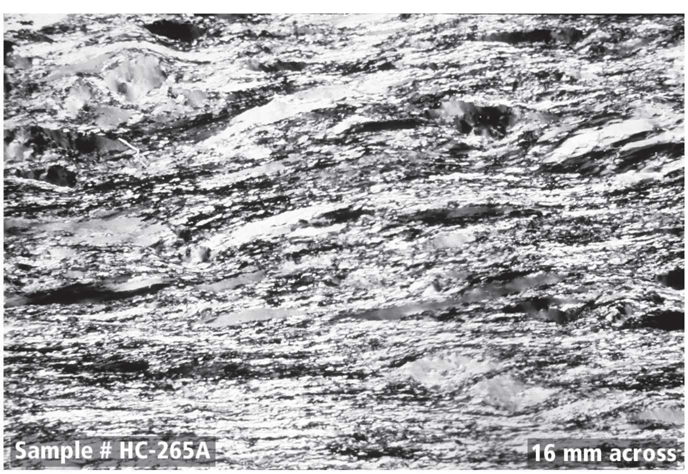

FIGURE 14. Photomicrograph of pristine quartz-ribbon mylonite from the Hondo Group in the northern Picuris Mountains. Quartz deformation microstructures including S-C fabrics and core-and-mantle structures show no evidence of later annealing. Thin section is cut parallel to mineral lineation and perpendicular to foliation.

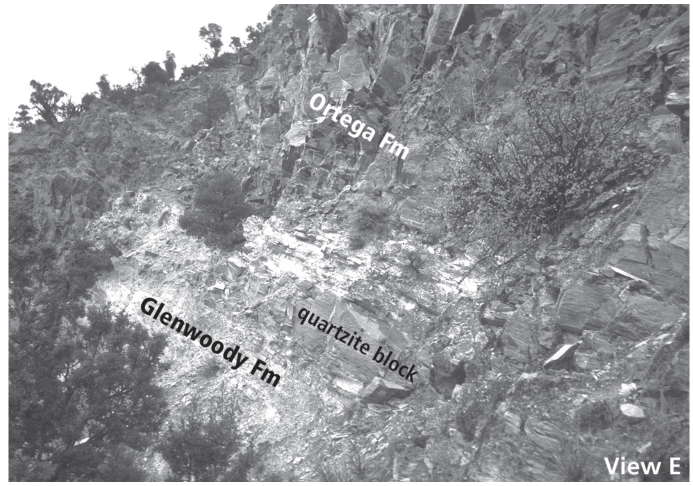

FIGURE 15. View east of the contact zone between the Glenwoody Formation and Ortega Formation. Pink schist of the Glenwoody Formation is separated from dark gray quartzite of the Ortega Formation by the south-dipping Pilar shear zone -- a several-meter-thick zone of mylonites with down-dip quartz lineations and imbricated blocks of quartzite.

For at least 6 m below the quartzite, the Glenwoody Formation schist contains flattened and stretched, asymmetric, dynamically recrystallized quartz megacrysts with fine-grained quartz tails (Fig. 16) that indicate north-directed (reverse in present orientation) ductile shearing. Just below the quartzite is a crumbly, altered, schistose horizon that contains well-developed, macroscopic S-C structures (Fig. 17) that also indicate north-directed ductile shearing, although thin sections typically reveal granoblastic quartz and feldspar textures due to later annealing.

The base of the Ortega Formation and quartzite blocks just below the contact contain a variety of spectacular, pink and gray quartz-ribbon mylonites. The mylonitic foliation is bedding-parallel and displays a well-developed, down-dip quartz rod lineation. The quartzites show no evidence of post-kinematic annealing, and asymmetric, quartz megacrysts indicate top-to-the-south (normal) shearing (Fig. 18). Small shear zones and thicker, schistose shear zones also exist within the basal quartzite.

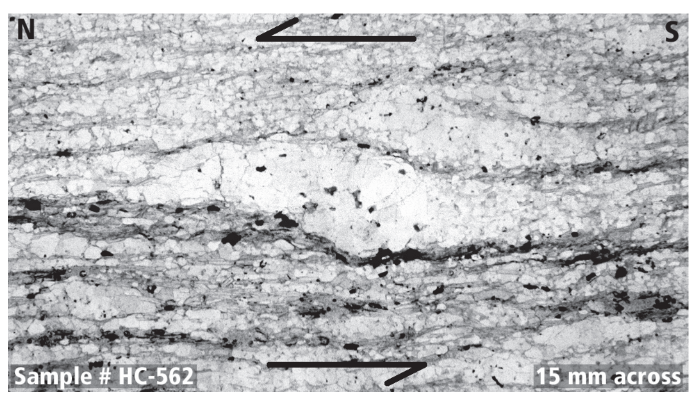

FIGURE 16. Plane light photomicrograph of asymmetric quartz porphyroclast in Glenwoody Formation, Pilar cliffs. The porphyroclast is composed of a coarse-grained core and fine-grained recrystallized tails interpreted to record north-vergent ductile shearing of Ortega Formation over Glenwoody Formation. Thin section is cut parallel to mineral lineation and normal to foliation.

