



## ***The Pecos greenstone belt--A Proterozoic volcano-sedimentary sequence in the southern Sangre de Cristo Mountains, New Mexico***

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# THE PECOS GREENSTONE BELT: A PROTEROZOIC VOLCANO-SEDIMENTARY SEQUENCE IN THE SOUTHERN SANGRE DE CRISTO MOUNTAINS, NEW MEXICO

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## INTRODUCTION

Proterozoic igneous and metamorphic rocks are exposed in several approximately north-trending belts in the Sangre de Cristo Mountains of north-central New Mexico and south-central Colorado. In New Mexico, with the exception of the Picuris Range, these rocks received little detailed geologic attention prior to the mid-1970's. Recent mapping has delineated an extensive volcano-sedimentary terrane (hereafter informally called the Pecos greenstone belt) that seems analogous to Archean greenstone belts in the Canadian Shield. The Pecos greenstone belt occupies an area of some 650 km<sup>2</sup>, mainly in the headwaters area of the Pecos River northeast of Santa Fe (figs. 1 and 2). It is defined by a closely interrelated assemblage of metamorphosed subaqueous basalts and locally important felsic metavolcanic rocks, iron-formation, and meta-sedimentary rocks, some of volcanic provenance. The Pecos greenstone terrane is faulted on the west, and is intruded by voluminous plutonic and apparently subvolcanic rock. Although rocks of the greenstone terrane are at least twice folded, variably metamorphosed in the greenschist and amphibolite facies, and intruded by the abundant igneous rocks, fine details of primary sedimentary and volcanic features are preserved locally. These features serve to identify the original nature of the units, but they are not recognizable widely enough to make simple work out of regional mapping. Volcanic and sedimentary rocks both exhibit marked variation in lithology and thickness over short distances. Detailed mapping in areas of continuous exposure allows the construction of local stratigraphic columns (Riesmeyer, 1978), but the delineation of a general stratigraphic succession for the entire greenstone belt is not yet possible.

This paper defines the geologic and geographic boundaries of the Pecos greenstone belt; describes the present state of knowledge of the general geology, petrology, geochronology and economic potential of the terrane; outlines important remaining problems; and speculates on the tectonic setting of the terrane and on a possible faulted extension of the terrane that has a high potential for the occurrence of volcanogenic massive sulfide deposits.

## FIELD WORK

This summary is based mainly on field work carried out during the summers of 1976 and 1977 by the U.S. Geological Survey and the New Mexico Bureau of Mines and Mineral Resources to assess the mineral resources of the Pecos Wilderness and proposed additions, collectively called the Pecos Wilderness study area (fig. 1). Moench started work in 1976, but the main effort was in 1977 when both authors and their

assistants worked together. Robertson mapped previously in the Rociada area to the east (fig. 1), and since the completion of the mineral survey, he has been studying the Doctor Creek area, west of the Pecos mine (fig. 2). Arthur Montgomery laid much of the foundation of knowledge of the Precambrian geology of the region (Miller and others, 1963; Montgomery, 1953), and without the benefit of his work, this synthesis would not have been possible.

Shortly before our field work, David Mathewson mapped the Precambrian rocks in a broad area south of Elk Mountain and Cowles (fig. 2) for his Ph.D. thesis (in progress) at the New Mexico Institute of Mining and Technology. During our study, Grambling (this guidebook) mapped part of the quartzite terrane southeast of Truchas (fig. 1); and Marcus Moench (son of the second author) mapped two small but critical areas at the northern boundary of the greenstone terrane (upper Pecos River and Rio Mora, fig. 2), in partial fulfillment of B.A. degree requirements at Hampshire College. We are grateful to these men for their contributions.

## GEOLOGIC SETTING

The Pecos greenstone belt is bounded on the west by the Pecos-Picuris fault, a major north-south break originally mapped by Miller and others (1963) in the southern Sangre de Cristo Range. The crest of the range, west of the fault, is both topographically and geologically higher than the east side and comprises an extensive plutonic terrane whose granitic intrusives previous workers have collectively called the Embudo Granite (Fullagar and Shiver, 1973; Miller and others, 1963; Montgomery, 1953). In fact, at least one third of this plutonic terrane consists of massive inclusions probably in part correlative with rocks of the greenstone terrane but now mainly high-grade biotite gneiss, feldspathic gneiss and amphibolite.

On the north, the Pecos greenstone belt is bounded by an apparently older, compositionally mature quartzite terrane, previously correlated by Montgomery with the Ortega Formation of the Picuris Range (Miller and others, 1963). The quartzite terrane is characterized by extensive stratigraphic layers of nearly pure quartzite and highly aluminous schist. As shown by J. Grambling (unpublished mapping) in the quartzite terrane southeast of Truchas (fig. 1), at high stratigraphic levels the quartzites are micaceous and less pure, and the schist layers contain interbedded layered amphibolite, probably metamorphosed basaltic flows and volcanoclastic rocks. Although included in the quartzite terrane in this paper, these rocks seem transitional to the predominantly metasedimentary

