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1990, pp. 151-159. https://doi.org/10.56577/FFC-41.151

in:

Tectonic Development of the Southern Sangre de Cristo Mountains, New Mexico, Bauer, P. W.; Lucas, S. G.; Mawer, C. K.; McIntosh, W. C.; [eds.], New Mexico Geological Society 41st Annual Fall Field Conference Guidebook, 450 p. https://doi.org/10.56577/FFC-41

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PROTEROZOIC GEOLOGY OF NORTHERN NEW MEXICO: RECENT ADVANCES AND ONGOING QUESTIONS

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Abstract—Proterozoic supracrustal rocks in northern New Mexico have been divided into four lithotectonic packages: (1) mafic metavolcanic sequences (1765–1720 Ma), interpreted to have formed in volcanic arcs; (2) the Vadito Group, felsic metavolcanics and metasediments (1720–1700 Ma), deposited in a continental rift or back-arc basin; (3) the Hondo Group interbedded quartzites and pelitic schists (1700–ca. 1690 Ma), deposited on a shallow marine shelf; and (4) a sequence of felsic metavolcanic and metasedimentary rocks (1660–1650 Ma), suggested to have formed in an arc or back-arc setting. The rocks record a major, northwest-directed, crustal shortening event that involved ductile thrusting in massive units and multiple generations of folds in schistose units. Evidence exists for at least two subsequent deformational events: south-directed shearing on subhorizontal ductile faults and right-lateral shearing and faulting on steep north-trending structures. Most rocks were metamorphosed in the amphibolite facies (500°C, 4 kb) although granulite facies gneisses occur in two ranges below subhorizontal ductile faults. Although significant refinements have been made in tectonic models for the evolution of the Proterozoic rocks, important questions remain in several areas including: the tectonic setting of the major lithotectonic units and the nature of their contacts; the timing of deformation and metamorphism; controls on the production of regionally constant metamorphic conditions; and the timing and controls on uplift and stabilization of the Proterozoic crust.

INTRODUCTION

During the past decade, significant advances have been made in describing and interpreting the Proterozoic geology of northern New Mexico. New work has focused specifically on stratigraphic relationships (Grambling and Codding, 1982; Wobus, 1985; Soegaard and Eriksson, 1985, 1986; Williams, 1987; Bauer and Williams, 1989), metamorphic petrology (Grambling and Williams, 1985; Grambling, 1986; Smith, 1988; Grambling et al., 1989) or structural geology (Nielsen and Scott, 1979; Holcombe and Callender, 1982; Williams, 1987; Bauer, 1988). However, until recently, tectonic models for the evolution of the Proterozoic rocks have been rather generalized, and no comprehensive model is currently available. In fact, some of the most recent results suggest that the tectonic history may be significantly more complex and more long-lived than was previously thought (Robertson et al., 1990).

The purposes of this paper are first, to summarize some of the recent work that has been important to the evolving models of Proterozoic tectonism, and second, to identify ongoing questions or problems, critical to the development of a more complete tectonic model. In addition, this paper will hopefully serve as a background for a more general discussion of the geology of the southern Rocky Mountains and the influences that the Proterozoic rocks have had on younger events.

PROTEROZOIC GEOLOGY OF NORTHERN NEW MEXICO

Early Proterozoic rocks ranging in age from approximately 1800 to 1600 Ma are exposed from Mexico to southern Wyoming in a broad orogenic belt that extends eastward in the subsurface and is re-exposed in central North America (Karlstrom and Bowring, 1988; Hoffman, 1988). Two transverse exposures of the orogen exist in the southwestern U.S. These are the northwest-trending transition zone of central Arizona (Karlstrom and Bowring, 1988), and a north-trending belt along the Rio Grande rift in New Mexico and Colorado (Fig. 1). In northern New Mexico, Proterozoic exposures occur in fault-bounded uplifts that, east of the Rio Grande rift, core the southern Sangre de Cristo Mountains, and, west of the rift, core the Tusas Mountains of the Brazos uplift (Fig. 2).

Stratigraphic relationships

Proterozoic rocks of New Mexico have a complex and locally conflicting nomenclature. Stratigraphic correlations among lithologic units are complicated by a multiphase deformational history that has repeated, doubled or omitted key units. Recently, Bauer and Williams (1989) proposed revisions to the nomenclature that incorporate the results of numerous structural and stratigraphic studies (see references in Bauer and Williams, 1989). The new nomenclature represents a consensus of many of the current workers and may reflect a growing confidence in the regional stratigraphy.

The supracrustal Proterozoic rocks can be divided into four broad, apparently age-specific, lithotectonic packages or groups (Fig. 2). These are: (1) sequences dominated by mafic metavolcanic rocks (approximately 1765–1720 Ma); (2) the Vadito Group, a sequence of felsic metavolcanic and metasedimentary rocks (1720–1700 Ma); (3) the Hondo Group, a sequence of quartzites and pelitic schists (1700–1690 Ma);

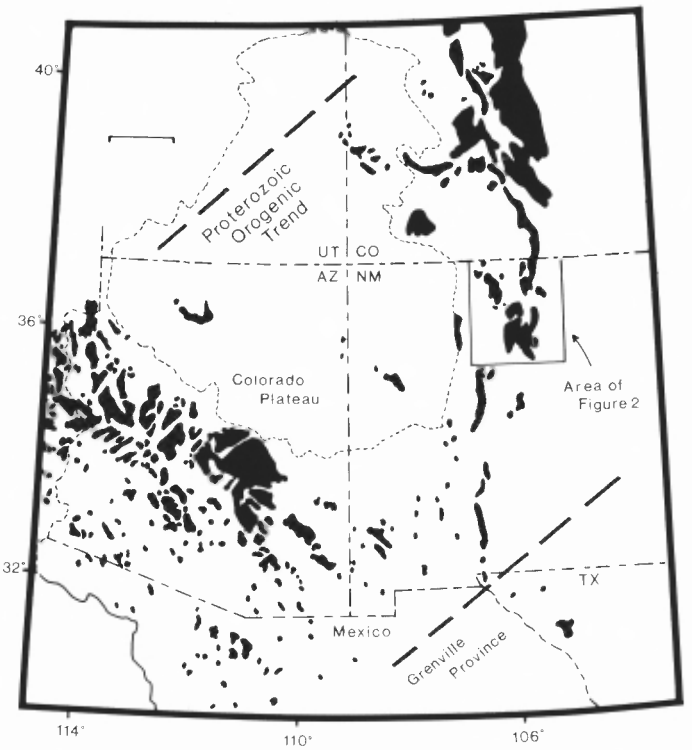


FIGURE 1. Distribution of Proterozoic rocks in the southwestern U.S. showing the approximate boundaries of the Early Proterozoic orogenic belt.

