AN OVERVIEW OF THE PROTEROZOIC GEOLOGY IN THE THOMPSON PEAK–GLORIETA BALDY AREA, SANTA FE COUNTY, NEW MEXICO

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Abstract—The Thompson Peak–Glorieta Baldy area of the southern Santa Fe Mountains, New Mexico, exposes a variety of Proterozoic metasedimentary, mafic and felsic metavolcanic, and granitic rocks. The supracrustal rocks have been referred to as the Dalton Canyon succession or the McClure septum. However, this paper proposes that the supracrustal rocks be designated the Thompson Peak metamorphic suite. A reevaluation of metamorphic mineral assemblages (Grt+Bt+St, Bt+St+Sill) and new thermobarometry data from these rocks shows that peak metamorphic temperatures and pressures are significantly higher than previously estimated. Temperatures ranged from 600 to 680 °C depending on location, and the pressure is estimated at 5–6 kbar. This relatively high-temperature metamorphism appears to be related to heat from ~1650 Ma granitic plutons that bound the supracrustal rocks. The relative timing of metamorphism and deformation is bracketed by a strongly deformed quartz porphyry that intrudes the supracrustal rocks and a crosscutting, weakly deformed to undeformed two-mica granite. The quartz porphyry yields an age of ~1655 Ma (U/Pb zircon) giving an upper limit to the absolute timing of this tectonism; the age of the two-mica granite is unknown. The rocks of the Thompson Peak metamorphic suite are interpreted to be the northernmost exposure of the Mazatzal (1660–1640 Ma) crustal province, and represent sedimentary, volcaniclastic and volcanic rocks deposited near the margin of the older (1700 Ma) Yavapai crustal province and subsequently metamorphosed and deformed during the 1650–1600 Ma Mazatzal orogeny.

INTRODUCTION

The Santa Fe Range, just east of Santa Fe, New Mexico (Fig. 1), represents the southernmost extent of the Sangre de Cristo Mountains. Bounded by the Picuris–Pecos fault to the east and the Rio Grande rift to the west, this uplift consists of Proterozoic metamorphic and igneous rocks. Moench et al. (1988) presented a regional geologic map covering almost the entire Santa Fe Range. The northern two-thirds of the range is a large plutonic complex with screens and pendants of migmatitic supracrustal rocks (Metcalf, 1990); the southern third is characterized by a relatively large, continuous package of supracrustal rocks bounded by granites to the north and south. The Garcia Ranch–Borrego fault divides the supracrustal rocks in the Thompson Peak–Glorieta Baldy area from similar rocks farther to the west. Moench et al. (1988) referred to these supracrustal rocks as the McClure septum, whereas Robertson and Condie (1989) called these rocks the Dalton Canyon succession. However, I suggest that the supracrustal rocks in the southern Santa Fe Mountains be given a more formal, lithodemic designation, the Thompson Peak metamorphic suite.

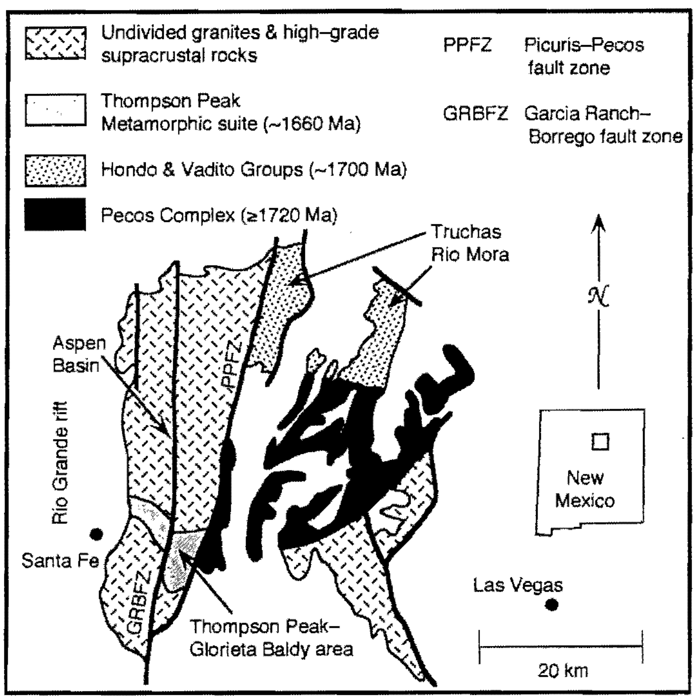

FIGURE 1. Regional map showing the location of the Santa Fe Mountains and the Thompson Peak–Glorieta Baldy area in New Mexico.