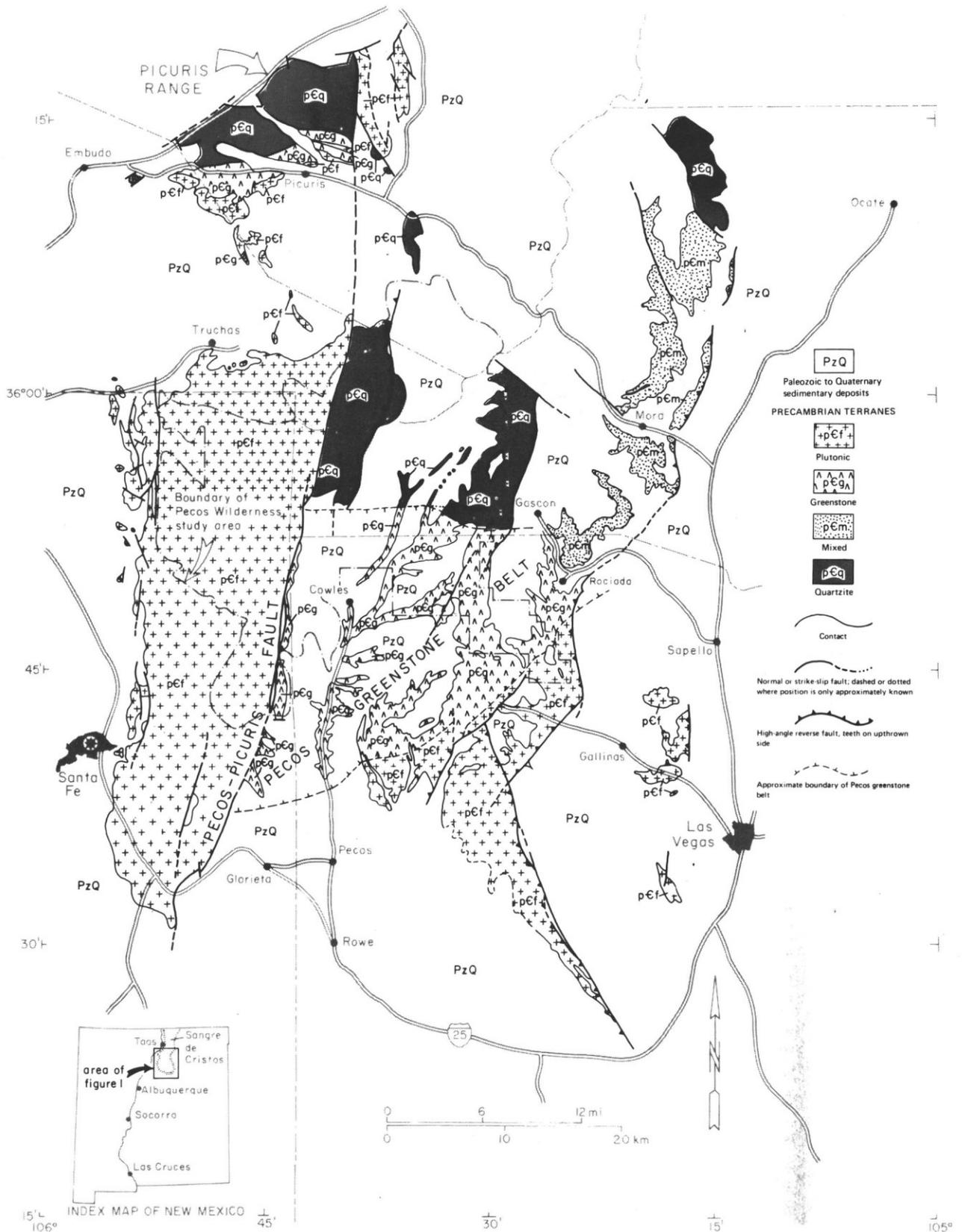


Figure 1. Precambrian geology of the southern Sangre de Cristo Mountains showing four general Precambrian terranes. Compiled, with modifications in some areas, from: Bachman and Dane, 1962; Baltz, 1972, 1978; Budding, 1972; A. J. Budding and J. M. Robertson (unpub. mapping in the Rociada area); Cepeda, 1972; Jeffrey Grambling (unpub. mapping in the Truchas Peaks-Pecos Baldy area); Long, 1974, 1976; David Mathewson (unpub. mapping in the southeastern part of the greenstone terrane); Miller and others, 1963; Montgomery, 1953; Northrop and others, 1946; Riesmeyer, 1978; J. M. Robertson (unpub. mapping in the Doctor Creek area); R. H. Moench and J. M. Robertson (unpub. map of the Pecos Wilderness study area).

