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Christopher K. Mawer and Paul W. Bauer

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PRECAMBRIAN ROCKS OF THE ZUNI UPLIFT: A SUMMARY, WITH NEW DATA ON DUCTILE SHEARING

CHRISTOPHER K. MAWER[1] and PAUL W. BAUER[2]

[1]Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131; [2]New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801

Abstract—We present a brief synthesis of previous work on the Precambrian Zuni metaigneous complex (ZMC), a review of methods for determining protoliths of felsic schists and gneisses, new data on microscopic kinematic indicators in the ZMC and some speculation on possible relationships between the ZMC and other Precambrian terrains in central and northern New Mexico. The informally named ZMC mainly consists of metamorphosed and deformed, felsic to ultramafic schists, gneisses and foliated plutonic rocks. Regional metamorphic conditions peaked at lower amphibolite grade. U-Pb zircon isotopic ages from felsic igneous rocks indicate their crystallization at about 1655 my (Bowring and Condie, 1982). Precambrian rocks are host to several generations of abundant fluorite mineralization which is confined to narrow veins. The original fluorite source may be an unexposed pluton.

The felsic schists and gneisses are problematic in terms of both protolith and structural analysis. Because contact relationships are poorly exposed and tectonized, and three-dimensional shapes are unknown, we look to internal features for protolith determination. For protolith data, thin sections are cut perpendicular to the extension lineation; for kinematic data, sections are cut parallel to the extension lineation and parallel to the foliation. Most of the felsic schists in the ZMC appear to be metaigneous rocks, probably rhyolites and tuffs. Well-developed sense-of-shear criteria consisting of rotated porphyroclasts, asymmetric microfolds and shear bands indicate a tectonic history of early, more penetrative, north-directed ductile shearing followed by later, more discrete, south-directed normal shearing. The Precambrian igneous rocks of the Zuni uplift, along with much of the exposed Precambrian crust in central New Mexico, may have formed between 1640 and 1680 my. Subsequent tectonism perhaps involved north-verging thrusting, folding, and crustal thickening, followed by south-verging shearing, faulting, crustal relaxation and thinning.

INTRODUCTION

The Zuni uplift of west-central New Mexico is a northwest-southeast elongate, Precambrian-cored arch on the eastern edge of the Colorado Plateau. The uplift is flanked by outward-dipping Permian and Triassic rocks on the east, west and north, and Quaternary basalt on the south. Proterozoic rocks are exposed in four areas in the central area of the range (Fig. 1). The largest exposure extends about 30 mi (48 km) between N.M. 53 and Bluewater Creek. The highest point in the Zuni Mountains (Mount Sedgwick, 9256 ft) occurs in this exposure. Three smaller exposures lie to the northwest, between Bluewater Creek and McGaffey.

Investigation of Precambrian rocks in the Zuni Mountains has been relatively limited. Early mapping and more recent studies of geochemistry, isotope geology and fluid inclusions have focused on the occurrence and origin of Precambrian-hosted fluorspar mineralization. The focus of this paper is four-fold: (1) to review our present understanding of the Precambrian evolution of rocks in the Zuni Mountains; (2) to constrain better the protoliths of the felsic schists and gneisses that form much of the largest Proterozoic exposure; (3) to discuss the somewhat cryptic yet ubiquitous microstructural kinematic indicators of ductile shearing within these schists; and (4) to speculate briefly on how these rocks might relate to other Precambrian exposures in New Mexico.

ROCK TYPES

Goddard (1966) has produced the only regional study of Precambrian rocks in the Zuni Mountains (Fig. 2). His excellent map (scale 1:31,680) of the large southern exposure showed 17 rock types, 6 of which have appreciable areal extent. Five of these are varieties of variably deformed granitoids, whereas the sixth is a fine-grained felsic schist interpreted to be a metarhyolite. The remaining volumetrically minor units are lenses, dikes, xenoliths and irregularly shaped bodies of felsic to ultramafic plutonic, hypabyssal and volcanic rock. The quartzite of Goddard (1966) actually appears to be a strained and metamorphosed volcanic and/or volcaniclastic rock, rather than an orthoquartzite. The biotite schists of Goddard contain mainly chlorite, hornblende, epidote, quartz, feldspar, muscovite and opaques. Our limited reconnaissance work has discovered no unequivocal metasedimentary rocks in Goddard's map area. Although admittedly some volcaniclastic metasedimentary rocks could exist, most of the terrane appears to be metaigneous.

