Proterozoic plutonism and regional deformation—new constraints from the southern Manzano Mountains, central New Mexico

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Abstract

The relative importance of Early Proterozoic versus Middle Proterozoic deformation and metamorphism in the southwestern U.S. is currently a topic of debate. The Manzano Mountains of central New Mexico are an ideal testing ground for evaluating the principal opposing models of Proterozoic orogenesis. The range contains well-exposed granitoids of Early and Middle Proterozoic age and diverse deformational character, porphyroblast microstructures, and major structures such as refolded folds, regional mylonitic foliations, and ductile shear zones.

The dominant, northeast-striking, subvertical foliation (S) and associated upright folds (F) represent regional shortening (D_s) after crystallization of the 1656 Ma Monte Largo pluton. Greenschist-grade S is particularly well developed along the pluton margins. In contrast, the 1427 Ma Priest pluton crosscuts F, folds and is largely nonfoliated. Regional northwest-southeast shortening is therefore bracketed between 1656 Ma and 1427 Ma, consistent with the chronology of deformation established from other plutonic rocks in New Mexico and southern Colorado. In general, 1690-1650 Ma plutons are moderately to highly deformed, whereas 1450-1350 Ma plutons are weakly deformed to undeformed. The distribution and kinematic significance of 1.4 Ga and post-1.4 Ga deformations remain controversial, but regional data suggest that Middle Proterozoic events were superposed on Early Proterozoic metamorphic terranes that record the northwest-southeast convergent assembly of the southwestern U.S.

Introduction

The timing of Proterozoic orogenic events in New Mexico is controversial. U-Pb zircon data indicate that volcanogenic sequences and granodioritic plutons record crustal accretion in the interval 1750-1650 Ma. One view is that an important phase of deformation and metamorphism was associated with assembly of crustal terranes during this 100 m.y. orogenic interval; this phase was followed by relative tectonic quiescence that was interrupted by magmatic events at ca. 1.4-1.1 Ga (Bowring and Karlstrom, 1990; Karlstrom and Bowring, 1991; Bowring, 1991; Bauer et al., 1991; Bauer, 1993; Bauer and Williams, in press). An alternate view is that the regional structures and tectonic foliation and the regional amphibolite-grade metamorphic assemblages formed during a complex interplay of contractional and extensional deformation at ca. 1.4 Ga and later (Grambling et al., 1989; Thompson et al., 1991; Grambling and Dallmeyer, in press; Daniel et al., 1992).

Timing of deformation in New Mexico comes principally from two sources, U-Pb and 40Ar/39Ar geochronology. U-Pb zircon ages on granitoids can constrain deformational and metamorphic histories of orogenic belts if the relative timing of deformation, metamorphism, and plutonism is established by detailed field and microstructural work (e.g. Paterson and Tobiisch, 1988). The mountains of New Mexico contain dozens of Proterozoic granitoids that range in composition, emplacement age, nature and degree of deformation, and field relationship to country rock. Condie and Budding (1979) listed 31 Proterozoic plutons in central and south-central New Mexico alone. To date, U-Pb zircon isotopic ages based on concordia diagrams have been published for only nine of these plutons (Bauer and Pollock, 1993). Of these, six have either large uncertainties or are presented without data in abstracts or as personal communications, and only a limited number have had detailed field and structural studies. Nevertheless, most workers have noted that plutons older than about 1650 Ma are strongly deformed and that plutons of ca. 1450 Ma are only weakly deformed or nondeformed (Williams, 1990; Bauer et al., 1991; Bauer, 1993; Bauer and Williams, in press). This generalization is supported by recent work in the Magdalena Mountains of central New Mexico, where Bauer et al. (1991) and Bauer and Williams (in press) showed that regional tectonism took place at 1660 Ma by comparing precisely dated deformed and undeformed Early Proterozoic igneous rocks. Similarly, Karlstrom and Bowring (1988, 1991, 1993) documented a 90 m.y. interval (1740-1650 Ma) during which deformation took place in Arizona, including a pulse at ca. 1650 Ma in southern Arizona, termed the Mazatzal orogeny.