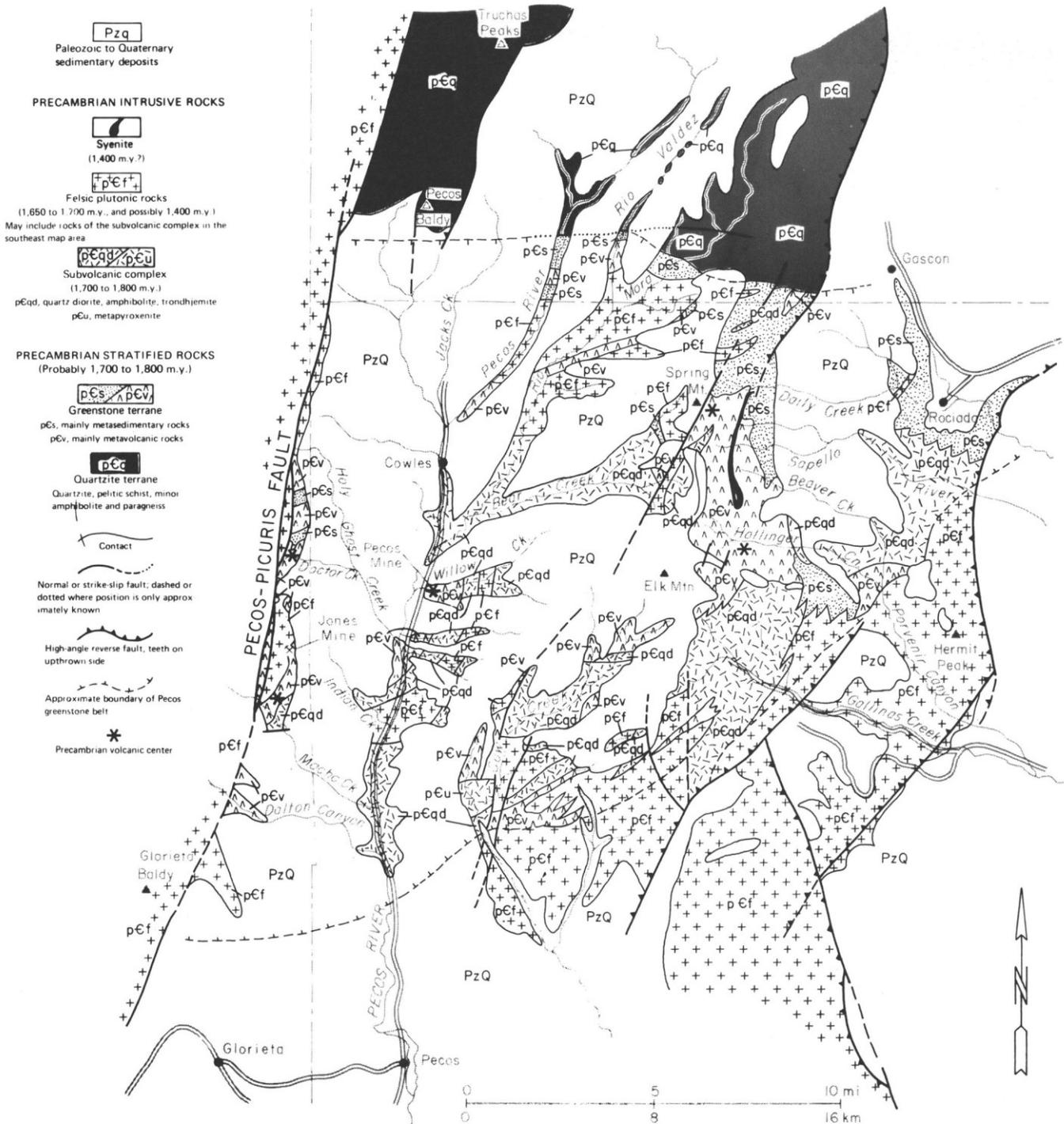


Figure 2. Geologic sketch map of the Pecos greenstone terrane, showing known volcanic centers. Data modified from R. H. Moench and J. M. Robertson (unpub. map of the Pecos Wilderness study area, 1:48,000); J. M. Robertson (unpub. mapping in the Rociada and Doctor Creek area); David Mathewson (unpub. mapping south of Elk Mountain and Willow Creek); and Riesmeyer (1978) from Macho Creek to the Jones mine.

assemblage of the greenstone terrane. Similar rocks are exposed locally near the eastern margin of the quartzite terrane block west of Gascon (figs. 1, 2).

In the upper Pecos River and Rio Valdez areas, the boundary between the greenstone and quartzite terranes is marked by an east-trending pre-Mississippian fault (fig. 2), but farther east predominantly metasedimentary rocks belonging to the greenstone terrane rest apparently unconformably on quartzite of the quartzite terrane, as described in the section on stratigraphic and facies relationships.

Northeast of the Pecos greenstone belt is a mixed terrane composed of arkosic metasediments (now quartz-feldspar paragneiss) interbedded with aluminous quartz-mica schist, quartzite and thin layers of talc-silicate rock (fig. 1). Amphibolite is present, but appears to be mainly intrusive metadiabase. The mixed terrane is more or less intermediate in composition between the greenstone and quartzite terranes. It may be approximately equivalent to the predominantly metasedimentary part of the greenstone terrane, but appears to have more abundant clean quartzite and less abundant originally volcanic amphibolite than that part of the greenstone terrane. Rocks of the mixed terrane appear to have been enriched locally (between Rociada and Mora) in silica and potassium (as potassium feldspar and/or muscovite), possibly derived in part from the simple pegmatites found in the area.

On the south, the greenstone terrane is bounded by a plutonic terrane whose rocks are broadly similar to the granitic rocks exposed west of the Pecos-Picuris fault. This southeastern boundary of the greenstone terrane is broadly gradational, and is defined by southward-decreasing amounts of amphibolite and metasedimentary rocks included in the granitic rocks (David Mathewson, unpublished mapping).

Part of the eastern boundary of the greenstone terrane is marked by one of several high-angle reverse faults that have thrust Precambrian rocks over Paleozoic strata (Baltz, 1972, 1978; Baltz and Bachman, 1956).

## DETAILED LITHOLOGIES

Precambrian rocks are exposed in approximately one-third of the 650 km<sup>2</sup> area of the Pecos greenstone belt. They are overlain unconformably by as much as 600 m of Paleozoic carbonate and clastic rocks in the remaining two-thirds of the area (fig. 2). Three assemblages of Precambrian rock types are exposed within the area: (1) metavolcanic rocks, with minor interbedded volcanoclastic metasedimentary rocks and iron-formation; (2) metasedimentary rocks, including metamorphosed feldspathic sandstone, aluminous shale or mudstone, conglomerate, small amounts of volcanoclastic graywacke, thin layers of carbonate rocks, and possibly distal clastic facies of iron-formation; and (3) intrusive rocks, both subvolcanic and plutonic, that crosscut the stratified metasedimentary and metavolcanic rocks of the greenstone terrane. Metavolcanic and metasedimentary rocks each make up approximately 25 percent of the greenstone terrane; intrusive rocks comprise the remaining 50 percent. Although the metasedimentary and metavolcanic rocks are complexly interstratified, the terrane divides into a predominantly metasedimentary part and a richly metavolcanic main body.

