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PRECAMBRIAN DEFORMATIONAL HISTORY OF THE PICURIS MOUNTAINS NEW MEXICO'

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INTRODUCTION

The Picuris Mountains are located in north-central New Mexico approximately 20 km southwest of Taos (fig. 1). These deformed and metamorphosed Precambrian rocks form a wedge-shaped basement high which extends 26 km west-southwest from the main body of the Sangre de Cristo Mountains. To the north and west are Tertiary sedimentary and volcanic rocks of the San Luis Valley. To the south, Tertiary sedimentary rocks of the Espariola basin separate the Picuris Mountains from other Precambrian rocks (Manley, 1979). To the east, upper Paleozoic sediments of the southern Sangre de Cristo Mountains rest unconformably on Precambrian units. At the eastern edge, the Picuris Mountains are 16 km wide including associated Paleozoic units, but taper to a point near Dixon (fig. 1). In profile, the range consists of three topographic steps with the lowest step in the west. Each step is related to a northwest-trending fault along which part of the movement is down to the west (fig. 2). A more complete description of the physical features is given by Montgomery (1953, p. 2-4).

Since Just's (1937) and Cabot's (1938) early reconnaissance surveys, significant progress has been made in the understanding of Precambrian rocks of northern New Mexico, particularly in the Picuris Mountains. Montgomery (1953) produced an excellent regional map, stratigraphic succession and petrologic description of the Picuris Mountains which has served as a basis for the more recent detailed work. Montgomery's report was revised in a much broader work by Miller and others (1963). Nielsen (1972) proposed a deformational history based on mesoscopic structural analysis and mineral paragenesis. Long (1974, 1976) subdivided the intrusive rocks into four magmatic events (spanning a minimum of 300 m.y.) based on field relationships, composition and available isotopic data. Most recently, Holdaway (1978) has analyzed metamorphic assemblages to determine equilibrium pressures and temperatures of metamorphism. Isotopic studies by Fullagar and Shiver (1973) and Gresens (1975) provide a time reference which, in combination with the other data, yields a coherent general picture of Precambrian history from approximately 1800 m.y. B.P. until 1200 m.y. B.P.

GENERAL STRATIGRAPHY

The Precambrian rocks of the Picuris Mountains have been divided into three major units: the Ortega Group, Vadito Group and the Embudo Granite. The group status for the major metamorphic units was suggested by Long (1974). Subdivision of these groups into formations is based on detailed field work by Nielsen (1972), Long (1976) and Scott (1979). The stratigraphic sequence differs in detail while retaining many of the general divisions of Montgomery (1953) (fig. 3).

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Ortega Group

The Ortega Quartzite is a thick, typically gray, coarse-grained vitreous metaquartzite with andalusite-rich or kyanite-rich layers. Below the quartzite, Gresens and Stensrud (1974) have identified a metarhyolite which crops out only along the north western edge of the Picuris Mountains. However, throughout most of the area, the Ortega Quartzite is the oldest exposed unit. The Rinconada Formation comprises an alternating succession of phyllites, metaquartzites and garnet-staurolite schists (Nielsen, 1972) (fig. 3). Each member is unique in either stratigraphic position or lithologic character such that the original six subdivisions can and have been used to teach basic lithologic mapping to undergraduates. The Pilar Formation consists of two distinctive carbonaceous members: a lower black slate and an upper gray-black garnet phyllite. Long (1976) has subdivided the Upper Pilar Phyllite into four members and renamed these the Piedre Lumbre Formation. The regional extent of these subdivisions has not been examined, and therefore, the original, simpler Pilar Formation subdivision will be retained for this report.

Vadito Group

Long (1976) has outlined three formational units within the Vadito Group. The lowest unit is the Marquenas Quartzite which is generally a clean, crossbedded gray quartzite with distinctive metaconglomerate beds. Recent detailed mapping within the Marquenas Quartzite has revealed from bottom to top: (1) a laterally continuous conglomerate near the base; (2) a distinctive quartzite with characteristic lenticular or flaser bedding; (3) a massive, sparsely crossbedded quartzite; and (4) an upper conglomerate sequence (Scott, 1979). Above the Mar-

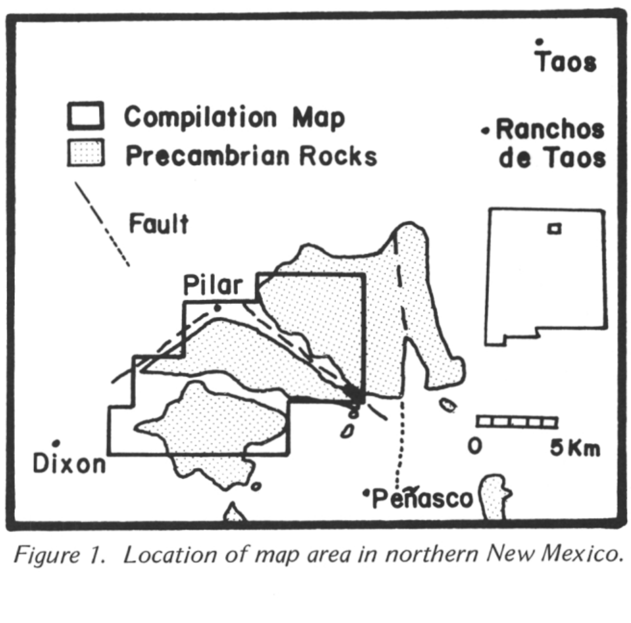

Figure 1. Location of map area in northern New Mexico.

