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Joseph R. Marcoline, Steven Ralser, and Laurel B. Goodwin

New Mexico Geology, v. 22, n. 3 pp. 57-63, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v22n3.57

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NEW MEXICO GEOLOGY

NM Bureau of Mines & Mineral Resources
New Mexico Tech
Earth Science for the 21st Century

ISSN 0196-948X
Volume 22, No. 3, August 2000

Science and Service

Field and microstructural observations from the Capilla Peak area, Manzano Mountains, central New Mexico

by *Joseph R. Marcoline*, *Steven Ralser**, and *Laurel B. Goodwin*, Department of Earth and Environmental Science,New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801
*Corresponding author (ralser@nmt.edu)

FIGURE 1—Capilla Peak area, Manzano Mountains, central New Mexico.

Abstract

Proterozoic rocks in the Capilla Peak area preserve evidence, at all scales, for multiple deformation events. The dominant north-northeast-striking, east-dipping foliation (S_2), with a downdip mineral lineation, overprints an older foliation. In schists and metarhyolites, S_2 is a crenulation cleavage, whereas in quartzites, S_2 is a mylonitic fabric. Two generations of amphibole are preserved in amphibolites, an older, core-forming actinolite and a younger hornblende. The hornblende defines the S_2 foliation.

Microstructures in the quartzite mylonites vary from fine grained and equigranular to monocrystalline ribbons. All quartzite mylonites have a strong *c*-axis crystallographic preferred orientation. The quartzite mylonite microfabric and the presence of hornblende in the amphibolites indicate that deformation associated with D_2 occurred under upper greenschist to lower amphibolite facies conditions. Kinematic indicators associated with the S_2 foliation (e.g. S-C surfaces, porphyroclast systems) dominantly indicate an east-side-up sense of shear. A minority (ca 5%) record a west-side-up sense of shear. This variation in sense-of-shear indicators is interpreted to suggest a strain history that reflects general shear (simple shear plus flattening strain). The Proterozoic rocks exposed in the Capilla Peak area are interpreted to represent a part of a large, lower amphibolite facies, ductile shear zone, which was active at ca 1.4 Ga.

Introduction

The Proterozoic tectonic history of the southwestern United States is complex, with deformation and/or metamorphic events occurring at ca 1.65 Ga, 1.4 Ga, and 1.0 Ga (Karlstrom and Bowring, 1988; Grambling et al., 1989; Heizler et al., 1997). In New Mexico, the timing of deformation events is generally constrained to be contemporaneous with or younger than plutonism associated with crustal accretion at 1,750–1,650 Ma and older than the comparatively undeformed 1,400–1,450 Ma plutons. The timing of regional deformation has, in the past, generally been considered to accompany accretion of the continental crust at ca 1.65 Ga (e.g. Karlstrom and Bowring, 1988; Bauer and Williams, 1994), with only minor deformation accompanying metamorphism and pluton emplacement at ca 1.4 Ga. However, more recent observations have shown that deformation at ca 1.4 Ga is extensive and regional in nature, often completely overprinting the structures associated with deformation at 1.65 Ga (Lanzirotti et al., 1996; Marcoline et al., 1999; Williams et al., 1999; Ralser, 2000).

Locally, the timing of individual deformation events can be more accurately tied down. In central New Mexico the timing of deformation can be constrained in a number of areas. In the Magdalena Mountains, for instance, Bauer and Williams (1994) demonstrated deformation at ca 1,660 Ma. In the Manzano Mountains (Fig. 1), two phases of deformation are constrained to be younger than the 1,656 ± 10 Ma Monte Largo granodiorite (U/Pb zircon, Bauer et al., 1993), which is strongly deformed. The comparatively undeformed 1,427 ± 10 Ma

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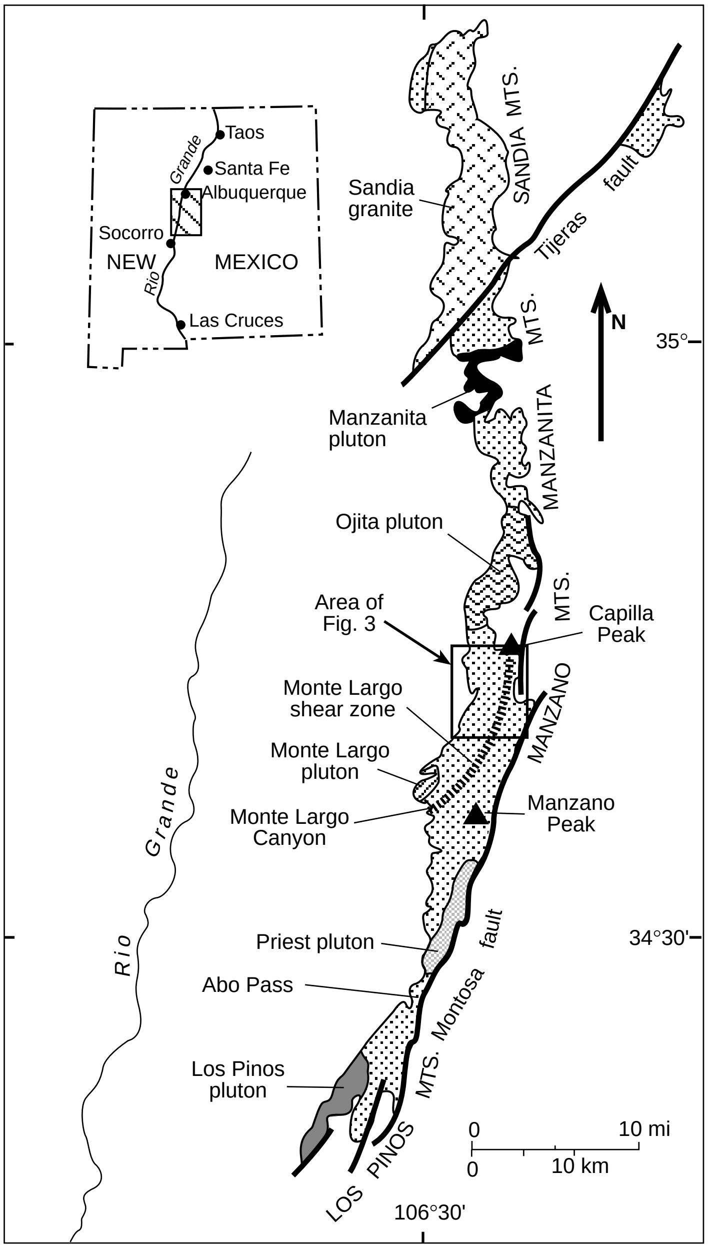