### Metavolcanic Rocks

Metamorphosed volcanic rocks are exposed most widely in the central and western parts of the greenstone terrane, and become decreasingly abundant toward the northeastern margin

of the belt. The volcanics are compositionally bimodal, and are broadly similar to suites found in some Archean greenstone belts such as those in the western Vermilion District, north-eastern Minnesota (Morey, 1978) and South Surgeon Lake, Ontario (Franklin, 1978). The most abundant rock type within the volcanic suite is fine- to medium-grained amphibolite, or metabasalt, that locally exhibits relict vesicles, pillows and pillow breccia. Preliminary chemical data, mostly from the south-central part of the area, show these rocks to be chiefly low-potassium tholeiites (Robertson and others, 1978).

Concentrations of more felsic volcanics, pyroclastics and iron-formation are developed locally within the western and east-central parts of the belt. These concentrations, typically less than 2 km in longitudinal section and characterized by discordant, domal accumulations of flows, pyroclastics and cherty iron-formation, are called "volcanic centers" in this report. It is of interest to note that these volcanic centers, although similar to volcanic areas or felsic "breccia domes" described by Goodwin (1962) in the Abitibi greenstone belt of eastern Ontario, are an order of magnitude smaller than their apparent Archean counterparts. Five centers are shown on Figure 2: one at the confluence of Willow Creek and the Pecos River, and defined by rocks exposed at the Pecos mine (Riesmeyer, 1978); one along Doctor Creek about 5 km west of the Pecos mine (Robertson, unpublished mapping); one along the north side of Macho Creek about 7 km southwest of the Pecos mine (Riesmeyer, 1978); and two less well-defined volcanic centers in the central part of the belt northeast of Spring Mountain and Elk Mountain, respectively. Associated with the Doctor Creek center are layers of probable welded felsic tuff, suggesting that this center may have been emergent, at least briefly and locally. The felsic volcanics and pyroclastics account for approximately 10-15 percent of the total volcanic suite.

Reworked volcanic rocks, mainly felsic in composition, and cherty iron-formation, both massive and banded, constitute another 5 percent or more of the volcanic terrane. The reworked volcanics are both crystal-rich and crystal-poor; lithic fragments are not common; pumice is rare. Most of these rocks were probably tuffs, or at least tuffaceous, but their fine-grained matrix is so completely recrystallized that original glass shards cannot be identified.

Mapping by Riesmeyer (1978) around the Macho Creek volcanic center has defined three cycles of basaltic to rhyolitic volcanism, each capped by iron-formation with or without accompanying volcanoclastic sediments. It is not yet known whether similar multiple cycles are represented in other centers.

### Metasedimentary Rocks

Metasedimentary rocks exhibit regular changes in lithologic character and relative abundances of rock types from southwest to northeast across the Pecos greenstone belt. In the west, where metavolcanic rocks predominate, the associated metasedimentary rocks are metashales and minor very immature volcanoclastic metagraywackes or meta-subgraywackes, rich in detrital magnetite, locally graded and intimately interbedded with the metavolcanic rocks. This metasedimentary assemblage becomes increasingly arkosic eastward, showing less evidence of a volcanic source. Thin layers of talc-silicate rock and marble occur in the east-central part of the greenstone terrane.

In the northeastern most part of the terrane, feldspathic meta-sandstones predominate, associated with lenticular bodies of conglomerate (quartz-rich near the quartzite-greenstone terrane boundary, polymictic farther south), aluminous meta-shale, and minor calc-silicate rocks. Thin layers of quartzite are increasingly abundant toward the east; iron formation becomes sparse. Scattered layers of amphibolite are the most likely rocks of volcanic origin in the east, but many of these bodies are slightly and locally discordant to the enclosing strata, and therefore, probably are intrusive in origin.

Although the term "iron-formation" usually refers to laminated rocks containing at least 15 percent iron, and commonly containing layers of chert (Gross, 1965), we use the term more broadly to include a wide variety of probably genetically related rocks (including some true iron-formation) that occur in the Pecos greenstone belt. A nearly continuous spectrum seems to exist between probably chemically deposited iron-rich, cherty sediments (now massive to irregularly layered or laminated fine-grained quartz-hematite, quartz-magnetite and quartz-pyrite rocks) and essentially clastic accumulations of purplish ferruginous quartzite or magnetite-rich quartz-mica-epidote schist showing graded bedding and cross-stratification. These two apparent end members may occur closely together (even in the same hand specimen). A tendency exists, however, for the originally cherty iron-formation to occur in and very near the known volcanic centers, whereas the clastic iron-formation most commonly is interbedded with other clastic meta-sedimentary rocks more peripheral to the centers. Similar varieties of "mutually gradational and contrasting facies of iron-formation" associated respectively with volcanic and sedimentary rocks are described by Goodwin (1962) in the Archean Abitibi greenstone belt of eastern Ontario.

