Geology of Trampas quadrangle, Picuris Mountains, Taos and Rio Arriba Counties, New Mexico

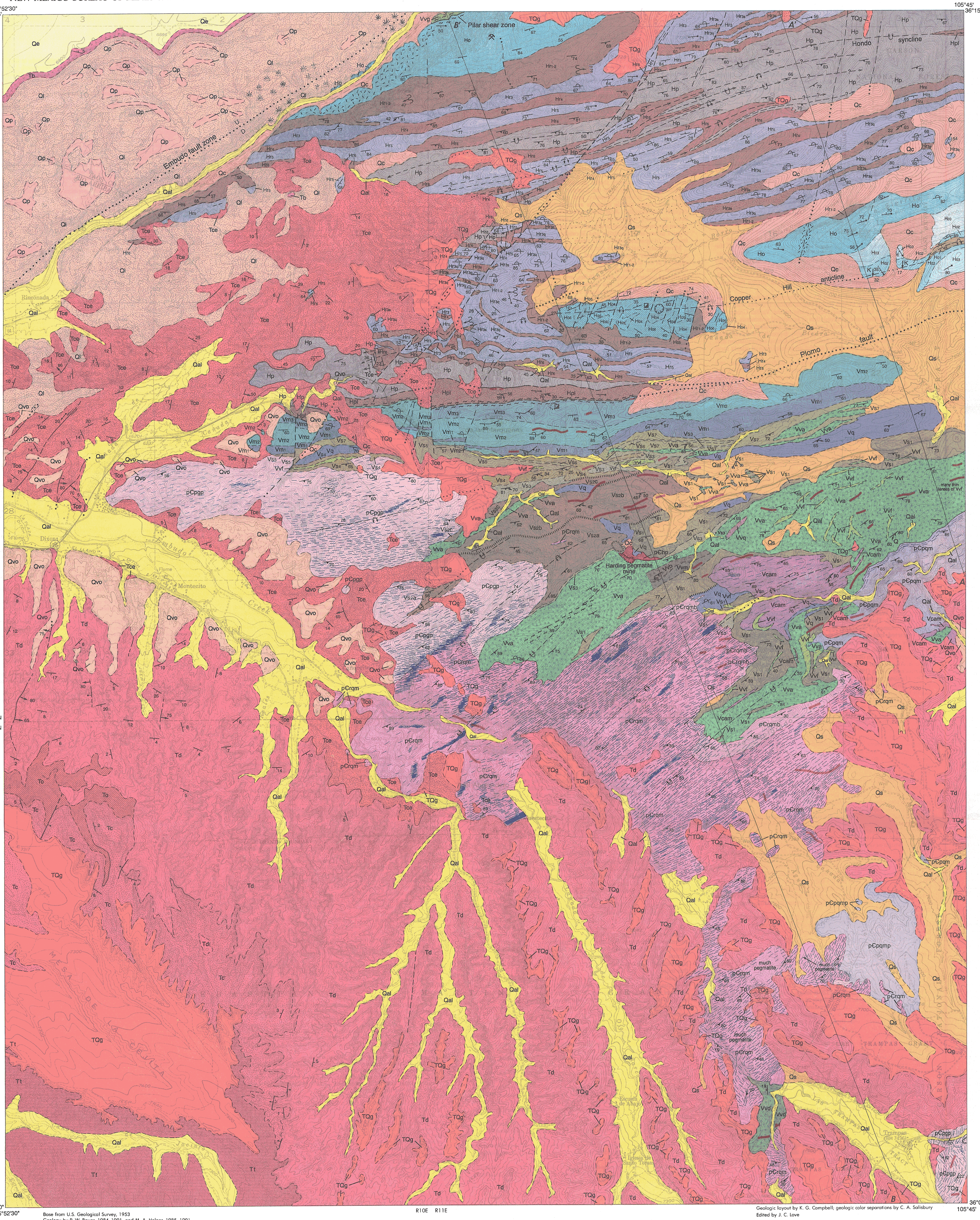
by Paul W. Bauer[1] and Mark A. Helper[2], 1994

[1]*New Mexico Bureau of Mines & Mineral Resources, Socorro, New Mexico 87801*
[2]*Department of Geological Sciences, University of Texas at Austin, Austin, Texas 78713*

Other contributors: David A. Bell, Jonathan F. Callender, Rose McCarty Emanuel, Michael S. Hall, Rodney J. Holcombe, Phillip E. Long, Kim Manley, Sharon Mosher, Kent C. Nielsen, Maureen Wilks, and Michael L. Williams

105°52'30" 36°15'

105°45' 36°15'



T23N
T22N

36°07'30" 105°52'30"

36°07'30" 105°45'

Base from U.S. Geological Survey, 1953
Geology by P. W. Bauer, 1984–1991, and M. A. Helper, 1985–1991

R10E R11E

Geologic layout by K. G. Campbell; geologic color separations by C. A. Salisbury
Edited by J. C. Love

Contact—Dashed where approximately located; dotted where concealed; hatchured where gradational

Fault—Dashed where approximately located; dotted where concealed; queried where inferred

High-angle fault—Ball and bar on downthrown side

Low-angle fault—Sawteeth on upper (overthrust) plate

Direction and plunge of fault striae

Shear zone—In Proterozoic rocks

Brecciated area—In Proterozoic rocks

Strike and dip of beds

- Inclined beds in Tertiary rocks
- Inclined beds in Proterozoic rocks; top uncertain
- Inclined beds in Proterozoic rocks; upright
- Overturned beds in Proterozoic rocks

Strike and dip of dominant foliation—In Proterozoic rocks

Direction of plunge of intersection lineation—Between bedding and dominant foliation of Proterozoic rocks

Direction of plunge of mineral extension lineation—In Proterozoic rocks; K = kyanite, Q = quartz

Anticline—Showing direction of plunge; dashed where approximately located; dotted where concealed; queried where doubtful

Overturned anticline—Showing direction of plunge; dashed where approximately located; dotted where concealed; queried where doubtful

Syncline—Showing direction of plunge; dashed where approximately located; dotted where concealed; queried where doubtful

Overturned syncline—Showing direction of plunge; dashed where approximately located; dotted where concealed; queried where doubtful

Area of many plunging folds

Pegmatite

Vertical shaft

Portal or adit

Prospect pit or quarry

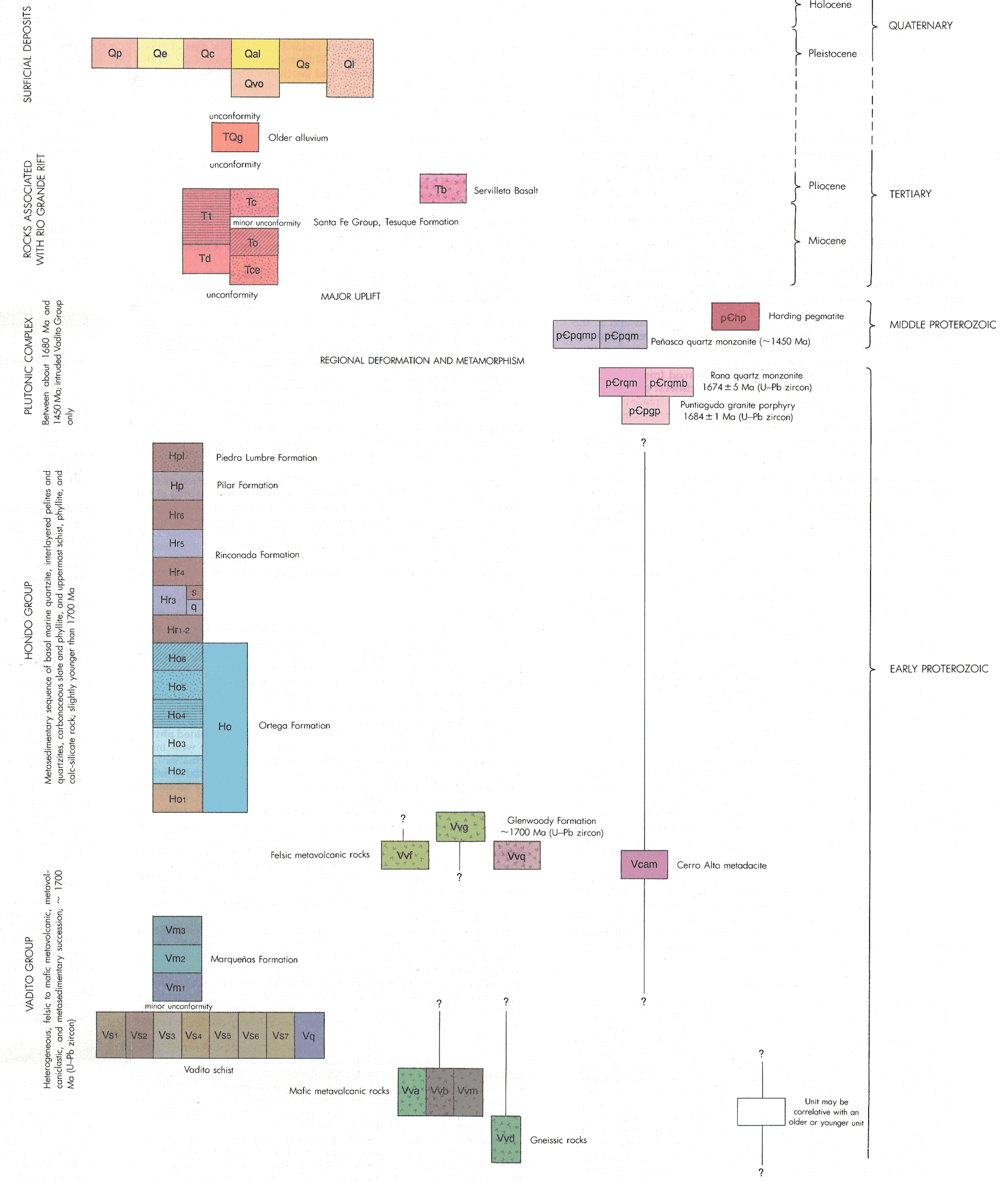
Mine dump

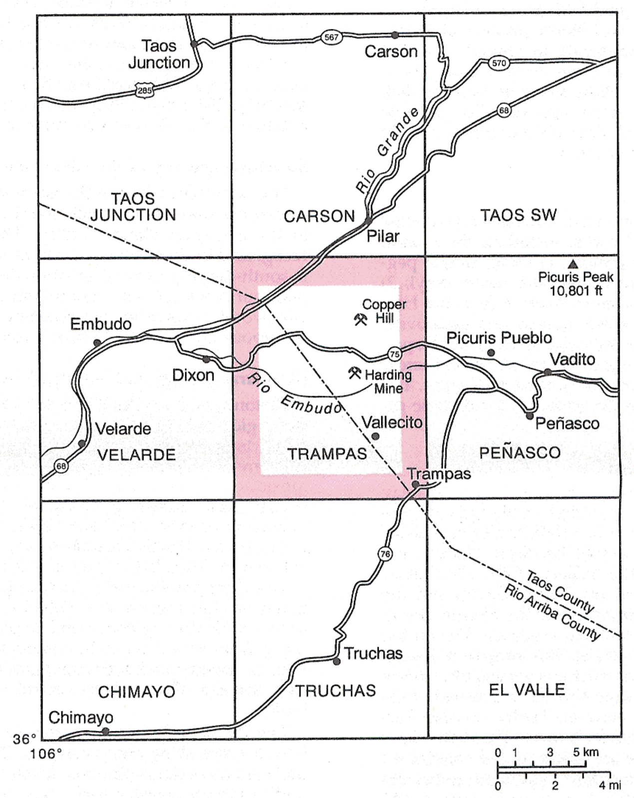
Minor prospect

Orientation and intensity of tectonic foliation—In granitic rocks

Marsh

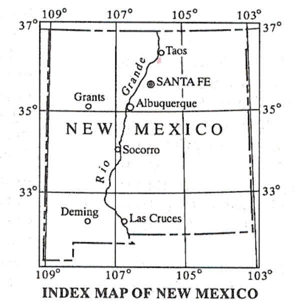
CORRELATION OF UNITS





TRUE NORTH
MAGNETIC NORTH
10°40'
APPROXIMATE MEAN DECLINATION, 1993

Sorting beryl at the Harding pegmatite mine. From left to right: Arthur Montgomery, Flaudio Griego, A. E. Archuleta, the mule Beryl, Juan Romero, Eliseo Griego, and Pablo Rendon. Photo by Laura Gilpin, 1953. © 1981, Laura Gilpin Collection, Amon Carter Museum, Fort Worth, Texas, negative no. A 4731.6.