Fitzsimmons (1967) briefly described the Precambrian rocks of the northwestern Zuni Mountains. He noted that rock types there are similar to those found to the southeast. Gneissic and foliated granitic rocks are abundant; amphibolite, gabbro, quartz-mica schist and diorite are minor.

In a study on the origin of ultramafic and orbicular rocks in a 13

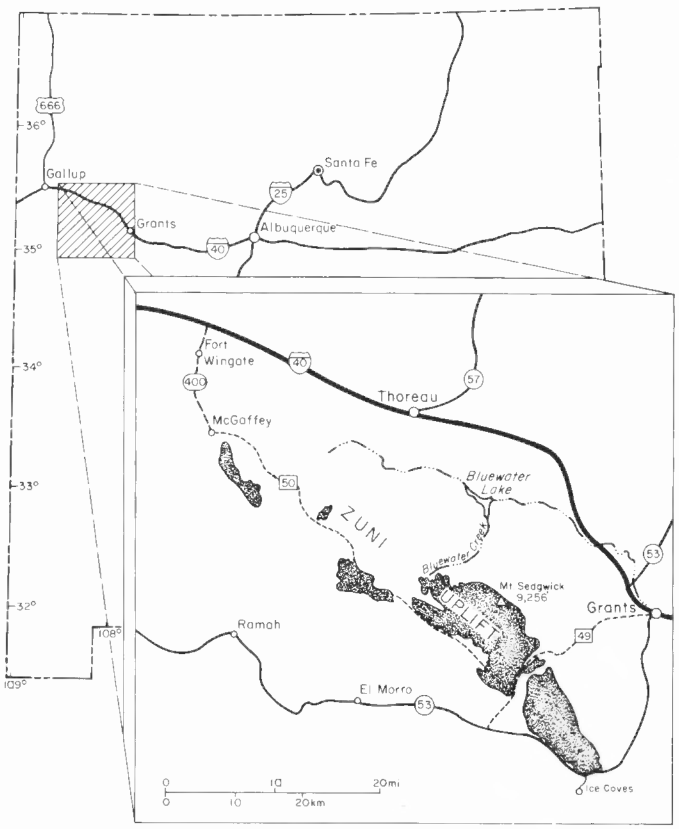

FIGURE 1. Location map of Precambrian rocks (stippled pattern) exposed in the Zuni uplift, New Mexico.