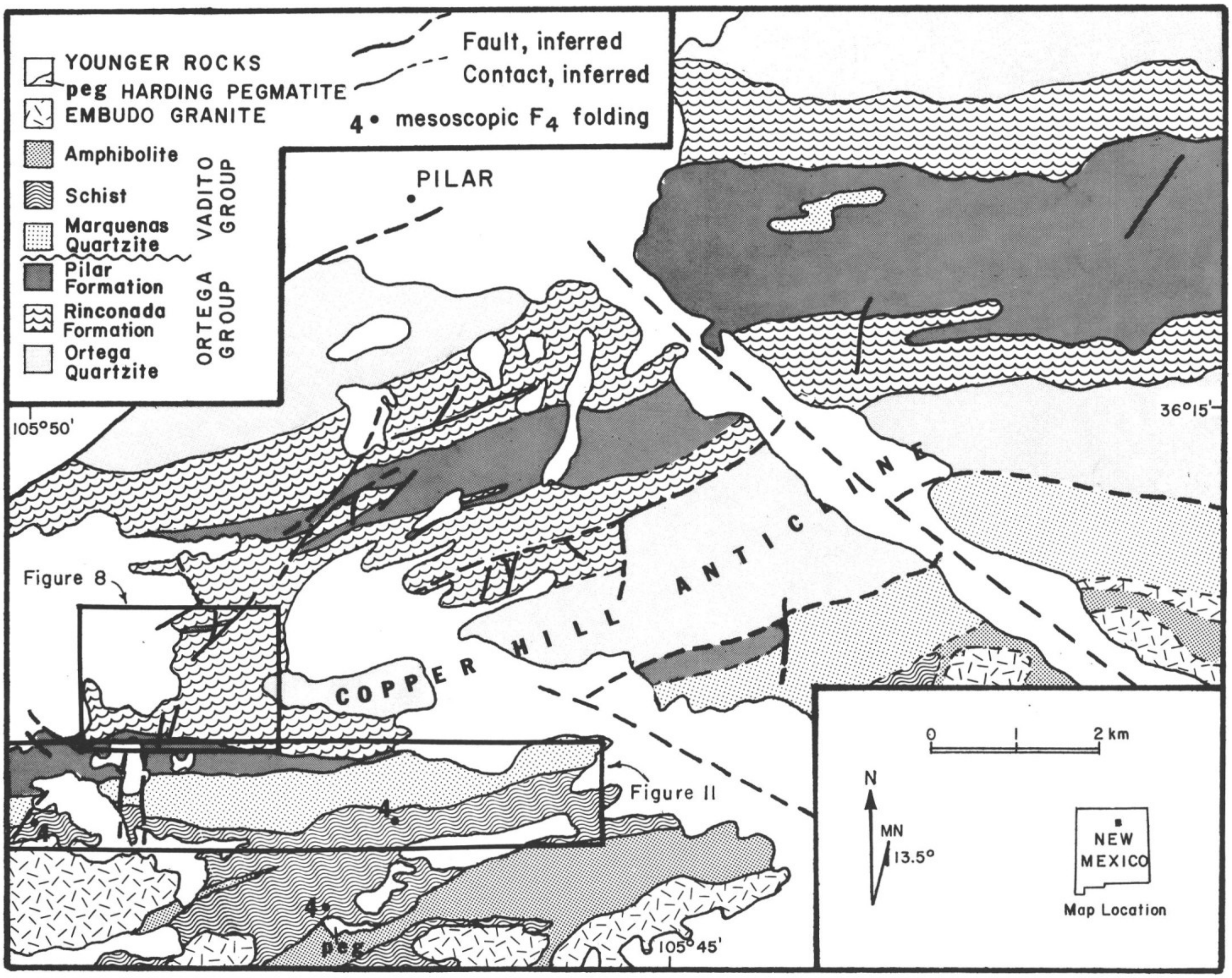

Figure 2. Compilation map of the western portion of the Picuris Mountains based on Miller and others (1963), Nielsen (1972), Long (1974) and Scott (1979).

quenas Quartzite is a thick unnamed muscovite-quartz schist sequence with discontinuous friable quartzites and amphibolites. Within this schist unit are layers which contain significant amounts of andalusite, cordierite and garnet. The upper unit in the Vadito Group is a heterogeneous amphibolite including volcaniclastic units as well as flows.

The contact between the Vadito and Ortega groups has been affected by deformation (see east side, fig. 2). However, based principally on lithologic evidence such as clasts in the conglomerates and crossbed orientation, most authors have interpreted this contact as an unconformity (Long, 1976; Montgomery, 1953; Nielsen, 1972; Scott, 1979). Gresens and Stensrud (1974) used regional stratigraphic relationships to suggest that the Vadito Group is older than the Ortega Group, and that the contact is a major fault. Present detailed work in the Marquenas Quartzite supports the unconformity interpretation (Scott, 1979).

Embudo Granite

Four major units have been identified as part of the Precambrian intrusive sequence (Long, 1974). The initial intrusion (Cerro Alto Metadacite) is followed, in turn, by the Puntiagudo Granite Porphyry, the Rana Quartz Monzonite and the Penasco Quartz Monzonite. The bulk of the pegmatites postdates the Pehasco Quartz Monzonite. A complete discussion of these intrusions is given by Long (1976).