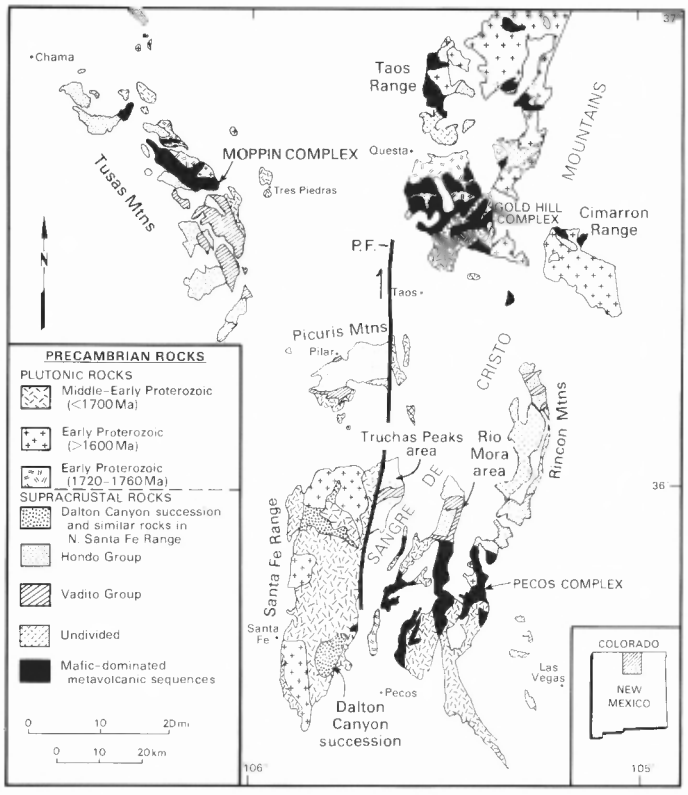


FIGURE 2. Generalized geologic map showing the distribution of Proterozoic rocks in north-central New Mexico. P.F. = Picuris-Pecos fault zone. Modified from Bauer and Williams (1989). Some data come from unpublished maps by J. M. Robertson and J. A. Grambling.

and (4) a sequence of felsic metavolcanic and metasedimentary rocks (1660 to 1650 Ma) including the Dalton Canyon succession. Detailed descriptions and extensive references are presented in Robertson et al. (1990) and Bauer and Williams (1989). The four units are briefly summarized below.

Mafic metavolcanic sequences

The oldest supracrustal rocks in northern New Mexico occur in "mafic metavolcanic sequences" (Bauer and Williams, 1989; Robertson et al., 1990). These include the Moppin Complex of the Tusas Mountains, the Pecos Complex of the southern Sangre de Cristo Mountains and the Gold Hill Complex of the Taos Range (Fig. 2). Other smaller sequences may be present in northern New Mexico, and several have been described in central New Mexico (Robertson et al., 1990). Two of the mafic sequences have well constrained ages, the Gold Hill Complex, 1765 Ma (S. A. Bowring, oral commun., 1986), and the Pecos Complex, 1720 Ma (Bowring and Condie, 1982). The Moppin Complex may have been intruded by the 1755 Ma Maquinita Granodiorite (Wobus and Manley, 1982), but contact relationships are unclear.

The mafic sequences are dominated by chlorite schist and/or amphibolite with lesser amounts of feldspathic schist and gneiss, pelitic schist, conglomerate and banded iron-formation. Locally preserved volcanic and sedimentary structures including pillows, graded beds and relict phenocrysts suggest that the sequences represent an interbedded series of mafic metavolcanics and immature metasediments. The sequences are associated with a diverse suite of metaplutonic rocks ranging from local ultramafic sills and stocks to larger tonalite, quartz monzonite or granodiorite bodies dating from 1750 to 1645 Ma (Barker, 1958; Reed, 1984; Bowring et al., 1984; S. A. Bowring, oral commun., 1986). Geochemical analyses indicate that mafic sequences are similar to high-K tholeiitic or calc-alkaline rocks (Barker and Friedman, 1974; Bingler, 1974; Robertson and Moench, 1979; Klich, 1983; Condie and McCrink, 1982; Smith, 1988; Robertson and Condie, 1989) and may have accumulated in an arc or back-arc setting (Condie, 1986). The diversity of ages between the Gold Hill and Pecos Complexes suggests that more than one arc terrane may be present. No basement for the mafic sequences has yet been identified.

Vadito Group

The Vadito Group is a heterogeneous package of supracrustal rocks dominated by feldspathic schist and gneiss. Rocks of the Vadito Group are well exposed in the Tusas, Picuris, Taos and Rio Mora uplifts, but their thickness, lithologic assemblage and contact relations are variable. Extreme thickness variations are well documented in the Tusas Mountains where the Vadito Group is less than 100 m thick in the northern part of the range but is at least several kilometers thick with no exposed base in the south. The dramatic thickness variation is at least partly due to later tectonism, but primary thickness variation is also suspected. U-Pb analyses on zircons from felsic metavolcanic rocks, primarily from the Tusas Mountains, yielded ages of approximately 1700 Ma (L. T. Silver, oral commun., 1984). One apparently metavolcanic, felsic gneiss from the Taos Range has yielded a preliminary age of 1724 Ma (S. A. Bowring, oral commun., 1986).

The Vadito Group is distinct from the mafic supracrustal sequences in several ways, including its dominance of felsic over mafic rocks, its regional extent, its trace element geochemistry, its age and its lack of associated plutons. The most distinctive component of the Vadito Group is quartz-muscovite-feldspar schist interpreted as metamorphosed and locally altered tuffs. These rocks are interlayered with clastic metasedimentary lithologies including: crossbedded, muscovitic quartzite, arkosic quartzite, biotite-muscovite schist and pelitic schists. Metaconglomerate horizons and amphibolites are not common, but where present they are important marker beds in the somewhat monotonous Vadito section (Williams, 1987).

A regionally extensive horizon characterized by Mn-bearing metamorphic minerals (Mn-andalusite, piemontite and other anomalous phases) occurs near the top of the Vadito Group. The layer is 1 to 100 m thick and can be traced almost continuously across individual uplifts. It is exposed across northern New Mexico, and similar Mn-bearing rocks are exposed in Proterozoic rocks of the Needles Mountains, Colorado (Burns et al., 1980) and at a major schist/quartzite contact near Phoenix, Arizona (Thorpe and Burt, 1980). The manganese mineralization is believed to have formed early in the geologic history, perhaps by hydrothermal alteration or lateritic weathering during the final stages of Vadito volcanism.

Hondo Group

The Vadito Group is overlain by the Hondo Group (Bauer and Williams, 1989), formerly the Ortega Group. The Hondo Group is most easily recognized by its basal unit, the Ortega Formation, a clean, massive, crossbedded quartzite greater than 1 km in thickness. The base of the quartzite is conglomeratic in the Tusas Mountains, but elsewhere conglomerates are rare. Dark-colored crossbeds, defined by hematite and other oxides, are present in most exposures. Soegaard and Eriksson (1985) interpreted sedimentary structures, facies relationships and paleocurrent directions in the quartzite to indicate that it accumulated on a tide-dominated shallow marine shelf with a source to the north or northwest.

In the Truchas Peaks and Rio Mora areas, several schist and amphibolite units, interpreted to represent metamorphosed volcanics, are interlayered with the lower parts of the Ortega Formation. The presence of these units may indicate that the final phases of Vadito Group volcanism overlapped with the early phases of quartzite deposition (Grambling, 1979). Such an overlap has been observed in broadly correlative rocks in central Arizona (Conway, 1984). However, some contacts are clearly tectonic, and it is possible that the metavolcanic sections in New Mexico represent slices of the Vadito Group tectonically emplaced into the quartzite (Grambling et al., 1988).