INDEX MAP OF NEW MEXICO

SCALE 1:24 000

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

text begins on back

INTRODUCTION

The Picuris Range of north-central New Mexico is a Precambrian-cored, fault-bounded, wedge-shaped uplift that projects westward from the southern Sangre de Cristo Mountains. This isolated range lies approximately 20 km (12.4 mi) southwest of Taos and includes an area approximately 15 km by 30 km (9.3 mi by 18.6 mi). The Picuris block forms part of the constriction that separates the en echelon Española and San Luis Basins in the northern Rio Grande rift. The southeastern margin of the San Luis Basin is a major hinge fault, called the Embudo fault zone, that separates the east-tilted basinal block from the west-tilted Picuris block (Baltz, 1978). Before rifting, this region represented a broad Laramide structural high between the Great Plains and the Colorado Plateau (Baltz, 1978). Baltz (1978) showed that the Precambrian rocks in the Picuris area were high in Oligocene and early Miocene time. The present deeply eroded, Precambrian-cored Picuris block has remained high at least since 5–3 Ma when it was rapidly uplifted (Manley, 1984).

To the north, west, and south of the Picuris block, basement rocks are bounded by Tertiary sedimentary and volcanic rocks associated with the Rio Grande rift. These Tertiary units are found within the San Luis Basin to the north and the Chamisal–Peñasco reentrant of the Española Basin to the south. To the east, basement rocks are either in fault contact with or are unconformably overlain by upper Paleozoic sedimentary strata of the southern Sangre de Cristo Mountains. Northwest of the Picuris Range in the 1,000-ft-deep Rio Grande gorge, the river has cut through the flat-lying Tertiary sediments and basalts of the Taos Plateau (elev. 7,000 ft). Several Quaternary/Tertiary geomorphic surfaces along the northern and southern flanks of the range onlap basement rocks and are dissected by arroyos.

The Trampas 7½-min quadrangle is located at the westernmost point of the wedge-shaped Picuris uplift. The Rio Grande gorge and Embudo fault zone cross the northwest corner of the quadrangle. Early Proterozoic metamorphic rocks are exposed across most of the northern half of the Trampas quadrangle. To the west these rocks are blanketed by Neogene Santa Fe Group (Tesuque Formation) sedimentary rocks. In the northwest corner of the quadrangle the Rio Grande cuts through Tertiary sediments and basalts of the Rio Grande rift. Landslide deposits cover most of the river valley slopes. Except for scattered outcrops of Proterozoic rock, the southern half of the quadrangle is covered by Tesuque Formation sedimentary units and Pliocene–Pleistocene surficial deposits. Two areas of economic importance within the Trampas quadrangle are the Harding pegmatite mine and the Copper Hill mining district.

The rugged mountains within the quadrangle have deep, steep-walled canyons separated by sharp ridges; 2,866 ft of relief exist between the elevations of 8,666 ft at La Sierrita (Copper Ridge) and 5,800 ft along the Rio Grande near the town of Rinconada. Climatic conditions and vegetation vary considerably over the range. At lower elevations, particularly along the southern slopes, precipitation is low, and scattered pinon pine and juniper are the predominant flora. At higher elevations and in the central canyons, ponderosa pine and aspen form dense forests. Outcrop exposure likewise varies from excellent in many of the dryer areas to poor on heavily forested slopes and in the wetter valleys.

Two state highways traverse the map area. The road from Española to Taos, NM–68, parallels the Rio Grande in the northwest quadrant, and NM–75 runs east–west across the central part of the quadrangle. The western edge of the Picuris Pueblo Grant follows the eastern boundary of the quadrangle. The villages of Dixon and Rinconada lie within the west-central map area, and Trampas is at the southeast corner of the quadrangle. Other small communities are scattered along the many gravel roads south of NM–75.

This study of the Trampas quadrangle is an outgrowth of Bauer's mapping of the Proterozoic geology in the eastern Picuris Mountains in 1983–1987. The geology shown on this map is a combination of earlier work by Helper and the numerous contributors and mapping done by Bauer in 1988 and 1989 for the New Mexico Bureau of Mines and Mineral Resources. The Copper Hill area has long served as a unique teaching laboratory for geology students. For 25 yrs geologic mapping in this area has been an integral part of field camps for such schools as the University of North Carolina, University of Texas at Austin, University of Texas at Dallas, Southern Methodist University, University of New Mexico, New Mexico Tech, Louisiana State, University of South Florida, and others. This is the first of six 7½-min quadrangles covering the entire mountain range that will be published by the New Mexico Bureau of Mines and Mineral Resources.

ACKNOWLEDGMENTS—The New Mexico Bureau of Mines and Mineral Resources provided support for mapping and drafting of the quadrangle. Special thanks to Frank Kottlowski, former State Geologist and Director, for supporting the work. Reviews by Jeff Grambling and Chris Mawer improved the map and manuscript.

PRECAMBRIAN GEOLOGY

Numerous studies have addressed the problems of stratigraphy and structural evolution of Proterozoic rocks in the Picuris Mountains (Montgomery, 1953; Nielsen, 1972; Long, 1976; Scott, 1980; Holcombe and Callender, 1982; Hurd, 1982; McCarty, 1983; Bell, 1985; Bauer, 1987a). Montgomery (1953) mapped the entire range in reconnaissance fashion and interpreted the structure. His accurate field mapping has proven to be extremely useful during our study, and his rock descriptions and interpretations of structures are excellent and are highly recommended to interested readers.

All Precambrian supracrustal rocks in the region are of Early Proterozoic age and appear to be polydeformed and metamorphosed to amphibolite facies. Granitic plutons in the southern Picuris Mountains range in age from about 1680 Ma to 1450 Ma (Bell, 1985). In general, metasedimentary rocks crop out in the northern part of the area, and metavolcanic and plutonic rocks crop out to the south. Several major north- and northwest-striking, high-angle faults disrupt the section.

Rock units

The Trampas 7½-min quadrangle contains extensive exposures of south-dipping Early Proterozoic metamorphosed supracrustal and plutonic rocks that can be divided into three lithostratigraphic groups. Precambrian stratigraphic nomenclature employed on this map is based on that proposed by Bauer and Williams (1989), which is partly derived from Just (1937), Montgomery (1953), Miller et al. (1963), Nielsen (1972), Long (1976), and Scott (1980). In the northern part of the map area, the metasedimentary Hondo Group consists mainly of ridge-forming quartzites, pelitic schists, and various phyllites. To the south, structurally above the Hondo Group, is the heterogeneous metavolcanic–metavolcaniclastic–metasedimentary Vadito Group, which includes the Marqueñas Formation. Intrusive into the southern Vadito Group are at least four granitoids that range in age from about 1680 Ma to 1450 Ma (Bell, 1985). In the extreme north-central map area, structurally below the Hondo Group, is a homogeneous sequence of feldspathic metavolcanic–metavolcaniclastic(?) quartz-eye schists called the Glenwoody Formation. Stratigraphic and temporal relationships between the three major lithostratigraphic units are uncertain due to tectonization along their mutual contacts. However, based on stratigraphic relationships in nearby mountain ranges, the Vadito Group probably lies stratigraphically beneath the Hondo Group (Bauer and Williams, 1989), and the Glenwoody Formation is most likely part of the uppermost Vadito Group (Bauer, 1987b).

Additional and more detailed lithologic descriptions and sedimentologic interpretations are presented in Montgomery (1953, 1963), Nielsen (1972), Gresens and Stensrud (1974), Long (1976), Nielsen and Scott (1979), Scott (1980), McCarty (1983), Soegaard and Eriksson (1985, 1986), and Bauer (1987a, 1993).

Vadito Group

The Vadito Group is a heterogeneous succession of complexly interlayered, metamorphosed volcanic, volcaniclastic, and clastic sedimentary rocks with a minimum apparent thickness of 3–4 km (1.9–2.5 mi). Rock types within this group change considerably along strike, pinch out and reappear, and probably represent deformed felsic and mafic volcanic rocks interlayered with volcaniclastic and epiclastic sediments. Crossbeds in Vadito Group quartzites suggest an overall younging to the north (Bauer, 1987b). In the Trampas quadrangle the group generally consists of, from north to south, the Marqueñas Formation, the Vadito schist, and the Vadito amphibolite (Long, 1976).

The Marqueñas Formation is a 600-m-thick (2,000-ft-thick) sequence of micaceous, crossbedded quartzite and clast-supported, polymictic metaconglomerate apparently deposited on a braided alluvial plain (Soegaard and Eriksson, 1986). Clasts in metaconglomerates consist of approximately 66% quartzite, 34% felsic schist, and small amounts of vein quartz, mafic schist, and calc-silicate rock (Mawer et al., 1990). The Marqueñas Formation was originally deposited as part of the upper Vadito Group and now is overturned and in fault contact with younger Hondo Group rocks to the north.

Vadito Group schists include a variety of fine-grained phyllitic schists and micaceous quartzites that are interlayered with lesser amounts of quartz–muscovite–feldspar schist, amphibolite, and quartzite, all of which thicken, thin, and pinch out along strike. Rare crossbeds are present in the quartzites. McCarty (1983) interpreted the schist unit as having been a sequence of fine- to medium-grained graywackes, micaceous quartz sandstones, pelitic shales, minor basalt flows, and volcaniclastic sedimentary rocks that were intruded by minor felsic and mafic sills and dikes. A possible depositional setting for these rocks is in a continental shelf basin or intracratonic basin in which the accumulation of graywackes is punctuated by influxes of quartz sand, pelitic mud, volcaniclastic sediment, and basalt flows. A preliminary unpublished U–Pb zircon age from felsic metavolcanic schist north of the Harding mine is ca 1695 Ma (S. A. Bowring, pers. comm. 1993).

The contact between the Marqueñas Formation and the Vadito Group schist is poorly exposed. If the boundary represents a depositional surface of conglomerate atop graywacke, then the contact is unconformable because of the disparity between the depositional environments of the shallow-water conglomerate and the deeper-water graywacke sequence.

The Vadito Group amphibolite unit consists of two main amphibolite bodies, a large body to the south of the schist and a smaller body to the southeast. Primary volcanic features such as pillows, pillow breccias, and relict vesicles are uncommon (Long, 1974). McCarty (1983) interpreted the amphibolite unit as having been a mafic volcaniclastic sequence intruded by felsic dikes and sills.

Most of the Vadito Group in the Picuris Range is lithologically similar to the Vadito Group in adjacent ranges. In the Tusas Mountains, Vadito Group felsic metavolcanic rocks have yielded U–Pb zircon ages of about 1700 Ma (L. T. Silver, pers. comm. in Williams, 1987). Rocks of the Vadito Group are lithologically, texturally, and geochemically similar to modern incipient rift assemblages (Condie, 1986; Grambling and Ward, 1987; Williams, 1987; J. M. Robertson, pers. comm. 1987; M. L. Williams and S. Seaman, pers. comm. 1993).

Glenwoody Formation

The Glenwoody Formation (Bauer and Williams, 1989) is exposed in cliffs along the Rio Grande in the north-central part of the map area. The unit consists of approximately 180 m (600 ft) of layered, relatively homogeneous feldspathic quartz-eye quartz–muscovite schist. Thin sections from throughout this unit show anhedral to euhedral quartz megacrysts in a fine-grained matrix of quartz, muscovite, and feldspar. The only major variation in mineralogy is due to manganese and rare-earth-element enrichment in the uppermost 30 m (100 ft) of the section (Codding et al., 1983).

The Glenwoody Formation and the Vadito Group are nowhere in contact in the Picuris Mountains, and therefore structural and stratigraphic relationships between the two remain unknown. However, in the Vadito Group type section of the Tusas Mountains (Bauer and Williams, 1989) very similar feldspathic quartz-eye muscovite schists are found near a transitional zone of uppermost Vadito Group just beneath the Hondo Group. The Glenwoody Formation probably represents a similar stratigraphic unit that was originally deposited near the top of the Vadito Group.

Textures throughout the Glenwoody Formation are consistent with a volcanic protolith such as a rhyolitic ash-flow tuff (Bauer, 1987a; Vernon, 1986). The manganese-rich zone at the top of the Glenwoody Formation may have originated by either: 1) a deep weathering zone on the Glenwoody Formation (Grambling and Williams, 1985b) or 2) hydrothermal manganese enrichment of seawater during the waning stages of volcanism and subsequent deposition of manganese on and with clay minerals (Williams, 1987).

A preliminary U–Pb zircon age of about 1700 Ma was reported by L. T. Silver (unpubl. data 1990) for feldspathic quartz–muscovite schist of the Glenwoody Formation. This age probably represents the crystallization of the felsic volcanic protolith. Several Rb–Sr and K–Ar ages from this unit range from 1708 Ma to 1316 Ma (Bauer and Pollock, 1993). Similar 1700-Ma felsic metavolcanic rocks in the Tusas Mountains have geochemical signatures similar to volcanic rocks in modern continental rifts or continental margin back-arc basins on or near continental crust (Robertson et al., 1993).