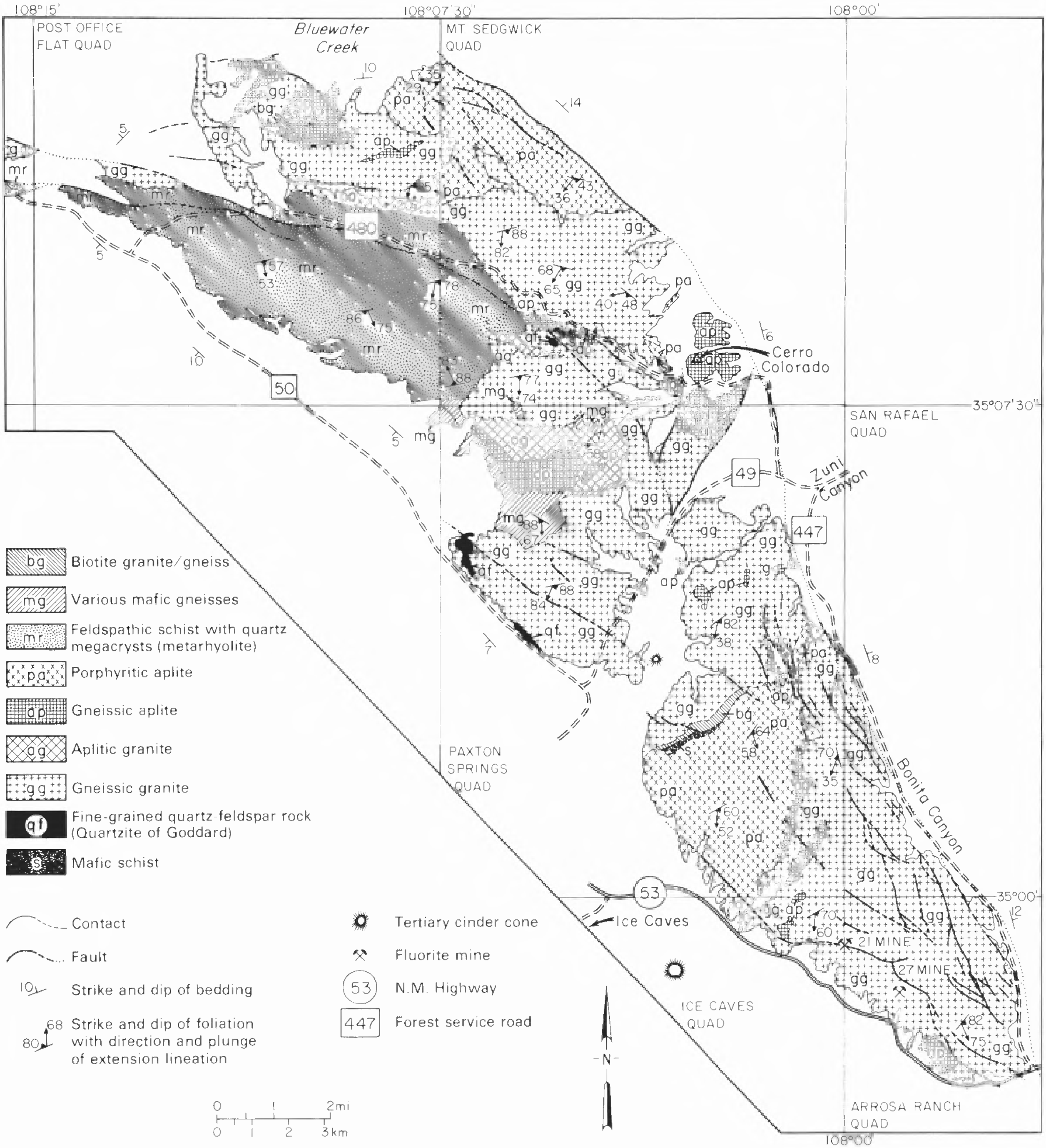

FIGURE 2. Generalized geologic map of Precambrian rocks of the southeastern Zuni uplift. Modified from Goddard (1966).

km² area of the west-central Zuni Mountains, Lambert (1983) mapped 18 Precambrian units. Most of these units are volumetrically minor. Some lenses and pods of ultramafic rock retain original igneous textures.

No stratigraphy is apparent in the Zuni Mountains. Contacts are poorly exposed, and in previous mapping studies chronologic order was at least partially deduced by foliation intensities and inferred intrusive contacts, both of which are criteria difficult to evaluate quantitatively, and therefore suspect. This poorly exposed terrane is metamorphosed and highly deformed, and may not conform to the law of superposition. We therefore suggest that the Precambrian rock sequence in the Zuni Mountains be given the informal lithodemic term Zuni metaigneous complex.

METAMORPHISM

In general, metamorphic index minerals are rare in the Zuni Mountains. Based on petrographic examination of granitic rocks, Emanuel

(1982) suggested that metamorphism in the Zuni metaigenous complex peaked at upper greenschist to lower amphibolite conditions. Lambert (1983) found abundant hydrous minerals in ultramafic rocks, and concluded that low-grade hydrothermal alteration may have been followed by low- to medium-grade metamorphism which formed the assemblage chlorite-talc-dolomite-FeCr spinel. Features observed in deformed granitoids and rhyolites, such as subgrains and dynamically recrystallized grains in quartz, and subgrains in feldspars, suggest to us a deformation temperature of lower amphibolite grade conditions.