This paper presents new, preliminary metamorphic and structural data and summarizes the existing structural and metamorphic information detailed in two MS thesis studies (Fulp, 1982; Renshaw, 1984) and an unpublished geologic map of the area south of Glorieta Baldy (Wakefield, 1983). A simplified geologic map of the area (Figure 2) is compiled from the maps of those workers and Daniel (unpubl.). The goal of this paper is to synthesize the new and old metamorphic and structural data for the southern Santa Fe Mountains and discuss how these rocks fit into the overall Proterozoic tectonic evolution of New Mexico. However, significant problems remain in understanding the nature of the metamorphism and deformation in this area.

PROTEROZOIC ROCKS

The Proterozoic rocks exposed in the Glorieta Baldy–Thompson Peak area include metamorphosed supracrustal rocks and at least four granitic bodies (Fig. 2). The northern margin of the Thompson Peak metamorphic suite is intruded by a quartz porphyry that grades into biotite granite towards the north (Moench et al. 1988; Daniel, unpubl.). Another two-mica granite crosscuts both the supracrustal rocks and the quartz porphyry/biotite granite. The southern margin of the complex is bounded by a coarse-grained biotite granite (Shaggy Peak granite). As noted above, this paper proposes a more formal designation of the Thompson Peak metamorphic suite for the supracrustal rocks. This lithodemic designation encompasses all of the supracrustal rocks in the Thompson Peak–Glorieta Baldy area. Given that metasedimentary and metavolcanic rocks are present, it is appropriate that these rocks be considered a metamorphic suite, and Thompson Peak (10,554′) is the most prominent peak in the area where these rocks are exposed. Supracrustal rocks exposed west of the Garcia Ranch–Borrego fault zone (Moench et al. 1988; Daniel, unpubl.) are also included in the Thompson Peak metamorphic suite. In the Aspen Basin area, ~15 km to the north (Fig. 1), partially melted supracrustal rocks occur as screens and pendants within a vast plutonic complex (Metcalf, 1990). Although these rocks could be high-grade equivalents of the Thompson Peak metamorphic suite, they are not included at this time because the nature of the transition between these two areas is poorly understood.

Supracrustal rocks

The supracrustal rocks are divided into seven map units (Fig. 2). These include quartzite, quartz-mica schist, mica-feldspar schist, biotite and pelitic schists, amphibolite, felsic schist, and a mixed amphibolite, felsic schist, quartz-mica schist unit (Table 1). Primary depositional features that show stratigraphic facing is rare and no stratigraphic succession is