The Ortega Formation is conformably overlain by the Rinconada Formation, a sequence of pelitic schists and quartzites. The quartzites, unlike the Ortega Formation, are relatively thin, contain considerable

plagioclase and ferromagnesian silicates, and have a relatively reduced oxide assemblage. The schists are known for their coarse euhedral porphyroblasts of staurolite, andalusite, chloritoid, biotite and garnet. The Rinconada Formation is overlain by the Pilar Formation, a black, graphitic phyllite and the Piedra Lumbre Formation consisting of pelitic or calcareous schist and quartzite. Soegaard and Eriksson (1985) interpreted the Rinconada Foramtion and overlying schists to represent the storm-dominated, outer shelf equivalents of the Ortega Formation. However, some questions exist about this interpretation, at least on the scale of northern New Mexico, because the thicknesses of the Ortega and Rinconada Formations do not vary with position on the postulated shelf.

Deposition of the Hondo Group began at approximately 1700 Ma, the age of the underlying Vadito Group. The younger limit is poorly constrained. One small felsic intrusion, approximately 1691 Ma (J. A. Grambling and S. A. Bowring, oral commun., 1986), may cut the upper members of the Hondo Group in the southern Truchas Range, and pegmatites interpreted to be 1644 Ma appear to cut the Hondo Group in the Sangre de Cristo Mountains (Bowring et al., 1984; Reed, 1984). However, neither of these age constraints is unequivocal because of complex or poorly exposed field relationships. U-Pb analyses on detrital zircons from the Ortega Formation yielded ages between 1700 Ma and 1850 Ma (Maxon, 1976; Aleinikoff et al., 1985; S. A. Bowring, oral commun., 1987). One component of these zircons might have been derived from the underlying Vadito Group, but another component must have been derived from older rocks elsewhere.

1660–1650 Ma felsic volcanic and sedimentary sequences

Metamorphosed felsic volcanic rocks with U-Pb zircon ages of 1660–1650 Ma (Robertson et al., 1990) are present in several localities in northern New Mexico (Fig. 2). The best-known example, the Dalton Canyon succession of the southern Santa Fe Range, was described by Moench and Erickson (1980), Fulp (1982), Renshaw (1984) and Fulp and Renshaw (1985). In other Proterozoic exposures, felsic plutonic rocks have ages in this range, but no volcanic equivalents have been recognized (Robertson et al., 1990). Rocks of this age are apparently more abundant in central New Mexico (Robertson et al., 1990). Examples are found in most uplifts including the Manzano, Lemitar, Magdalena, Chupadera, Lemitar and Pedernal Mountains (references in Robertson et al., 1990).

The 1660–1650 Ma rocks make up a minor component of the exposed Proterozoic section of northern New Mexico, and their tectonic significance is poorly understood. Briefly, the rocks consist of a heterogeneous package of felsic volcanic rocks and immature metasediments, typically pelitic schists and quartzofeldspathic schists and gneisses. Mafic metavolcanic rocks are relatively minor. The sequences are interpreted to have been intruded by shallow synvolcanic aplitic and porphyritic intrusions. Based on trace and major element geochemistry, Condie (1986) suggested that the metavolcanic rocks may have formed in an arc or back-arc setting in or near continental crust. Contact relations between these sequences and the older Hondo Group metasediments are poorly understood, but many recent workers suspect that the two sequences were tectonically juxtaposed (Grambling et al., 1988; Thompson et al., 1989; Robertson et al., 1990).

Plutonic rocks

Plutonic rocks are an important component of the Proterozoic geology of northern New Mexico. As noted above, deformed calc-alkaline intrusives are associated with the 1765–1720 Ma mafic sequences (Robertson et al., 1990). A broad array of felsic plutonic rocks range in age from approximately 1700 to 1650 Ma, spanning the gap between the 1700 and the 1650 Ma volcanic sequences (Robertson et al., 1990). These make up a significant component of the exposed Proterozoic rocks in several ranges (Williams, 1987). Finally, granitic rocks in the age range 1500–1400 Ma, commonly termed "anorogenic granites" (Anderson, 1983), are widely exposed in northern and central New Mexico (Robertson et al., 1990).

Plutonic rocks make up a large proportion of the exposed rocks in the Santa Fe Range (Miller et al., 1963; Metcalf, 1985, 1986). The rocks have been grouped under the general name Embudo Granite (Miller et al., 1963), but a number of plutons are certainly present. Three broad rock types or intrusive sequences have been distinguished: (1) quartz diorite to tonalite; (2) granodiorite to granite; and (3) pink, two-mica granite (Moench and Robertson, 1980; Metcalf, 1986). The first two types are foliated; the third is weakly foliated or unfoliated and intrudes the other two. Mafic gneiss and migmatized supracrustal rocks occur locally; a large migmatized, pelitic, roof pendant occurs in the Aspen basin area in the central Santa Fe range (Metcalf, 1985). The geochronology of the plutonic rocks is not well constrained, but some plutonism apparently occurred around 1670–1600 Ma (Brookins and Laughlin, 1983; Grambling et al., 1988).

Robertson et al. (1990) summarized the recent nomenclature and age constraints for many of the Proterozoic plutonic rocks in New Mexico. The paucity of geochronology and of detailed structural and petrologic data in most ranges severely limits the degree to which these rocks can be incorporated into the geologic history of the region. It is important to note, however, that plutons seem to display distinctive geographic relationships with respect to supracrustal assemblages. Specifically, intrusive rocks rarely intrude the Vadito or Hondo Groups. Exceptions include the possibly crosscutting stock in the southern Truchas Peaks area and felsic plutons (1680–1450 Ma) in the southern Picuris Mountains that intrude a sequence of rocks tentatively correlated with the Vadito Group. The lack of intrusive rocks, especially in the Hondo Group, might suggest that these rocks were tectonically emplaced above the mafic assemblages. Alternatively, plutonic rocks may preferentially intrude along certain crustal pathways, perhaps along major lithotectonic boundaries.

Structural characteristics and deformation history

Recent structural and tectonic interpretations of Proterozoic geology of northern New Mexico are based primarily on structural investigations in four main areas: the Tusas Mountains (Wobus, 1985; Smith, 1986; Williams, 1987; Gableman, 1988), the Picuris Mountains (Holcombe and Callender, 1982; Bauer, 1988), the Rio Mora area (Grambling and Codding, 1982; Grambling et al., 1988), and the Truchas Peaks area (Grambling, 1979; Grambling et al., 1988). Most of these studies are consistent with a tectonic history involving a single heterogeneous crustal shortening event, perhaps resulting from a major plate collision. However, recent work in the Taos Range (Smith, 1986; Grambling et al., 1989) and Cimarron Range (Grambling, 1990) and preliminary work in the Manzano Mountains of central New Mexico (Thompson et al., 1989) suggest instead that the deformation history may be rather complicated, involving phases of extension and perhaps more than one shortening event.

As presently understood, Proterozoic structures can be divided into three broad phases. Phase 1 structures are associated with an early shortening event that may reflect the major episode of Early Proterozoic mountain building in northern New Mexico. The subsequent phases of deformation might be considered "adjustment" phases. These are commonly associated with shearing, folding and faulting (in places on a very significant scale) of the assembled Proterozoic rocks. Phase 2 is characterized by subhorizontal, south-verging mylonites, interpreted to have formed during crustal extension (Grambling et al., 1988). The youngest ductile structures recognized in northern New Mexico, here termed phase 3, are right-lateral, strike-slip faults and shear zones (Robertson et al., 1990). The two "adjustment" phases of deformation, phase 2 and phase 3, may have played a role in the metamorphism, stabilization and uplift of the Proterozoic terranes. However, many aspects of these events are only presently being recognized (J. A. Grambling, oral commun., 1990). It must also be noted that additional deformational events have been suggested to post-date phase 3 structures (Thompson et al., 1989) in central New Mexico, but these do not appear to have significantly affected the geometry of rocks to the north.