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Evidence for major deformational and metamorphic events at 1.4–1.0 Ga comes from 40Ar/39Ar dating of metamorphic minerals and study of the contact aureoles of ca. 1450 Ma plutons. Recent studies have shown that 40Ar/39Ar hornblende ages in New Mexico are generally in the range of 1450–1350 Ma (Grambling and Dallmeyer, 1990; Grambling and Dallmeyer, in press). Because peak regional metamorphism was near 550–600°C, hornblende ages have been interpreted to record cooling through 500–550°C, shortly following peak regional metamorphism and deformation. These workers suggested that apparent differences in degree of deformation of 1.65 Ga and 1.4 Ga plutons reflect partitioning of strain around the young plutons rather than different deformational histories. Muscovite ages are substantially younger (1350–1000 Ma) and were interpreted to reflect reheating of crustal blocks to around 350°C during discrete Middle Proterozoic events. Muscovite ages that differ across major ductile faults were interpreted to reflect late juxtapositions (Thompson et al., 1991; Grambling et al., 1992). Alternatively, Bowring and Karlstrom (1990) interpreted the young 40Ar/39Ar data as cooling ages related to 1450 Ma and 1100 Ma magmatic events and associated differential uplift of crustal blocks long after Early Proterozoic regional deformation and metamorphism.

In this paper we present new U–Pb zircon isotopic data for two granitoids in the southern Manzano Mountains and briefly describe their structural/metamorphic settings. The new data provide a chronologic background for ongoing and much-needed future detailed structural and petrologic work on these plutons. The Manzano Mountains may turn out to be a key locale for reconciling the two competing orogenic models because of the combination of well-exposed granitoids of Early and Middle Proterozoic age and diverse deformational character, porphyroblast microstructures, and major structures such as refolded folds, regional mylonitic foliations, and ductile shear zones. Our current view is that existing data are best explained by a model in which Early Proterozoic tectonic and metamorphic fabrics were variably affected by multiple Middle Proterozoic events.

Geology of the Manzano Mountains

Both the Monte Largo and Priest plutons were originally named and described by Stark (1956) in his excellent field study of Precambrian rocks of the southern Manzano Mountains. Subsequent work includes: 1) Myers and McKay (1972, 1974)—generalized geologic maps of the southern Manzano Mountains; 2) Bolton (1976)—Rb-Sr geochronology of the Priest pluton; 3) Myers (1977)—map of the southern part of the Priest pluton; 4) Condie and Budding (1979)—a study of Precambrian rocks of central New Mexico, including geochemistry of the Monte Largo and Priest plutons; 5) Maxwell and Wobus (1982)—a map of the Manzano Wilderness study area; 6) Bauer (1982, 1983a, 1983b)—map and structural analysis of the southern Manzano Mountains; and 7) Thompson et al. (1991)—metamorphic petrology and 40Ar/39Ar thermochronology of parts of the southern Manzano Mountains. The Monte Largo pluton (Monte Large granite of Stark, 1956) intrudes metasedimentary rocks on the western flank of the range, between West Bartolo Canyon and Monte Largo Canyon (Fig. 1). The Priest pluton (Priest granite of Stark, 1956) is exposed over 5 km (3.1 mi) to the south, along the Laramide-age (?) Montosa fault (Fig. 1). Separating the two plutons is a steeply dipping, north-east-striking succession of amphibolite, mafic schist, quartzofeldspathic schist, pelitic schist, and phyllite, muscovite quartzite, and crossbedded quartzite (Stark, 1956; Bauer, 1983b). Bowring et al. (1983) reported a U–Pb zircon age of about 1680 Ma for a metamorphic suite on the northeastern flank of the Monte Largo pluton. Bauer (1983a) concluded that a simple stratigraphic sequence does not exist in the southern Manzano Mountains. Instead, supracrustal rocks have been completely deformed by at least three deformational events and are stacked along layer-parallel (now subvertical), ductile thrusts. The predominant structures in the range are tight to isoclinal, gently to moderately plunging, upright, second-generation folds (F2) that fold a layer-parallel schistosity (S2) and rare associated isoclinal folds (F3). F2 sheath folds have been found in the southern Manzano Mountains (S. Raiser, pers. comm. 1993). Sets of broad folds (F3) and crenulation cleavages (S3) cut across F2 folds. Bauer (1982) reported that regional metamorphism accompanied the D1 and D2 deformations and that the post-tectonic Priest pluton displays a sillimanite-grade, contact-metamorphic aureole.

Monte Largo pluton

The Monte Largo pluton is located on the western flank of the range at the junction of the Tome NE, Tome SE, Capilla Peak, and Manzano Peak 7½-min quadrangles (Fig. 2). Variably deformed granodiorite, quartz monzongite, and granitic rock are exposed over an area of about 4 km² (1.5 mi²) that is bounded on three sides by strongly deformed quartzite and phyllite (Blue Springs schist of Stark, 1956). The granodiorite is medium grained and consists mainly of altered feldspar (30–40%, much is now sericite), quartz (20–25%), chloritized biotite, rare hornblende (altered to chlorite and biotite), and epidote. Minor phases include calcite, apatite, zircon, tourmaline, and altered sphene. Mafic enclaves are common in the granodiorite; pegmatites are rare. Stark (1956) reported apophyses of granitic rock within phyllite, and recent mapping identified quartzite blocks surrounded by granite, all tectonized but apparently in an intrusive contact. Condie and Budding (1979) noted that major and trace-element concentrations in the Monte Largo pluton are out of place in the Ojita pluton of the northern Manzano Mountains (Fig. 1). To date, the Ojita pluton has not been mapped nor isotopically dated.