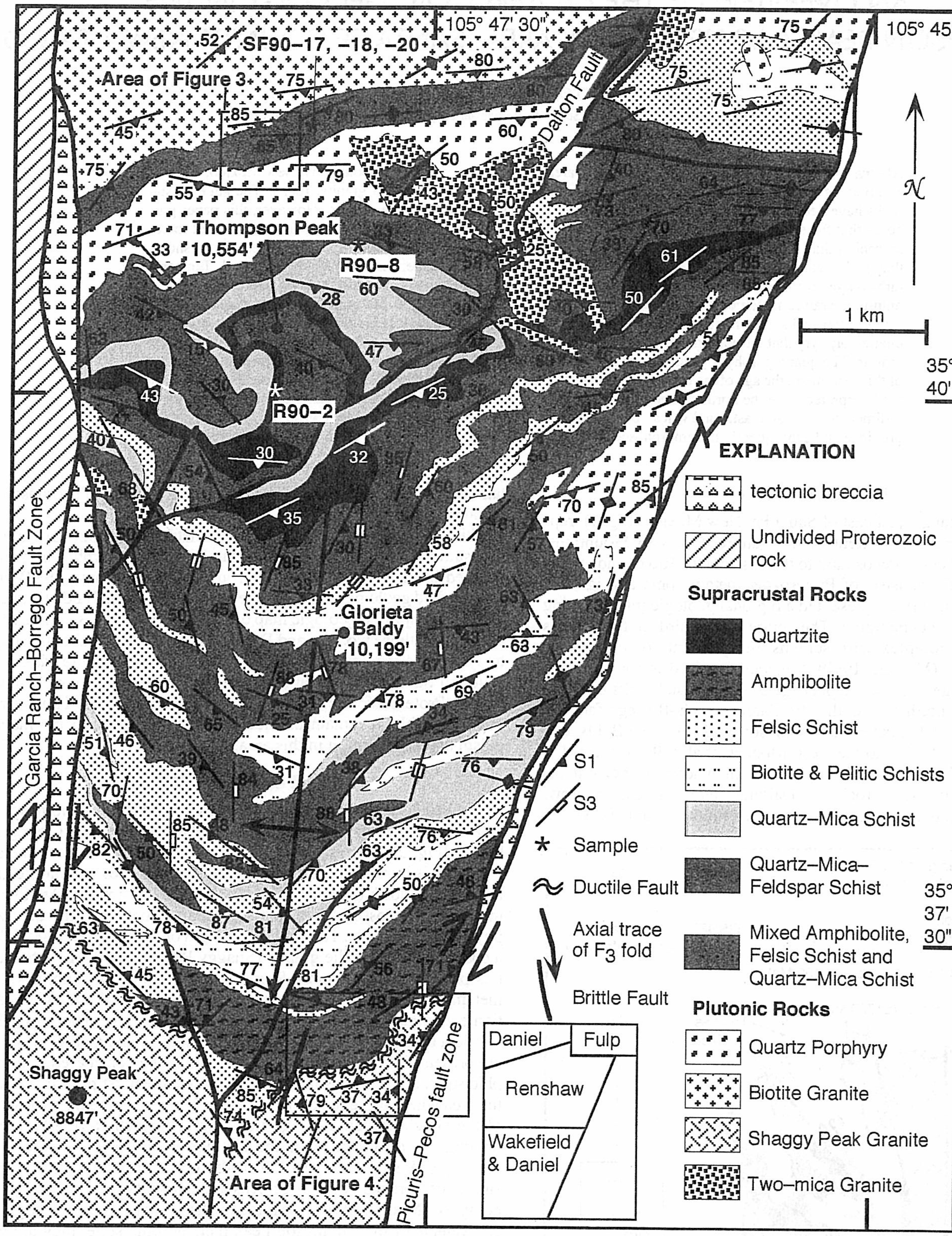

FIGURE 2. Generalized geologic map of Proterozoic rocks in the Thompson Peak–Glorieta Baldy area.

yet recognized in these rocks. Descriptions of the map units used in Figure 2 are summarized below and draw heavily from Fulp (1982) and Renshaw (1984), where more detailed descriptions may be found.

Metasedimentary rocks

Quartz-mica-feldspar schist is exposed throughout the central part of the area (Fig. 2). These rocks are light brown to brown-gray, medium to fine grained and dominated by quartz with lesser plagioclase, muscovite and minor biotite. K-feldspar, garnet and chlorite occur locally. Crossbeds defined by oxide mineral concentrations also occur locally. Micas define a foliation (S_1) commonly parallel to compositional layering (S_0).

The biotite and pelitic schist unit is heterogeneous with biotite-rich schist dominant in the southern part of the map area but more pelitic schists, mafic phyllite and feldspar-quartz-magnetite phyllite to the north.

TABLE 1. Outline showing how the map units in Figure 2 correspond to map units from earlier workers.