Early shortening—phase 1

Most Proterozoic rocks in northern New Mexico preserve evidence of an early deformation involving heterogeneous crustal shortening.

Structures associated with this event dominate the rocks of the Tusas, Picuris, Truchas and Rio Mora ranges and probably comprise an important component of the structures, especially away from shear-dominated areas, in most other ranges. Typically, phase 1 structures can be divided into three or more overprinting generations, interpreted to reflect progressive stages in the ongoing orogeny. The intensity and general character of the generations vary from region to region.

Most Proterozoic terranes can be divided into geographically distinct domains distinguished by the number and intensity of the overprinting structures or fabrics (Williams, 1987; Bauer, 1988). Although some domains are dominated by primary volcanic and sedimentary structures, most have one or more strong deformational fabrics. The earliest is invariably a penetrative, bedding-parallel schistosity with a strong, generally north-trending, mineral lineation. Small intrafolial folds are common, but large-scale folds are rare. The bedding-parallel schistosity is typically refolded by several generations of upright to overturned folds with shallowly west-plunging axes and steeply south-dipping axial surfaces. These folds, commonly large synclines cored by Hondo Group rocks, dominate the map patterns of most ranges. Axial surfaces of earlier folds tend to have shallower dips than those of later folds. Cleavages range from weak to well-developed, and mineral lineations tend to plunge steeply down dip, to the south. The youngest fabric seen in many regions is a weak north-trending, steeply dipping crenulation cleavage that cuts all earlier structures.

Phase 1 shortening was apparently accommodated by ductile thrusting and imbrication of relatively massive units, especially the Ortega Formation (Fig. 3). The large, map-scale, synclinal folds that characterize most exposures are interpreted to occur beneath ductile thrust ramps along which older rocks were carried northward over Hondo Group rocks. Complexly folded domains are typically adjacent to the ramp regions of large ductile thrusts. The ramps and underlying synclines seem to have acted as buttresses against which these rocks were shortened.

Small-scale kinematic indicators that corroborate the postulated northward vergence are rare or nonexistent in most rocks. Apparently, most kinematic indicators were either recrystallized during the later metamorphism or overprinted by later structures. Recently, Williams (unpubl., 1990) has noted that some metamorphosed rhyolites preserve asymmetric recrystallized tails on quartz phenocrysts that consistently indicate northward transport. These relatively dry rocks seem to have been less susceptible to later deformation and recrystallization.

South-verging (extensional?) deformation—phase 2

Proterozoic rocks in many uplifts display local kinematic evidence for south-verging shearing, and several uplifts contain major south-verging shear zones. Although timing relations are equivocal, many of the shear fabrics are interpreted to post-date phase 1 structures. One important south-verging shear zone has been described in the northern Taos Range and western Cimarron Mountains (Grambling and Smith, 1986; Smith, 1988; Grambling et al., 1989). Here, a folded but regionally subhorizontal mylonitic contact separates amphibolite-grade quartzite from underlying granulite-facies gneiss. Near the contact, rocks display a well-developed schistosity and NW- or SE-plunging mineral lineation. Unlike many of the rocks described above, small-scale deformational features, especially kinematic indicators, are well-preserved. Asymmetric porphyroclasts, S-C fabrics and mica fish consistently suggest southward vergence.

In other ranges, evidence for this phase of deformation is more subtle. In the Tusas Mountains, small-scale asymmetric folds, offset relationships on some ductile faults and rare asymmetric porphyroclast tails

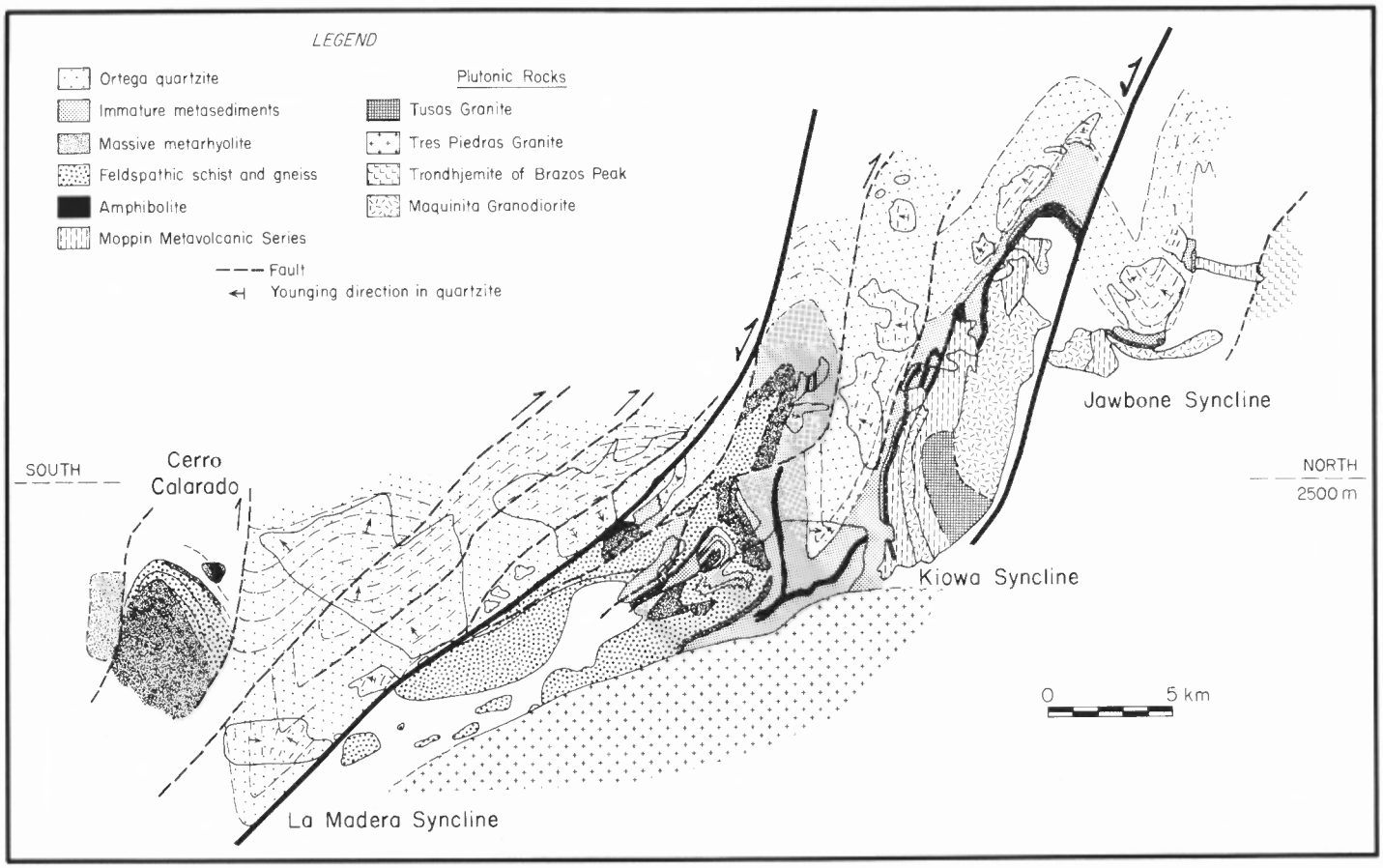


FIGURE 3. Down-plunge projection of Proterozoic rocks in the Tusas Mountains. The plane of projection strikes N10°E and dips between 30°E and 60°E depending on the plunge of fold axes in the associated structural domain. Fold axes within each domain are approximately parallel. Heavy solid lines are zones with microstructural evidence for late-stage, south-directed shearing.