Country rocks were originally designated "Blue Springs schist" by Stark (1956). This unit includes a number of distinctive and mappable rock types (Fig. 2). Quartzite horizons contain crossbedding and distinctive, banded hematite-rich zones, indic-
and both are folded by the large $F_3$ antiform, suggesting that pluton and country rock were deformed together during northwest-directed $F_3$ shearing and isoclinal folding. This folding represents continued attenuation of the $S_1$ tectonite layering on $F_2$ fold limbs. Late, low-angle, top-to-the-northwest shear bands ($S_3$) in the schist may represent a discrete, low-temperature event superposed on $F_2/F_3$ or a continuation of the top-to-the-west contraction. The pluton locally contains an $S_2$ crenulation cleavage that is axial planar to the large $F_3$ antiform. Such structures indicate that thrusting and shortening postdated pluton crystallization.

The $S_1$ cleavage developed at approximately greenschist grade, as shown by pervasive, synformational reaction softening of plagioclase to sericite and quartz and retrogression of biotite in the pluton to chlorite. The relative persistence of quartz phenocrysts is compatible with the observation that quartz can be stronger than reaction-softened feldspars at greenschist and amphibolite grades (Williams and Burt, in press). Adjacent pelitic schist also contains greenschist-grade assemblages of chlorite, quartz, muscovite, and actinolite. The absence of a contact-metamorphic aureole around the pluton suggests shallow emplacement and/or elimination of contact-metamorphic features by postpluton, retrograde greenschist-grade deformation. Abundant pegmatites in the metarhyolite, which have been folded, boudinaged, and disconnected like tectonized pods of partial melt, suggest the possibility that earlier, high-temperature metamorphism and deformation ($pre-S_1$ in granite) did affect country rocks (in agreement with Shastri, 1993, in Los Pinos Mountains).

Priest pluton

In striking contrast to the predeformational ($pre-S_1$) Monte Largo pluton, deformational and metamorphic fabrics around the Priest pluton record events that were superposed on the $D_1$ and $D_2$ fabrics described above. The Priest pluton is a 10-km-long (6-mi-long), north-trending, elongate intrusion that lies within the Manzano Peak and Scholle 71лиз-min quadrangles (Fig. 1). The pluton is bounded on the east by the Thumeros and Monte Largo faults, and both are folded by the large $F_3$ antiform, suggesting that most of the regional deformation predated pluton emplacement. In the country rocks the earliest foliation ($S_1$) is a schistosity that is typically subparallel to bedding in quartzites. $S_1$ is folded by upright, shallowly plunging $F_3$ folds that have a subvertical, axial-plane crenulation cleavage ($S_3$) that is especially well developed in schistose units. Shear-sense indicators in mylonitic quartzites show west-side-up shearing on $S_1$ (Goodwin et al., 1992; Fig. 6A), consistent with asymmetric folds mapped by Bauer (1983b). In these mylonites, quartz grains typically exhibit straight to moderately curved boundaries and low aspect ratios; undulatory extinction is uncommon. These features are compatible with deformation during amphibolite facies conditions (cf. Simpson, 1985; Goodwin et al., 1992), which is consistent with mineral assemblages in adjacent pelitic schists (Thompson and Karlstrom, 1993). Along the western pluton margin, the $F_2$ enveloping surface of folded $S_1$ tectonite layering is truncated by the subvertical pluton margin. Because $F_3/F_2$ structures here are...
similar in style and orientation to those near the Monte Largo pluton, we correlate them and thus conclude that their development is restricted to the time interval that separates crystallization of the two plutons.

The Priest pluton contains a variably developed, broadly greenschist-grade, mylonitic foliation (S₃) that is northeast-striking and generally parallel to S₂ in the country rock. S₃ is the only ductile tectonite fabric found in the Priest pluton. This fabric is most intense along the pluton margin and in pegmatite and aplite dikes near the margin. In the pluton, S- and C-surfaces record east-side-up shear (Fig. 6B). In contrast with S₂, S₃ is associated with features that suggest deformation during greenschist facies conditions (Goodwin et al., 1992). Strongly elongate, undulose, quartz ribbons, having subgrain development along grain margins, are common. Feldspar grains are typically fractured. S₃ formation therefore must have postdated the locally high temperatures (700°C or more) associated with pluton emplacement. We correlate this S₃ with S₂ near the Monte Largo pluton because of its low-temperature character and similar shear sense.