Hondo Group

The Hondo Group is a 2-km-thick (1.25-mi-thick) or thicker, transgressive sequence of mature terrigenous metasedimentary rocks that crop out in several of the major Precambrian-cored uplifts of northern New Mexico. The basal unit of the Hondo Group (Ortega Formation) consists of, in a simplified sense, a lower reddish-weathering, crossbedded quartzite and an upper pure, white to gray, massive, crossbedded quartzite. See text of map units for more complete lithologic descriptions. 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 the rock types vary along strike, nearly all formations and members are readily distinguishable throughout the range, and nearly all contain abundant stratigraphic younging criteria.

Based on sedimentological analyses, Barrett and Kirschner (1979) concluded that the Rinconada Formation was deposited as interbedded sand and mud in deltaic, fluvial, and shallow-marine environments in an east-elongate trough. Soegaard and Eriksson (1985) deduced that the Hondo Group accumulated on a broad, continental, shallow-marine shelf that gently sloped to the south and southeast. These rocks represent a transgression during which sediment input initially matched basin subsidence but ended with the drowning of the outer shelf and deposition of black, carbon-rich basinal muds.

The Piedra Lumbre Formation, the youngest unit of the Hondo Group in the Picuris Mountains, appears in two separate outcrop belts. In the northeastern exposure, the Pilar Formation–Piedra Lumbre Formation contact is gradational. The southern exposure of Piedra Lumbre Formation, however, is a fault-bounded block, in which Piedra Lumbre is faulted against the Marqueñas Formation to the south along the Plomo fault and against the Pilar Formation to the north. Unknown thicknesses of Piedra Lumbre–Pilar Formations and uppermost Vadito Group are faulted out in this area.

No radiometric dating constrains the time of deposition for the Hondo Group in the Picuris Mountains. If the Ortega Formation did rest in primary stratigraphic contact on the Glenwoody Formation before faulting, then the Hondo Group probably accumulated shortly after 1700 Ma. In support of this, Grambling (1986) 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.

The Hondo Group developed subsequent to rifting on a stable continental shelf during a first-order sea level rise (Soegaard and Eriksson, 1985). 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, pers. comm. in Williams, 1987). This range of ages implies that although one source of the Ortega Formation could have been the underlying felsic volcanic rocks of the Vadito Group, another source was apparently unknown rock(s) elsewhere (Williams, 1987).

Stratigraphy of the Hondo Group at Copper Hill

The east-trending Copper Hill closely approximates the anticlinally folded contact between the Ortega Formation and the less-resistant Rinconada Formation. Remnants of uneroded Rinconada schists flank Copper Hill on all sides, and isolated patches are exposed across the eastern part of the hill. Only the uppermost 40 m (131 ft) of the kilometer-thick Ortega Formation are exposed on Copper Hill, mostly in abandoned mine workings, adjacent to minor faults, and in a north-trending valley (Rattlesnake Canyon) that cuts the western end of Copper Hill.

In the Copper Hill area the Ortega Formation is divided into three lithologic units, designated Oq_1, Oq_2, and Oq_3 by Williams (1982). These units correspond to *Ho4*, *Ho5*, and *Ho6* on this map. The lowermost unit (*Ho4*) is massive, clean, blue-gray quartzite with distinctive dark-gray bands that commonly define trough cross-stratification. The quartzite consists of >95% recrystallized, equigranular quartz and minor amounts of kyanite, muscovite, hematite, ilmenite, rutile, sphene, zircon, and other heavy minerals. Dark crossbed surfaces are defined by hematite and minor amounts of ilmenite and rutile. Muscovite and kyanite are disseminated throughout the massive quartzite and also exist as local concentrations on crossbed surfaces.

Ho5 is a sugary to vitreous, 3–5-m-thick (10–16-ft-thick) quartzite characterized by kyanite-covered weathering surfaces and opalescent quartz megacrysts. In thin section the quartz grains are bimodal with 2–3 mm quartz grains scattered in a matrix of 0.1–0.5 mm polygonal quartz. Kyanite is present in thin, well-foliated layers and as disseminated crystals within the massive quartzite layers, but unlike *Ho4*, kyanite-rich layers are not associated with hematite concentrations.

The uppermost Ortega Formation unit on Copper Hill (*Ho6*) consists of clean, white, sugary quartzite interlayered with pods, lenses, and layers of massive, knobby, gray, andalusite-bearing quartzite. Thicknesses of individual layers vary along strike from a few centimeters to several meters. In thin section the quartzite contains equigranular, polygonal quartz grains and disseminated, weakly aligned muscovite and kyanite. A characteristic mineral in the uppermost Ortega Formation is fuchsite, a green chromium-bearing muscovite (J. A. Grambling, pers. comm. 1991). Andalusite-rich layers contain abundant ovoid, 1–5 mm andalusite porphyroblasts that are extremely poikiloblastic, with >50% included quartz, and that are typically surrounded by a rim of coarse-matted muscovite. Accessory minerals (hematite, rutile, and tourmaline) are rare, and original cross-laminations are absent. The andalusite-rich layers in *Ho6* probably represent original, aluminum-rich sedimentary horizons in the sandstone.

Nielsen's (1972) original Rinconada Formation stratigraphy of four schists and two quartzites, based on exposures on the south limb of the Copper Hill anticline, has been revised to accommodate along-strike and across-strike variations in the units elsewhere in the quadrangle. The six units are designated, from oldest to youngest, *Hr1-2* to *Hr6*. Detailed descriptions of these units are in the map explanation. Although *Hr6* and *Hr5* are everywhere similar to their type designations, *Hr4* has been expanded to include a variety of thin pelitic schists, calc-silicate rocks, marbles, and quartzites that crop out north and east of Copper Hill between the *Hr5* and *Hr3* quartzites. *Hr3*, a crossbedded quartzite, includes two mappable thin schist units west, north, and northeast of Copper Hill. The thin green quartzite described by Nielsen (1972) separating the *Hr2* schist from the *Hr1* schist is apparently a local facies restricted to the southern limb of the Copper Hill anticline. Without this marker bed the distinction between the two units, which are similar in grain size and mineralogy away from Copper Hill, is not readily apparent. However, based on a study in sec. 8 and to the northeast of the map area in Hondo Canyon, Holdaway and Goodge (1990) stated that *Hr1* consists of muscovite + quartz + biotite + andalusite + spessarite (± staurolite, hematite–ilmenite, sillimanite, magnetite, plagioclase), whereas *Hr2* contains muscovite + quartz + biotite + staurolite + almandine + ilmenite + garnet + plagioclase. On this map the two units have been merged into a single unit, designated *Hr1-2*.

Cerro Alto metadacite

The Cerro Alto metadacite is a fine-grained, gray, foliated, stocklike body that sits within supracrustal rocks of the Vadito Group in the east-central part of the map area. Adjacent plutonic rocks appear to cut the main metadacite body, and thus Long (1976) concluded that the metadacite is the oldest granitic body in the area. Bell (1985), however, found no evidence for later intrusion of the Cerro Alto metadacite by the Puntiagudo granite porphyry or the Rana quartz monzonite and concluded that the Cerro Alto body was contemporaneous with the Vadito amphibolite. Field relationships on this matter are unclear. The pluton is either part of a larger subvolcanic complex that was emplaced at a shallow depth in the Vadito Group before intrusion of the Puntiagudo and Rana plutons or a volcanic unit interlayered in the Vadito Group.

Puntiagudo granite porphyry

The Puntiagudo granite porphyry consists of subequant, subhedral, Carlsbad-twinned, 1-cm-long microcline phenocrysts and rounded quartz phenocrysts in a plagioclase, K-feldspar, biotite, muscovite matrix. Modally, the rock ranges from quartz monzonite to granodiorite. The pluton is well foliated and crosscuts some Vadito Group rocks along sharp contacts. The intrusion nowhere penetrates rocks of the Hondo Group. Bell (1985) noted that the Puntiagudo intrudes the Vadito schists but does not intrude the Vadito amphibolite, and he reported a U–Pb zircon age of 1684 ± 1 Ma.

Rana quartz monzonite

The Rana quartz monzonite is the most widely exposed of the plutonic rocks in the southern Picuris Range. The Rana is well-foliated, medium-grained biotite quartz monzonite to granodiorite, with a discontinuous fine-grained, gradational border zone. This body also is strongly discordant with Vadito Group country rocks. Bell (1985) suggested that this unit intrudes Vadito schist but not Vadito amphibolite. In the one area where the Rana pluton is in contact with the Vadito amphibolite, the fine-grained border zone that everywhere else rims the pluton is absent. The Puntiagudo–Rana contact zone typically has well-defined foliation aligned parallel to the contact. In some areas the Rana pluton intrudes Puntiagudo rocks. Bell (1985) reported a U–Pb zircon age of 1674 ± 5 Ma.

Peñasco quartz monzonite

Long (1976) found the Peñasco quartz monzonite to be the youngest plutonic body in the southern Picuris Range. The contact between Peñasco and country rock is generally parallel to country-rock contacts in the pluton's northern exposure. Peñasco rocks are less foliated than the other granitoids in the area, although locally the pluton exhibits a well-developed border foliation that is defined by both aligned feldspar laths (magmatic foliation) and flattened and aligned quartz and biotite grains (solid-state foliation). It is a biotite–sphene quartz monzonite to granodiorite that locally contains abundant, large (as much as 9 cm long) megacrysts of Carlsbad-twinned microcline and mafic xenoliths along its borders. Bell (1985) reported a poorly constrained U–Pb zircon age, based on a single point, of about 1448 Ma. L. T. Silver (unpubl. data 1990) reported a U–Pb zircon age of about 1460 Ma for the Peñasco pluton.

Pegmatites

Pegmatites are common in the southwestern Picuris Range and cut most granitic rock types and many supracrustal rocks, including the Hondo Group. Long (1974) divided them into five groups: 1) small, simple pegmatites with microcline, quartz, albite, muscovite, and green beryl; 2) larger, variably zoned bodies with unusual mineralization (e.g. the Harding pegmatite); 3) small, zoned bodies of albite, quartz, and muscovite; 4) small dikes of pegmatite–aplite; and 5) medium-size dikes of K-feldspar, plagioclase, quartz, and tourmaline. These pegmatites commonly cut across abundant, deformed quartz veins that are present in most rock types. The Harding pegmatite is described in detail in the section on economic geology.

Structural geology

All supracrustal rocks in the Picuris Range are polydeformed and display overprinted tectonite fabric. The deformation of Proterozoic rocks is complex; in general it consists of shortening and north-directed progressive shearing and folding. During crustal shortening imbricate blocks were transported northward (Grambling et al., 1988; Williams, 1987, 1991; Bauer, 1987a, 1993). On the mountain range scale, the Vadito Group and the Glenwoody Formation occupy similar positions below the Hondo Group in the northern and southern areas of Proterozoic exposure. Within the Trampas quadrangle, the boundary that separates Vadito Group from Hondo Group south of Copper Hill is a south-dipping ductile reverse fault, known as the Plomo fault. South of Copper Hill, near NM–75, a 2-m-wide (6.5-ft-wide) pod of Pilar Formation is caught between Piedra Lumbre Formation and Marqueñas Formation along this fault zone. Quartzite clasts in Marqueñas Formation metaconglomerate are flattened and constricted in a mylonitic foliation that parallels the fault contact. Kinematic indicators (asymmetric porphyroclasts) in the Marqueñas Formation indicate north-directed ductile shearing of Vadito Group up and over Hondo Group. South of the fault, Vadito Group rocks young to the north and therefore are overturned. North of the fault, Hondo Group rocks on the south limb of the Copper Hill anticline young to the south and thus are right side up. The amount of slip along this southern shear zone is unknown but must be on the order of kilometers, judging from the juxtaposition of inverted Vadito and upright Hondo Groups. Apparent stratigraphic throw increases to the east, as the Pilar and Rinconada Formations are successively cut out until Vadito Group rocks rest directly on the Ortega Formation.

The contact between the Glenwoody Formation and overlying upright Ortega Formation is abrupt and well exposed along the Pilar shear zone in the Pilar cliffs of the northwestern part of the range. In the contact zone, a variety of pink and gray quartzose mylonites containing large asymmetric porphyroclasts and shear bands indicates south-directed shearing. In contrast, just below the quartz mylonite is a schistose zone containing S–C structures that suggest north-directed shearing. A well-developed extension lineation defined by quartz rods plunges southward downdip on foliation surfaces. The intensity of shear strain appears to decrease away from the Ortega Formation–Glenwoody Formation contact.

In the following text four broad subdivisions of Precambrian structures are described on the basis of their timing with respect to the major folding: 1) phase-1 structures that predate folding, 2) phase-2 fold structures, 3) small-scale phase-3 structures that formed after folding, and 4) mesoscopic phase-4 folds that overprint all earlier structures. Evidence suggests that at least phases 1 and 2 represent a single progressive deformation rather than independent deformational events (Bauer, 1987a; Williams, 1991).