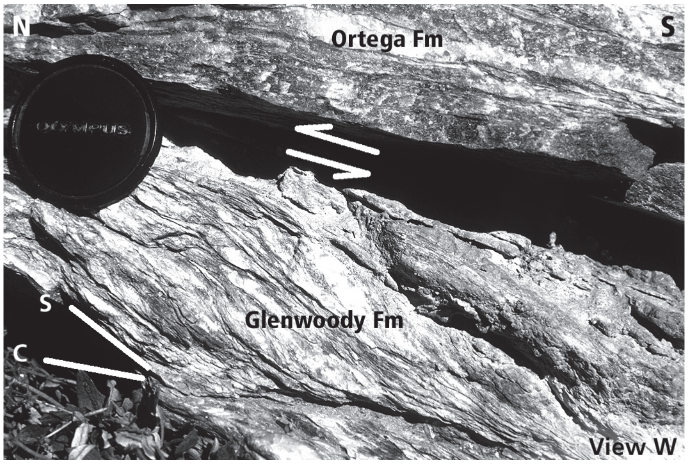

FIGURE 17. Field photograph of S-C structures in a schistose mylonite zone of the Pilar shear zone at the Glenwoody/Ortega contact is interpreted to record north-vergent ductile shearing of the Ortega Formation over the Glenwoody Formation. Camera lens cover for scale.

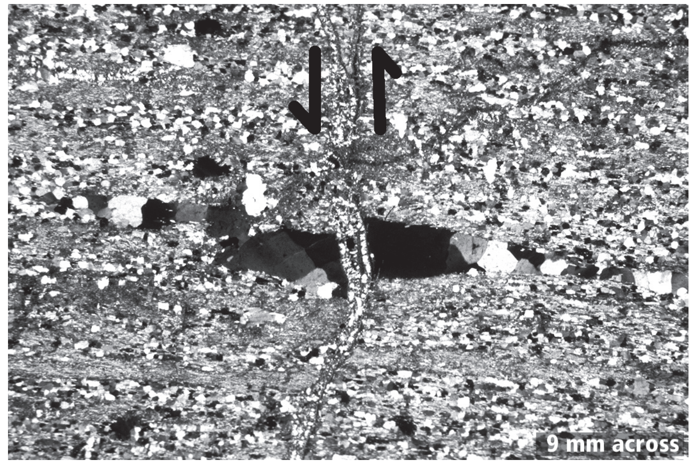

FIGURE 19. Photomicrograph of feldspathic, quartz-eye schist of the Glenwoody Formation from 3 m below the Pilar shear zone in the Pilar cliffs. A thin, vertical, calcite-filled fault offsets the quartz eye. The Proterozoic rocks of the Pilar cliffs have experienced a long history of Cenozoic deformation along the Embudo fault zone.

In the Pilar cliffs, the Proterozoic ductile features are overprinted by locally pervasive brittle fault structures that are probably related to Cenozoic slip and fluid flow along the Embudo fault. High-angle faults and calcite veins are common from the mesoscopic to microscopic scale (Fig. 19).

Plomo fault

The Plomo fault is best exposed south of Copper Hill, in Arroyo del Plomo near NM-75, where a 2-m-wide pod of Pilar Formation is caught up in a steeply south-dipping ductile fault zone that separates the Piedra Lumbre and Marqueñas Formations. South of the contact, quartzite clasts are strongly flattened in a mylonitic foliation that parallels the contact. Well-developed stretching lineations, defined by elongated clasts, plunge down-dip to the south. Asymmetric recrystallized tails on porphyroclasts in the Marqueñas Formation indicate north-vergent (reverse) shearing (Bauer, 1993).