FIGURE 2—Location map, showing simplified geology of the Manzano Mountains (modified from Bauer et al., 1993).

Priest pluton (U/Pb zircon, Bauer et al., 1993) is interpreted to have intruded late syntectonic to the younger phase of deformation. This interpretation is supported by the presence of a strongly deformed granitic dike that has a U/Pb age of 1,438 ± 6 Ma (Ralser et al., 1997). Detailed ^{40}Ar/^{39}Ar geochronologic studies in the Capilla Peak area, in the central Manzano Mountains (Fig. 2), also suggest that the dominant structural fabric formed during 1.4 Ga tectonism (Marcoline, 1996; Marcoline et al., 1996, 1999). Localized deformation in the Priest pluton is related to the Grenville orogeny at ca 1,000 Ma (Heizler et al., 1997).

In this paper, we summarize structural relationships and deformation conditions in the Proterozoic rocks in the Capilla Peak area. Our goal is to document the structural relationships in this area in order to better understand the character and significance of 1.4 Ga deformation in New Mexico. This area straddles the northern extent of the Monte Largo shear zone (MLSZ; Bauer, 1983; Thompson et al., 1991), which separates lower amphibolite facies rocks in the south from upper greenschist facies rocks to the north (Thompson et al., 1991, 1996).

Location and regional geology

The Manzano Mountains are an eastward-tilted fault block composed primarily of Proterozoic metasedimentary, metavolcanic, and plutonic rocks. The mountain range is approximately 70 km long and 15 km wide and defines the eastern margin of the Rio Grande rift between the Manzanita Mountains and Abo Pass (Fig. 2). The study area is in the central Manzano Mountains, located between Capilla Peak and Trigo Canyon (Figs. 2, 3).

Three major lithologic units are recognized in the Capilla Peak area (Stark, 1956; Stark and Dapples, 1946; Reiche, 1949; Bauer, 1982): the Blue Springs Schist, the Whiterock quartzite, and the Sevilleta Metarhyolite. The Blue Springs Schist is composed of intensely folded metasiltstones, phyllites, and muscovite-chlorite schists (Stark 1956; Bauer 1982). Boudinaged quartzites within the Blue Springs Schist are now interpreted as transposed sedimentary layers but were initially believed to be saddle reefs (Stark, 1956).

The Whiterock quartzite consists of a series of quartzite mylonites interlayered with rocks of the Blue Springs Schist and Sevilleta Metarhyolite. These quartzite mylonites represent localized high-strain zones within a larger deformation zone (Marcoline, 1996). In Monte Largo Canyon these quartzite mylonites define the MLSZ (Bauer, 1983; Thompson et al., 1991), where it crops out as a discrete 3-m-wide shear zone.

The Sevilleta Metarhyolite (Stark and Dapples, 1946), is exposed predominately on the east side of the range in the Capilla Peak area (Fig. 3). The metarhyolite is pink to brown, well foliated, and lineated. In lower strain areas, the metarhyolite contains 1–2 mm equidimensional quartz and feldspar phenocrysts. Amphibolite layers (1–20 m wide and 400 m long) occur within the Sevilleta Metarhyolite and are interpreted to be deformed and metamorphosed early mafic dikes (Stark and Dapples, 1946). The amphibolites are petrologically complex, containing two amphibole phases, hornblende and actinolite, along with plagioclase, biotite, quartz, epidote, and minor amounts of titanite and Fe–Ti oxides. The mineral assemblages in different amphibolites all indicate formation under amphibolite grade conditions (Marcoline et al., 1999).

The stratigraphic relationships between these units are unclear, although it is

NEW MEXICO GEOLOGY

Science and Service

ISSN 0196-948X

Volume 22, No. 3, August 2000

Editors: Jane C. Love, Nancy S. Gilson, Bonnie Frey, and Susan Voss

Cartographers: Kathryn E. Glesener and Leo Gabaldon

Published quarterly by New Mexico Bureau of Mines and Mineral Resources a division of New Mexico Institute of Mining and Technology

Subscriptions: Issued quarterly, February, May, August, November; subscription price $10.00/calendar year.

Editorial Matter: Articles submitted for publication should be in the editor's hands a minimum of five (5) months before date of publication (February, May, August, or November) and should be no longer than 20 typewritten, double-spaced pages. All scientific papers will be reviewed by at least two people in the appropriate field of study. Address inquiries to Jane C. Love, Editor of *New Mexico Geology*, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801-4796.