### Intrusive Rocks

Two main suites of Precambrian intrusive rocks are exposed within the Pecos greenstone belt: (1) an inferred subvolcanic complex of amphibolite, well foliated quartz diorite and trondhjemite, and minor metamorphosed pyroxenite, probably the same general age as the volcanic assemblage; and (2) a plutonic complex, mainly granitic to tonalitic in composition, and grossly similar to rocks assigned to the Embudo Granite by Montgomery (Miller and others, 1963) in the plutonic terrane west of the Pecos-Picuris fault. The two complexes have been mapped separately throughout the Pecos Wilderness study area, as shown on Figure 2, but much of the felsic plutonic complex shown southeast of Cow Creek and Elk Mountain actually may contain abundant rocks of the inferred subvolcanic complex.

#### *Subvolcanic complex*

Rocks of the subvolcanic complex are exposed primarily in the central and southeastern parts of the greenstone belt. Mafic rocks in the complex mainly consist of medium- to coarse-grained amphibolite, massive to poorly foliated and commonly mesh-veined with quartz diorite or more felsic varieties. Such rocks are exposed well in a number of places along the Pecos River between Dalton campground and Cowles, and along the lower reaches of the Rio Mora and Bear Creek (fig. 2). Additional detailed mapping may demonstrate that some of these amphibolite bodies are really mafic meta-volcanic rocks, but at present, all amphibolite that is not clearly extrusive is assigned to the subvolcanic complex. Meta-diabase is associated closely with basaltic lavas in the east-

central part of the belt, and displays both concordant and discordant relations. These rocks are distinguished from the mafic flows by their coarser grain size and distinct remnants of diabasic to ophitic textures.

Felsic rocks are represented by well foliated, grayish, medium- to fine-grained quartz diorite and trondhjemite. The most extensive exposures of these rocks are along the middle part of Bear Creek, and in the lower parts of Hollinger Canyon and Beaver Creek 3 to 4 km northwest of Hermit Peak. Riesmeyer (1978) has mapped a smaller body of trondhjemite that intrudes the base of the volcanic center in Macho Creek, near the west side of the belt.

Tabular bodies of ultramafic rocks as much as several hundred meters thick and 1 km long are exposed in several areas along Cow Creek (fig. 2) where they are interlayered with well foliated amphibolite. They are concordant, lack conspicuous chilled margins, and are extremely coarse-grained (as much as 2 cm), suggesting emplacement as sills into previously heated country rocks. The ultramafic rocks are metapyroxenites, now composed of complexly intergrown tremolite, chlorite, and carbonate and opaque minerals.

Mafic and felsic rocks are about equally abundant in the subvolcanic complex. The ultramafic sills are a minor component, making up less than 5 percent of the total.

#### *Plutonic complex*

The plutonic complex contains a wide textural and compositional variety of granitic rocks and pegmatite. Rocks in the complex generally were emplaced in the order from dark to light. The darker rocks include gray hornblende-biotite tonalite, granodiorite and minor granite; most bodies have a pronounced secondary foliation. Pink, medium- to coarse-grained alkali feldspar-biotite granite is abundant in the central part of the greenstone belt, and is exposed particularly well along the Pecos River for several kilometers north and south of its confluence with Indian Creek and along the east side of Cow Creek. Toward the eastern margin of the belt (along the eastern tributaries of the Rio Mora and at the head of Bear Creek), and locally west of the Pecos-Picuris fault (south of Macho Creek), this pink granite appears to grade into pink quartz porphyries and porphyritic granite of hypabyssal aspect. All of these granitic rocks may be massive to conspicuously foliated. Granitic pegmatites are distributed widely in the southern and eastern parts of the greenstone terrane, and typically, form thin, steeply dipping dikes or pods that crosscut foliations of the enclosing rocks.

A sill-like body of syenite, about 5 km in length and as much as a few hundred meters thick, intrudes a thick section of metabasalts in the east-central part of the greenstone terrane. The syenite and associated small bodies of lamprophyric rocks (or melasyenite) form a narrow north-trending belt that extends across the headwaters of Beaver and Daily Creeks, and the Sapello River. These alkalic rocks are deformed and metamorphosed variably. Their precise relationship with nearby granites of the plutonic complex is not yet known.

### STRATIGRAPHIC AND FACIES RELATIONSHIPS

Relationships between rocks of the quartzite terrane and those of the greenstone terrane, and between the predominantly metasedimentary and metavolcanic parts of the greenstone terrane itself are important problems that have not been

solved completely. From evidence seen along upper Rio Mora, Montgomery (Miller and others, 1963) inferred that metasedimentary rocks of the greenstone terrane (his Vadito Formation) rest unconformably on quartzite of the quartzite terrane (his Ortega Formation). Unpublished mapping by Marcus Moench is in accord with Montgomery's. From north to south, Moench recognized the following succession: (1) a thin discontinuous layer of chlorite-amphibole schist, probably mafic metashale; (2) hematitic quartz-sillimanite schist, interpreted as metamorphosed lateritic soil; (3) metaconglomerate, containing abundant rounded pebbles and cobbles of quartzite derived from the quartzite terrane in the lower part, but having feldspar-rich clasts and matrix in the upper part, suggesting an important contribution of felsic volcanic material; and (4) an intertonguing body of quartz-feldspar paragneiss (tuffaceous metasandstone) and aluminous schist that contains a single thin layer of nearly pure quartzite; this body contains sparse amphibolite.