DEFORMATIONAL HISTORY

General Structural Setting

Figure 2 illustrates the pervasive east-west fabric of the Picuris Mountains. The northern belt of Ortega Quartzite is the core of a large isoclinal anticline in which the metarhyolite is exposed (Gresens and Stensrud, 1974). The black phyllites and slates of the Pilar Formation crop out in a synclinal trough. The

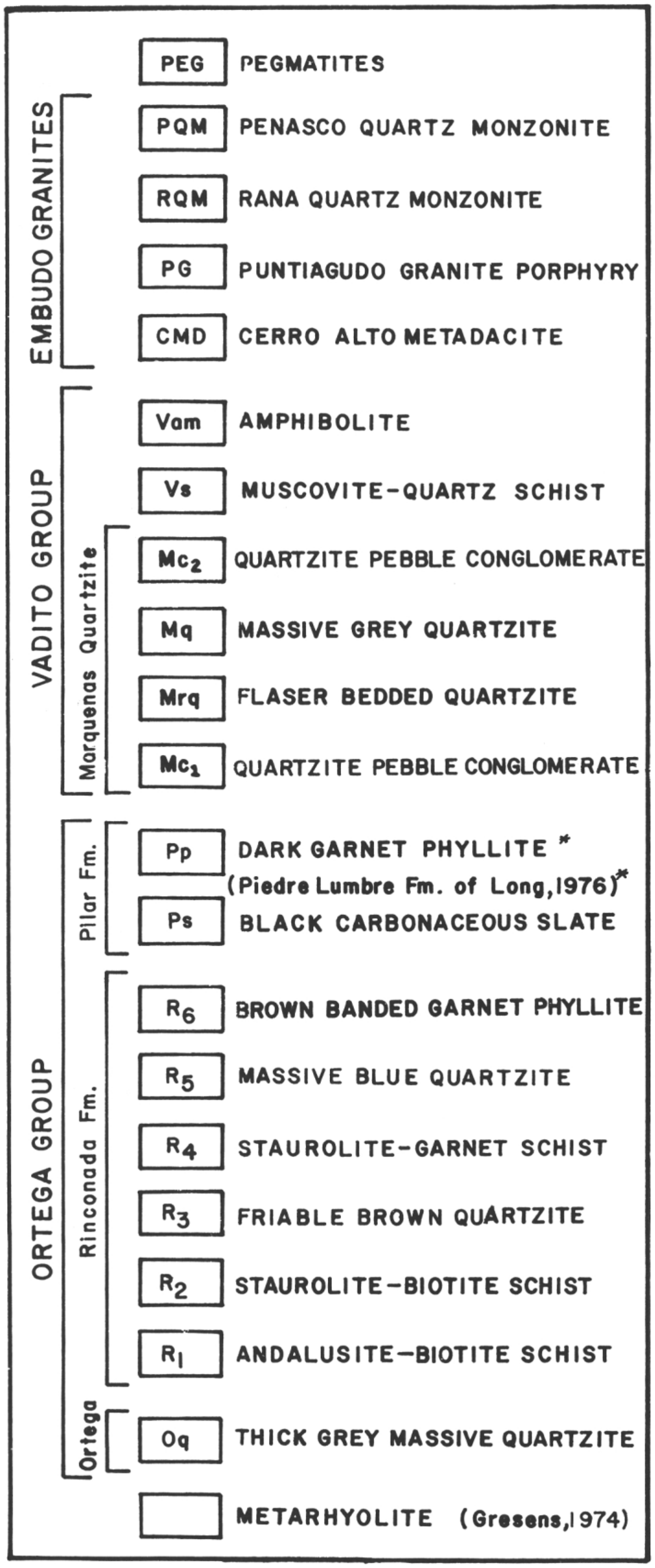

Figure 3. Stratigraphic succession of the Picuris Mountains compiled from Nielsen (1972), Long (1976) and Scott (1979).

southern belt of Ortega Quartzite contains the axis of the Copper Hill anticline. All of these large folds have variable bearing and plunge, but generally plunge to the west-southwest. The southern limb of the Copper Hill anticline is the location of the principal Vadito Group outcrops and the Embudo Granite. Also, in the southern limb and in the eastern portion of the area, Vadito units are in fault contact with the Ortega Quartzite (fig. 2). Three generations of faulting can be observed. The oldest faults are shear zones subparallel to axial surfaces of the large-scale folds mentioned above. Disrupting these older faults is a series of oblique-slip faults which trend either northeast-southwest or northwest-southeast. The largest fault is the Pilar-Vadito fault along which there has been both left-lateral and dip-slip movement (Montgomery, 1953). Finally, there are normal faults offsetting Tertiary sediments.

Deformational Sequence

Ortega Group

A detailed mesoscopic analysis was conducted in the pelitic Rinconada units around the plunging nose of the Copper Hill Anticline (Nielsen, 1972) (fig. 2). Four deformational events were recognized and these are summarized in Table I. The major fabric elements described include original bedding, three axial-plane cleavages, and a discontinuous ductile offset. Original bedding is expressed in conglomerate layers, crossbedding and small-scale ripple cross-lamination. Si is the axial-plane cleavage of rootless isoclinal folds and is usually parallel to bedding (fig. 4). These early small-scale folds were noted at several localities, but as yet, no large-scale F1 closure has been identified. S2 is a schistosity which is axial-planar-to-tight upright and overturned asymmetric folds (fig. 5). By far, this second fold pattern is the dominant form seen in the Picuris Mountains. S3 is a distinctive crenulation cleavage with a generally steep dip and N2OW strike (fig. 6). S4 reorients the earlier surfaces about northeast-trending ductile shear zones (fig. 7).

Four domains were selected to analyze the fabric data in the detailed mapping area (fig. 8). Using the axial trace of the Copper Hill anticline, Domain I represents the south limb, Domain II represents the north limb, Domain III is the area

Figure 4. Intrafolial rootless isoclinal fold found in the Upper Rinconada Formation (R6).