Circulation: 1,000

Printer: University of New Mexico Printing Services

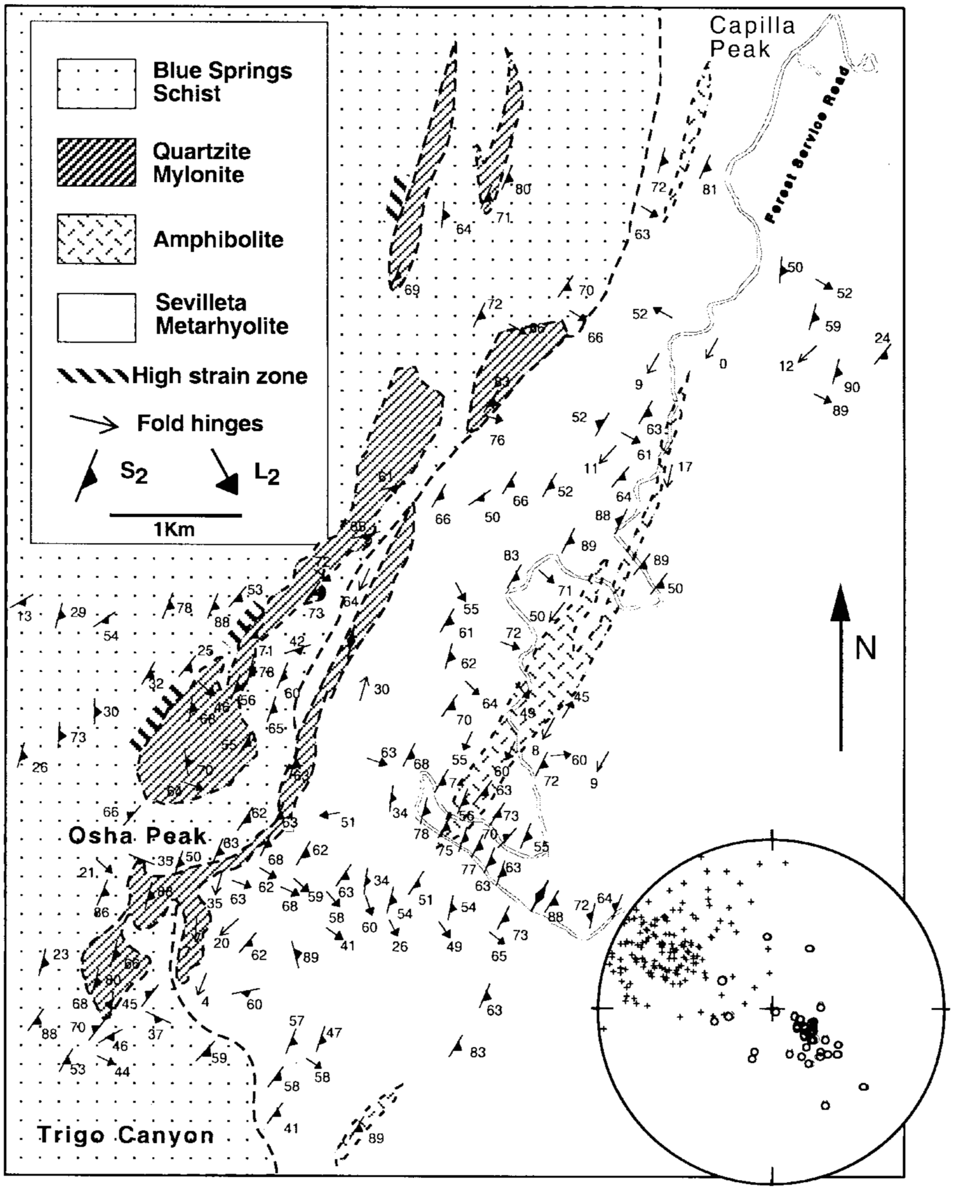

FIGURE 3—Geologic map of the Capilla Peak area showing the distribution of units, the main foliation (**S_2**), and lineation (**L_2**). Poles to foliation (**+**)and mineral lineations (**o**) are plotted on a lower hemisphere equal area projection.

believed that the Sevilleta Metarhyolite is the oldest unit, based on Rb–Sr isochrons with an age of 1,700 ± 58 Ma (Bolton, 1976) and a U–Pb zircon age of 1,680 Ma (Bowring et al., 1983).

Structure

The dominant structure in the central Manzano Mountains is a pervasive, northeast-striking, steeply southeast-dipping foliation (S_2; Fig. 3). In the schistose units, this foliation is a crenulation cleavage, cutting a well-defined earlier foliation (S_1). In the non-schistose units, S_2 is the main foliation. As this S_2 foliation is interpreted to have formed during tectonism at 1.4 Ga (Marcoline et al., 1999; Ralser, 2000), it will be described in detail in this paper. The macrostructural and microstructural nature of this foliation will be described from west to east (Blue Springs Schist, quartzite mylonites, Sevilleta Metarhyolite, amphibolites) in the following sections. We will describe *c*-axis crystallographic preferred orientations observed in the quartzite mylonites in the final part of this section.