Unit 4 is truncated on the south by granite, which obscures the relationship between the predominantly metasedimentary, conglomerate-bearing succession and the abundantly volcanic main part of the greenstone terrane. However, this relationship is exposed farther east in the broad belt of stratified Precambrian rocks that lies east of Spring Mountain (fig. 2). Here, quartzite is bordered on the south by mafic schist and hematitic quartz-sillimanite schist (similar to units 1 and 2 in Rio Mora), and then by a thick body of interbedded quartz-feldspar paragneiss (some spectacularly crossbedded) and amphibolite. A thick lens of volcanic-cobble metaconglomerate is exposed near the southern contact of the paragneiss-amphibolite body. Farther south, quartz-feldspar paragneiss, amphibolite, aluminous schist, and thin layers of calc-silicate rock and marble are interbedded and interfolded; farther south (just east of Spring Mountain), this assemblage appears to intertongue with extensive metabasaltic amphibolites, with local accumulations of felsic volcanics and iron-formation.

Although many details still have to be worked out within this eastern metasedimentary-metavolcanic belt, we are confident that the quartzite terrane is overlain to the south by a mainly sedimentary part of the greenstone terrane, which in turn, grades farther south by lateral facies change to the main volcanic body of the greenstone belt.

### CORRELATION WITH ROCKS IN THE PICURIS RANGE

Montgomery (Miller and others, 1963) applied the name Vadito Formation to the assemblages of metavolcanic and immature metasedimentary rocks in the Pecos greenstone belt on the basis of gross lithologic similarities to the type Vadito Formation of the Picuris Range. This correlation seems valid, although the greenstone belt is more complex both lithologically and stratigraphically than its presumed equivalent in the Picuris Range. Rather than formally extending the Vadito Formation from the Picuris into the southernmost Sangre de Cristos, however, we prefer to define a less formal "greenstone terrane," exposed in both places, that very likely represents faulted segments of a single, original volcano-sedimentary sequence. Likewise, the compositionally mature quartzite terrane immediately to the north and stratigraphically below the Pecos greenstone belt can be equated with a broadly similar quartzite terrane (the Ortega Formation) in the Picuris Range. For the present, correlation of Precambrian terranes seems more appropriate (and realistic) than correlation of Pre-

cambrian formations, particularly in view of the lithologic variability, structural complexity and discontinuous exposure that characterize the Precambrian of northern New Mexico.

### STRUCTURE

The most prominent structural feature in the southern Sangre de Cristo Mountains, and one which forms the western boundary of the Pecos greenstone belt, is the Pecos-Picuris fault (fig. 1). This fault dips steeply, and extends at least 85 km from the southern end of the Sangre de Cristo Mountains north to the Picuris Range and beyond (Miller and others, 1963). Based on his correlation of Precambrian rocks across the fault, Montgomery inferred that about 37 km of right-slip movement took place in Precambrian time (Miller and others, 1963, p. 16). From structural and stratigraphic evidence, Sutherland has suggested that the west side of the fault was upthrown in Mississippian and Pennsylvanian time, and again during the Laramide orogeny, when a vertical throw of about 450 m was produced (Miller and others, 1963, p. 40, 47).

Several other important north- to northeast-trending faults cut the Pecos greenstone terrane, and one forms part of the terrane's eastern boundary (fig. 1). Many of these breaks are sinuous west-dipping high-angle reverse faults whose west sides have moved upward relative to the east sides.

As shown on Figure 2, the boundary between the quartzite and greenstone terranes in the upper Pecos River and probably also in Rio Valdez is marked by an east-trending pre-Mississippian fault. This fault is defined along the Pecos River, as mapped by Marcus Moench, by the juxtaposition of a folded north-facing succession of quartzites and schists of the quartzite terrane against an apparently south-facing succession of schists, metaconglomerate and metavolcanic rocks. The fault line is at the south edge of a prominent outcrop of quartzite, and is marked by a coarse quartzite talus, firmly cemented by quartz sandstone of the type that is found commonly at the base of the Paleozoic succession in the region.

In Precambrian time, rocks of the Pecos greenstone belt were metamorphosed variably to the greenschist and amphibolite facies, and they were folded at least twice. Structural relationships are defined best in the quartzite terrane, where stratigraphic layers are extensive and sedimentary features are preserved sufficiently for detailed determination of stratigraphic and structural relationships. There, as demonstrated by Grambling (this guidebook) in the quartzite terrane southeast of Truchas, by the authors and associates farther east, and by Montgomery (1953) and Nielsen (1972) in the Picuris Range, the dominant structural pattern is defined by large, tight to isoclinal folds that trend east-west, plunge gently, and tend to be overturned to the north; these folds have an axial-plane schistosity. In the Truchas Peaks-Pecos Baldy area, these folds are deformed by younger north-trending warps whose axial surfaces are subparallel to the Pecos-Picuris fault. As suggested by Montgomery (Miller and others, 1963, p. 16), these warps may represent drag produced by right-slip movement along the Pecos-Picuris fault. In the quartzite terrane west of Gascon (fig. 1), the east-trending folds and the accompanying early foliation were reformed strongly by northeast-trending folds. In large areas, especially along the east side of the Pecos Wilderness study area, east-striking bedding and foliation that dip steeply south are bent to north-south strikes and rather gently westerly dips. The surfaces of west-dipping bedding and

foliation commonly have conspicuous slickensides and mulions that plunge apparently uniformly southwest.