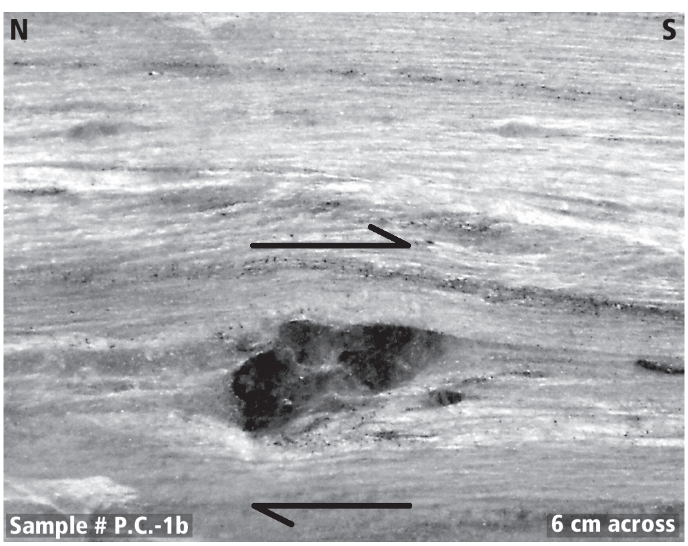

FIGURE 18. Photograph of slabbed and polished quartz-ribbon mylonite from the Ortega Formation quartzite in the Pilar shear zone of the Pilar cliffs. Asymmetric quartz megacryst is interpreted to represent south-vergent ductile shearing of the Ortega Formation over the Glenwoody Formation. Rock is cut parallel to mineral lineation and perpendicular to foliation.

Near the Plomo fault in the western Picuris Range, Vadito Group rocks young to the north, whereas most Hondo Group rocks young to the south (Holcombe and Callender, 1982). In contrast, in the eastern Picuris Mountains, both groups are overturned to the north. This variation exists because the Plomo fault truncates the southern limb of the Copper Hill anticline in the western Picuris Range and cuts progressively upsection eastward until the anticline is absent (Fig. 2). The amount of slip on the fault is unknown but must be considerable, judging from juxtaposition of opposite-facing stratigraphic sections in the Copper Hill area (Bauer, 1993). At the very least, several kilometers of section are missing south of the fault (Fig. 3).

DISCUSSION

Summary and Interpretation of Pilar Cliffs Area Stratigraphy

There are three supracrustal rock packages in the Picuris Mountains: 1) the Vadito Group, a heterogeneous sequence of metamorphosed volcanic, volcaniclastic, and clastic sedimentary rocks; 2) the Glenwoody Formation, a sequence of 1700 Ma, metamorphosed and altered felsic volcanic rocks deposited around 1700 Ma; and 3) the Hondo Group, a thick pile of metaclastic, shallow marine sediments. The Vadito Group and Glenwoody Formation are nowhere in contact, yet they occupy identical structural positions against the base of the Ortega Formation on either limb of the Hondo syncline. Stratigraphic and temporal relationships among the Vadito, Glenwoody, and Hondo sections are indeterminate due to deformation along their mutual contacts. However, the presence of the regionally extensive Mn-rich marker horizon at the top of the Glenwoody Formation suggests that little if any of the uppermost part of the Pilar cliffs schist section has been sheared out.

Local and regional observations support the following interpretation of these field relationships. The upper part of the Vadito Group was a heterogeneous sequence of volcanic and sedimentary rocks that originally graded upward into the sedimentary Hondo Group (Fig. 3). The Glenwoody Formation is part of the uppermost Vadito Group, perhaps correlative with the section sheared out in the southern Picuris Mountains. In the northern Picuris Mountains, the transitional volcanic-sedimentary section between the Glenwoody and Ortega Formations has been sheared out, if it ever existed there.

Summary and Interpretation of Pilar Cliffs Structural History

The major structure in the Picuris Mountains is the gently west-plunging, tight to isoclinal, northward-verging F2 Hondo syncline in the Hondo Group. The Pilar cliffs are the northern, right-side-up limb of the syncline. In the north-central Picuris Mountains, the Ortega Formation is doubled in thickness by a D1 or D2 imbrication. The west-to-east along-strike footwall transition from Glenwoody Formation to Ortega Formation below the Pilar shear zone may to due to different levels of exposure across the Phanerozoic(?), northwest-striking Pilar-Vadito fault (Fig. 2).

Supracrustal rocks have undergone a progressive deformational history that resulted in the formation of several principal generations of structures. D1 is characterized by a development of a north-verging ductile thrusting(?), a pervasive schistosity, and localized zones of high simple shear strain rather than by large fold structures. D2 involved major folding in the Hondo Group and juxtaposition of the Vadito, Hondo and Glenwoody sections along north-verging ductile shear zones. The final ductile deformation resulted in moderate cleavage development and perhaps south-vergent shearing along the Pilar shear zone.