Macrostructural relationships

S_2 exhibits significant variation in character and orientation in the Blue Springs Schist. In the phyllites and quartz-rich zones of the muscovite-chlorite schists, S_2 is a well-developed planar foliation, striking approximately 030° and dipping from 60° to 80° southeast. However, in quartz-poor zones of the muscovite-chlorite schist, the S_2 orientation is variable. S_2 anastamoses around the numerous folded quartz layers, with strikes ranging from 0° to 50° and dips varying from 60° to 90° southeast. Asymmetrical chevron-style crenulations, with limbs 1–3 cm in length and with axial planar S_2, are locally evident. The metasiltstones are characterized by small-scale disharmonic folding of the compositional layering. The S_2 foliation is poorly developed and highly irregular in orientation in the metasiltstones. The foliation is axial planar to the disharmonic folds, which may explain the large variation in orientation of S_2.

Intensely deformed Blue Springs Schist is found in three distinct, narrow zones less than a meter wide, which are characterized by a well-developed, planar S_1 foliation. The most continuous of these high-strain zones is located on the western contact between the quartzite mylonite and the Blue Springs Schist (Fig. 3). Two other highly deformed zones are located along strike within the Blue Springs Schist, adjacent to one of the smaller quartzite mylonite layers. The contacts between the highly deformed zones and the more typical schist are gradational. Away from the highly deformed zones the schist contains abundant quartz-rich layers. Nearer to the deformed zones, the quartz-rich layers become discontinuous and boudinaged. No quartz-rich layers were observed in the high-strain zones.

In quartzite mylonites, S_2 is a strong mylonitic foliation that strikes approximately 025° and dips from 60° to 80° southeast. S_1 is only preserved in lower strain zones as open to isoclinally folded surfaces. The development of S_2 is controlled by mica content in the quartzite mylonites; S_2 is best developed in areas with a higher mica content.

The Sevilleta Metarhyolites are, in general, characterized by a strongly developed north-northeast-striking foliation (S_2) with a locally well developed downdip lineation (Fig. 3). S_1 is only observed in a few locations where S_2 is poorly developed. The S_2 foliation is defined by aligned biotite and lens-shaped quartz and feldspar porphyroclasts. F_2 folds in the metarhyolite plunge shallowly to moderately to the south-southwest and include both small 0.5–1-m isoclinal folds and 3–5-m open folds. An S_2 axial planar foliation is only locally observed in the folded areas.

S_2 in the amphibolite layers ranges from weakly to strongly developed and is typically parallel to the foliation in the surrounding metarhyolite. One amphibolite layer contains distinctive less deformed 'pods' as large as 10 cm in diameter. These pods have length to width ratios ranging from 1:1 to 2:1 and contain 1–3-mm, unaligned, green to black amphibole crystals. A strong foliation wraps around the pods. The pods are sigmoidal in shape and asymmetric with respect to the main foliation, consistently recording east-side-up shearing. Several 0.5–1-m-scale asymmet-

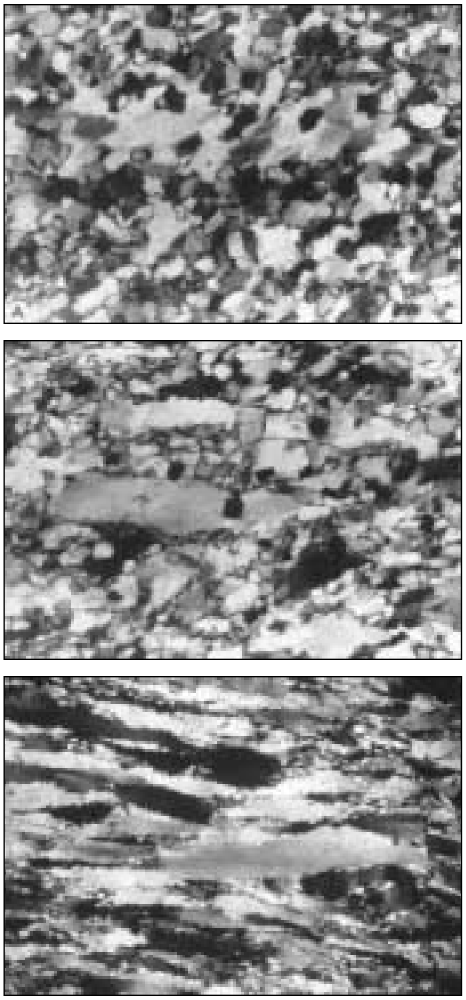

FIGURE 4—Photomicrographs showing the variation in microstructures developed in the quartzite mylonites. Three groups can be recognized based on microstructures. **A**) Group 1 is characterized by equant recrystallized quartz grains 0.1–0.25 mm in size. Note the recrystallized relic grain, and the grain-shape preferred orientation trending from bottom left to top right. **B**) Group 2 is characterized by a bimodal grain-size distribution with large elongate grains parallel to the main foliation and fine equigranular crystals. **C**) Group 3 is characterized by 1–20-mm, slightly undulose monocrystalline quartz ribbons. All photomicrographs normal to the foliation and parallel to the lineation; S_2 is horizontal; width of photos—**A** and **B**, 0.5 mm; **C**, 3 mm.