The structure of the greenstone terrane is dominated by northeast trends of bedding and foliation, curving locally to east-west and north-south trends. In contrast to the quartzite terrane, however, the structure of the greenstone terrane is difficult to work out, because the subaqueous volcanic environment that is represented produced no extensive marker beds. Instead, abrupt facies changes are the rule; reliable top-facing criteria, such as pillows in basalts and graded bedding, are difficult to find. Tight east-trending and northeast-trending folds with axial-plane foliation are exposed in outcrops, and the map patterns shown at 1:48,000 (Moench and Robertson, 1979) suggest the presence of major northeast-trending folds. It remains to be determined if these northeast-trending folds are superimposed on older east-trending folds or instead represent the older pattern deflected 45 degrees or so from the original easterly trend. In the southeast corner of the greenstone terrane, along Hollinger Canyon, northeast-trending folds appear to be deformed by east-trending folds that may represent a third folding, depending upon the correct interpretation of the northeast-trending folds. The young east-trending folds in this area conform to the borders of granitic intrusives that mark the edge of the belt and therefore, may be related to the emplacement of the intrusives.

### GEOCHRONOLOGY

The geochronology of the Pecos greenstone belt is not well known. Model lead ages on galena from the Pecos and Jones mines give dates of 1,710 m.y. and 1,720 m.y., respectively (Stacey and others, 1976). Unless modified by metamorphism, these ages seem appropriate for both the massive sulfide deposits and the enclosing felsic volcanic rocks. Silver (in Stacey and others, 1976) has dated, by the U-Pb zircon method, a well foliated quartz diorite, exposed just west of the greenstone terrane across the Pecos-Picuris fault, at approximately 1,650 m.y. Insofar as this rock may be coeval with petrologically similar quartz diorite bodies that intrude the greenstone terrane, this date represents a minimum age for the belt.

Wetherill and others (1965) report ages of 1,280 m.y. (K/Ar) and 1,459 m.y. (Rb/Sr)\* on biotite from the Pidlite pegmatite near the northeast margin of the greenstone belt. The disparity of the two ages has not been reconciled.

Trondhjemitic rocks from southern Colorado and northern New Mexico (along the upper Rio Brazos in the Tusas Mountains) have Rb/Sr or U/Pb isochron ages of 1,700 m.y. to 1,800 m.y. (Barker and others, 1974, 1976). If trondhjemites of the subvolcanic complex in the Pecos greenstone belt are also part of this petrologic province, then they presumably share a common genesis and have similar ages. Geochemical work now in progress should help to characterize more accurately trondhjemitic rocks in the greenstone terrane.

The Embudo Granite of Montgomery (1953) in the Picuris Range has been dated by Fullagar and Shiver (1973) at  $1,638 \pm 40$  m.y. using Rb/Sr whole-rock methods. Subsequent mapping by Long (1974, 1976), however, has shown that the Embudo of the Picuris Range actually consists of at least three separate and petrologically distinct granitic plutons. Furthermore, Long (1974) suggests that field relations support a re-interpretation of Fullagar and Shivers' data to give a 1,400 m.y. age for one of the plutons. It is clear that new, more geolog-

ically precise samples need to be collected and dated in the Picuris Range.

The sill-like body of syenite in the eastern part of the greenstone terrane may be coeval with similar alkalic rocks in southern Colorado that are approximately 1,400 m.y. in age.

Additional dates for northeastern New Mexico are tabulated by Callender and others (1976).

### ECONOMIC GEOLOGY

Giles (1974, 1976) was the first to publish data on the massive sulfide potential of the southern Sangre de Cristo Mountains, although reconnaissance mapping by Montgomery (Miller and others, 1963) had noted the presence of mafic and felsic metavolcanics in the area. Detailed mapping around the Pecos mine by Riesmeyer (1978) convincingly documents the volcanogenic nature of that deposit. Riesmeyer and Robertson (this guidebook) describe the geology and ore deposits of the Pecos mine.

As shown by the mineral survey of the Pecos Wilderness study area (Moench and others, 1979), a high potential for the occurrence of massive sulfide deposits exists near the volcanic centers at Willow, Macho and Doctor creeks. Although mainly covered by Paleozoic sedimentary rocks, the triangular area bounded by these three centers also has high massive sulfide potential. The Hollinger Canyon and Spring Mountain volcanic centers are less well known, and therefore, must be assigned a lower potential.

Copper-zinc-lead prospects have been reported from the eastern part of the greenstone terrane and westernmost part of the mixed terrane (mainly in the Rociada District) but these are generally small, discontinuous quartz lenses or vein-like bodies not obviously associated with volcanic rocks (Harley, 1940, p. 52-56; Lindgren and others, 1910, p. 114-116). Zones of finely disseminated sphalerite plus variable amounts of chalcopyrite and galena occur in one or more highly contorted carbonate horizons northeast of Rociada, but low grade and apparently spotty distribution make these occurrences of limited economic interest.

Ultramafic sills along the southern margin of the belt contain some disseminated pyrite, but remain largely unexplored.

Granitic pegmatites are exposed especially well high along the east-facing flanks of the Sangre de Cristo Mountains between Elk Mountain and Gascon Point. In the Elk Mountain district, several pegmatites have yielded small amounts of scrap mica and even smaller quantities of tantalum, uranium and rare earths (Jahns, 1946, p. 275-285; Redmon, 1961, p. 71-76). The Pidlite mine, located along the western edge of the Rociada district about 8 km northwest of Rociada, has produced several hundred short tons of lepidolite and several short tons of microlite (Jahns, 1953; Sheffer and Goldsmith, 1969).