Amphibolite-grade metamorphic isograds are parallel to the western and northern margins of the Priest pluton, suggestive of a contact aureole (Grambling et al., 1992). Isograds crosscut
FIGURE 6—Microstructures from Estadio Canyon along the west margin of the Priest pluton. A, photomicrograph of mylonitic quartzite; C-surfaces (C) and shear bands (SB) indicate a west-side-up shear sense on S1. Sample no. E-7a. Field of view is 6.5 mm. B, photomicrograph of S- and C-surfaces in Priest pluton indicating east side up on S1. Sample no. E-3. Field of view is 1.3 mm.

and Karlstrom, 1993), suggesting a complex overprinting of contact metamorphism on earlier regional metamorphic assemblages and reactivation of old (S1/S2) foliations during and after pluton emplacement.

Geochronology

Before this study, no isotopic ages existed for the Monte Largo pluton, and the only constraint on the Priest pluton was an Rb-Sr isochron age of 1470±30 Ma (Bolton, 1976). In New Mexico Rb-Sr isochrons commonly yield ages that are significantly younger than U-Pb zircon ages (Bauer and Pollock, 1993).

A 50 lb sample of the Monte Largo pluton was collected for U-Pb zircon geochronology from the location shown in Fig. 2 as NM-51 (UTM coordinates 3832700mN, 362500mE). In thin section the sample consists of rounded and elongated quartz megacrysts in an altered matrix of fine-grained white mica, chlorite, and quartz. Quartz megacrysts average about 3 mm in diameter and are composed of a mosaic of subgrains that show strong undulose extinction. Feldspars have been completely replaced by mica, chlorite, and quartz. The fine-grained, foliated micaeous matrix wraps around quartz grains. Minor phases include Fe-oxide minerals and zircon. The sample was crushed, sieved (<100 mesh), and concentrated at the New Mexico Bureau of Mines and Mineral Resources. The mineral concentrate contained abundant euhedral zircon. A three point concordia diagram yields an upper intercept age of 1656±10 Ma for the Monte Largo pluton (Fig. 7).
isotopic age of 1664±3 Ma (Bowring et al., 1983), regional deformation was constrained at ca. 1660 Ma (Bauer et al., 1991; Bauer and Williams, in press). This conclusion is consistent with our inference that the ca. 1656 Ma Monte Largo pluton was emplaced before D₄ regional northwest–southeast shortening, whereas the 1427 Ma Priest pluton crystallized after D₄ shortening.

Regional D₄ deformation was accompanied by greenschist- to amphibolite-grade metamorphism and resulted in west-side-up shearing. In contrast, post-1427 Ma D₄ deformation took place at greenschist-grade conditions and resulted in east-side-up shearing in the Monte Largo pluton and along the Priest pluton margin. It remains unclear how, or if, the prepluton and postpluton deformations were related. If D₄ deformation was part of a progressive regional shortening, then deformation had greatly waned during Priest pluton emplacement, and structural vergence had reversed during post-1427 Ma convergence. Alternatively, D₄ strain continued with deformation related to post-1427 Ma convergent tectonism and thermal events related to the Grenville (or pre-Grenville) orogeny. The latter idea is supported by ⁴⁰Ar/³⁹Ar muscovite cooling ages of 1300 Ma and younger from central and northern New Mexico (J. A. Grambling, pers. comm. 1992), which are compatible with new data indicating 1.3–1.2 Ga deformation in the Llano uplift of Texas (Walker, 1992).

Thus, available data seem best interpreted by a tectonic model that involved 1.66 Ga northwest–southeast shortening, followed by 1.4 Ga pluton emplacement and then by additional shortening at ca. 1.3 Ga. The character of the 1.4 Ga event remains controversial. However, the recognition of a complex history of overprinting of Middle and Early Proterozoic thermal and deformational events is a first step toward evaluating the extent, thermal regimes, and kinematic history of 1.4 Ga deformation and metamorphism in the Southwest.

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**References**


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that we must seriously consider that the tracks may be allied to *Tetrasauropus*. If this interpretation is correct then this is also the first report for this ichnogenus in North America. It is accepted, at least by some ichnologists, that the Lower Jurassic ichnogenus *Otozoom* is attributable to a prosauropod and that it is similar to *Pseudotetrasauropus* and *Tetrasauropus*. Given that *Otozoom* and another prosauropod track *Navahopus* are both known in the Lower Jurassic of the western United States and that Late Triassic skeletal remains of at least one prosauropod are known, it is reasonable to infer that prosauropod tracks should occur at this time. The ichnogenus *Tetrasauropus* and *Pseudotetrasauropus* warrant further study to determine their distribution in western North America and to establish if they are of prosauropod affinity, as proposed by Ellenberger.

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