Table 1. Summary of Deformational Events

Surface	Lineation	Fold
S_0—Bedding: based on primary structures: crossbedding, ripple marks and conglomerate beds.		
S_1—Schistosity parallel to S_0 over most of the area except in a few localities where S_1 cuts S_0 in rootless intrafolial folds.	L_1—$S_1 \wedge S_0$ parallel to axis of 1st phase folds; generally obscured due to parallelism of S_1 and S_2 strikes.	F_1—Rootless intrafolial folds with axial plane cleavage, S_1. Usually thin isoclinally folded quartzite layers with micaceous cores.
S_2—Schistosity parallel to axial plane of 2nd phase folds, usually subparallel to S_1 and intersecting at low angles. Locally transposes S_1 and S_0.	L_2—$S_2 \wedge S_1$ and $S_2 \wedge S_0$ parallel to axis of 2nd phase folds. Characterized by tabular mineral alignment and uncommon crinkle lineation.	F_2—Most abundant style, ranging from open asymmetric overturned to very tight folds with axial planes dipping steeply southeast. Large-scale F_2 folds have well developed congruent drag folds.
S_3—Crenulation cleavage which cuts S_2, S_1 and S_0. Strike varies from 330 to 010 with nearly vertical dip.	L_3—$S_3 \wedge S_1$ and $S_3 \wedge S_0$ parallel to axis of 3rd phase folds. Characterized by strong crinkle lineation and a few mineral alignments such as hair-like biotite alignment in quartzose layers. $S_3 \wedge S_2$ is also a crinkle lineation.	F_3—Broad open folds produced by nearly vertical slip in the S_3 surfaces. As a result, F_2 axes show culmination and depression while S_2 varies only slightly.
S_4—Discontinuous ductile offsets which reorient earlier surfaces. Appear localized along NE-trending zones.	L_4—$S_4 \wedge S_1$ and $S_4 \wedge S_0$ irregular crenulations and fractures.	F_4—Open to tight folds with variable plunge generally steep to SE.

around the nose near the Ortega Quartzite contact, and finally, Domain I-a represents the data around the small fold structure in the southwest corner of the area. Data from Domain I characterize the general pattern in that each of the three well developed cleavages shows distortion (fig. 8). S1 is deformed about a southwest-plunging axis which corresponds to the observed F2 mesoscopic fold axes. Also, a gentle warp of Si is observed in the elongate maxima. The normal of this second great circle corresponds to the concentration of L3. A similar open-fold pattern is apparent in the S2 data (fig. 8). In addition, L2 linears are deformed about a great circle. Finally, S3 also appears deformed. In Domain la, the distortion of the three principal foliations is more pronounced and produces three calculated fold axes. Assuming that this later folding is homogeneous plane folding, then the three separate axes can be used to calculate a common axial surface or S4 (fig. 9). Such a calculation yields a plane with an orientation of N66E, 71°SE and agrees fairly well with the N58E measurement recorded for the S4 ductile offset (fig. 7).

Vadito Group

Although a comparable structural analysis has not been done in the Vadito Group, reconnaissance work has revealed

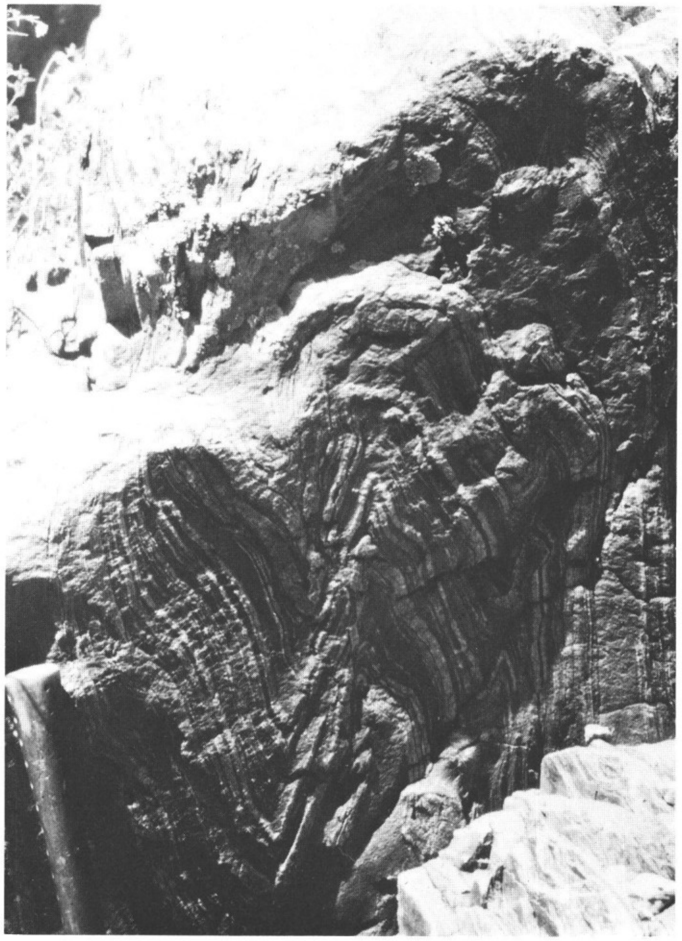

Figure 5. Typical second-generation folding which is slightly overturned and asymmetric with well developed axial-plane cleavage.

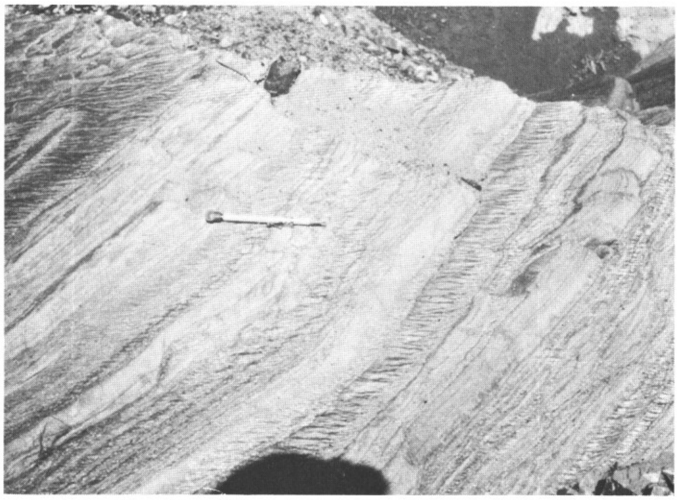

Figure 6. Well developed crenulation cleavage associated with F_3 folding.