suggest that a component of south-verging motion may have occurred along the Hondo Group–Vadito Group contact. Similar south-verging fabrics have been described near the Vadito Group–Hondo Group contact in the northwestern Picuris Mountains (P. W. Bauer, unpubl., 1990). In both regions, fold axes plunge shallowly toward the west, and stretching lineations plunge south, both parallel to the earlier trends. However, the south-verging nature of the microstructures is in direct contrast to the geometry of the earlier, large-scale structures. Despite the northward vergence of virtually all macroscopic structures, the deformational history apparently involved a component of south-verging strain. This may represent a relatively minor relaxation after the culmination of shortening, or alternatively, it may be related to the larger south-verging shear zones in the Taos and Cimarron Ranges, suggested to reflect a younger (extensional?) deformational (Grambling et al., 1989).

Strike-slip shearing and faulting—phase 3

The youngest ductile structures in northern New Mexico are vertical, north-trending, dextral shear zones and faults. Two examples are: (1) the well-known Picuris-Pecos fault that cuts the Santa Fe, Truchas and Picuris ranges (Miller et al., 1963; Grambling, 1979; Robertson and Moench, 1979; Bauer, 1988; Moench et al., 1988); and (2) the Fowler Pass fault in the Cimarron Mountains (Robinson et al., 1964; Wobus, 1989; Grambling, 1990). Other important dextral faults may exist in northern New Mexico, but evidence is obscured or complicated by structures related to the Rio Grande rift.

The dextral faults or fault systems display evidence for ductile and brittle deformational phases. Ductile structures include intense subvertical cleavages, near-horizontal lineations, grain-size reduction, asymmetric porphyroclasts and megacrysts, and, near the Picuris-Pecos fault, a large-scale reorientation of lithologic contacts. Brittle structures include brecciation, silicification and discrete offset of some Proterozoic and Paleozoic units (Miller et al., 1963; Robertson et al., 1990). Veins of relatively undeformed granite, interpreted to be related to the 1450 Ma Sandia Granite, cut a dextral shear zone in the Sandia Mountains of central New Mexico (Mawer et al., 1989). This, along with the clearly ductile deformational structures, suggest that the north-trending faults were active in Proterozoic time, probably before 1450 Ma. The presence of offset Paleozoic units documents the long-lived activity of these structures.

The onset of the strike-slip shearing and faulting may signal an important phase or transition in the Proterozoic evolution of northern New Mexico and in the evolution of the southern Rocky Mountains in general. As noted, the Proterozoic rocks apparently accumulated or accreted along a northeast-trending margin. Most early fold axes trend to the east or northeast, and early lineations plunge to the north or northwest. In contrast, north-trending faults seem to have played an important role in the evolution of the region throughout the Phanerozoic. The onset of strike-slip shearing may reflect the development of a set of fundamental north-striking weaknesses in the crust that have persisted to some extent from the Proterozoic to the present. Although the north-trending weaknesses were apparently active by 1400 Ma, they may have been initiated even earlier. The final generation of structures associated with phase 1 of deformation are upright, north-trending folds and cleavages in schistose rocks, and north-striking vertical faults in massive quartzites (Williams, 1982; Bauer, 1988). The onset of dextral shearing may indicate the establishment of a cooler and more stable Proterozoic crust, but the basic trends, important from the Middle Proterozoic to the present, may have been established during the original accretion of the rocks.

Metamorphic petrology

Until recently, virtually all metamorphic rocks in northern and central New Mexico were believed to have crystallized at conditions near the aluminum silicate triple point (Grambling, 1986). However, granulite facies rocks have recently been documented in the Taos range (Grambling and Smith, 1986; Smith and Grambling, 1986; Grambling et al., 1989) and in the Cimarron Mountains (Grambling, 1990). Two other known exceptions to the regional amphibolite grade conditions are: (1) the southern Santa Fe Range where granulite facies rocks are associated with migmatites (Metcalf, 1985, 1986) and (2) central New Mexico where greenschist facies rocks have been described in some apparently fault-bounded terranes (Thompson et al., 1989).

Rocks that crystallized near the aluminum silicate triple point (approximately 500°C, 3.8 kb) crop out throughout the Tusas, Picuris, Truchas, Rio Mora, Rincon and in parts of the Taos and Cimarron ranges. Triple-point rocks are also known from Proterozoic ranges in central New Mexico, including the Sandia, Manzano and Pedernal uplifts (Grambling, 1986). Schistose rocks typically contain quartz, plagioclase, muscovite, biotite and hematite-ilmenite with varying amounts of garnet, staurolite and one or more aluminum silicates. Assemblages with coexisting kyanite, andalusite and sillimanite have been documented in the Picuris, Truchas, Rio Mora and Tusas ranges, but in several localities andalusite has been stabilized by the presence of Mn^{3+} (Grambling and Williams, 1985). Isotherms and isobars are nearly horizontal, cutting most large-scale folds (Grambling, 1979, 1986; Grambling et al., 1989). This is consistent with most microfabric data which consistently suggest that the peak of metamorphism coincided with, and outlasted, the final phases of folding. The rocks are interpreted to have crystallized along a counterclockwise P-T path, with a slight increase in pressure during heating and nearly isobaric cooling (Grambling, 1986; Grambling et al., 1989).

Granulite-facies rocks from the Taos and Cimarron Ranges are sillimanite-K-feldspar gneisses. Muscovite is interpreted to be a retrograde phase. Temperature estimates based on garnet-biotite equilibrium are generally greater than 700°C, and pressures, based on garnet-plagioclase-sillimanite-quartz and garnet-plagioclase-biotite-muscovite are estimated to have been 7 kb or greater (Grambling et al., 1989). Migmatites of the Santa Fe Range are interpreted to have crystallized at temperatures between 650 and 700°C and at pressures greater than 4 kb (Metcalf, 1985, 1986).

Grambling et al. (1989) suggested that regional metamorphism in northern New Mexico may be closely related to low-angle extensional, ductile faulting (phase 2, above). In the Taos Range, granulite facies rocks are immediately below a south-verging ductile shear zone, and amphibolite facies (triple point) quartzites occur immediately above. Grambling et al. (1989) postulated that similar ductile faults may exist beneath amphibolite-facies rocks in other ranges, and that crustal extension may have played an important role in providing heat for the high-grade and medium-grade metamorphism. Significant questions remain concerning the timing of crustal shortening, metamorphism and extension in northern New Mexico (see below).

DISCUSSION

Tectonic history of northern New Mexico

The early Proterozoic history of northern New Mexico involved assembly and accretion of a suite of volcanic arcs, probably oceanic island arcs that represent juvenile additions of crustal material. This accretionary phase spanned an interval from 1765 to 1720 Ma and may have been significantly longer, as no older age limit exists in New Mexico. The overlying Vadito metavolcanic rocks and Hondo Group metasediments are interpreted to have been deposited on a somewhat stabilized crust, perhaps beginning with a period of rifting. Soegaard and Eriksson (1985) interpreted the onset of Hondo Group deposition to signal the establishment of a stable continental margin. The stability was apparently rather short-lived because volcanic rocks were again deposited at approximately 1660 Ma. It is important to emphasize that the transition between major lithologic packages, such as the mafic sequence–Vadito Group contact, may represent a lateral rather than vertical transition. Discrete depositional/tectonic environments may have been juxtaposed during later crustal shortening and/or extension (Grambling et al., 1988).