Structural geology of the Hondo Group

Phase-1 is characterized by the earliest recognized foliation (S_1). This is a bedding-parallel schistosity defined by aligned muscovite, opaque minerals, inequant quartz grains, and flattened quartz and feldspar megacrysts, and it is most apparent in quartz-rich rocks. In most schists S_1 appears to have been transposed and modified by subsequent cleavage formation. Associated with S_1 is the earliest lineation, L_1, a downdip mineral alignment best seen in quartzite and defined by elongate grains of kyanite, muscovite, sillimanite, and quartz. Small, intrafolial isoclinal folds found locally may be phase-1 folds.

Phase-2 folds are the predominant structures in the Hondo Group. Well-preserved crossbeds in many quartzites and graded beds in some schists and phyllites provide excellent stratigraphic control in these structures. Phase-2 folds are inclined, tight to isoclinal, and shallowly east to west plunging. Axial surfaces dip 40°–80°S. On a macroscopic scale, phase-2 folding is best illustrated by the Hondo syncline, the dominant structure in the Picuris Mountains. It is a tight, shallowly west plunging fold with axial surface dipping 65°S. Dip values of modal S_0 range from an average of 60°S on the northern limb to 66°S on the overturned southern limb. As illustrated by the shape of the thick, mechanically stiff Ortega Formation, the map-scale fold geometry is simple. In detail, however, thinly interlayered units of the Rinconada, Pilar, and Piedra Lumbre Formations, with differing competencies, have folded disharmonically and noncylindrically. Numerous map-scale minor folds exist in the Rinconada and Pilar Formations. Outcrop-scale folds in the Hondo Group are also abundant.

Either S_1 or S_2 is generally the dominant foliation in rocks of the Hondo Group. Within *Hr4*, *Hr6*, and the Pilar Formation, S_2 is nearly coplanar with S_0–S_1 and axial planar to phase-2 folds. Foliation development in the Hondo Group is highly dependent on lithology. The most phyllitic units (*Hr6*, parts of *Hr4*, and Piedra Lumbre Formation) commonly contain three distinct, well-developed, penetrative cleavages: S_1, subparallel to compositional layering; S_2, at a small angle to S_1; and one or more later, crosscutting crenulation cleavages. In quartz-rich rocks S_0–S_1 is generally the dominant macroscopic foliation.

One fold of particular interest is the Copper Hill anticline in the northeastern map area. This structure has been the focus of numerous studies (Montgomery, 1953; Nielsen, 1972; Holcombe and Callender, 1982; Williams, 1982; Williams and Bauer, in press) and is unique in that it is the only large anticline recognized in the Hondo Group of the Picuris Mountains. The structure is tight and has an overturned northern limb. It plunges approximately 20°W, and its steeply south dipping axial surface folds a phase-1 schistosity along with compositional layering. In style and orientation the Copper Hill anticline resembles other phase-2 folds. The anticline can be traced east to the southern flank of La Sierrita (Copper Ridge) where the crest and southern limb have been removed by the combined effects of the southern shear zone and erosion. Farther east, in the Peñasco quadrangle, there is no evidence of the anticline, probably because the Plomo fault cuts upsection into the Hondo Group. The Copper Hill anticline is interpreted to be a phase-2 fold, cogenetic with the Hondo syncline.

Rocks in the Copper Hill area are deformed by a heterogeneous suite of brittle and ductile structures, possibly of diverse ages, that are here collectively termed phase-3 structures. *Ho6* and overlying Rinconada Formation schists contain phase-3, open, north-trending mesoscopic folds and small-scale crenulations. Phase-3 structures in the more massive *Ho4* and *Ho5* quartzites consist of north-trending vertical fractures and faults, generally with minor slips. It is not known how, or if, these dilatant brittle structures are affiliated with the shortening-related crenulations. The late-stage brittle structures played a critical role in the concentration of metallic minerals at Copper Hill. Apparently, during phase 3, the mechanically weak schists and andalusite quartzites deformed by ductile processes whereas the clean quartzites failed brittly (Williams and Bauer, in press).

The latest ductile structures recognized in the quadrangle are phase-4 folds that overprint all earlier surfaces and crenulations. In *Hr6* on the south limb of the Copper Hill anticline, S_4 is a west–northwest-striking crenulation cleavage that is axial planar to upright open-to-close box folds or to upright chevron folds. Phase-4 folds are similar in orientation to phase-2 folds but are more angular. Phase-4 structures appear to influence outcrop patterns over much of the western Picuris Mountains.

Structural geology of the Vadito Group

The structural history of the Vadito Group seems to be comparable with that of the Hondo Group. Useful sedimentary structures are limited mainly to crossbeds in the Marqueñas Formation and in other smaller scattered orthoquartzite bodies. All beds dip to the south, and most young to the north. Rocks in the Vadito Group contain an S_1 bedding-parallel foliation defined mainly by aligned micas in quartzose rocks. Associated with S_1 is a locally well developed downdip extension lineation (L_1) defined by aligned quartz, muscovite, and biotite grains on S_1 surfaces and by aligned, constricted clasts in metaconglomerates. Phase-1 folds are uncommon. A well-developed, regionally penetrative foliation (S_2) is the dominant fabric. This foliation is a schistosity in some rocks and a crenulation cleavage in others. Mesoscopic phase-2 folds are relatively common in the Vadito Group, though not as abundant or spectacular as those in the Hondo Group. In the Harding pegmatite mine area, where Vadito Group rocks are best exposed, large folds contain an S_2 axial-plane cleavage (Montgomery, 1953; McCarty, 1983; Bell, 1985). Mesoscopic folds are similar in style and orientation to the phase-2 structures in the Hondo Group.

Structural geology of the Glenwoody Formation

The dominant fabric in the Glenwoody Formation is a well-developed, somewhat anastomosing foliation that is parallel to compositional layering in the overlying Hondo Group. This is the earliest structural element recognized in these rocks, and in most areas it is the only foliation visible. A south-dipping mineral lineation defined by elongate quartz, muscovite, and tourmaline grains is ubiquitous on foliation surfaces. Textures in the Glenwoody Formation are probably due to the overprinting of primary tuffaceous layers by a secondary layer-parallel, shear-related foliation.

Structural geology of the plutonic rocks

Pluton ages from the Picuris Mountains are consistent with others from the region that fall into the ranges of 1700–1650 Ma and 1500–1400 Ma (Robertson et al., 1993); however, contact relations in the Picuris Mountains are not typical of the region. In general, granitoids in northern New Mexico exhibit certain geographic relationships with respect to the various supracrustal successions (Williams, 1990). Exclusive of the Picuris Mountains, intrusions in the Vadito and Hondo Groups are extremely rare. In the southern Picuris Mountains, however, parts of the Vadito Group are extensively intruded by pretectonic and syntectonic granitic plutons.

The older granitic rocks are strongly foliated and contain anastomosing zones of high shear strain. Foliation strikes of east to northeast are consistent with the regional trend of phase 2 in the Vadito Group. Interestingly, from south to north, toward the Plomo fault, pluton foliations (as well as country-rock foliations) gradually shift from northeast striking to east striking. This may be related to ductile shearing along the Plomo fault.

The Puntiagudo granite porphyry (1684 ± 1 Ma) crosscuts some Vadito Group rocks along sharp contacts. The Rana quartz monzonite (1674 ± 5 Ma) contains a discontinuous, foliated, fine-grained border zone, truncates Vadito Group country rock, and intrudes the Puntiagudo pluton. The Peñasco quartz monzonite (ca 1450 Ma) is generally weakly foliated except on its northern boundary where it grades to a well-foliated border region, which is consistent in orientation with the regional grain.

Some data exist for determining the relative timing of pluton emplacement and regional deformation. Both magmatic and tectonic foliations are developed in the older plutons. Magmatic foliations are defined by an alignment of feldspar megacrysts. Typically, feldspar alignment is parallel to a solid-state foliation characterized by flattened and constricted quartz grains and aligned micas. Foliation patterns in plutons are generally consistent with those in wall rocks. Wall-rock foliations do not wrap around plutons; instead, foliations can be traced continuously from wall rock into pluton. Unfortunately, the northwest-trending belt of intrusions in the southern Picuris Range is covered to the south by Cenozoic deposits. This makes it difficult to apply some of the criteria for timing of pluton emplacement with respect to regional deformation as described by Paterson et al. (1989). Field evidence, however, suggests that along their northeastern edges the 1680-Ma granitoid bodies are infolded with country rock around northeast-trending fold hinges. This is supported by local exposures of Rana quartz monzonite in which aplitic layers within coarser-grained granitic rock are folded around a northeast-trending axis with a well-developed axial cleavage that is parallel to the regional foliation.

Data support the interpretation that the 1680-Ma plutons were emplaced syntectonically with respect to the phase-1 and/or phase-2 structures associated with crustal shortening; whereas the 1450-Ma pluton was emplaced during a mild or waning stage of tectonism. Clearly, the Peñasco pluton has not seen all of the deformation that has affected the country rock and the older plutons.

The main belt of 1680-Ma intrusions trends northwest through the southwestern part of the range. The southwest margins of the plutons are everywhere covered by Cenozoic deposits, so shapes and contact relations are not known. It is possible that the plutons in the Picuris Mountains are continuous with, or part of, the vast terrain of largely unmapped plutons in the Santa Fe Range to the south.

Metamorphism

Mineral assemblages and garnet–biotite geothermometry indicate medium-grade (amphibolite facies) metamorphism. Peak metamorphic conditions were close to the aluminosilicate triple point (500°C, 4.0 kb; Holdaway, 1978; McCarty, 1983; Grambling and Williams, 1985a; Bauer, 1987a) at or near the time of major folding (Nielsen, 1972; Long, 1976; McCarty, 1983; Bauer, 1987a). In many rocks of the Hondo Group, two aluminosilicate polymorphs stably coexist (Williams, 1982), and in several locations all three coexist (Holdaway, 1971; Bauer, 1987a). The spatial distribution of these minerals may be due to the combination of near horizontal isograds and extreme local topographic relief. Sillimanite + kyanite rocks are found at lower elevations, whereas andalusite + kyanite rocks are found at higher elevations. Most rocks show minimal retrograde metamorphic effects.

Precambrian tectonic history

Field data support the following interpretation of stratigraphic 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. The Marqueñas Formation is a unit of the upper Vadito Group that is now in fault contact with the Hondo Group. The Glenwoody Formation is part of the uppermost Vadito Group, perhaps correlative with a section that has been faulted out in the southern Picuris Range. In the northern Picuris Mountains, the transitional volcanic–sedimentary section between Glenwoody Formation and Ortega Formation has been faulted out, if it ever existed.

With this stratigraphy, one model for the structural evolution and juxtaposition of units in the Picuris Range begins before 1700 Ma with eruption of mafic and felsic volcanic rocks (parts of the Vadito Group and Glenwoody Formation) and accumulation of associated sediments. Mature shallow-marine sediments (Hondo Group) then accumulated along a basin margin. Vadito Group felsic volcanism probably represents the final stage of stabilization of continental crust before Hondo Group accumulation and also may have provided one source for the great thickness of quartz sand that blanketed the region after 1700 Ma.

A dynamic and complex interplay of shearing, folding, plutonism, and metamorphism is recorded in the Picuris Range. The Hondo and Vadito Groups were deeply buried at ca 1680 Ma by a major orogenic event that greatly thickened the crust. The nature of phase-1 deformation is unknown. During crustal shortening granitoids were emplaced in the Vadito Group, and north-vergent phase-2 structures developed in a single progressive deformational event. As folding evolved an intense axial-plane cleavage (S_2) formed. Minor, bedding-parallel ductile faults and shear zones accompanied folding in the Hondo Group. Although heterogeneous shearing occurred throughout the section during phase-2 deformation, the highest shear strains were localized beneath the thick, mechanically stiff Ortega Formation along both limbs of the Hondo syncline. The Plomo and Pilar shear zones may have developed as a consequence of lockup on the Hondo syncline and Copper Hill anticline. During north-directed ductile faulting, the Vadito Group and associated plutons moved from a deeper structural level to adjacent to the Hondo Group along the Plomo fault. In the Copper Hill area, where the Plomo fault cut away from the base of the Ortega Formation, overturned (i.e. northward-younging but southward-dipping) Marqueñas Formation was juxtaposed against southward-younging and southward-dipping Hondo Group rocks on the southern limb of the Copper Hill anticline.

Data on the subsequent tectonic history of the Picuris Range are scarce. Daniel (1992) found that a Vadito Group garnet–biotite–plagioclase schist from the southwestern Picuris Range yielded a P–T path of decompression from about 5 kb to 3 kb at approximately 530°C. Other workers have recently proposed a major extensional event over much of New Mexico in Proterozoic time (Grambling et al., 1989).