Fulp (1982)	Wakefield (unpub. map)	Renshaw (1984)	This Study
		Gray quartzite	*Not shown on Figure 2
Two–mica schist Heterogeneous unit Quartz–sericite phyllite Feldspar–rich phyllite Interlayered phyllite and felsite			*Not shown on Figure 2
	Qtz–Ms schist	Qtz–mica schist	Qtz–mica schist
	Qtz–feldspar schist	Qtz–Ms–feldspar schist Qtz–Pl–mica schist	Qtz–mica–feldspar schist
Biotite phyllite	Biotite phyllite	Phyllite–Pelitic schist	Biotite and pelitic schists
Quartzite	Quartzite	Ms quartzite	Quartzite
Felsite Mottled fragmental rock	Felsite Meta–felsic tuff	Felsic phyllite	Felsic schist
Amphibolite, mafic phyllite, metadiabase	Amphibolite		Amphibolite
		Long Walk Canyon and Thompson Peak heterogeneous units	Mixed amphibolite, felsic schist, quartz–mica schist
Quartz porphyry Quartz feldspar aphanite	Meta–quartz porphyry	Quartz porphyry	Quartz porphyry Biotite granite
Granite	Granite	Two–mica granite	Two–mica granite Shaggy Peak granite

Green-gray pelitic schist is dominated by quartz, muscovite and plagioclase, with lesser biotite and chlorite. Coexisting sillimanite (fibrolite), garnet and staurolite occur within this unit (Renshaw, 1984). Mafic schist is a minor component, characterized by hornblende, plagioclase, quartz, oxides, with minor epidote and biotite, and is interpreted to have a volcaniclastic protolith.

Quartzite is exposed in the northern half of the area around Thompson Peak (Fig. 2). These rocks are characterized by a light gray color, fine grain size with quartz and muscovite as the major components and minor biotite, oxides and locally feldspar. S_1, defined by aligned micas, is parallel to compositional layering (S_0).

The quartz-mica schist unit is somewhat variable in composition and includes small pods or lenses of quartz-biotite-hornblende schist and garnet-staurolite-biotite schist. The quartz-mica schist consists of quartz and muscovite, minor plagioclase and biotite, and garnet and chlorite locally.

Metavolcanic rocks

Rocks in the felsic schist unit are generally fine grained, orange to light gray, and dominated by quartz, muscovite, microcline and plagioclase, minor biotite and rare garnet. They are interpreted as metamorphosed felsic volcanic rocks, although Renshaw (1984) did not rule out the possibility of a sedimentary protolith for his felsic phyllite unit.

Amphibolites are distributed throughout the Thompson Peak metamorphic suite and dominate the mixed amphibolite, felsic schist, quartz-mica schist unit. Amphibolites range from black to green, are typically medium to fine grained, with blue-green hornblende, plagioclase, quartz, and sphene, ± epidote, ± garnet, ± biotite. Chlorite commonly replaces biotite and is interpreted as retrograde. Within the mixed unit, amphibolite is intimately interlayered with quartz-mica-feldspar schists, plagioclase-hornblende-biotite schist, feldspathic schist and mafic phyllite. Quartz porphyroclasts within the schists and quartzites occur locally and are interpreted as relict pebbles. Crossbedding is observed locally (Renshaw, 1984). Assuming that not all of the interlayering is tectonic, the lenses and stringers of schist and quartzite suggest that these rocks originated as clastic and volcaniclastic sediments with coeval mafic to intermediate flows and shallow dikes and sills; an interpretation favored by both Fulp (1982) and Renshaw (1984).