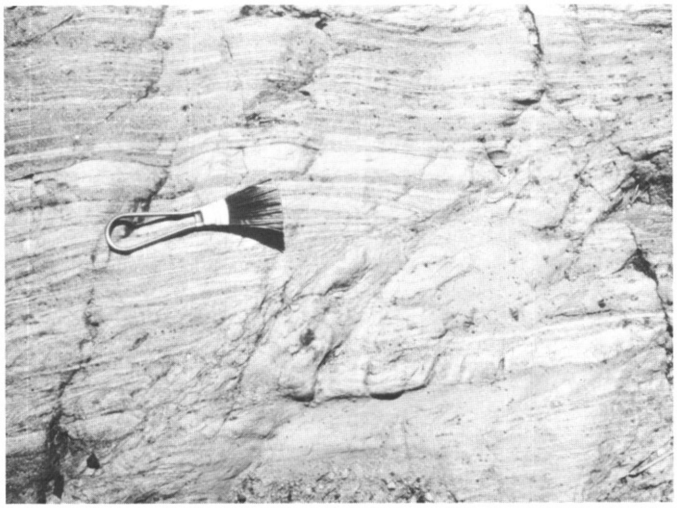

Figure 7. Northeast-trending ductile shear-zone characteristic of F_4 folding found in the Rinconada Formation southwest of Copper Hill.

the presence of S2, S3 and S4 and the associated folding. Major differences encountered are: (1) the absence of the intrafolial F1 folds; (2) weak development of the crenulation cleavage which is restricted to the lower units of the Vadito Group; and (3) the strong development of S4 and associated southeast plunging folds. The absence of the early folds is thought to be related to incomplete coverage and less favorable lithologies. For example, the Rinconada is characterized by finely layered phyllites; whereas, the Vadito consists of generally thick schists or quartzite. The development of the shallowly plunging southwest-trending folds associated with S2 surfaces is not so apparent in the Vadito. This subdued expression and the similarly weak development of the S3 crenulation is thought to be related to the strong expression of F4, partic- ularly in the area of greatest exposure immediately south of Copper Hill anticline (fig. 2).

Locations of F4 folds in the Vadito Group are shown in Figure 2. These folds are widely scattered and appear to be dismembered quartzite or amphibolite units within the thick schist unit. Near the Harding Pegmatite, bedding in the quartzite knobs describes a southeast-plunging fold system associated with a strong northeast-trending cleavage (fig. 10). The structure is apparent only because of the strong lithologic contrast between the schist and the quartzite.

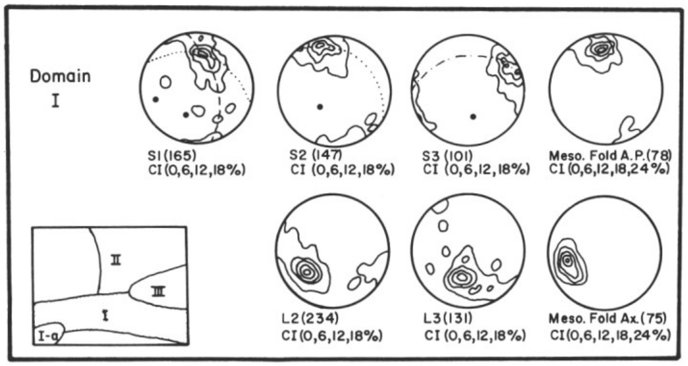

Figure 8. Data from Domain I, the south limb of the Copper Hill anticline (Nielsen, 1972).

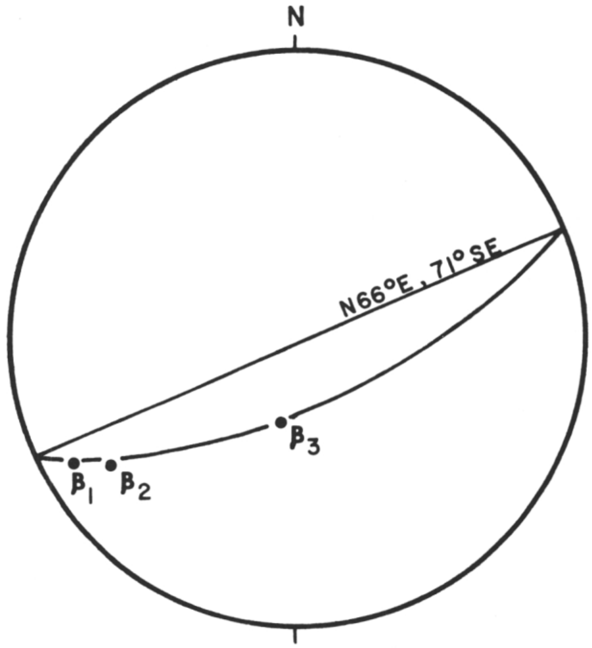

Figure 9. Calculated S_4 surface based on data in Domain I-a (Nielsen, 1972).