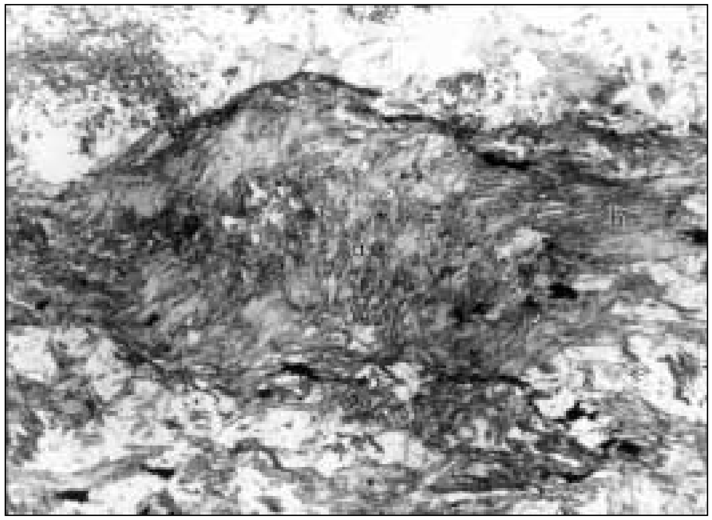

FIGURE 5—Photomicrograph showing two amphibole phases. Actinolite (**a**) forms cores and has inclusion trails nearly perpendicular to the foliation-forming, green euhedral hornblendes (**h**). Width of photo is 4.5 mm; S_2 is horizontal.

ric sigmoid-shaped structures within the amphibolite layers are also observed. These structures are similar to the pods but contain an internal foliation parallel to, but weaker than, the surrounding foliation.

Microstructural relationships

The character of the Blue Springs Schist is as variable microscopically as it is at the outcrop scale. In general, the S_2 crenulation cleavage is best developed adjacent to the quartzite mylonites. With better S_2 development, the cleavage-plane spacing decreases. In zones with a large amount of quartz, recrystallized grains preserve a grain-shape preferred orientation at a 45° angle to S_2.

The major quartzite mylonite units can be divided into three groups on the basis of microstructures. The first group is characterized by 0.1–0.25-mm, recrystallized quartz grains with a strong to moderate grain-shape preferred orientation that defines a foliation at an angle between 45° and 60° from S_2 (samples ML 11-3, ML 7-15, and ML 6-2; Fig. 4A). The second group of quartzite mylonites is characterized by fine-grained, 0.1–0.25-mm, recrystallized quartz grains with 1–3-mm-long monocrystalline quartz ribbons (samples ML 7-1 and ML 7-3; Fig. 4B). The third group is characterized by 3–20+ mm-long monocrystalline quartz ribbons (samples ML 1-2, ML5-10; Fig. 4C). The ribbons exhibit undulose extinction with minor subgrain formation. S-C fabrics are locally present in the third group of quartzite mylonites. In all mylonite samples, micas are included within the recrystallized quartz grains as well as between grains, indicating a significant degree of grain boundary mobility and suggesting deformation at a high temperature or slow strain rate (e.g. Lister and Dornsiepen, 1982).

The metarhyolites are characterized by 1–2-mm quartz and feldspar porphyroclasts in a fine-grained (0.1–0.25 mm) foliated quartz and feldspar matrix. Although the majority of the feldspar porphyroclasts show orthorhombic symmetry with respect to the foliation (ϕ-type, see Passchier and Trouw, 1996), scattered asymmetric ∂-type porphyroclasts are also present. Asymmetric strain shadows, defined by recrystallized quartz, are developed around feldspar phenocrysts. Although these porphyroclasts show evidence for both west- and east-side-up sense of shear, the latter group is dominant.

The amphibolites exhibit complex microstructures and are dealt with in more detail elsewhere (Marcoline, 1996; Marcoline et al., 1999). They preserve older actinolite and younger hornblende, plagioclase, biotite, quartz, and epidote. The older anhedral actinolite is crosscut and overgrown by the foliation-forming euhedral hornblende (Fig. 5). Actinolite contains inclusion trails that record an older foliation parallel to the crystallographic cleavage planes and nearly perpendicular to the well-defined hornblende foliation. Hornblende both rims the actinolite and defines the S_2 foliation. Hornblende rims and foliation-forming grains show mutual crosscutting relations. The composition of the hornblende is consistent with formation at lower amphibolite facies conditions (Marcoline, 1996; Marcoline et al., 1999).

Quartz *c*-axis crystallographic preferred orientations

In general, *c*-axis crystallographic preferred orientations (CPOs) develop due to a reorientation of crystal axes as a result of dislocation slip (e.g. Hobbs et al., 1976; Van Houtte and Wagner, 1985; Williams et al., 1994). Dislocation slip occurs when the shear stress resolved on the slip plane in a particular slip direction reaches a critical value, the critical resolved shear stress (Hobbs, 1985; Van Houtte and Wagner, 1985). As with microstructural studies, CPO studies cannot provide unique constraints on the deformation conditions, because both intrinsic factors (e.g. temperature, strain rate) and extrinsic factors (e.g. strain history) can influence the development of CPOs (e.g. Hobbs, 1985). Increasing temperature has the same effect as decreasing strain rate. Slip systems that have a high critically resolved shear stress (CRSS) at low temperatures or fast strain rates (e.g. prism slip in quartz) have a much lower CRSS at higher temperatures or slower strain rates. Such changes in the operating slip systems are reflected in the CPOs that develop (e.g. Tullis et al., 1973; Lister and Hobbs, 1980; Schmid and Casey, 1986). The strain history also has a profound effect on the CPOs that develop; with a coaxial strain history, symmetric CPOs develop, whereas with a noncoaxial strain history, asymmetric CPOs develop (e.g. Lister and Hobbs, 1980). The sense of asymmetry can be used to determine the sense of shear (e.g. Schmid and Casey, 1986).