Intrusive rocks

Quartz porphyry

Quartz porphyry intrudes the northernmost part of the Thompson Peak metamorphic suite with a separate body exposed southeast of Thompson Peak, along the Picuris–Pecos fault (Fig. 2). These orange rocks are characterized by large, polycrystalline, round to ellipsoidal quartz eyes (2–8 mm in length) within a fine-grained (0.5 mm) groundmass of quartz, K-feldspar, plagioclase and muscovite, with minor biotite and magnetite. A fine-grain border phase, lacking quartz eyes, occurs locally along the contacts with the supracrustal rocks (Fulp, 1982; Renshaw, 1984). The intensity of deformation within this unit is variable, with both low-strain and high-strain domains. Renshaw (1984) documented inclusions of supracrustal rock inside the quartz porphyry and noted parallel foliations in both rock types. U/Pb zircon ages of 1650 Ma ±10 Ma (Fulp, 1982) and 1660 Ma ±10 Ma (Renshaw, 1984) were reported for the northern and southeastern quartz porphyry bodies. The northernmost quartz porphyry grades abruptly into a more biotite-rich granite towards the north (Moench et al, 1988; Daniel, unpubl.). The contact between the quartz porphyry and the Thompson Peak metamorphic suite is interpreted as a deformed intrusive contact.

Biotite granite

A red to orange biotite granite is exposed in the northern edge of the study area. The granite is fine to medium grained and dominated by quartz, K-feldspar and plagioclase, with minor biotite. Typically, this granite is well foliated, although both lower strain and higher strain domains are present. Relatively large quartz eyes are a distinctive feature in this granite. This rock is very similar in appearance to the quartz porphyry but has more biotite, little muscovite and the matrix grain size is slightly larger. No well-defined contact was observed between the biotite granite and quartz porphyry and the distinction between the two units (Fig. 2) is based primarily on the difference in biotite and muscovite content. This granite is interpreted to be coeval with the quartz porphyry (~1650 Ma) and may represent a deeper level of that unit.

Two-mica granite

The two-mica granite is light orange or pink, medium to fine grained (≤ 1 mm) and weakly foliated to unfoliated. It intrudes both the quartz porphyry and the Thompson Peak metamorphic suite northeast of Thompson Peak; small isolated bodies also occur southwest of Thompson Peak (Fig. 2). The granite typically contains more muscovite than biotite with quartz, plagioclase and microcline. Renshaw (1984) noted a narrow, resistant, silicified aureole adjacent to the intrusive contacts. Both Fulp (1982) and Renshaw (1984) observed inclusions of supracrustal rock, indicating an intrusive contact. The discordant contact relations and lack of deformation indicate this granite is post-kinematic with respect to the deformation and metamorphism experienced by the Thompson Peak metamorphic suite. The absolute age of this granite is not known.

Shaggy Peak granite

The Shaggy Peak granite bounds the southern margin of the Thompson Peak metamorphic suite. This coarse-grained biotite granite is characterized by relatively large K-feldspar and plagioclase phenocrysts with quartz, biotite and oxides. The granite is pervasively foliated with a well developed mineral lineation defined by stretched quartz grains and aligned micas. A narrow (~30 m wide), medium- to fine-grained border phase characterized by abundant muscovite and an absence of biotite is developed at the contact with the Thompson Peak suite. This contact is not well exposed but dips ~40° to the north and is interpreted as a high strain zone (see below). No inclusions of country rock were noted in the granite, nor have dikes or apophyses of the granite been traced into the amphibolite, suggesting that this contact is a tectonic contact or a sheared intrusive contact. The age of this granite is not known.

Age and regional setting of the Thompson Peak metamorphic suite

The Thompson Peak metamorphic suite is near the Yavapai–Mazatzal crustal province boundary proposed by Karlstrom and Daniel (1993) that divides older rocks (>1700 Ma, Yavapai crustal province) from younger rocks (~1660 Ma, Mazatzal crustal province). Although the absolute age of the Thompson Peak suite is not known, it must be older than ~1655 Ma, which is the age of the quartz porphyry that intrudes the suite. A reasonable estimate of these age of the rocks can be made based upon the ages of similar rocks to the south. Mixed felsic and mafic metavolcanic rocks interlayered with immature metasediments and quartzites are exposed in the Manzano, Los Pinos and Magdalena mountains (~150–200 km to the south; Bauer, 1983; Bowring et al. 1983; Robertson et al. 1993; Bauer and Williams, 1994). These supracrustal rocks are all intruded by strongly deformed ~1655 Ma granite. Felsic metavolcanic rocks from these areas are dated at ~1660 Ma (Bowring et al. 1983; Bauer et al. 1993; Bauer and Pollock, 1993). Similarity with the Proterozoic rocks exposed in the Manzano Mountains suggests an age of ~1660 Ma for the Thompson Peak metamorphic suite, and it is assigned to the Mazatzal crustal province.