GEOCHRONOLOGY

Whole-rock Rb-Sr analysis of granitic rocks and metarhyolite west of Mt. Sedgwick yielded isotopic ages of 1485 ± 90 my and 1385 ± 30 my, respectively (Brookins et al., 1978). These authors noted that the metarhyolite age must have been reset during some later thermal event, because it is clearly intruded by granitic rock. U-Pb zircon analyses of foliated granitic rock and felsic metavolcanic rock (metarhyolite) yielded isotopic ages of coeval volcanism and plutonism at about 1655 my (Bowring and Condie, 1982). Because post-crystallization hydrothermal alteration and metamorphism appear to have disturbed the Rb-Sr systematics of the rocks of the Zuni metaigneous complex, the U-Pb age probably better approximates time of crystallization. Metaigneous rocks of the Zuni complex range widely in composition and texture, and it is possible that plutons range in age as well.

GEOCHEMISTRY

A whole rock chemical study of 57 silicic rocks from the core of the Zuni Mountains determined a range of SiO_2 values from 62.66% to 78.16%, with most samples between 70 and 76% (Brookins, 1982). In a statewide survey of Precambrian pluton geochemistry, Condie (1978) reported averaged geochemical analyses for samples of granitic gneiss from near Mt. Sedgwick, gneissic aplite from Cerro Colorado and a granitic rock from near Oso Ridge. In Condie's four-fold classification of plutons, each of these granitic rocks fell into different categories. The Mt. Sedgwick samples were high-Ca, the Cerro Colorado samples were high-Si, and the Oso samples were high-K. Condie concluded that the high-Ca rocks formed by about 50% partial melting of siliceous granulite in the lower crust, whereas high-Si and high-K rocks formed from 65–75% fractional crystallization of shallow high-Ca magmas.

Plutonic rocks of the Zuni complex are representative of a late- or post-orogenic association (Condie, 1978; Brookins and Rautman, 1978). Emanuel (1982) noted that according to the criteria of Hyndman (1974), the igneous complex of the Zuni Mountains is best categorized as an intra-cratonic assemblage.

ECONOMIC GEOLOGY

Fluorspar was discovered in the area in 1908, and the earliest recorded production began in 1918. Eighty-six percent of the Zuni Mountains Fluorspar District production was from the Sec. 21 and Sec. 27 veins discovered in 1938 (Williams, 1966). Ore was shipped by rail from Grants to a flotation mill in Los Lunas. Following shutdown of the mill in 1953, the district has remained inactive. The U.S. Geological Survey studied the Zuni Mountains fluorite deposits in the 1940's (Weissenborn, 1944; Goddard, 1945; Rothrock et al., 1946). In the 1950's, when uranium and associated fluorite were discovered in the Todilto Limestone near Grants, interest in the area was renewed. Numerous studies have concluded that the limestone-hosted uranium and the Precambrian-hosted fluorite are co-genetic (Emanuel, 1982; Goddard, 1951; Gilkey, 1953; Rapaport et al., 1952; Peters, 1956; Gableman, 1956; McLaughlin, 1963). Although Goddard (1966) ascribed the fluorite mineralization to the Laramide orogeny, an earlier geologic event may have been involved in uranium-fluorite mineralization (Rapaport et al., 1952; Bergelof and Wampler, 1965; Kelley, 1967), and later intrusion and mineralization may also have occurred in the mid-Tertiary (Laughlin and West, 1976).

In the Zuni Mountains Fluorite District, fluorite generally is present in narrow veins and is marked by four generations of mineralization that precipitated at about 2300 m depth between 140–200°C (Emanuel, 1982). The original source for the mineralization may have been an underlying felsic pluton (Emanuel, 1982; Laughlin and West, 1976; Ander et al., 1980).

STRUCTURAL GEOLOGY

Much of the central Zuni metaigneous complex is composed of variably deformed, foliated, felsic schists and gneisses. What is to be made of such rocks in outcrop, in terms of protolith determination and structural analysis? Three possibilities for protolith exist: (1) the schist or gneiss was originally an arkose or impure sandstone; (2) the schist or gneiss was originally a granite, aplite or pegmatite; or (3) the schist or gneiss was originally a rhyolite or felsic tuff.