Economic geology

Harding pegmatite mine

The Harding pegmatite is one of the most thoroughly studied pegmatite bodies in the world. It was first mined in the early 1920's for lepidolite, a lithium-bearing silicate used in the manufacture of heat-resistant glass. During World War II microlite, tantalite–columbite, beryl, and spodumene were extracted. This was the only mine in the world that produced appreciable volumes of microlite, and between 1950–1955 752 tons of beryl were extracted, making this mine the largest producer in the United States. For many years the mine was owned and operated by Dr. Arthur Montgomery. In 1974 he donated the mine to the University of New Mexico for preservation as an outdoor laboratory of a unique, world-class mineral deposit. An excellent summary of the research and mining history is found in Jahns and Ewing (1976).

The Harding pegmatite is the largest of a series of complex zoned pegmatites emplaced in the Vadito Group. The east–west trend of the pegmatite bodies coincides roughly with the schist–amphibolite contact, although the pegmatite crosscuts the more steeply dipping country rock. Many of these pegmatites are internally zoned with prominent cores of massive quartz surrounded by alkali feldspars, quartz, muscovite, garnet, and beryl. The main Harding pegmatite body has an exposed length of approximately 335 m (1,100 ft) and an exposed thickness ranging from a few meters to approximately 76 m (250 ft) in the main quarry area. The major minerals now present in the mine include quartz, albite, microcline, muscovite, lepidolite, and spodumene. Principal accessory minerals are apatite, beryl, garnet, microlite–pyrochlore, and tantalite–columbite. In addition, at least 44 other minor accessory minerals have been identified (Jahns and Ewing, 1976).

Although no granitic rocks crop out in the proximity of the mine, several Precambrian granitic plutons, including pegmatitic phases, are exposed to the west, south, and east. Brookins et al. (1979) concluded that the pegmatite was injected as a volatile-rich magma at about 600°C at a depth of 6.0–7.5 km. Based on experimental phase equilibria, London (1984) deduced that lithium-rich pegmatites such as the Harding might crystallize and recrystallize over a broad P–T interval (e.g. over relatively long periods of time). Northrup and Mawer (1990) proposed that the pegmatite was emplaced late syntectonically in the Vadito Group along a dilatant shear zone. Although several workers attempted to isotopically date the pegmatite, reported ages differ considerably. At least 38 radiometric ages have been reported for the Harding pegmatite (Bauer and Pollock, 1993). Nearly all are Rb–Sr mineral ages, which range from 1899 Ma on cleavelandite to 718 Ma on microcline. S. A. Bowring (pers. comm. 1991) reported a U–Pb zircon age of about 1400 Ma for the pegmatite. This is probably close to the age of crystallization. Although the magmatic source of the pegmatite is unknown, it appears most closely related in time to the Peñasco quartz monzonite, which does contain a coarse pegmatitic phase in the southeast map area.

References for the Harding pegmatite include Montgomery (1953), Long (1974), Jahns and Ewing (1976), Register (1979), Brookins et al. (1979), Bauer et al. (1991), and a pamphlet containing a walking tour published by the University of New Mexico Department of Geology.

Copper Hill mining district

The discovery of gold, silver, and oxidized copper minerals on Copper Hill resulted in extensive prospecting between 1900 and 1905 (Lindgren et al., 1910). Mining began about this time in the area of the Champion vein on the western half of Copper Hill. The "Champion mine" consisted of two shafts and the 100-m-long (328-ft-long), south-trending Champion adit that connected the shafts. Attempts at mining the deposits were unsuccessful, and for 65 yrs the hill remained undisturbed. Until recently, all significant mineralization was considered to be localized in the major, north-trending quartz veins that cut Copper Hill. Lindgren et al. (1910) described the ore as "veins of glassy quartz carrying copper, silver, and gold." Williams (1982) identified disseminated clumps of chalcocite, malachite, and chrysocolla in samples of homogeneous, recrystallized quartzite of the Ortega Formation. This disseminated mineralization was of considerable interest during the most recent exploration activity because of the possibility that the copper represented an originally syngenetic stratabound accumulation. Exploration included determining if high concentrations of ore minerals exist at depth below Copper Hill. Most recently, in 1990, Phelps–Dodge explored for gold in several deep drill holes on Copper Hill. Much of the following discussion is taken from the work of Williams and Bauer (in press).

Copper Hill is cut by near-vertical, north- to northeast-trending quartz veins, from several centimeters to more than 1 m (3 ft) thick, that are consistent in orientation and thickness along strike. The Champion vein, the largest and best exposed, consists of two or more en echelon veins, each bordered by a several-centimeter-wide zone of micaceous quartzite. In thin section the vein quartz is composed of polyhedral, undulose, interlocking, 1-cm quartz crystals. Most veins also contain as much as 1% finely disseminated kyanite, muscovite, and small sericite clumps that may represent altered kyanite.

Quartz veins on Copper Hill fill the north-trending, phase-3 fractures in *Ho4* and *Ho5*. No veins penetrate *Ho6* quartzite or the overlying Rinconada Formation schists. Instead, the veins ponded beneath these unfractured schistose rocks, a relationship best exposed at the southern end of the Champion vein where large lenses of vein quartz are layered along the base of *Ho6*. These mushroom-shaped lenses were apparently emplaced along the foliation at the upper termination of the Champion fracture system. After emplacement, a number of the quartz veins on Copper Hill underwent one or more periods of fracturing or brecciation with subsequent annealing of quartz.

Rocks of the Copper Hill mining district are well known for their diverse suite of oxidized copper minerals. The abundance of these minerals and crosscutting quartz veins in the Ortega Formation, as well as the green chromium-bearing mica fuchsite, gives Copper Hill its distinctive blue-green color and makes it a landmark in the Picuris Mountains. Most of the ubiquitous copper-stained quartzite, however, was not present at the original erosion surface of Copper Hill; instead, it accumulated on the dumps for the 50 or more shafts, prospect pits, and adits on the hill.

Mineralized samples from the Copper Hill district contain anomalous copper, silver, arsenic, antimony, and gold. The most common copper oxide and copper sulfide minerals are malachite, chrysocolla, chalcocite, cuprite, and covellite. Argentite, stibiconite, and tetrahedrite have also been reported (Lindgren et al., 1910). Three principal styles of mineralization are present: 1) quartz-vein-hosted copper minerals, 2) disseminated copper minerals in quartzite, and 3) oxidized copper minerals filling fine fractures in quartzite and quartz veins.

Mineralized quartz veins can still be found in the Champion adit and in several other prospect pits and adits. Although no quartz veins are exposed in the shafts, mineralized quartz is still on the dumps. The mineralized veins consist of white to glassy quartz, scattered dark-colored clumps of copper oxides and sulfides, and abundant malachite and chrysocolla-stained fractures. No alteration was observed in the Ortega Formation adjacent to the mineralized veins, except for a thin zone of mica-rich quartzite that borders the Champion vein. The most common quartz-vein mineralization is characterized by irregularly shaped clumps of fine-grained copper minerals and iron oxides that are completely enclosed within massive vein quartz. Terminated quartz crystals on the walls of several clumps suggest that open spaces may have been present at one time within the quartz veins. Locally, copper mineralization appears to have replaced kyanite crystals and fine muscovite clumps within the quartz veins.

Disseminated copper mineralization was identified in the Ortega Formation at Copper Hill by Williams (1982). It consists of opaque, star-shaped clusters (0.1–1.0 mm) of oxidized copper minerals, iron oxides, and rare copper sulfides isolated in a matrix of recrystallized, equigranular quartzite. Disseminated mineralization is almost exclusively within *Ho4* quartzite. Malachite, hematite, and muscovite exist in most samples. Chalcocite, covellite, and cuprite are found locally. Mineralized clusters contain 10–70% copper and variable amounts of silver, gold, arsenic, antimony, sulfur, and aluminum (Williams, 1982). Replacement may be an important mechanism for the development of most, if not all, disseminated mineralization. Most disseminated mineralization is adjacent to mineralized quartz veins. Williams (1982) concluded that the disseminated mineralization probably does not represent an originally syngenetic accumulation of copper minerals in the Ortega Formation.

Narrow fractures containing malachite and chrysocolla are characteristic of most *Ho4* samples and of most quartz veins on Copper Hill. In thin section the mineralized fractures cut across optically continuous quartz grains and also cut the disseminated and quartz-vein-hosted copper minerals. The fracture-filling copper mineralization can be distinguished from the two other types because of the restricted mineral composition, primarily malachite and chrysocolla with no sulfide phases, and because of the lack of elements such as silver, arsenic, and antimony that are characteristic of the vein-hosted and disseminated mineralization. The fracture-filling copper minerals probably represent one of the youngest features on Copper Hill as they cut all other forms of copper mineralization. The fracture-filling copper minerals may represent a remobilization of the vein-hosted and disseminated varieties.

All observations are consistent with the hypothesis that mineralization occurred after phase-2 folding and the peak of metamorphism but coincided with phase-3 deformation and retrograde metamorphism (Williams and Bauer, in press).

In the fall of 1991, New Mexico Abandoned Mine Land Bureau (Energy, Minerals and Natural Resources Department, Santa Fe, New Mexico) personnel supervised the backfilling of all of the shafts and adits in the Copper Hill district. These mine exposures are now inaccessible, although volumes of mine tailings remain at several sites. Most of the mineralized areas on Copper Hill are on private land, and therefore permission should be gained before a visit.

Glenwoody mining camp

The Glenwoody Bridge in the north-central map area marks the location of a short-lived gold mining operation by the Glen–Woody Mining and Milling Company. The bridge was built in 1902 on the piers of an old government bridge, and a townsite was constructed north of the river. The company attempted to develop what was thought to be a large low-grade gold deposit in the Glenwoody Formation. An experimental, 50-ton, water-powered cyanide mill was built south of the bridge. Operations were abandoned when gold recovery turned out to be much less than anticipated. Most of the gold was contained in quartz veins that cut the Glenwoody Formation.

CENOZOIC GEOLOGY

Any existing Paleozoic and Mesozoic sedimentary cover has been eroded from the Precambrian crystalline basement rock in the main block of the Picuris Range. All Phanerozoic units within the Trampas quadrangle are Miocene or younger. These deposits lie unconformably on Proterozoic strata in the western and southern parts of the map area as well as in topographic lows within the range. Paleozoic rocks rest unconformably on Precambrian basement rocks to the east and southeast of the Trampas quadrangle. Farther east, in the Sangre de Cristo Mountains, tremendous thicknesses of Paleozoic strata overlie crystalline basement rocks.

Within the quadrangle, investigation of Cenozoic geology has been limited to the work of Steinpress (1980) in the northwest quadrant and Manley (1976) in the southwest corner. In addition, Long (1976) mapped a number of Cenozoic units in his study of Precambrian rocks in the southern half of the Trampas quadrangle.

Stratigraphy

Within the Trampas quadrangle, Cenozoic units consist of sedimentary rocks of the Santa Fe Group, overlying basalts and alluvium associated with the Rio Grande rift, and Quaternary surficial deposits such as landslides, eolian sand, and alluvium.

The Tesuque Formation (Miocene to Pliocene) of the Santa Fe Group was originally defined near Santa Fe by Baldwin (1956). In the Picuris Range, Miller et al. (1963) described this sequence as buff-colored, poorly sorted, weakly consolidated sand, silt, gravel, volcanic ash, clay, and breccia that ranges in thickness from 500 to 3,500? ft (from 150 to 1,065? m). Much of this unit was derived locally from Paleozoic and Precambrian rocks, and in the map area the unit sits unconformably on Precambrian basement. Rock types typically change considerably along strike. Steinpress (1980) made a detailed study of Cenozoic stratigraphy in the western Picuris Range near the town of Dixon, where the Santa Fe Group is the predominant Cenozoic unit. His stratigraphic nomenclature is used on this map.

Basalt of the Pliocene Servilleta Formation forms the mesa in the northwest quadrant of the map area and also caps a small, isolated knob just south of the Rio Grande. Manley (1976) reported an age of 2.8 Ma for the basalt layer on Black Mesa to the southwest of the map area. Limited exposure of the basalt suggests that it erupted onto a nearly flat erosional surface of the Tesuque Formation.

The Ancha Formation consists of fan-deposited sand and gravel of several different ages that overlie the Tesuque Formation. Miller et al. (1963) considered the Ancha Formation to be Quaternary in age and the upper member of the Santa Fe Group. They suggested that this material represented a very large, dissected, once-continuous sheet and could be separated from recent alluvial deposits by position and consolidation. Manley (1976) thought that the Ancha Formation was post-Santa Fe Group and suggested that it may not be appropriate to name all such gravels the Ancha Formation. Long (1976) followed Manley's suggestion by informally naming these the gravel deposits of Cejita Mesa in the southwestern Trampas quadrangle. Steinpress (1980) called these deposits Pliocene(?)–Pleistocene(?) high-surface gravels. On this map these units are called older alluvium (*TQg*) and probably represent remnants of west-sloping pediment surfaces.