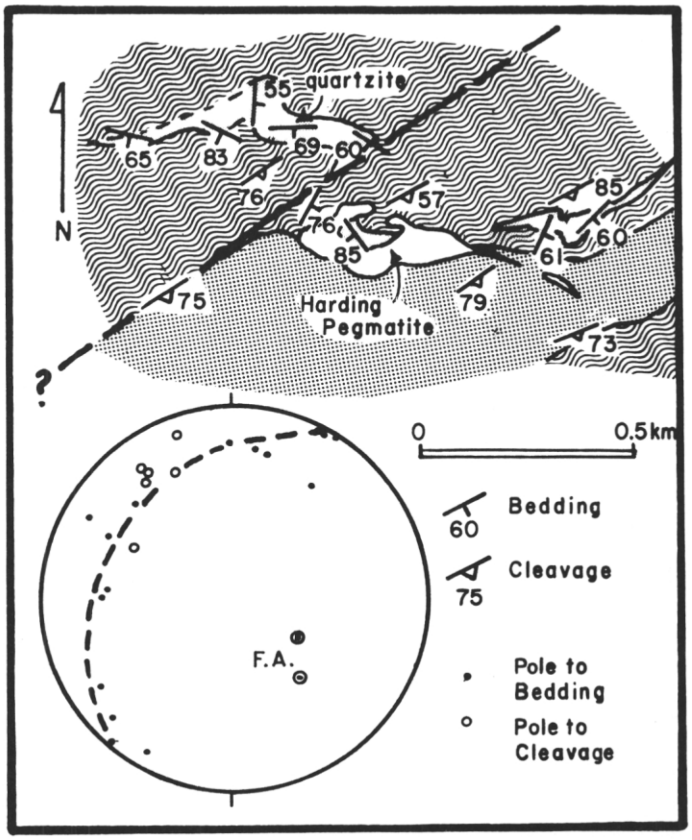

Figure 10. Bedding and cleavage measurements from the quartzite layers near the Harding Pegmatite, illustrating a southeast-trending fold system. Units same as Figure 2 except for addition of quartzite units within schist.

Additional information concerning the development of this S4 surface is observed in the strained pebbles of the Marquenas Quartzite (Scott, 1979). Measurement of pebble distortion can be described in three distinct zones along strike (fig. 11). In the west, pebbles show an elongation direction with a steep southeasterly plunge contained within the foliation plane. The foliation in this region is the well developed S2 cleavage, and therefore, these strained pebbles are interpreted as a fabric generated during F2. In this case, the principal elongation is at high angles to the southwest-trending F2 axes. The second zone is referred to as a transition zone by Scott (1979) and is characterized by decreased strain magnitude and more random orientation for the pebbles (fig. 11). Within this transition zone, the Marquenas Quartzite is deflected northward, the northeast-trending cleavage becomes dominant in the Vadito schist units, and units within the Ortega Group are highly appressed (fig. 2). The eastern zone shows a strong elongation direction and higher strain values except that, in this case, the pebbles plunge shallowly to the southwest. In the eastern zone, elongation also appears to be at high angles to the fold axes which plunge steeply to the southeast, the inferred F4 trend. Consequently, the strain pattern is interpreted as the superposition of F4 on F2 across a rather narrow northeast-trending transition zone.

METAMORPH ISM

A survey of metamorphic textures in the Rinconada and Pilar formations has revealed a general increase in metamorphic grade during the initial two folding events and retrograde conditions during the last two events (Nielsen, 1972). Preferred orientation of muscovite and biotite, and the association of garnets characterize the earlier surface (Si). S2 surfaces produce local transposition of Si and recrystallized muscovite and biotite. Holdaway (1978) also has noted a preferred orientation of kyanite and chloritoid associated with these early events. The most distinctive microfabric in the Rinconada