The immature metasedimentary, metavolcaniclastic and metavolcanic rocks that make up the Thompson Peak suite reflect both volcanic and continental source areas. The occurrence of interlayered volcanic rocks with volcaniclastic and quartzofeldspathic sediments suggests volcanism and sedimentation were coeval. Although the tectonic setting for the rocks in the Thompson Peak suite is not well understood, they probably were deposited along the margin of the older (>1700 Ma) Yavapai continent, possibly in a back-arc basin.

DEFORMATION

The supracrustal rocks and quartz porphyry in the Thompson Peak–Glorieta Baldy area have experienced three or possibly four Proterozoic folding events and preserve at least three penetrative fabrics. Two major fault systems, the Picuris–Pecos and Garcia Ranch–Borrego fault zones, cut the Thompson Peak metamorphic suite. Episodic Proterozoic and Phanerozoic movements have been proposed for these fault systems (Miller et al. 1963; Fulp, 1982; Renshaw, 1984).

Folding events

At least three distinct generations of folds are recognized within the Thompson Peak suite. The earliest generation of folds (F_1), defined by compositional layering, occur as rare, isoclinal, rootless folds observed in outcrop and thin section. They are recognized most often in quartzite and quartz-mica schists, where aligned micas define a well developed axial plane foliation (S_1). Most commonly, compositional layering (S_0) and S_1 are parallel. This composite S_0/S_1 fabric appears to be the dominant fabric throughout the suite. The orientation of this fabric is quite variable but the trace of the S_0/S_1 foliation parallels the lithologic contacts shown in Figure 2.

The second folding event (F_2) is responsible for the map-scale fold closures south of Glorieta Baldy. Defined by S_0/S_1 surfaces, these folds are commonly open to tight, with steeply-dipping axial planes and plunge moderately to the west and southwest. An axial plane foliation (S_2) is associated with these folds and varies from a crenulation cleavage to a spaced cleavage with distinct quartz and mica domains. This foliation strikes to the northeast and dips steeply to the southeast or northwest. Renshaw (1984) did not recognize any F_2 folds in his study area, but did describe a series of map-scale and macroscopic folds east of Thompson Peak. These folds are open to tight, with upright, northwest-striking axial planes and plunge shallowly to the southeast. No axial plane foliation was observed in these folds. Renshaw (1984) believed that these folds were not related to the F_2 folds south of Glorieta Baldy, but instead were related to a later fold event (F_3, of Renshaw, 1984) that was restricted to the Thompson Peak area.

The youngest event (F_3) refolds the Thompson Peak suite into a broad, open antiform (Fig. 2). This fold is characterized by an upright axial plane and plunges shallowly to the south. A north-striking, steeply-dipping crenulation cleavage (S_3) is interpreted to be the axial plane foliation to this fold. This foliation is recognized throughout the Thompson Peak suite.

Ductile shear zones

Map-scale shear zones were not reported by Fulp (1982) or Renshaw (1984). However, both studies present descriptions and photographs of rocks that suggest high strain zones are present along the northern margin of the Thompson Peak metamorphic suite. Both low strain and high strain domains are recognized in the northern and eastern exposures of the quartz porphyry. Low strain domains are characterized by round to slightly ellipsoidal quartz eyes, whereas high strain domains show mylonites with extreme flattening and shearing of the quartz eyes. S–C fabrics are also observed in these rocks with the S-plane defined by the alignment of quartz eyes and the C-plane defined by the alignment of micas. S–C fabrics in the northern quartz porphyry unit dip steeply to the east and show a dextral strike-slip movement with a component of reverse movement (Fig. 3). Similar high strain domains are recognized in the biotite granite.