Long (1976) described younger terrace gravels, which presumably are derived directly from the gravel deposits of Cejita Mesa, and brown sand–soil deposits that may be eolian. The ages of these units are unknown. Landslide deposits are common along the Rio Grande in the northwestern map area, and small playa deposits are common behind toreva blocks in the landslide terrain.

Erosion and deposition of sand and gravel occurs at present in a number of active streams in and around the Picuris Range. Within the mountain range, recent alluvial and colluvial deposits are common.

Structural geology

The Embudo fault (Muehlberger, 1979), which lies buried in the northwestern map area, is the major crustal structure in the Trampas quadrangle. The fault is a segment of the much larger northeast-trending Jemez lineament, which has been a zone of crustal weakness since late Precambrian time (Muehlberger, 1979). The Embudo fault connects the en echelon Española and San Luis rift basins along the structurally complex Picuris constriction. Muehlberger (1979) estimated that structural relief across the fault was at least 10,000 ft (3,000 m). A number of different interpretations of this fault zone have been published (Montgomery, 1953; Kelley, 1978; Manley, 1978, 1979; Muehlberger, 1979; Aldrich, 1986). In a regional kinematic framework, the rhomb-shaped Picuris crustal block, bounded by the Embudo, Picuris–Pecos, Tijeras–Cañoncito, and Pajarito fault systems, has rotated counterclockwise (Muehlberger, 1979; Aldrich, 1986; Aldrich and Dethier, 1990) from a pivot point near Pilar. According to Muehlberger (1979) and Aldrich (1986) this resulted in reverse faulting along the segment between Pilar and the Taos area, down-to-the-south normal faulting southwest of Pilar (including the present map area), and minor(?) left-lateral slip along the southwestern trace of the fault zone.

Approximately 1 mi (0.6 km) northeast of Rinconada, in the northwestern map area south of the main Embudo fault, a complex zone of numerous small-displacement faults marks the northernmost part of the Velarde graben (Manley, 1979). Steinpress (1980) found evidence for both normal and left-lateral strike-slip movement along these faults in the Trampas quadrangle; however, he noted that the left-lateral slip could be minor compared to the normal slip. Several low-amplitude folds are associated with faulting. Although Steinpress (1980) reported no evidence of faulting during accumulation of Tesuque Formation in his map area, Muehlberger (1979) described high-angle reverse faults in Tesuque Formation farther to the northeast. Steinpress (1980) also concluded that most of the deformation occurred before 2.8 Ma (deposition of Servilleta Formation basalts) and that there is no evidence of Quaternary faulting in the map area. Aldrich (1986) reported major transcurrent movement on the Embudo fault zone during the Pliocene that has subsequently slowed.

A system of northeast-trending, east-stepping en echelon faults that cut Proterozoic and Cenozoic units and that parallel the Embudo fault are present in the west-central map area. Although originally thought to be Precambrian in age (Montgomery, 1953; Nielsen, 1972), mapping by Hall (1988) has shown that the longest fault strand in this zone offsets the base of Pliocene–Pleistocene pediment gravel (*TQg* of map). Movement along the en echelon faults is complex and demonstrably involves left-lateral and down-to-the-northwest slip, similar to that postulated for the Embudo fault zone northeast of Pilar (Muehlberger, 1979; Aldrich, 1986). Using the orientation of fault laminae on slickensided surfaces (S42°W,40°) at the northeast terminus of the longest fault and using the separation defined by distinctive blue quartzite marker beds in *Hr4*, Hall (1988) calculated 840 m (2,756 ft) of net slip—539 m (1,768 ft) of vertical slip and 643 m (2,110 ft) of horizontal slip—in sec. 8 near the northern terminus of the fault. Estimates of net slip decrease southwest along the trace of the main fault into sec. 24 (Hall, 1988). Distinctive, blue or white, well-cemented quartzite breccias are present along all fault traces where exposed in Hondo Group quartzites.

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DESCRIPTION OF UNITS

Nomenclature used for Precambrian rocks follows the suggestions of Bauer and Williams (1989). Subdivision of the Santa Fe Group generally follows that of Steinpress (1980)

Surficial deposits

Qal **Alluvium (Holocene and latest Pleistocene)**—Unconsolidated clay, silt, sand, and gravel on floodplains and in valley bottoms along modern drainages. Thicknesses variable

Qp **Playa deposits (Holocene and latest Pleistocene)**—Small playa deposits located on Quaternary landslide deposits in the northwestern map area. Generally found behind rotated toreva blocks

Qe **Eolian sand (Holocene and latest Pleistocene)**—Well-sorted, thin sand deposits that cover Servilleta Formation basalt flows in the northwestern map area. Thickness generally less than 3 m (10 ft)

Qc **Colluvium (Holocene and latest Pleistocene)**—Poorly sorted, unconsolidated slope debris, talus, and slump blocks on slopes and in steep valleys; silt- to boulder-size. Locally derived from upslope bedrock. Thickness variable

Qs **Older alluvium and eolian deposits, undivided (late and middle Quaternary)**—Brown-tan sand and silt, with lithic fragments and pebble layers, on upland surfaces. Locally includes colluvium of *TQg*, *Qvo*, and *Qal*. Thicknesses variable

Ql **Landslide deposits (Quaternary)**—Lobate deposits of chaotic sandstone and angular basalt blocks along the Rio Grande in the northwestern map area. Marked by hummocky topography and toreva blocks. Derived from Servilleta Formation basalt and underlying poorly consolidated sands of the Santa Fe Group. Locally includes colluvium. Thickness variable

Qvo **Fluvial terrace deposits, older (Pleistocene)**—Several levels of fluvial deposits of unconsolidated sand and gravel along present drainages. Clasts predominantly well-rounded Precambrian quartzite and Paleozoic sedimentary rocks. Three distinct terraces exist on the north side of Embudo Creek. As much as 20 m (66 ft) thick

Pliocene and Miocene rocks related to the Rio Grande rift

TQg **Older alluvium (early Pleistocene and Pliocene)**—Poorly sorted sand and gravel deposits, typically with layers containing large, rounded boulders of Proterozoic quartzite. Found on high erosional pediment surfaces, where it commonly forms colluvial veneer on underlying units. Locally discontinuous, especially on Mesa de la Cejita. Covers the Oso surface of Manley (1976). Maximum thickness of 10 m (33 ft)

Tb **Servilleta Formation, basalt (Pliocene)**—Dark-gray olivine tholeiitic basalt flows of the Taos Plateau volcanic field; typically with vesicular and pahoehoe textures. K–Ar isotopic age of 2.8 Ma reported by Manley (1976) from flow west of map area on Black Mesa. 20–25 m (66–82 ft) thick

Tt **Santa Fe Group, undivided (Miocene)**—Light-brown, poorly sorted conglomerate, sandstone, siltstone, and claystone of Mesa de la Cejita in the southwestern map area that represent piedmont deposits derived from the Sangre de Cristo Mountains to the east. Conglomerates contain clasts of Precambrian quartzite and granite. Part of Manley's (1977) Tesuque Formation (middle Miocene). Lapilli beds from southeast of Mesa de la Cejita yielded a zircon age of 10.8 Ma (Manley, 1976); however, both older and younger sedimentary rocks are included in the Tesuque Formation (Galusha and Blick, 1971)

Tc **Cejita Member of Tesuque Formation of Santa Fe Group (late Miocene)**—Coarse fluvial conglomerate and sandstone. Grayish-brown, well-sorted conglomerate contains rounded clasts of Precambrian quartzite and granite, Paleozoic sedimentary rocks, minor quartz, and Tertiary volcanic rocks. Represents the deposit of a major stream flowing westward from the Sangre de Cristo Mountains. Large crossbeds are exposed locally. Unconformably overlain by *TQg* alluvial gravels. Interfingers with *Tt*. At least 100 m (328 ft) thick

To **Ojo Caliente Sandstone of Tesuque Formation of Santa Fe Group (Miocene)**—Well-sorted, buff eolian sandstone; dominant grain size is fine sand. QFL proportions average 62% quartz, 28% feldspar, and 10% lithics. LvLsLm ratio averages 82% Lv, 8% Ls, and 10% Lm. Thin, reddish-brown, finely laminated siltstone horizons are found locally. Tabular crossbeds are common; sets over 4 m (13 ft) in height. Transport was from southwest to northeast. Conformably overlies and interfingers with Dixon member. Disconformably underlies the Cejita Member along sharp erosional contact. Deposited at 13–12 Ma (Steinpress, 1980). Approximately 250 m (820 ft) thick

Td **Dixon member of Tesuque Formation of Santa Fe Group (middle Miocene)**—Interbedded conglomerate (30%), sandstone (55%), and mudrock (15%). Greenish conglomerates contain pebble- to cobble-size clasts of Paleozoic sedimentary rocks. Sandstones are subarkose to arkosic arenite and generally gray to buff. Most mudrock is reddish-brown siltstone. Sandstone QFL percentages average 61% quartz, 24% feldspar, and 15% lithics. LvLsLm percentage averages 69% sedimentary lithics. Contains thin calcareous interbeds and rare debris-flow deposits. Represents distal alluvial-fan and braided-stream deposits derived from Paleozoic rocks of the Sangre de Cristo Mountains to the east–southeast. Interfingers with Chama–El Rito Member and Ojo Caliente Sandstone. Contact between Dixon and underlying Chama–El Rito is drawn at the base of the lowermost conglomerate in which clasts of Paleozoic sedimentary rocks predominate over clasts of Tertiary volcanic rocks. In the southeastern map area, Dixon member directly overlies Precambrian basement. Probably deposited between 14 Ma and 12 Ma (Steinpress, 1980). Thickness ranges from 260 to 450? m (853–1476? ft)

Tce **Chama–El Rito Member of Tesuque Formation of Santa Fe Group (middle Miocene)**—Sequence of nonfossiliferous sandstone (50%), conglomerate (42%), and minor mudrock interbeds (8%). Conglomerates are generally purplish to gray due to predominance of pebble-size clasts of Tertiary volcanic rocks. Sandstones are pinkish gray to buff and poorly to moderately sorted. Sandstones are transitional between arkoses and volcanic arenites. Siltstone and clayey siltstone beds are reddish brown and generally less than 1 m (3 ft) thick. Sandstone QFL percentages average 39% quartz, 31% feldspar, and 30% lithics. LvLsLm percentage averages 80% volcanic lithics. Beds of white calcareous volcanic ash, less than 2 m (6.5 ft) thick, are found locally. Clasts in basal part of unit are predominantly from Precambrian rocks. Fluvial and alluvial sedimentary structures are common. Represents braided-stream deposits on a distal piedmont alluvium derived from a volcanic terrane to the northeast. Covers Precambrian basement erosional surface that has considerable relief. Interfingers with Dixon member. Age is about 18–14 Ma (Steinpress, 1980). Pinches out to the southeast. Thickness ranges from 480 m to 0 (from 1575 ft to 0)