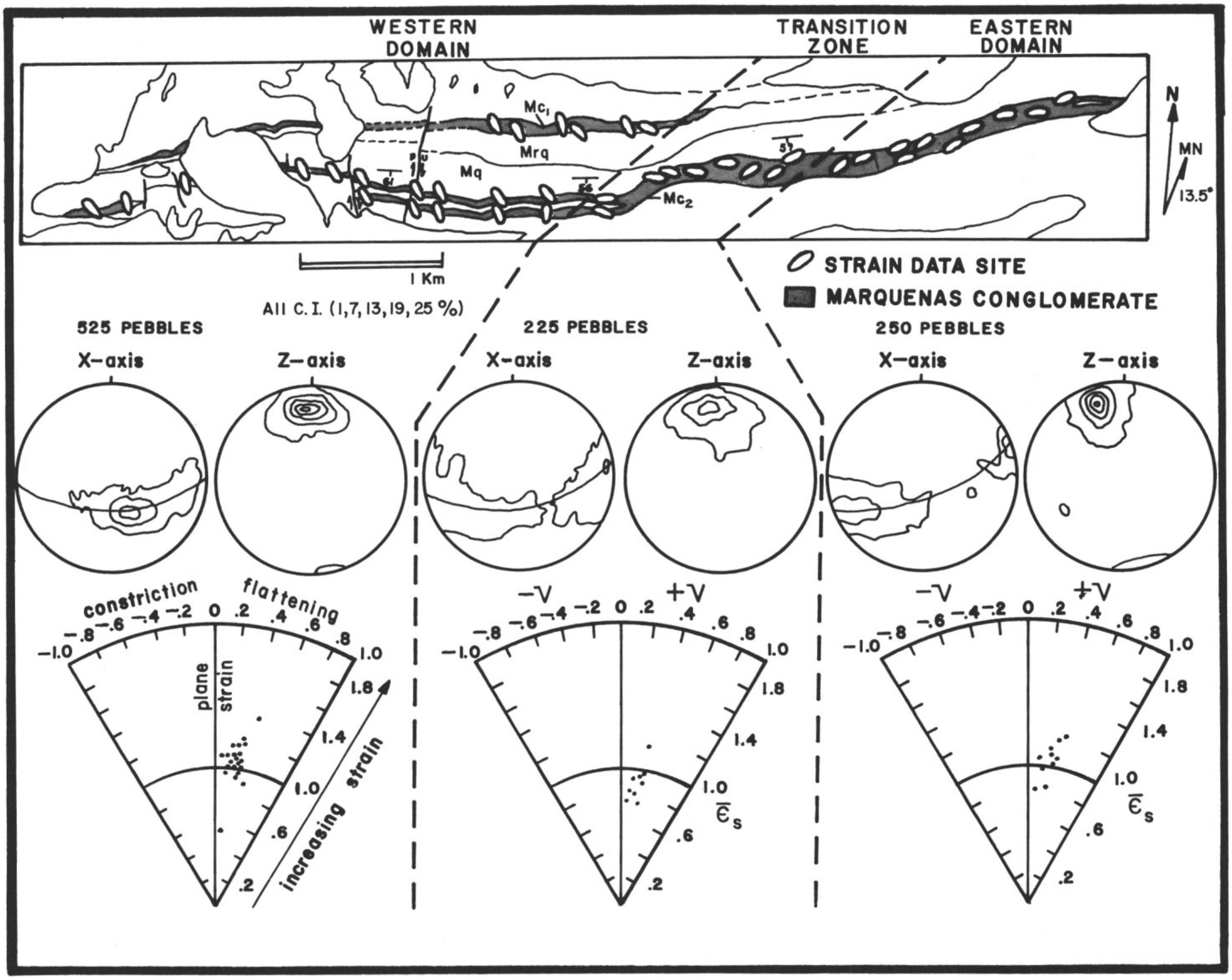

Figure 11. Strained-pebble data from the conglomerates of the Marquenas Quartzite. Data indicate a significant change in principal elongation direction across a narrow transition zone. In the transition zone, lower strain magnitudes are observed on the modified Hsu diagrams (after Hossack, 1968).

Formation is the development of large, randomly oriented poikiloblastic biotite, garnet and staurolite (Nielsen, 1972; fig. 12). In addition, andalusite and sillimanite have been recorded by Holdaway (1978), who believes that these coarse, undeformed minerals reflect the peak of metamorphism and that these minerals approached equilibrium conditions. The S3 surface deforms the $2 alignment either by gentle crenulation or by discrete zones of realignment (fig. 13). Both biotite, and more commonly, chlorite are associated with the S3 surfaces. Retrograde reactions of biotite and staurolite to chlorite, and almandine to iron oxides are associated with 53 (Holdaway, 1978). No characteristic minerals have been identified with $4 in the Ortega Group; however, in the Vadito Group, a penetrative cleavage in muscovite-quartz schist strongly suggests recrystallization of muscovite during F4 folding.

Textural observations in the Vadito units agree with the proposed thermal peak after F2 folding (Long, 1976). Long (1976) also noted recrystallization of muscovite associated with F3. F4 deformation apparently affected the foliated Rana Quartz Monzonite and was followed by localized epidote alteration (Long, 1976), suggesting higher temperatures associted with F4 than were proposed originally by Nielsen (1972).

Holdaway (1978) has produced the first quantification of pressure-temperature conditions in the Picuris Mountains. Using the occurrence of chloritoid-Al silicates in the Ortega Quartzite and the association staurolite-almandine with minor graphite in the Rinconada Formation, Holdaway was able to determine a temperature of 532 ± 20°C at about 3.7kb pressure. Long (1976) concluded that pressures and temperatures were somewhat less in the Vadito Group, principally because of the common occurrence of andalusite and the absence of sillimanite.

SUMMARY

From the preceeding data, an updated model can be outlined for the evolution of the Picuris Mountains (fig. 14). First-phase deformation involving the Ortega Group has been interpreted as recumbent isoclinal folding. However, until a large-scale structural relationship can be established, the possibility of early soft-sediment deformation should be considered. The primary sedimentary structures are oriented consistently with respect to F2 folds; and consequently, the entire width of the Picuris Mountains is inferred to be a single limb of an initial fold. Second-phase folding produced tight to nearly isoclinal folds. These folds have wave-lengths of approximately 4 km and undetermined amplitudes. The axial surface for this fold system strikes east-west and dips steeply to the south. The axis of F2 folds plunges 20° to 30° west-southwest and the principal elongation of pebbles plunges steeply southeast. Locally, this deformation was intense enough to transpose bedding and Si. Third-phase folding produced culmination and depression of F2 axes. S3 is an axial-plane cleavage with a generalized strike of N2OW and nearly vertical dip. West of Copper Hill (fig. 2), F4 produced localized ductile offsets which reoriented the earlier surfaces about a calculated N66E axial surface. The trend of the zone of offset appears to be more nearly N50E (see fig. 2). Southeast of Copper Hill, F4 becomes more sign if-

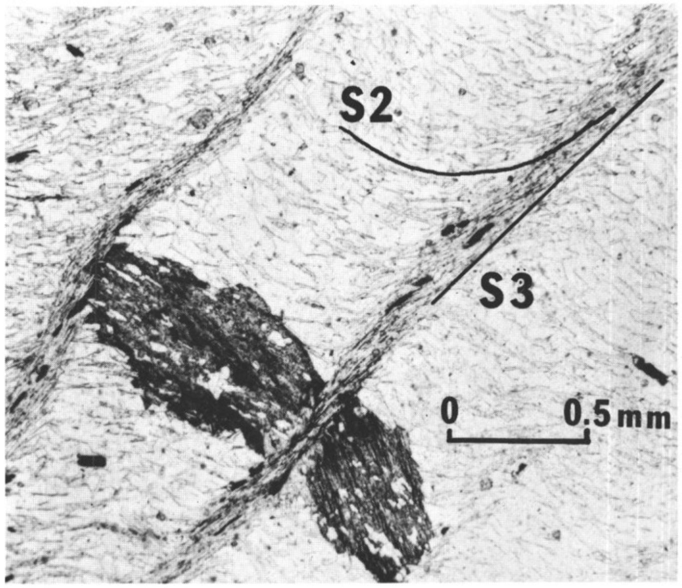

Figure 13. Maximum development of S_3 crenulation cleavage.