Two hundred *c*-axis orientations were

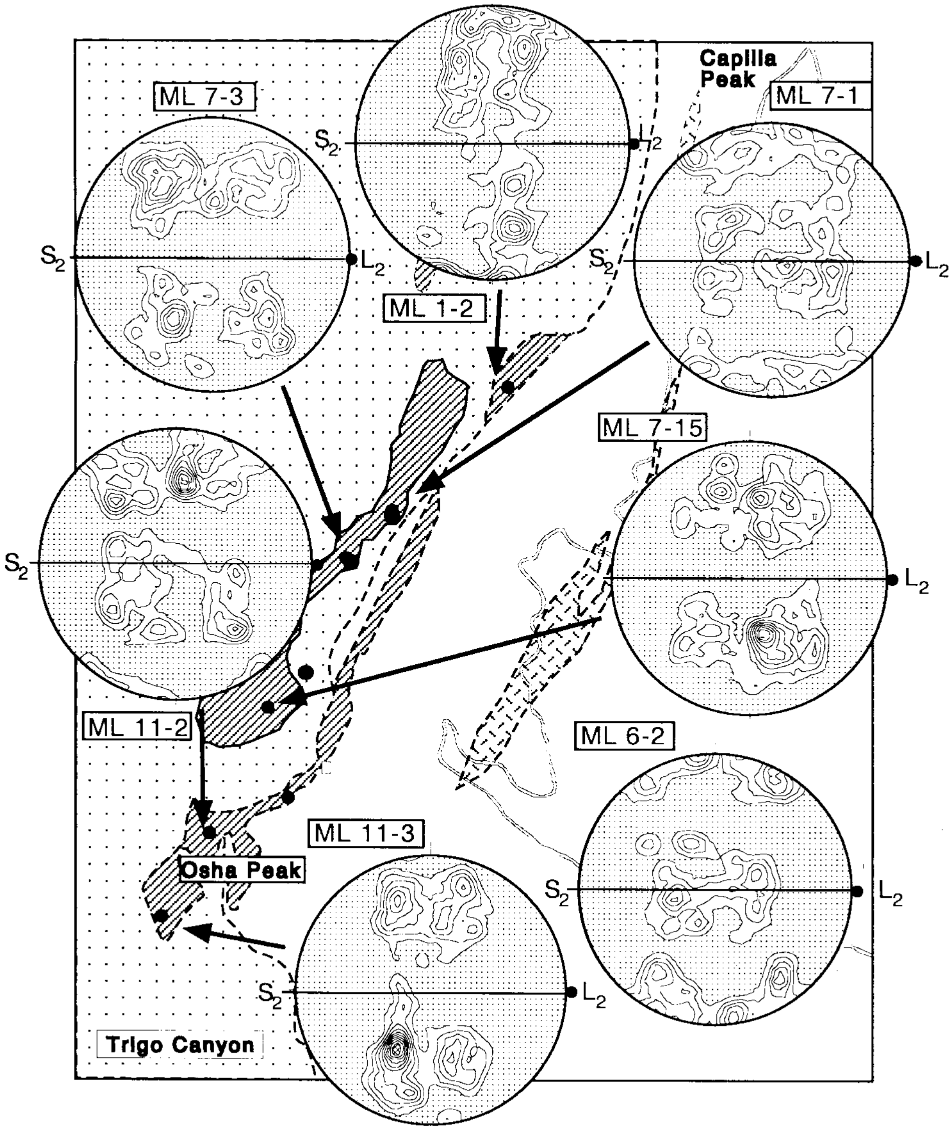

FIGURE 6—Geologic map of the Capilla Peak area showing location of quartzite mylonites where *c*-axes have been measured and showing equal area, lower hemisphere plots of 200 quartz grains. Contours represent multiples of uniform distribution.

measured from thin sections cut perpendicular to the lineation and foliation from each of seven representative quartzite mylonite samples from the Capilla Peak area (Fig. 6). Data were then plotted on equal area, lower hemisphere projections and rotated so that the trace of the foliation is horizontal and the lineation is horizontal and plunging to the right on each plot.

Three different patterns are observed in the quartzite mylonite samples. Incomplete small circle girdles about the pole normal to the foliation are developed in three samples (ML 11-3, ML 7-3, and ML 7-15; Fig. 6). In each girdle, two maxima are symmetrically distributed on either side of the pole to the foliation; however, the size of the maxima on either side of the pole to the foliation vary. Samples ML 6-2, ML 7-1, and ML 11-2 have *c*-axis distributions that range from normal to the foliation to perpendicular to the lineation, within the foliation plane (Fig 6). The maxima in these three samples are relatively symmetric, in both distribution and size, about the pole to the foliation. These plots are different from the first group of plots in that the maxima are located preferentially in the center and in the outer top and bottom portions of the plot. The CPO of sample ML 1-2 differs from those of the other samples, in that a relatively symmetric *c*-axis girdle is approximately normal to the lineation (Fig. 6).

Discussion

D_2 structures are developed throughout the Capilla Peak area and vary from a crenulation cleavage (with wavelengths from 0.5 mm to 5 cm) developed in the Blue Springs Schist to strongly foliated and lineated tectonites developed in the quartzites and metarhyolites. In most places S_1 is not visible. Zones of high strain formed during D_2 (characterized by a well-developed, planar foliation) are localized in the quartzite of the Blue Springs Schist, near the contact between the Blue Springs Schist and the quartzite mylonites, and in the Sevilleta Metarhyolite.