When interpreting the early stages of formation of a deformed rock mass, two factors are critical. These are *contact relationships* (upper, lower and lateral) and the *three-dimensional shape of the rock body*. These considerations necessarily assume the removal of any superimposed deformation and the restoration of original three-dimensional geometry. Thus, we could suggest that an arkose should have either conformable or unconformable upper and lower contacts, wedged or gradational lateral contacts and be wedge-shaped or broadly tabular in three-dimensional geometry. A granite should have nonconformable upper, lower and lateral contacts, and may be tabular or globular in three-dimensional geometry. Pegmatites or aplites generally occur as dikes with limited areal extent. A rhyolite or tuff would have conformable or unconformable upper and lower contacts, wedged lateral contacts and a lensoidal three-dimensional geometry. In a deformed and metamorphosed rock mass, these criteria may be difficult or impossible to deduce.

In many areas of New Mexico, critical contact relationships are hidden or not preserved, and reconstruction of the original shape of the rock body is impossible due to lack of three-dimensional control and absence of reliable strain markers. We therefore must look to *internal features* preserved in the rock mass to point to its protolith. As the schists and gneisses are foliated, they are almost certainly deformed tectonically. In most exposures we have seen, a mineral extension lineation is observable on this foliation. This can be shown to be an extension lineation in the Zuni Mountains by the character of the lineation-defining features (boudinaged feldspar grains, elongated recrystallized quartz aggregates, mica grains with this lineation as zone axis) and by the symmetry argument. An important consideration is whether one should just study an outcrop at will, and if so inclined cut a randomly-oriented thin section. Will this help or hinder protolith determination? Will such an approach suggest new, or clarify old, structural arguments? Just *how* should one study such deformed rocks, and which sections or orientations are critical?

To determine protolith, it is best to study outcrop faces and thin sections oriented *perpendicular* to the extension lineation, as here original features are best preserved. For structural information, outcrop faces and thin sections oriented *parallel* to the extension lineation and perpendicular to foliation are critical, as here kinematic information is best developed. We stress that accurate orientation of study directions of outcrops and thin sections is essential.

In an overall sense, foliation in much of the central Zuni Mountains strikes NE-SW to E-W and dips moderately to steeply southwards (see Fig. 2). Goddard (1966) noted that foliation tended to have two major orientations over the whole of the mountain range, but as yet our reconnaissance survey has neither confirmed nor denied this. The extension lineation we have measured plunges essentially downdip and therefore southwards, but with a SW-to-SE spread in trend. As yet, we are uncertain whether this variation is due to later folding, later faulting or inhomogeneous ductile deformation.

Protolith determination

1. In arkoses, crossbedding is commonly preserved (though the topset-foreset angle may bew severely reduced by deformation). Quartz contents may be high—up to 70% or so—and thus unrepresentative of common felsic igneous rocks. Felspar grains may preserve rounded detrital shapes.

2. Rhyolites (or tuffs) generally show diagnostic, abundant "quartz eyes." These are easily observed in outcrop and hand sample. In thin section, the "quartz eyes" are seen to be individual quartz grains, commonly square in section and embayed (original beta-quartz phenocrysts). They show strong internal deformation (undulose extinction, subgrains, etc.), and are engulfed in a fine-grained, strongly foliated feldspar-quartz-white mica groundmass. The "eyes" are preserved through quite strong deformation, as most strain is taken up in the groundmass.

3. Granites tend to have common or ubiquitous K-feldspar porphyroclasts that are generally preserved through intense deformation. If not apparent in hand samples, they can almost always be seen in thin section. This holds for pegmatites and seems to hold for aplites as well. The K-feldspar porphyroclasts are *not* seen in association with "quartz eyes," as any quartz in such deformed granites, aplites or pegmatites is completely recrystallized and forms part of the groundmass, perhaps in ribbon-shaped areas. The K-feldspar porphyroclasts may be up to several cm in diameter, but are commonly only several mm in highly-deformed rocks. No matter what diameter, they are tectonically rounded and sheathed in finely recrystallized K-feldspar grains. The porphyroclasts show undulose extinction and usually have well-developed microcline twinning.