Precambrian granitic rocks

Pegmatite—Includes both simple (quartz–K-feldspar–plagioclase–muscovite) pegmatites and complex zoned pegmatites containing rare minerals. Simple pegmatites are by far the most abundant in the map area. Pegmatite bodies typically are dikes or lenses, locally aligned parallel to country-rock foliation. Thicknesses range from 2 cm to 15 m (from 1 inch to 50 ft). No apparent spatial relationship between pegmatite bodies and plutonic bodies, and no evidence to suggest that pegmatites are connected to plutons at depth. More than one generation of pegmatite formation is represented, and at least one generation is younger than the youngest granite at 1450 Ma (Long, 1976)

pЄhp **Harding pegmatite**—Complex asymmetrically zoned pegmatite body in the Vadito Group. Disk-shaped body elongate downdip and inclined in a plane that dips 10°–15° south. Approximately 350 m (1148 ft) long; thickness ranges from 1 m (3 ft) at edge to approximately 25 m (82 ft) at core. Major minerals include quartz, albite, microcline, muscovite, lepidolite, and spodumene. Principal accessory minerals are beryl, garnet, microlite, and tantalite–columbite. About 40 other minerals have been identified. Lath-shaped spodumene crystals as much as 5 m (16 ft) long. In general, from top to bottom, the eight lithologic units of the body are: beryl zone, quartz zone, quartz–lath spodumene zone, "spotted rock" unit, rose muscovite–cleavelandite unit, cleavelandite unit, perthite zone, and aplite zone. Replacement features are common. Moderate ductile deformation in pegmatite body, surrounding schist, and amphibolite country rock

pЄpqmp **Pegmatitic phase of Peñasco quartz monzonite**—Coarse-grained quartz–K-feldspar–plagioclase granitic body having pronounced myrmekitic texture. Distinctive intergrowth of plagioclase and vermicular quartz is common. No visible foliation. In the southeastern map area. Probably represents a high-level phase of the Peñasco quartz monzonite

pЄpqm **Peñasco quartz monzonite**—Biotite quartz monzonite to granodiorite. Composed of quartz, plagioclase, microcline, and biotite. Euhedral 1 mm sphene crystals common. Accessory minerals are muscovite, allanite, epidote, magnetite–hematite, apatite, and zircon. Locally contains tabular megacrysts of Carlsbad-twinned microcline as much as 9 cm in length. Myrmekite and albite rims on plagioclase are common. Massive to weakly foliated, except locally along contacts where foliation is well developed. A magmatic foliation is locally defined by aligned feldspar megacrysts. Generally concordant with country-rock contacts and foliation. No compositional border zone. Mafic microgranitoid inclusions common, especially near borders. Intrudes Rana quartz monzonite. U–Pb zircon isotopic age of about 1450 Ma (Bell, 1985)

pЄrqm **Rana quartz monzonite**—Medium-grained biotite quartz monzonite to granodiorite. Composed of quartz, plagioclase, microcline, and lesser amounts of biotite and magnetite–hematite. Accessory minerals are sphene, allanite, zircon, apatite, and epidote. Plagioclase extensively altered to sericite, epidote, and clinozoisite. Generally well foliated rock having local areas of weak foliation and zones of ductile shearing. Foliation is generally parallel to the dominant foliation in country rock. Contact with Puntiagudo granite porphyry is ductile shear zone. Contains a discontinuous fine-grained border zone of leucocratic muscovite granite (*pЄrpmb*). In general, strongly discordant with compositional layering in country rock. U–Pb zircon isotopic age of 1674 ± 5 Ma (Bell, 1985)

pЄrqmb **Border phase of Rana quartz monzonite**—Includes fine-grained porphyritic granite of quartz–muscovite–plagioclase–microcline and medium-grained muscovite granite and quartz monzonite. Accessory minerals are allanite, epidote, zircon, hematite, biotite, and garnet. Distinctly more leucocratic than main body of Rana quartz monzonite. Contact is gradational. Border-zone rocks commonly project into country rocks as dikes or tongues. Well-developed foliation concordant with regional trend

pЄpgp **Puntiagudo granite porphyry**—Quartz monzonite to granodiorite. Phenocrysts of Carlsbad-twinned microcline (<1 cm) and rounded quartz in fine- to medium-grained matrix of plagioclase, K-feldspar, biotite, and muscovite. Accessory minerals are epidote, allanite, sphene, and zircon. Narrow, fine-grained border zone locally. Sharp, discordant contact with Vadito Group schists. Locally, thin dikes of fine-grained rock project into country rock. Contact with Rana quartz monzonite is a zone of intense ductile shearing. Pervasive, moderately to well-developed foliation is parallel to regional foliation. Similar plutonic rocks in the southeastern corner of the map area may be equivalents. U–Pb zircon isotopic age of 1684 ± 1 Ma (Bell, 1985)

Precambrian Hondo Group

Hpl **Piedra Lumbre Formation**—Includes several distinctive rock types: 1) quartz–muscovite–biotite–garnet–staurolite phyllitic schist having characteristic sheen on crenulated cleavage surfaces. Euhedral garnets are 1 mm, biotite books are 2 mm, and scattered anhedral staurolites are as much as 5 mm in diameter; 2) finely laminated, light-gray phyllitic quartz–muscovite–biotite–garnet schist and darker-bluish-gray, fine-grained biotite quartzite to metasiltstone. Quartzite layers range in thickness from 1 cm to 1 m (3 ft); and 3) light-gray to gray garnet schist and lenses of quartzite to metasiltstone. Calc-silicate layers exist locally. Original sedimentary structures, including graded bedding, preserved. Well-developed cleavage parallel to both layering and axial surfaces of small intrafolial isoclinal folds. Dominant layering in much of this unit is transpositional. Contact zone with Marqueñas Formation is characterized by a variable thickness of highly strained black phyllitic slate that is similar to Pilar Formation. This slate may be a tectonic slice caught along the shear zone between Piedra Lumbre and Marqueñas Formations. Poorly exposed, faulted contact zone with underlying Pilar Formation is phyllitic and has streaky transposition layers and rootless isoclinal folds. Apparent thickness of formation is approximately 100 m (328 ft) in sec. 24. The exposed strip of Piedra Lumbre Formation in the map area is fault bounded and does not represent the entire unit. Northeast of the map area, in the core of the Hondo syncline, the Piedra Lumbre Formation is thicker, contains a greater variety of rock types, and is gradational with the Pilar Formation

Hp **Pilar Formation**—Dark-gray to black, carbonaceous phyllitic slates. Extremely fine grained homogeneous rock except for rare from 1- to 2-cm-thick light-colored bands of quartz and muscovite that probably represent true bedding. In thin section, fine-grained matrix consists of quartz (50–70%), muscovite (15–30%), and prominent streaky areas of graphitic material. Lenticular porphyroblasts (0.1–0.5 mm) are altered to yellow-brown limonite. Pervasive slaty cleavage is locally crenulated. Small isoclinal folds locally. Basal, 1.5-m-thick, black to blue-black, medium-grained garnet quartzite is distinctive. Garnets are anhedral, oxidized, and red weathered. In secs. 19 and 20, an approximately 12-m-thick (40-ft-thick) layer of red-stained phyllite that resembles Piedra Lumbre Formation is interbedded with black slate. Because the southern contact is a fault zone, thickness and contact with Piedra Lumbre Formation may not be representative

Hr6 **Rinconada Formation, r6 schist member**—Tan, gray, silver quartz–muscovite–biotite–staurolite–garnet schistose phyllite interlayered with fine-grained garnetiferous muscovite quartzite. Euhedral staurolites (<5 cm) abundant in some layers. Small euhedral garnets (<2 mm) throughout. Strong parting along well-developed foliation. Sharp contact with *Hp*. Thickness is approximately 90 m (295 ft)

Hr5 **Rinconada Formation, r5 quartzite member**—Variety of white to blue, medium-grained quartzites interlayered with fine-grained schistose quartzites and quartzose schists. Measured section by Hall (1988), from top to bottom: 1) tan to white, friable, thinly layered, crossbedded micaceous quartzite; 2) blue, medium-grained, thickly layered, locally crossbedded, resistant saccharoidal quartzite; 3) white to tan, friable schistose quartzite interlayered with blue, medium-grained saccharoidal quartzite; thin layers of fine-grained quartz–muscovite–biotite schist; massive, 1.5-m-thick, blue, medium-grained quartzite at base; 4) tan, thinly layered, crossbedded micaceous quartzite interlayered with quartz-rich muscovite schist; 5) blue- and white-streaked, thickly bedded, crossbedded, medium-grained quartzite; and 6) tan, thinly layered, crossbedded micaceous quartzite interlayered with quartz-rich quartz–muscovite schist. Gradational contact with *Hr6*. Thickness is approximately 75 m (246 ft)

Hr4 **Rinconada Formation, r4 schist member**—Medium- to coarse-grained, silvery-gray quartz–muscovite–biotite–staurolite–garnet schist containing one or more distinctive, 0.5–2.0-m-thick (1.5–6.5-ft-thick) layers of glassy-blue quartzite; rusty-red-weathering, garnetiferous, white quartzite; massive, extremely hard, red-weathering, olive-brown biotite–staurolite–garnet–orthoamphibole rock; white, glassy hornblende quartzite; gray biotite–hornblende calc-schist; mylonitic, blue to pink and blue, glassy quartzite; and white to gray calcite marble. The latter four rock types are not present on the south limb of the Copper Hill anticline (see Nielsen, 1972) but are present on both the upright and overturned limbs of the Hondo syncline in secs. 7, 8, 9, and 10. A well-exposed reference section of this thicker *Hr4* sequence can be found on the south-facing slope and crest of the ridge making up the northern half of the SW1/4 of sec. 8 (Hall, 1988). Sharp contact with *Hr5*. Thicknesses range from approximately 50 m to 175 m (164–574 ft)

Hr3 (s, q) **Rinconada Formation, r3 schist member**—White, gray, bluish-green and blue, medium-grained, thinly to thickly bedded, resistant quartzite with abundant crossbeds (*Hr3q*). Unit thickens north and northeast of Copper Hill, where it includes two mappable layers of pelitic schist (*Hr3s*) that resemble *Hr4* and upper *Hr1-2*. Distinctive marker layer near center of member is 25-m-thick (82-ft-thick), white, thinly bedded, ridge-forming quartzite. Sharp contact with *Hr4*. Thickness is approximately 75 m (246 ft)

Hr1-2 **Rinconada Formation, r1-2 schist member**—Upper unit of gray to tan, red-weathering, coarse-grained quartz–muscovite–biotite–staurolite–albite–garnet schist containing 1–10-cm-thick layers of red-, gray-, or tan-weathering, fine-grained muscovite–garnet quartzite. Abundant staurolites are twinned, euhedral, and as much as 3 cm across; abundant garnets are euhedral and small (<2 mm). Strong parting along foliation plane. Sharp to gradational contact with *Hr3*. Lower unit of fine- to medium-grained, tan to silver quartz–muscovite–biotite schist having small euhedral garnets (<2 mm) and scattered euhedral staurolite twins (<1.5 cm). Near base of the lower unit are black biotite books (<2 cm), and on the upright limb of the Hondo syncline in sec. 7 are spectacular andalusite porphyroblasts as much as 8 cm across. Nielsen (1972) divided lower and upper units into r1 and r2, respectively, based on mineralogy. Thickness is approximately 265 m (870 ft)

Ho **Ortega Formation, undivided**—Gray to grayish-white, medium- to coarse-grained quartzite. Generally massive and highly resistant. Locally well crossbedded and kyanite or sillimanite bearing. Crossbeds defined by concentrations of black iron-oxide minerals. Aluminum-silicate minerals are concentrated in thin muscovite-schist horizons. Common accessory minerals are ilmenite, hematite, tourmaline, epidote, muscovite, and zircon. Gradational contact with Rinconada Formation. Thickness is approximately 800–1200 m (2625–3937 ft)

Ho6 **Ortega Formation andalusite quartzite**—Clean, white to tan, sugary quartzite interlayered with lenses and layers of massive, foliated, gray, knobby andalusite quartzite. Layers range from centimeters to meters thick. Fine muscovite and scattered kyanite, sillimanite, and fuchsite present in quartzite. Andalusites are large, lentil-shaped, poikiloblastic grains containing quartz inclusions (as great as 50%) and mantled by coarse muscovite crystals. Matrix is fine quartz, coarse kyanite, fine muscovite, euhedral rutile, and minor hematite and tourmaline. Equivalent to O_6 of Williams (1982). Mapped only on Copper Hill, where thickness is several meters

Ho5 **Ortega Formation kyanite quartzite**—Sugary to vitreous quartzite characterized by kyanite blades and vitreous opalescent quartz eyes. Bedding-parallel, kyanite-rich layers give unit a vague foliation. Fine muscovite grains scattered between quartz grain boundaries. Rutile is predominant heavy mineral. On Copper Hill, a foliated, muscovite–kyanite-stained rock containing kyanite and staurolite grains (<0.5 cm) overlies the kyanite quartzite. Equivalent to O_5 of Williams (1982). Mapped only on Copper Hill, where thickness ranges from 3 to 5 m (10–16 ft)

Ho4 **Ortega Formation massive gray quartzite**—Massive, light- to dark-gray, vitreous quartzite with dark layers of rutile, hematite, and ilmenite that define crossbedding. Fine muscovite commonly is present on quartz grain boundaries, and kyanite commonly is associated with dark layers. This unit is host to much of the fracture-filling, oxidized copper mineralization on Copper Hill and La Sierrita. Mineralization is related to upward migration of hot fluids during Precambrian retrograde metamorphism (Bauer and Williams, 1990). Upper part is equivalent to O_4 of Williams (1982). Mapped only on Copper Hill, where thickness is approximately 30 m (98 ft)

Ho3 **Ortega Formation mixed quartzites**—Various quartzites including reddish, coarse-grained quartzite; brown, medium-grained quartzite; gray quartzite; garnet-bearing, dark quartzite; and tan, crossbedded quartzite. Mapped only on La Sierrita. Thickness is approximately 250 m (820 ft)

Ho2 **Ortega Formation black quartzite**—Dark-gray to black, massive, medium-grained quartzite. Commonly crossbedded and generally contains a well-developed extension lineation defined by kyanite. Mapped only on La Sierrita. Thickness is approximately 200 m (656 ft)