Proterozoic rocks in northern New Mexico record one major collisional event. The timing of this deformation is loosely constrained to be younger than 1650 Ma, the age of the youngest penetratively deformed rocks. The collision apparently occurred from the southeast along a northeast-trending margin, but little is known about the size or

nature of the colliding body. The orogenic event may have been a major one if deformation of roughly correlative rocks in Arizona and Colorado represents the same collision (Hoffman, 1988). Grambling et al. (1989) proposed that the collisional event in New Mexico may have culminated in a phase of extensional deformation along discrete, subhorizontal shear zones. However, many details of this deformation are not well constrained, and no comparable event has yet been recognized in neighboring Proterozoic terranes (K. E. Karlstrom, oral commun., 1990). Prograde metamorphism occurred during crustal shortening, but the peak of metamorphism outlasted this deformation.

In northern New Mexico, tectonic events younger than the main crustal shortening event (and proposed extensional event) are limited to dextral shearing along vertical, north-trending structures. As noted, these structures may have had an influence on structural trends from the Late Proterozoic to the present. It should be noted, however, that recent workers have suggested that additional collisional events, younger than the onset of ductile shearing, may have affected rocks of central New Mexico (Thompson et al., 1989). All Proterozoic rocks were uplifted between 1400 Ma and the middle Paleozoic, but the timing and mechanism(s) of uplift remain controversial (see below).

Ongoing questions in Proterozoic geology

Although many important advances have been made in recent years, there are a number of significant questions about the tectonic history of the Proterozoic of northern New Mexico. These can be divided into three broad groups: (1) questions about the tectonic setting of major lithotectonic packages; (2) questions about the timing and significance of deformational phases or events; and (3) questions concerning the timing and controls on metamorphism and uplift of the Proterozoic rocks. Each of these is discussed briefly below.

Stratigraphic and lithologic relationships

Several important questions remain concerning the nature of the contacts between Proterozoic lithologic packages. Two contacts are particularly important: (1) the contact between the 1765–1720 Ma mafic metavolcanic sequences and the Vadito Group; and (2) the contact between the Hondo Group and 1660–1650 Ma metavolcanic packages. Both are fundamentally important for interpreting the early Proterozoic tectonic setting and history of the region.

Preliminary geochemical work on the Vadito Group suggests that it may have been deposited in a continental rift or back-arc environment near a continent (Robertson et al., 1990). As noted, the underlying mafic sequences are interpreted to have accumulated in an arc or back-arc setting, and isotopic investigations throughout central and southwestern North America suggest that these represent juvenile additions to the crust (Nelson and Depaolo, 1980). The Hondo Group, above the Vadito, is interpreted to have been deposited on a stable continental shelf (Soegaard and Eriksson, 1985). Some questions might be raised about the "stable shelf" interpretation if the observation that igneous rocks span the gap between 1700 and 1650 Ma is valid (Robertson et al., 1990).

A back-arc setting for the Vadito Group would seem compatible with the setting of the underlying mafic arc terrains. However, a continental-rift setting would seem compatible with the stable shelf environment interpreted for the overlying Hondo Group. If the Vadito Group accumulated in a continental rift, the mafic sequence–Vadito Group contact must represent a major tectonic transition, during which the mafic rocks were accreted and the crust stabilized (Soegaard and Eriksson, 1985). Data constraining the depositional setting of the Vadito Group are particularly critical to any tectonic model for the evolution of the region. As noted above, virtually all contacts between mafic sequences and the Vadito Group are tectonized and may have experienced significant tectonic transport. Major and trace-element geochemistry and detailed field investigations are under way to evaluate the setting of the Vadito Group in the Tusas Mountains where some of the most complete and least deformed exposures exist.

The nature of the contact between the Hondo Group and the 1660–1650 Ma metavolcanic sequences is equally problematical. It may reflect a transition from stable shelf deposition back to the convergent tectonism that ultimately led to the deformation of the entire Proterozoic sequence. Condie (1986) suggested that the volcanic rocks were deposited in an arc setting near continental crust. As with the Vadito Group, however, an alternative possibility is that the volcanic rocks were deposited in a geographically distinct but perhaps time-correlative setting and then were juxtaposed during later tectonism. The nature of this contact is extremely relevant for any attempt to merge the Proterozoic tectonic history of central New Mexico, containing abundant 1660–1650 Ma rocks, with that of northern New Mexico, dominated by 1700 Ma and older rocks.

Finally, the setting and timing of plutonic rocks in the Proterozoic of New Mexico remains both a poorly understood topic and a largely untapped resource for tectonic interpretations. As noted above, intrusive rocks are not uniformly distributed with respect to supracrustal assemblages. Petrologic and structural constraints on the tectonic setting of the plutonism should serve to limit the setting and history of the host rocks. One fundamental question, as suggested above, concerns the degree to which intrusive pathways are controlled by crustal composition, stratification or structure.

Timing of deformation and metamorphism

Most workers agree that, away from the relatively discrete, later structures, the complex and heterogeneous array of structures displayed in many ranges were formed during a crustal shortening event. However, the age and tectonic significance of this shortening event are two of the most controversial topics in Proterozoic research today. Deformation probably began after 1650 Ma, the youngest ages of deformed volcanic and plutonic rocks. However, if contacts between 1660–1650 Ma rocks and older rocks are entirely tectonic, deformation may have begun earlier, before the final accretion of the younger sequences. The younger constraint on the timing of deformation is approximately 1450–1400 Ma, the age of the largely untectonized "anorogenic" granites (Anderson, 1983; Mawer et al., 1989; Robertson et al., 1990) and the age of widespread resetting of isotopic systems including Rb-Sr and K-Ar (Ward, 1986) and Ar^{40}-Ar^{39} (J. A. Grambling, oral commun., 1990). The broad age range (1650–1450 Ma) during which the crustal shortening event could have occurred allows for three different models for the tectonic history of the region: (1) deformation and prograde metamorphism may have occurred soon after deposition at approximately 1650 Ma; (2) crustal shortening, with an early phase of metamorphism, may have occurred at 1650–1600 Ma, but the peak of metamorphism (and crustal extension?) may be younger, approximately 1450–1400 Ma; and (3) crustal shortening, extension and metamorphism may all have occurred at approximately 1450 to 1400 Ma.

Several pieces of evidence suggest, but certainly do not require, that one phase of crustal shorterning may have occurred around 1650 Ma. First, no supracrustal rocks younger than 1650 Ma have been identified in northern or central New Mexico nor in Arizona or southwestern Colorado. This suggests that depositional environments were dramatically modified at approximately 1650 Ma. Second, the Mazatzal orogeny in central Arizona, an interpreted continent-continent collision, is associated with deformation of roughly correlative metavolcanic and metasedimentary rocks between 1665 and 1600 Ma (Karlstrom et al., 1990; K. E. Karlstrom, oral commun., 1990). It is likely that a major crustal shortening event in Arizona would also be expressed in New Mexico. Finally, in the Magdalena Mountains of central New Mexico, Bowring et al. (1983) tentatively concluded that the 1654 Ma Magdalena granite cuts transposed layering and foliation in 1660 Ma metavolcanic rocks. This suggests that transposition occurred just prior to 1650 Ma.