Thus, it seems possible to determine unambiguously the protolith of many felsic schists. Very rarely is a schist so deformed or so hydrothermally altered as to make this distinction impossible. From the above criteria we believe that most or all of the felsic schists in the central Zuni Mountains are metaigneous rocks, comprising both rhyolite/tuff and granite. We have seen no evidence that metasedimentary rocks (such as the quartzite of Goddard, 1966—almost certainly a rhyolite or tuff) occur in the area.

Kinematic information

We are particularly interested in information about the sense of shear of the deformed rocks. The foliation and extension lineation form the framework in which to interpret this information. These features are parallel to principal strain directions—the extension lineation parallels the direction of maximum elongation, and the foliation contains this direction and is perpendicular to the direction of maximum shortening. Within this framework we look for *departures from homogeneous deformation and deformation symmetry*, such as asymmetric folds, rotated equant grains or shear bands. These and similar features, which can be reliably interpreted in terms of inhomogeneous simple shearing, show the polarity of that shearing (e.g., Passchier and Simpson, 1986).

Within the Zuni metaigenous complex, sense-of-shear criteria are widely developed, through textbook-quality examples appear only sporadically. This is a common problem in fine-grained, highly-deformed rocks—such rocks tend to accumulate strain by essentially homogeneous deformation accommodated by cyclic dynamic recrystallization. Great care must therefore be taken in interpreting the sense-of-shear criteria. The orientation of viewing planes must be carefully controlled, and a statistical approach must be adopted when determining overall sense of shear from asymmetry of the features.

We have observed three main sense-of-shear criteria in the schists of the central Zuni Mountains. These are rotated "quartz-eye" phenocrysts (in the deformed metarhyolites), asymmetric folds (also in the metarhyolites) and shear bands (mainly in strongly foliated mafic schists). Representative examples are shown in Figure 3.

As in many other areas of Proterozoic schist and gneiss in New Mexico, these rocks seem to record two discrete shearing episodes. Based on present geometry of foliation and lineation and consideration of the character of the sense-of-shear criteria preserved in the rocks, the earlier, more ductile, more penetrative episode appears to have been north- to northwest-directed ductile thrusting. The later, more discrete episode was south- to southeast-directed normal shearing.

We do not wish to speculate as yet on the large-scale tectonic significance of these shearing directions. Grambling et al. (1988) related similar shear senses in Proterozoic rocks bordering the Rio Grande rift to a two-stage orogenic history which involved early northwest-directed thrusting and crustal thickening followed by southeast-directed extensional collapse of the thickened orogenic belt.