The Monte Largo shear zone (MLSZ) has previously been interpreted as a narrow (3–5 m in width) shear zone characterized by quartzite mylonites (Bauer, 1983; Thompson et al., 1991). This interpretation is based on studies along the southern extent of the MLSZ in Monte Largo Canyon. Our observations along the northern extent of the MLSZ in the Capilla Peak area indicate that deformation associated with the shear zone is more widespread. This increase in width of the deformed zone is related to the number of quartzite layers present, which is greater in the Capilla Peak area (Fig. 3). Deformation associated with the MLSZ is spread over the zone encompassed by the quartzite mylonites.

Deformation under amphibolite facies conditions is indicated by both mineral assemblages and microstructures. The hornblende, which defines the S_2 foliation in the amphibolites and accompanying phases, suggests formation under amphibolite facies conditions (c.f. Spear, 1981; see Marcoline et al., 1999 for a detailed discussion). These hornblendes yield $^{40}Ar/^{39}Ar$ ages of ca 1,400 Ma, indicating that hornblende closed to Ar diffusion and was, therefore, at temperatures around the greenschist/amphibolite facies boundary (~450°–550° C) at ca 1,400 Ma. Other features related to D_2 deformation, in particular microstructures and *c*-axis CPOs, are consistent with lower amphibolite facies deformation. The microstructures in the quartzite mylonites range from fine grained and equigranular to large monocrystalline quartz ribbons. Some areas (e.g. sample ML 11-2) show coexisting zones of monocrystalline quartz ribbons and fine-grained equigranular microstructure. Such microstructures are consistent with deformation at upper greenschist to lower amphibolite facies conditions (Simpson, 1985; Hanmer and Passchier, 1991). Because the pressure and temperature at which deformation took place could not have varied significantly within the small area encompassing the quartzite mylonites, changes in these deformation conditions can not be called on to explain the differences in microstructure observed in the quartzite mylonites. The observed microstructure variations, therefore, must be the result of variations in either strain, strain rate, composition, and/or water content (e.g. Kronenberg, 1981). The mineralogy, including the presence of hydrous phases, is similar in all the quartzite mylonites, suggesting that neither mineralogy nor water content affect the microstructure that developed. All the quartzite mylonites are strongly deformed so a steady state microstructure could have developed. It is, therefore, most likely that

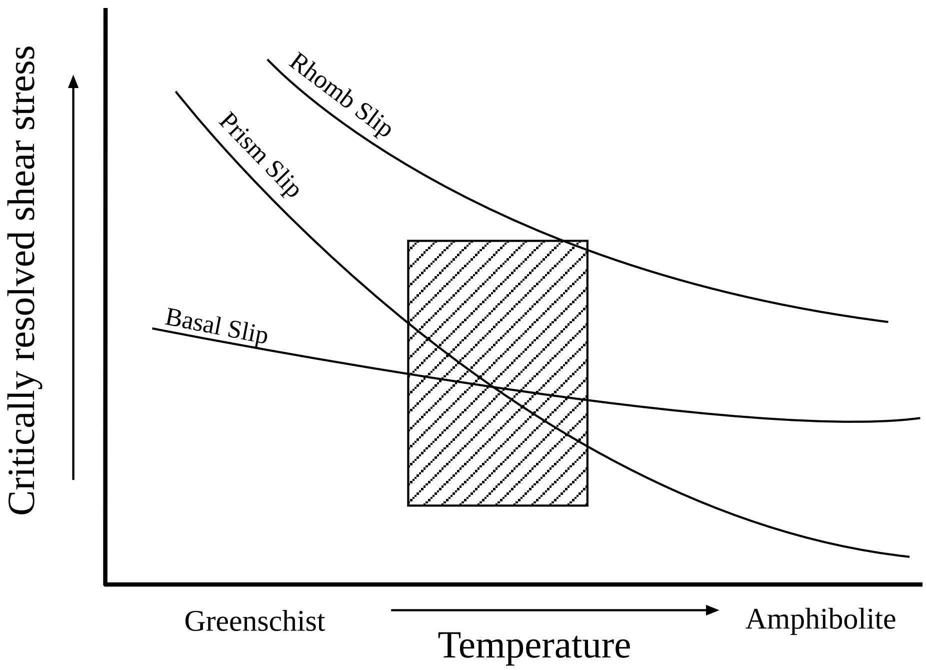

FIGURE 7—Plot of critically resolved shear stress versus temperature (Hobbs, 1985). The shaded area represents the approximate deformation conditions in the Capilla Peak area.

the observed microstructures reflect differences in strain rate rather than the alternatives.

The presence of only ∂-type porphyroclast systems, as opposed to σ-type porphyroclast systems, within the metarhyolites is striking. Previous workers have proposed that the dominance of ∂-type porphyroclast systems indicates that both the strain (rotation) rate was high relative to the recrystallization rate and that there was a component of extensional shear in the deformation (Passchier and Simpson, 1986; Hanmer and Passchier, 1991). Because we observe asymmetric fabrics and porphyroclast systems as well as a nearly orthorhombic symmetry in most quartzite mylonite *c*-axis CPOs, we believe that the observed deformation history resulted from a progressive, general, noncoaxial flow (Simpson and De Paor, 1993). Such an interpretation is consistent with the variable sense of shear determined from kinematic indicators in the Capilla Peak area (e.g. grain-shape preferred orientation, shear bands, asymmetric porphyroclast systems). The majority of these kinematic indicators indicate an east-side-up sense of shear, but approximately 5% of the kinematic indicators indicate a west-side-up sense of shear.