Based on microfabrics in the Tusas and Picuris Mountains (Williams, 1987; Williams and Bauer, unpubl., 1990), prograde and peak metamorphic conditions occurred during "phase 1" crustal shortening. However, the widespread resetting of Rb-Sr, K-Ar, and Ar^{40}-Ar^{39} isotopic systems between 1450 and approximately 1300 Ma (Ward, 1986; J. A. Grambling, oral commun., 1990) suggests that metamorphism was also occurring at this time. Thus, if deformation and prograde metamorphism occurred before 1600 Ma, then the rocks either cooled extremely slowly,

for several hundred million years (model 1, above), or the region experienced a reheating event during the middle or late Proterozoic that reset or partially reset the isotopic systems (model 2, above). Tectonic models involving slow retrograde cooling have been proposed for northern New Mexico by Grambling (1986) and for central Arizona by Karlstrom and Bowring (1990).

The main evidence that deformation and metamorphism occurred near 1450 or 1400 Ma (model 3, above) comes from the suggestion that metamorphism is associated with south-directed (extensional?) shearing in the Taos Mountains and Cimarron Mountains (Grambling et al., 1989) and from the interpretation that the peak of metamorphism was associated with the resetting of Rb-Sr, K-Ar and especially Ar^{40}-Ar^{39} isotopic systems (J. A. Grambling, oral commun., 1990). Because the peak of metamorphism corresponds with crustal shortening in several ranges, this model requires that shortening also occurred at approximately 1450 Ma. This model is neither consistent with the lack of supracrustal rocks younger than 1650 Ma nor with timing constraints in central Arizona, but it eliminates the need for prolonged metamorphism from 1600 to 1400 Ma and for multiple metamorphism for which there is no recognized evidence.

At present, there is no direct evidence to contradict the interpretation that an important phase of crustal shortening and prograde metamorphism occurred at approximately 1650–1600 Ma in northern New Mexico. A model, such as model 1 or model 2, above, involving early deformation and metamorphism with isotopic systems disturbed by continued or additional tectonothermal events seems most consistent with all existing data. Clearly, new constraints on the timing of deformational and metamorphic events is critical to establishing a comprehensive plate tectonic model for the Proterozoic of southwestern North America. Work is currently in progress to determine the ages of various components of the rocks with Ar^{40}-Ar^{39} (J. A. Grambling, oral commun., 1989) and U-Pb geochronology (S. A. Bowring, oral commun., 1989), but meaningful results will only be obtained when such isotopic studies are combined with detailed field mapping and structural analyses.

Controls on regional metamorphism and uplift

The large area over which triple-point metamorphic conditions are exposed at a nearly constant structural/stratigraphic level in northern New Mexico make the region unusual compared to other exposures in this orogenic belt, and with metamorphic terranes in general. Two components seem to be necessary for the preservation of the regional uniformity. First, nearly constant metamorphic conditions must be established throughout a (probably subhorizontal) lithologic package of rocks, and second, the rocks must be uplifted in a homogeneous way such that a constant structural (isobaric) level is exposed at the surface.

Two alternative models have been proposed for the development of subhorizontal isotherms and isobars in the Proterozoic rocks. Grambling (1986) suggested that deformation (crustal shortening) occurred with increasing P and T in a counterclockwise P-T-time trajectory and that isobaric cooling persisted for an extended period of time. Thus, the subhorizontal isotherms and isobars were superimposed on the already deformed rocks during the prolonged cooling history. Alternatively, Grambling et al. (1989) suggested that regional metamorphism may be directly related to low-angle extensional faulting. They postulated that metamorphic heating may have been related to the early phases of extension (Wickham and Oxburgh, 1985) and that later extension along regionally extensive low-angle shear zones juxtaposed a lower plate of granulite-facies assemblages against an upper plate of amphibolite-facies assemblages. Some aspects of this second model do not seem to be consistent with microstructural observations in several ranges where peak metamorphic conditions apparently overlapped with the culmination of crustal shortening (Williams, 1987; Bauer, 1988). Furthermore, major late-stage, south-verging shear zones have not been recognized in most uplifts in northern New Mexico; these shear zones must be postulated to exist at depth.

Most mountain ranges in northern New Mexico now expose, at an elevation of approximately 2 km, an isobaric surface that developed when the rocks were buried to approximately 12–15 km (Grambling, 1986). In some respects, the uplift history is among the most poorly known phases in the tectonic history. As with prograde metamorphism, several models can be suggested but none seem entirely satisfactory at present. Grambling et al. (1989) proposed that low-angle extensional structures could have served to unroof a large area to a relatively consistent crustal level. This unroofing may represent the culmination of an extensional event that began during metamorphism. Alternatively, Bowring and Karlstrom (1990) proposed, for rocks in Arizona, that the magnitude of uplift was isostatically controlled by a crust and mantle geometry that may have been imposed during accretion. A similar isostatically controlled process may be appropriate for Proterozoic rocks in New Mexico.

Few constraints exist at present to evaluate these models. Most Proterozoic rocks in New Mexico are well suited to P-T-time petrologic analysis. Such analyses have great potential for constraining both the prograde and the retrograde history of the rocks.

Regional tectonic history and correlations with other regions

Proterozoic rocks roughly correlative with those of northern New Mexico are widely exposed in the transition zone of central Arizona. Recently, Karlstrom and Bowring (1988) have divided the rocks into a series of tectonic blocks that are separated by near-vertical shear zones or faults. In the Mazatzal block, supracrustal rocks including metarhyolite, clastic metasediments and one or more thick orthoquartzite sequences (Conway and Silver, 1984; Karlstrom et al., 1990) are comparable in age and character to the Vadito and Hondo Groups. In the Sunflower block, rhyolitic rocks are known to be as young as 1620 Ma (Karlstrom et al., 1990), perhaps comparable to the younger felsic metavolcanic sequence in New Mexico. Rocks in the Mazatzal and Sunflower blocks were deformed in at least one major, northwesterly directed crustal shortening event involving folding, thrusting and ductile shearing.

Despite the obvious similarities, the interpreted tectonic history of the rocks in central Arizona is somewhat different from that in New Mexico. In Arizona, the tectonic models center on the relatively independent evolution of the crustal blocks and the steep shear zones that separate them. In New Mexico, steep faults do not seem to play an important role in the early deformational history. Instead, low-angle ductile thrusts and normal faults are most important. Part of the difference may arise from the perspective of the workers. However, other differences may reflect real differences in the characteristics of distinct parts of an evolving orogen. As the independently evolving models for the evolution of Arizona and New Mexico become better constrained, it will be increasingly necessary to incorporate the results for each region into a single model for the Proterozoic orogen.

ACKNOWLEDGMENTS

This work incorporates the results of a large number of workers, many of whom may not have been adequately referenced in the text. I apologize for any omissions. The manuscript was greatly improved by critical reviews by P. W. Bauer, K. E. Karlstrom, S. A. Bowring and S. J. Seaman. However, all errors and misinterpretations are solely the responsibility of the author.