Ho1 **Ortega Formation laminated schist**—Reddish to orange-brown to white quartz–muscovite schist containing thin layers of light, quartz-rich and darker, mica-rich schist. Exposed only in a small area in the core of the Copper Hill anticline in the easternmost map area. Base is unexposed

Precambrian Vadito Group

Vvf **Felsic schist, undivided**—Includes a variety of quartz–muscovite–plagioclase schists. Coarser-grained felsic rocks are tan to pinkish quartz–plagioclase–muscovite–biotite–opaque, slightly schistose units with polycrystalline quartz eyes (2–8 mm). Eyes are slightly flattened in foliation and probably represent relict phenocrysts in felsic volcanic rock. Trace minerals include sphene, apatite, and tourmaline. Finer-grained felsic rocks are similar in mineralogy to coarser units but lack the abundant quartz eyes. Small relict idioblastic garnets are rare. Small lensoidal bodies of tan to orange-red, garnet-bearing quartz–muscovite opaque schist are found locally. Many of the felsic schist bodies appear to be intrusive into Vadito Group schists. Preliminary U–Pb zircon concordia age of about 1695 Ma

Vvq **Quartz–biotite rock**—Lenses and discontinuous layers of gray quartz–biotite rock found in schist and amphibolite. Light- to medium-gray, fine-grained quartz–biotite (± muscovite) rock with local green epidote pods and veins. Other minerals identified in thin section include plagioclase, microcline, sphene, garnet, hematite, and ilmenite. These rocks are similar to sills of the Cerro Alto metadacite

Vcam **Cerro Alto metadacite**—Gray metadacite composed of fine-grained quartz, plagioclase, microcline, biotite, and muscovite. Relict phenocrysts of quartz and/or feldspar <4 mm long. Accessory minerals are epidote, allanite, sphene, magnetite, and zircon. Main mass of metadacite is a stocklike body with sharp intrusive contacts with country rock, especially along western margin. Abundant sills contained in adjacent amphibolites. Crosscut by other plutonic rocks and found as xenoliths within them. Moderately well developed foliation is parallel to regional trend. This body may be the remnant of a larger subvolcanic complex originally emplaced at a fairly shallow level within the Vadito Group

Vvg **Glenwoody Formation**—Feldspathic quartz–muscovite schist and quartzose schist exposed in cliffs in north-central map area. White, light-gray, pink, or green. Commonly contains megacrysts of feldspar and rounded and flattened quartz that are interpreted to be relict phenocrysts in altered felsic volcanic rock. Contact with overlying Ortega Formation is a ductile shear zone. Pervasive extension lineation in schist plunges south. Upper 100 m (328 ft) of schist is pinkish and contains anomalous manganese and rare-earth elements as well as unusual minerals such as piemontite, thulite, and Mn-andalusite. This formation occupies an identical structural position, below the synclinally folded Ortega Formation, as Vadito Group rocks in the southeastern Picuris Mountains and is therefore included with the Vadito Group. Preliminary U–Pb zircon concordia age of about 1700 Ma. May be equivalent to the ca. 1700 Ma Burned Mountain Formation of the Tusas Mountains, which is one of the youngest supracrustal units of the Vadito Group. Thickness unknown as base is not exposed

Vm3 **Marqueñas Formation northern metaconglomerate**—Predominantly composed of distinctive, extremely flattened and constricted quartzite pods. Micaceous quartzite matrix contains scattered clasts, as much as 10 cm long, of metasedimentary quartzite (66%), felsic schist (34%), and traces of vein quartz. Alternating lithologic layers that might have indicated original bedding are absent. This unit was described as a flaser-bedded quartzite (Nielsen and Scott, 1979). However, it is probably a transposed, originally thinly bedded pebbly quartzite (Holcombe and Callender, 1982). Gradational with Marqueñas Formation quartzite to the south. The contact between this unit and the Piedra Lumbre Formation is well exposed just west of US–75. Here, metaconglomerate contains abundant, rounded, highly flattened and constricted clasts of quartzite and felsic schist in a mylonitic schistose quartzite matrix. The highly strained nature of the northern Marqueñas Formation is probably due to major ductile shearing between the Hondo and Vadito Groups along the Marqueñas–Piedra Lumbre contact. Approximate thickness of 150–180 m (492–590 ft), 0.5 km (0.3 mi) east of Cerro de las Marqueñas

Vm2 **Marqueñas Formation quartzite**—Fine- to medium-grained, grayish, texturally immature, schistose quartzite. Can be divided into upper cross-laminated quartzite and lower massive gray quartzite (Scott, 1980). Abundant crossbeds ranging from small-scale features defined by black mineral laminae to large festoons with cross laminations several centimeters thick. Crossbeds are consistently north facing. Pebble-rich layers also define bedding. Contacts with adjacent metaconglomerates are gradational. Approximate thickness of 200 m (656 ft), 0.5 km (0.3 mi) east of Cerro de las Marqueñas

Vm1 **Marqueñas Formation southern metaconglomerate**—Polymictic metaconglomerate containing rounded clasts of quartzite (54%), silicic metavolcanic rock and quartz–muscovite schist (40%), and white vein quartz in a muscovite–quartzite matrix. Clasts are flattened and constricted in the dominant foliation; aspect ratios range from 1:2:3 to 1:2:6, with extremes of 1:2:16 or greater. In general, clast size increases southward and westward. Quartzite clasts are as long as 1 m (3 ft). Matrix averages about 30% of volume of rock. Minor phases in matrix include ilmenite, biotite, magnetite, hematite, zircon, and tourmaline. Contact with Vadito Group schists to the south might be unconformable or tectonic. The Marqueñas Formation may be equivalent to the Big Rock Formation of the Vadito Group in the Tusas Mountains. Approximate thickness of 150 m (492 ft), 0.5 km (0.3 mi) east of Cerro de las Marqueñas

Vs7 **Fine-grained quartz–muscovite–chlorite schist**—Includes several varieties of schist. Fine-grained quartz–muscovite schist with scattered porphyroblasts of staurolite and biotite (<3 cm) grades to fine-grained, pale-olive-green quartz–muscovite–chlorite schist with 1–2 mm garnets, 2–25 mm staurolites, and 0.5–2 mm biotites. Locally shows 1-mm-thick compositional layers of gray quartz-rich rock and <6-mm-thick layers of greenish quartz–muscovite–chlorite schist. Small grains (0.1 mm) of tourmaline, apatite, and sphene or monazite

Vs6 **Andalusite phyllitic schist**—Silver-blue to silver-green quartz–muscovite–chlorite schist with 4-cm, rounded knots of andalusite cores and alteration rims. 3-mm biotite porphyroblasts are randomly oriented. Local compositional layers, 0.5–2 cm thick, of white quartzite and silver-blue phyllitic schist. 20–40-cm-long elongate pods of granular quartz, chlorite, muscovite, and minor copper oxides are aligned in foliation

Vs5 **Streaky schist**—Dark-gray to green, fine-grained quartz–muscovite–opaque biotite schist. Streaky look results from 1–2-mm-thick, lense-shaped bodies of white quartz–plagioclase–muscovite schist and gray, opaque biotite–quartz–muscovite–chlorite schist. Locally, <2 mm biotite porphyroblasts are present. Lenses are strongly folded and transposed. Microscopic garnets have overgrown foliation

Vs4 **Streaky knotty phyllitic schist**—Silver-gray to silver-green, very fine grained to phyllitic quartz–muscovite–chlorite schist interlayered with white quartz-rich layers. Layering is discontinuous and probably transposed. Contains altered knots of muscovite and green chlorite and distinctive pods of fine- to medium-grained granular quartz. Gradational contact with streaky schist

Vs3 **Andalusite–biotite phyllitic schist**—Silver-blue to gray-green, very fine grained quartz–muscovite–chlorite phyllitic schist with black biotite porphyroblasts and coarse-grained andalusite knots. Compositional layering is defined by lenses and layers of light and dark phyllite and white quartzitic schist. Andalusites are 1–20 cm, dark-gray-blue, unaltered masses that are slightly flattened in plane of foliation and that contain included internal foliation trails. Black, randomly oriented biotite porphyroblasts average 4 mm. Minerals such as staurolite, plagioclase, and garnet present locally. Distinctive marker horizon of cordierite-bearing quartz–muscovite schist present near main amphibolite body. Cordierite porphyroblasts are gray, as much as 20 cm long, and typically exhibit orthorhombic (pseudohexagonal) crystal habit. Foliation wraps around cordierite porphyroblasts. In thin section cordierites are optically continuous and contain abundant quartz inclusions that define two relict included foliations. Gradational with *Vs1* to the northeast

Vs2 **Knotty quartz–muscovite(±biotite) schist**—Common rock type that is divided into three mappable subunits, *Vs2a*, *Vs2b*, and *Vs2c*, each with gradational contacts with the others. *Vs2a* is the most phyllitic unit; in general, these rocks become more quartzose and less phyllitic from northwest to southeast. All units contain altered knots of fine-grained muscovite, chlorite, and quartz. *Vs2a* is light-gray, fine-grained quartz–muscovite phyllitic schist with black speckles of biotite and opaques. *Vs2b* contains a variety of fine-grained quartz–muscovite–biotite schists with ubiquitous, scattered, rounded and elongated, altered porphyroblast knots. *Vs2c* is similar to *Vs2b* with the exception of less abundant knots of altered muscovite–chlorite–quartz. Knots may be altered cordierite porphyroblasts

Vs1 **Quartz–muscovite–biotite schist**—Relatively massive, light-gray, fine-grained quartz–muscovite schist with scattered flakes of black biotite (<1 mm). Compositional layers are defined by alternating quartz-rich and mica-rich horizons 1–25 mm thick. Similar to *Vs2* but lacks the distinctive altered knots

Vq **Micaceous quartzites and metaconglomerates, undivided**—Includes both lenticular micaceous quartzite bodies and scattered metaconglomerates. Micaceous quartzites are variably colored and consist mainly of granoblastic quartz grains, aligned muscovite grains, and layered concentrations of opaque minerals. Local conglomerate horizons delineate bedding. The major metaconglomerate unit in the area crops out southwest of Cerro Alto (referred to as the Embudo Creek quartzite by Bell, 1985). The metaconglomerate consists of rounded predominantly quartzite clasts in a quartz–muscovite matrix. Sedimentary features such as crossbeds and ripple marks are well preserved. Numerous thin lenses of quartzite and metaconglomerate, too thin to subdivide, are also found scattered within the amphibolite and schist units of the Vadito Group

Vva **Amphibolite**—Includes a wide variety of amphibolite bodies, lenses, and layers and textures. The large amphibolite body south and east of the Harding pegmatite is a complex unit containing metamorphosed and deformed volcanic, sedimentary, and volcaniclastic rocks. The predominant rock type is fine- to medium-grained, dark-gray-green to black, weakly foliated amphibolite composed of blue-green to olive-green hornblende (0.1–0.7 mm), interstitial quartz and plagioclase (0.1 mm), sphene, and epidote. Faint compositional layering is formed by 1–2-mm-thick, white layers. Epidote veins and zones are common, especially near pluton margins. Locally fragmental amphibolites contain white felsic fragments and gray lithic fragments that are elongated and flattened in foliation of fine-grained hornblende matrix. Subangular, gray quartzite clasts, black basaltic fragments, and epidote clasts also exist within the matrix. Other rock types within the large amphibolite body include biotite schist, metadacite, felsic schists, quartzite, metagabbro, and various schists. Thinner layers and lenses scattered throughout the Vadito schists are mainly fine- to medium-grained amphibolites that range considerably in texture and mineralogy

Vvb **Fragmental biotite schist**—Dark schistose matrix of biotite–quartz–plagioclase contains varying percentages of clasts of: 1) white, gray, red, and black, subrounded quartzite pebbles (1–15 cm); 2) dark-olive-green to brown, fine-grained lithic fragments that are strongly flattened in foliation; 3) white felsic fragments that are extremely flattened in foliation; and 4) boulder-size, dark-green-black, fine-grained amphibolites. Also contains metadacite lenses

Vvm **Mixed amphibolite, biotite schist, and other schists**—Undivided amphibolites, fragmental amphibolites, biotite schist, fragmental biotite schist, and various felsic to mafic schistose units

Vvd **Gneiss**—Gneissic dioritic rock interlayered with quartz–biotite gneiss, felsic gneiss, and quartz–muscovite–biotite schist. Grades into more schistose rock in southern area of outcrop. Coarse pegmatites are common. Exposed only in the southeastern map area, where it is intruded by Rana quartz monzonite

Geologic cross sections of Trampas quadrangle, Picuris Mountains, Taos and Rio Arriba Counties, New Mexico

by Mark A. Helper[1] and Paul W. Bauer[2], 1994

[1]Department of Geological Sciences, University of Texas at Austin, Austin, Texas 78713.
[2]New Mexico Bureau of Mines & Mineral Resources, Socorro, New Mexico 87801