Interpretations from crystallographic preferred orientations

In order to use CPOs to place constraints on the conditions under which deformation took place in the MLSZ, it is necessary to determine which deformation mechanism(s) was (were) operating to form the observed microfabric. A strong CPO indicates that deformation was primarily accommodated by dislocation slip (e.g. Hobbs et al., 1976; Van Houtte and Wagner, 1985), with the operating slip systems a function of the deformation conditions (Fig. 7; e.g. Hobbs, 1985). The most commonly reported slip systems in quartz are basal, prism, and rhomb planes with slip primarily in the <*a*> direction; however, evidence of slip in the <*c*> and <*c*+*a*> directions has also been observed (e.g. Price, 1985). Basal <*a*> slip dominates at greenschist facies conditions, basal <*a*> and prism <*a*> slip show approximately equal activity at amphibolite facies conditions, and prism <*a*> slip dominates at higher-grade conditions (e.g. Hobbs, 1985). Although determination of active slip systems can only be made unequivocally through detailed transmission electron microscope studies, an indication of which slip systems are operative can be obtained from *c*-axis CPOs (e.g. Schmid and Casey, 1986).

The apparent small circle girdles about the pole to the foliation in samples ML 11-3, ML 7-3, and ML 7-15 suggest either a predominantly flattening strain history (c.f. Tullis et al., 1973; Law et al., 1984; Price, 1985) or incomplete development of *c*-axis girdles during plane strain (c.f. compilation of Price, 1985). Compared to the CPO data of Schmid and Casey (1986), the *c*-axis CPOs from these samples suggest that deformation could have been predominantly accommodated by rhomb <*a*> slip. However, at all conditions, basal <*a*> and prism <*a*> slip are easier than rhomb <*a*> slip, suggesting that this interpretation is unlikely (Fig. 7). Alternatively, such *c*-axis CPOs could result from the almost equal activity of basal <*a*> and prism <*a*> slip (c.f. Ralser et al., 1991). Equal activity of basal <*a*> and prism <*a*> slip is consistent with amphibolite-grade conditions.

Only sample ML 1-2 shows a crossed-circle girdle normal to the lineation (Type I girdle of Lister, 1977). Both the CPO and the S-C microstructure of this sample indicate a large component of noncoaxial deformation. The CPOs in the other three samples (ML 6-2, ML 7-1, ML 11-2), consisting of *c*-axis maxima nearly normal to the lineation, both parallel and perpendicular to the foliation, are not as easy to interpret. They may reflect incomplete crossed girdles and, therefore, represent deformation under plane strain. The maxima, both normal to the foliation and in the foliation plane, result from the activity of a combination basal <*a*> and prism <*a*> slip.

Only weak asymmetries are observed in the CPOs. The majority of the samples (ML 11-2, ML 1-2, ML 7-3, ML 7-15, ML 6-2) are defined by the more populated northeast-southwest girdle, suggesting a weak component of east-side-up simple shear. In sample ML 11-3, the northwest-southeast girdle has a higher population than the northeast-southwest girdle and is interpreted to indicate a west-side-up sense of shear. This is consistent with the variability exhibited by other kinematic indicators.

Conclusions

The Proterozoic rocks currently exposed in the Capilla Peak area of the Manzano Mountains were all part of an upper greenschist to lower amphibolite facies, ductile shear zone active at ca 1.4 Ga (see also Marcoline et al., 1999; Ralser, 2000). The dominant north-northeast-striking foliation (S_2) is observed in all lithologic units and overprints at least one older foliation. Deformation related to S_2 is partitioned into high- and low-strain zones. In low-strain zones, deformation is expressed as small-scale folding, and if S_2 is present, it is a poorly defined crenulation cleavage. High-strain zones are characterized by a strong planar foliation, which completely overprints all evidence of the earlier deformation.

The quartzite mylonite microstructures within high-strain zones range from monocrystalline quartz ribbons to fine-grained equigranular crystals. As these quartzite mylonites are interpreted to have formed under similar pressures and temperatures, the observed variations are interpreted to result from changes in strain rate. The strong *c*-axis CPOs are interpreted to have formed predominantly by dislocation slip on basal and prism planes, indicating formation during an upper greenschist- to lower amphibolite-grade deformational event. This is consistent with metamorphic conditions determined from nearby amphibolites, where euhedral hornblende (parallel to the S_2 foliation) is interpreted to have formed under amphibolite facies conditions (Marcoline, 1996; Marcoline et al., 1996, 1999).

Kinematic indicators, including microscopic folds, S-C surfaces, asymmetric porphyroclast systems, and *c*-axis CPOs, in general, indicate an east-side-up sense of shear. However, rare porphyroclast systems in the quartzites and the Sevilleta Metarhyolite record a west-side-up sense of shear. These differing kinematic indicators suggest a strain history of progressive, general, noncoaxial flow (c.f. Simpson and De Paor, 1993); i.e. a combination of both simple shear and flattening.

Acknowledgments. This work was supported by National Science Foundation grant EAR-9316474. Critical reviews by E. A. Melis, K. Nielsen, and M. Williams are gratefully acknowledged.

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The editors wish to correct the erroneous statement: “The Romans used pozzolans found in southeastern France along the Rhine River.” from “Uses of fly ash from New Mexico coals,” *New Mexico Geology*, v. 22, no. 2, p. 25. A pozzolanic volcanic tuff called Rhenish Trass is mined near the Rhine in western Germany. It is used today in the manufacture of portland cement, and it may have been used by the Romans as