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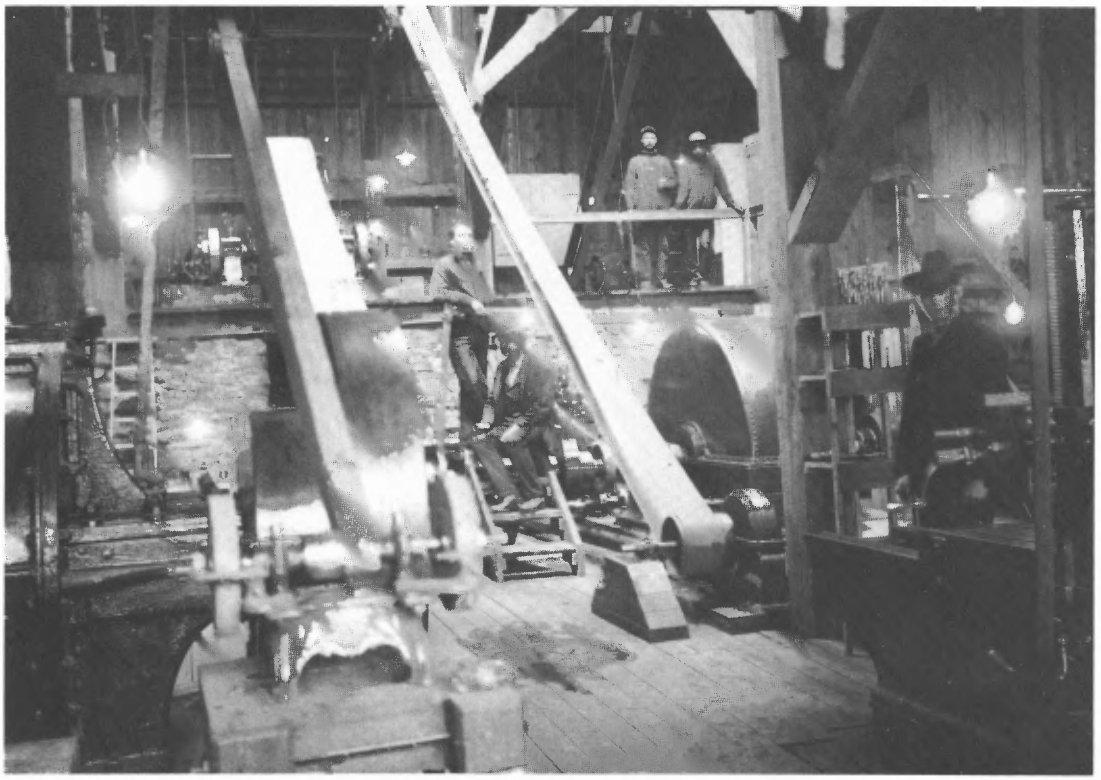
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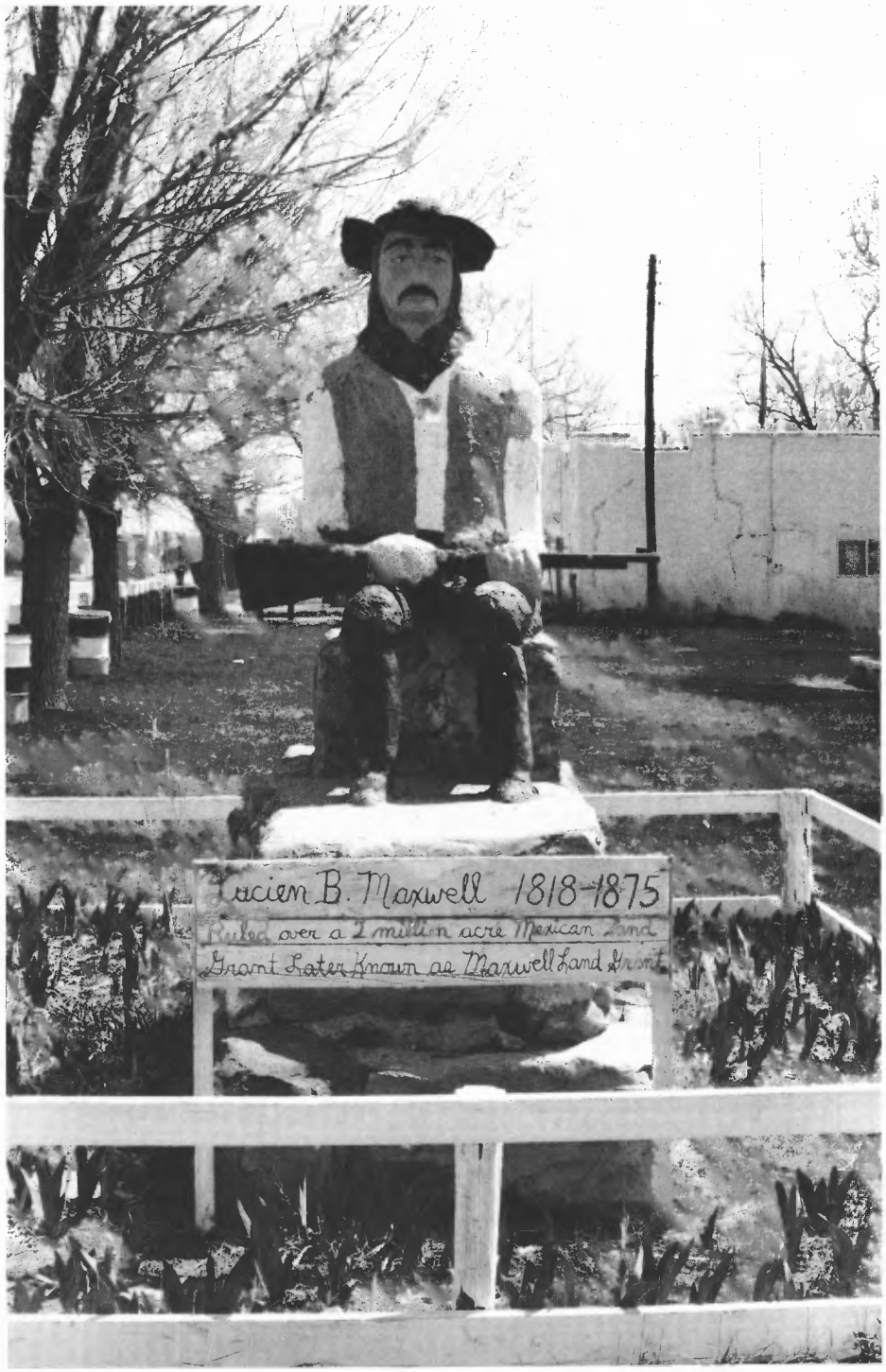
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The "great hope" of Twining was the mill and smelter erected near the base of Fraser Mountain during 1902. Metallurgy, rather than poorly designed equipment, would lead to its failure. The molten matte froze in the furnace, not once, but twice, doubtless due to improper fluxing. The above view is of the maintainance shop portion of the plant (note grinder, milling machine, etc.). Electric power was provided by Pelton water wheels which drove large motors such as that shown in the left of the photo. Although state-of-the-art, the plant was a nightmare of unguarded shafts, flywheels and open belts. Subsequent to its failure, the plant stood idle until destroyed by fire in 1932. Photo courtesy of Winifred Hamilton.



This sculpture of a misshapen Lucien B. Maxwell sits in the new Cimarron town plaza. It is doubtful that such diaphanous legs could have borne up such a massive torso. In spite of its ill-favored countenance, this monument is faithfully repainted each year by local citizens. Photo by P. W. Bauer.