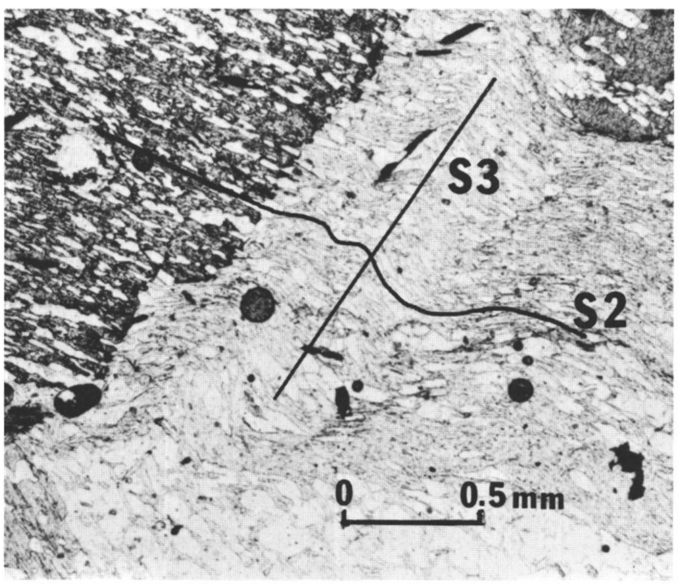

Figure 12. Poikiloblastic staurolite and biotite enclosing the principal muscovite foliation (S_2).

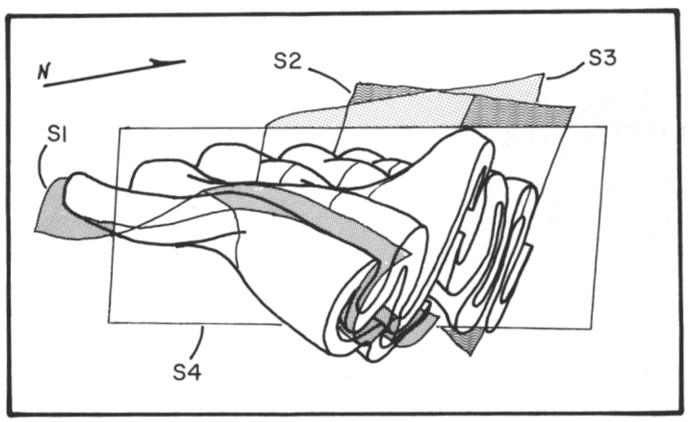

Figure 14. Schematic of fold surfaces in the Picuris Mountains.

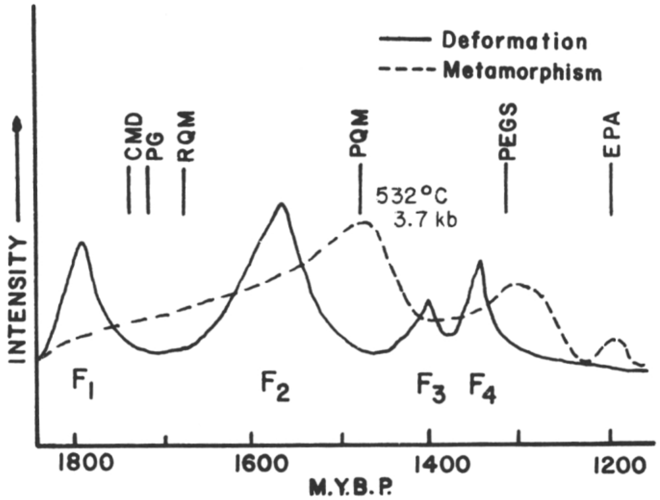

Figure 15. Summary of deformational, metamorphic and magmatic events in the Picuris Mountains. Abbreviations include Cerro Alto Metadacite (CMD); Puntiagudo Granite (PG); Rana Quartz Monzonite (RQM); Peñasco Quartz Monzonite (PQM); Harding Pegmatite (PEGS); Epidote Alteration (EPA) (after Long, 1976). Pressure-temperature conditions are for the Ortega Group only (Holdaway, 1978).

icant and fairly dominant in the Vadito schist units. This increased intensity suggests that the fault between the Vadito and Ortega groups to the east could be related to F4 shortening.

Metamorphism increased through the first two phases of folding, reaching a peak after the second phase (fig. 15). After the metamorphic peak, there was a decline with some local retrogressive effects. Third-phase folding took place when metamorphic conditions were sufficient for biotite, muscovite and chlorite to crystallize. Retrogression continued such that S3 surfaces served as planes along which fluids migrated, thus altering biotite and staurolite. F4 is generally low grade, but at least recrystallization of muscovite occurred.

Long (1976) evaluated existing isotopic data and placed revised time constraints on an earlier diagram by Nielsen (1972) (fig. 15). The ages of F1 folds, the Cerro Alto Metadacite and the Puntiagudo Granite are defined poorly and are listed by relative age only. The Rana Quartz Monzonite was dated at 1673 ± 41 m.y. by Fullagar and Shiver (1973). This pluton is thought to predate the F2 event. The Periasco Quartz Monzonite is 1470 m.y. in age according to Long's reasoning and unpublished U-Pb ages (Long, 1976). Finally, the Harding Pegmatite is thought to have a minimum age of 1300 to 1350 m.y. The steeply plunging southeast-trending fold at the Hard- ing mine is cut by the pegmatite, and therefore, the bulk of the pegmatite activity is believed to postdate F4. Mineral dates by Fullagar and Shiver (1973) and Gresens (1975) indicate a closing of the isotopic systems at 1200 m.y. B.P. This age has been assigned to epidote alteration by Long (1976). Therefore, approximately 500 m.y. of earth history are represented in the metamorphic terrain of the Picuris Mountains.

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