All rocks appear to have experienced lower to middle amphibolite facies metamorphism, with peak metamorphic conditions of about 4 kb and 500^{o}C. The nature of the Mazatzal-age metamorphism in the range remains uncertain. The principal metamorphism in the region may have been at 1.45-1.35 Ga, rather than during the 1.65 Ma Mazatzal orogeny, with the early metamorphism of Hondo Group rocks peaking at upper greenschist facies (Karlstrom et al., 2004).

The Pilar shear zone and Plomo fault both experienced north-directed ductile shearing, consistent with the overturned geometry and asymmetry of F2 folds. Because the Plomo fault cuts the Copper Hill anticline and the S2 foliation, at least some ductile movement on the Plomo fault post-dated F2 structures. The amount of displacement on the Plomo fault is unknown, but was probably large given the inverted stratigraphic sections in the southern Picuris Mountains (Bauer, 1993).

The south-directed movement of Hondo Group over Glenwoody Formation on the Pilar shear zone is opposite to all the other kinematic indicators in the range. Because the quartz mylonites are not annealed, the movement post-dates the north-verging deformation indicated by the pervasively annealed fabrics seen throughout the range. Local, south-directed shearing appears to be regional as similar top-to-the-south and top-to-the-east/southeast structures have been reported in the Tusas Range (Williams 1991), Taos Range (Grambling et al., 1989; Pedrick et al., 1998), Cimarron Mountains (Grambling and Dallmeyer, 1993; Pedrick et al., 1998), Rincon Range (Read et al., 1999), Manzano Mountains (Thompson et al., 1996), and Zuni Mountains (Mawer and Bauer, 1989).

Regional Tectonic Synthesis

One possible model for the tectonic evolution of rocks in the Pilar cliffs area begins with accretion and tectonism of mafic-dominated, juvenile continental crust as arcs or back-arcs prior to 1.7 Ga during the regional assembly of continental lithosphere in the Yavapai/Mazatzal orogenies. Although not exposed in the Pilar cliffs, mafic parts of the Vadito Group in the southern Picuris Mountains might belong to this early basement. Nearby occurrences include the Moppin Complex in the Tusas Mountains, the Gold Hill Complex in the Taos Range, and the Pecos Complex in the southern Sangre de Cristo Mountains. The mafic basement may have been buried and unroofed prior to deposition of the rhyolite-quartzite association at around 1.7 Ga based on reports of earlier tectonism of the mafic rocks (Karlstrom et al., 2004). The felsic-dominated Vadito Group accumulated on this relatively stable crust at 1.7 Ga, perhaps in a back-arc basin. The Glenwoody Formation, probably erupted from a large caldera complex, represents the last gasp of a regionally extensive felsic volcanogenic system.

Sometime after 1.7 Ga, the crust was locally stable enough to allow accumulation of thick, mature, shallow marine sediments (Hondo Group) in basins distributed over a large part of northern New Mexico, southern Colorado, and Arizona. Vadito Group felsic rocks may have provided source material for the great thickness of quartz sand that accumulated in these basins. As the 1.70-1.65 Yavapai/Mazatzal orogenic system evolved, the Vadito and Hondo Groups were buried to moderate crustal levels where they experienced a major phase of north-directed crustal shortening that involved a dynamic and complex interplay of shearing, folding, plutonism, and metamorphism. Most of the large fold and ductile fault structures in northern New Mexico formed during this foremost episode of thrusting and shortening (Williams et al., 1999; Karlstrom et al., 2004), including the north-vergent Hondo syncline, Pilar shear zone, and Plomo fault. The shear zones may have evolved as thrust faults that steepened as the crust shortened. The south-directed shearing along the Pilar shear zone may have been related to collapse of the overthickened crust of the Mazatzal mountain belt. Alternatively, it may have been related to the 1.45 Ga thermal event that produced the Peñasco quartz monzonite of the southern Picuris Mountains and similar plutons related to the intracontinental tectonism described by Karlstrom et al. (2004). Metamorphic studies over the southwestern region have revealed that rocks now exposed at the surface remained at approximately 10 km depth during a protracted tectonic pause between 1.63 and 1.48 Ga (Bowring and Karlstrom, 1990). The subsequent Neoproterozoic and Phanerozoic tectonic history of the Pilar cliffs area is beyond the scope of this paper, but a regional perspective is presented in Karlstrom et al. (2004), Williams et al. (1999), Grambling et al. (1988).

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