### SUMMARY, PROBLEMS AND SPECULATIONS

Recent detailed and reconnaissance geologic mapping in the southernmost Sangre de Cristo Mountains has delineated an area containing a lower Proterozoic (Precambrian X) metamorphosed volcano-sedimentary rock assemblage analogous in many ways to the Archean greenstone belts of the Canadian Shield. This area, mainly in the headwaters of the Pecos River, is called informally the Pecos greenstone belt. The belt is lithologically and structurally complex; its features are obscured by extensive Paleozoic cover, and are made difficult to map by 1,500 m or more of topographic relief and poor access.

\*All Rb/Sr data have been recalculated using  $X = 1.42 \times 10^4$  /yr.

The Pecos greenstone belt can be subdivided into a predominantly metasedimentary assemblage and an abundantly metavolcanic assemblage, both probably 1,700 to 1,800 m.y. old. In the eastern and northeastern parts of the greenstone terrane, metasedimentary rocks are exposed widely. The predominantly metasedimentary assemblage of the greenstone terrane grades southward and southwestward into the abundantly volcanic main part of the greenstone belt. This main part of the belt is composed principally of a strongly bimodal assemblage of metamorphosed tholeiitic subaqueous basalts and locally abundant felsic volcanic rocks, all interstratified in various proportions with metamorphosed shale and relatively minor volcanoclastic graywacke.

The richly volcanic part of the Pecos greenstone terrane appears to be underlain by a subvolcanic intrusive complex composed of massive, rather coarse-grained amphibolite, well foliated quartz diorite and trondjemite, and in the south, minor amounts of metapyroxenite.

Firm conclusions regarding the petrology, stratigraphic relations and overall tectonic setting of the Pecos greenstone belt must await the completion of geochemical studies and further detailed mapping in critical areas. The bimodal nature of the volcanic assemblage suggests a setting of tectonic extension, and it is thus appropriate to speculate that the sediments and volcanics of the Pecos greenstone belt accumulated in a marine fault basin (or basins) either within or marginal to a rifted continent (represented in part by the quartzite terrane) whose sediments have an obvious continental provenance. However, we need to learn more about the exact stratigraphic relationships between the quartzite and greenstone terranes, and between the predominantly sedimentary and mainly volcanic parts of the greenstone terrane itself. Preliminary data show a systematic change in Precambrian lithologies from southwest to northeast characterized by a decreasing subaqueous volcanic component and an increasing volume of shallower-water, stable-shelf to near-shore, nonvolcanic terrigenous sediments. The mixed terrane is a continuation of this shallowing (shoreward) nonvolcanic trend; arkosic metasandstone, aluminous schist and quartzite become the most important members of the rock assemblage. Farther to the northeast, the mixed terrane appears, on admittedly meager evidence, to merge with the quartzite terrane. Thus, the greenstone terrane grades, more-or-less continuously, into the quartzite terrane, suggesting that the two terranes are at least in part coeval, and merely different facies of the same chronostratigraphic interval in the lower Proterozoic of northern New Mexico. Similar quartzite-greenstone relationships are described by Schau (1977) in the Archean Prince Albert Group of the Northwest Territories, Canada. Locally, the two terranes described here may inter-tongue (Grambling, this guidebook), be in fault contact, or exhibit conformable or unconformable depositional relations. With time, continued subsidence (rifting?) appears to have expanded the area of active volcanism, creating a sort of volcanic onlap with rocks of the greenstone terrane locally overlying rocks of the quartzite terrane. The regional picture, however, is one of subaqueous volcanic assemblages and quartz-rich sedimentary assemblages accumulating more-or-less simultaneously in tectonically different but adjacent environments that were subject, through time, to relatively abrupt local uplift or depression.

A further important question is whether the greenstone terrane is continental, or instead represents the upper part of new (Proterozoic) oceanic crust, or is a combination of both. Rare-

earth-element studies may provide a partial answer to this last question, and preliminary data from mafic rocks in the southern two-thirds of the belt suggest that at least some of these rocks are chemically similar to typical mid-ocean ridge basalts (K. C. Condie, personal commun., 1978).

It is tempting to compare, and even correlate, the volcano-sedimentary rock assemblage of the Pecos greenstone belt with apparently similar rocks of the Yavapai Series in the Jerome-Prescott area of central Arizona. Anderson and Silver (1976) have called these Arizona rocks a greenstone belt, and dated the belt at  $1,775 \pm 10$  m.y. to  $1,820 \pm 15$  m.y. In spite of similar ages, the presence of massive sulfide deposits in both places, and crude geographic proximity, however, the Yavapai Series and the Pecos greenstone terrane exhibit some fundamental lithologic differences. Andesite and graywacke are abundant, and quartzite is scarce in the Yavapai Series, whereas intermediate rocks (especially andesites) are rare and quartzites relatively common (at least toward its eastern margin) in the Pecos greenstone belt. It is therefore premature to equate more than generally the two greenstone belts, particularly with respect to tectonic setting.

A major potential exists for volcanogenic massive sulfide deposits in the Pecos greenstone belt, particularly near and west of the Pecos mine where metavolcanic rocks are abundant and volcanic centers are recognized. Some of the most favorable ground there is truncated by the Pecos-Picuris fault. On the assumption that Montgomery (Miller and others, 1963) correctly correlated the generalized quartzite and greenstone terranes across the fault, the faulted extension of this favorable ground may be found a short distance south of the village of Picuris and west of the Pecos-Picuris fault (fig. 1). That area is covered largely by Paleozoic and younger sedimentary deposits, and the favorable metavolcanics may be present as highly metamorphosed inclusions and roof pendants within the abundant granitic plutonic rocks of the area.

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