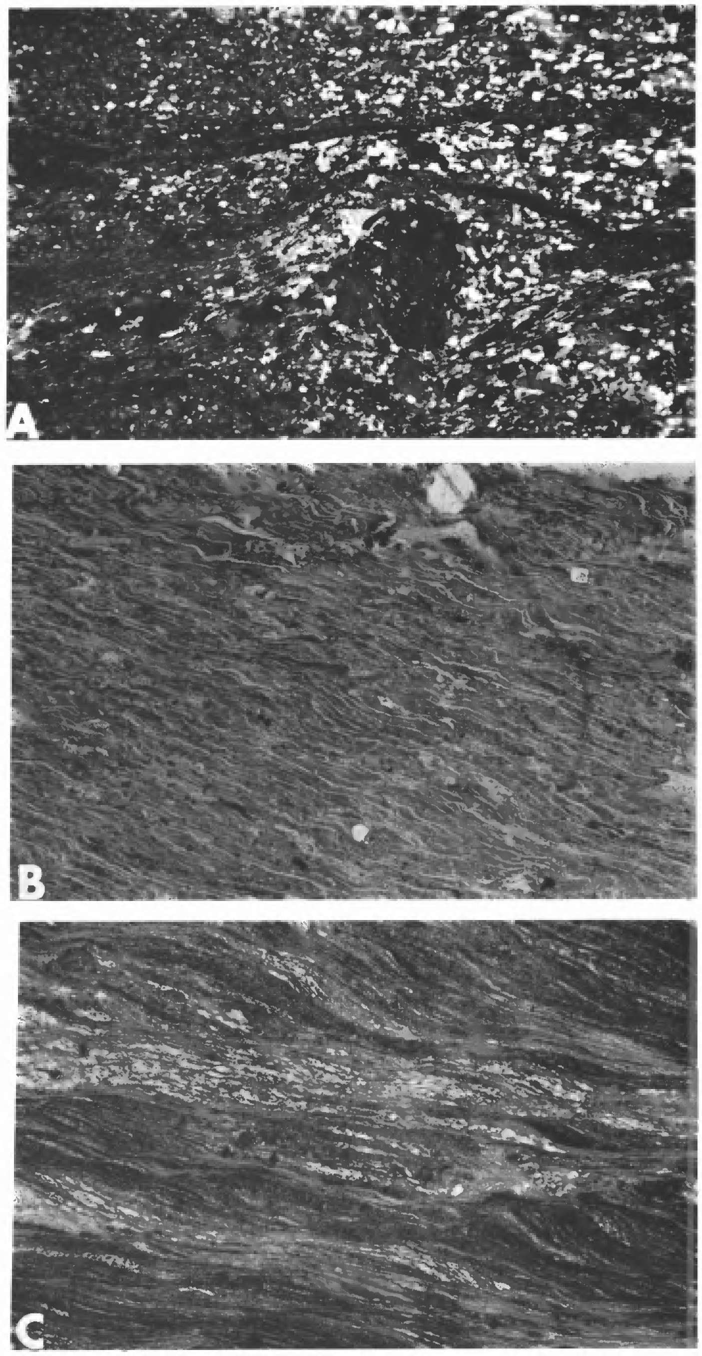

FIGURE 3. Representative photomicrographs of ductile kinematic indicators in Precambrian rocks of the southeastern Zuni uplift. All photographs are oriented with geographic north to the right and structural top upwards. A, Rotated "quartz-eye" in metarhyolite showing clockwise rotation, i.e., dextral shearing. This is an example of a delta-porphyroclast (Passchier and Simpson, 1986). Crossed nichols, 5.2 mm across. B, Small-scale folds in metarhyolite indicating dextral shearing. Plane-polarized light, 17 mm across. C, Shear bands in mafic schist indicating sinistral shearing. Plane-polarized light, 17 mm across.

COMPARISON WITH OTHER PROTEROZOIC TERRAINS IN NEW MEXICO

The rocks and the structural style of the Zuni metaigneous complex are remarkably similar to many other Proterozoic areas of New Mexico. Specifically, the large amounts of felsic magmatism have produced rock types and lithological assemblages similar to areas dominated by the Vadito Group in north-central New Mexico (Bauer and Williams, in prep.) and younger, ca. 1650 my, felsic metavolcanic rocks in central New Mexico (Bowring et al., 1983). The variety of igneous rocks and paucity of sedimentary rocks is similar to the Proterozoic terrain described by Woodward (1987) in the Sierra Nacimiento, 115 km to the northeast. Bowring et al. (1983) reported U-Pb zircon isotopic ages of metavolcanic rocks in the Magdalena Mountains of about 1650 my and the Manzano Mountains at 1650–1680 my. They concluded that much of the exposed crust in central New Mexico, including the Zuni Mountains, formed between 1640 and 1680 my.

The structural style of the Zuni metaigneous complex is also very similar to other Proterozoic areas in northern and central New Mexico. The nature of the ductile deformation (apparently involving repeated ductile shearing), and the vergence of the deformation (apparently early northwest-directed thrusting followed by southeast-directed low-angle normal shearing) has been documented in a number of areas (see Grambling et al., 1988, and references therein).

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Redonda Mesa near Mesa Lucero looking SE. Jurassic and Cretaceous strata below basalt capping mesa are cut by a fault. Photograph taken 6 February 1989 by Paul L. Sealey.