Preliminary work on the southern margin suggests that the contact between the Shaggy Peak granite and the Thompson Peak suite is an area of high strain. The main granite body shows a north-striking, moderately west-dipping foliation (Fig. 4). At the north margin of the granite this fabric appears to become reoriented parallel to the contact. Both the granite and the amphibolites are strongly foliated and lineated near the contact. S–C fabrics and asymmetric K-feldspar porphyroclasts in the granite give a top-to-the-southeast or east (thrust) movement sense. Microstructures from three samples collected across this contact show similar movement sense. Sample 93-46 (Fig. 5A) is from a felsic schist layer just north of the contact; SF93-37 (Fig. 5B), was collected from the muscovite-bearing border phase and SF93-18 (Fig. 5C), was collected approximately 1 km south of the contact. S–C fabrics within the felsic schist and the grain shape preferred orientation of quartz within the two granite samples all show the same reverse movement. Antithetic shear bands (normal movement) are also present within the granite.

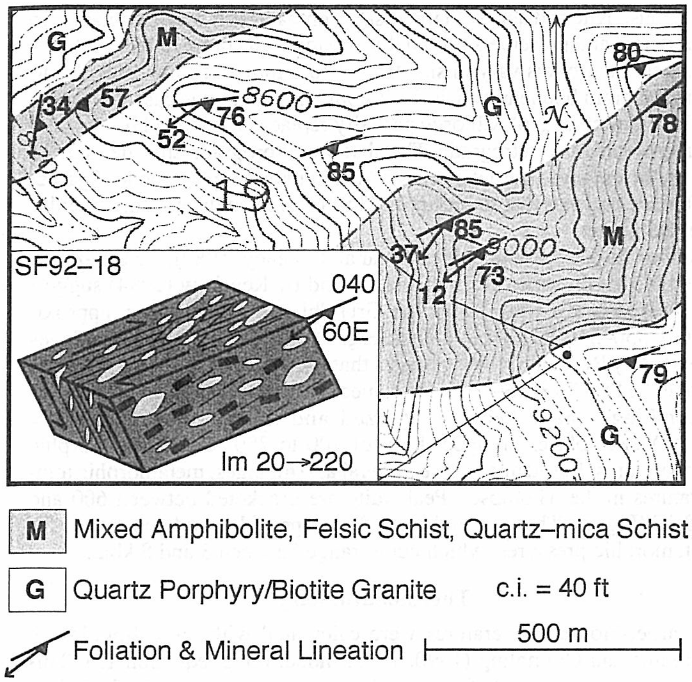

FIGURE 3. Detailed geologic map of the northern quartz porphyry unit and mixed amphibolite, felsic schist, quartz–mica schist unit. Inset figure shows S–C fabrics that dip steeply to the east and record dominantly right–lateral shear with a component of reverse shear.

Brittle shear zones

Two major north-trending, steeply-dipping brittle shear zones, the Picuris–Pecos and Garcia Ranch–Borrego fault zones, cut the Thompson Peak metamorphic suite (Figs. 1, 2). To the east, the Picuris–Pecos fault zone juxtaposes the ~1655 Ma Thompson Peak suite against the much older, ~1720 Ma, Pecos complex (Bauer and Williams, 1989; Robertson and Condie, 1989). To the west, the Garcia Ranch–Borrego fault zone offsets the western extension of the Thompson Peak suite 3–5 km to the north. Miller et al. (1963) examined the Picuris–Pecos fault system in the Picuris and northern Santa Fe Mountains. They proposed a movement history of ~37 km Proterozoic right slip, followed by Pennsylvanian west-side-up movement and Late Cretaceous–early Tertiary west-side-up displacement. Alternatively, Chapin and Cather (1981) and Karlstrom and Daniel (1993) proposed that much of the ~37 km of right-lateral strike-slip displacement occurred during the Laramide Orogeny. Younger, Cenozoic movement is also inferred but poorly constrained (Miller et al. 1963).

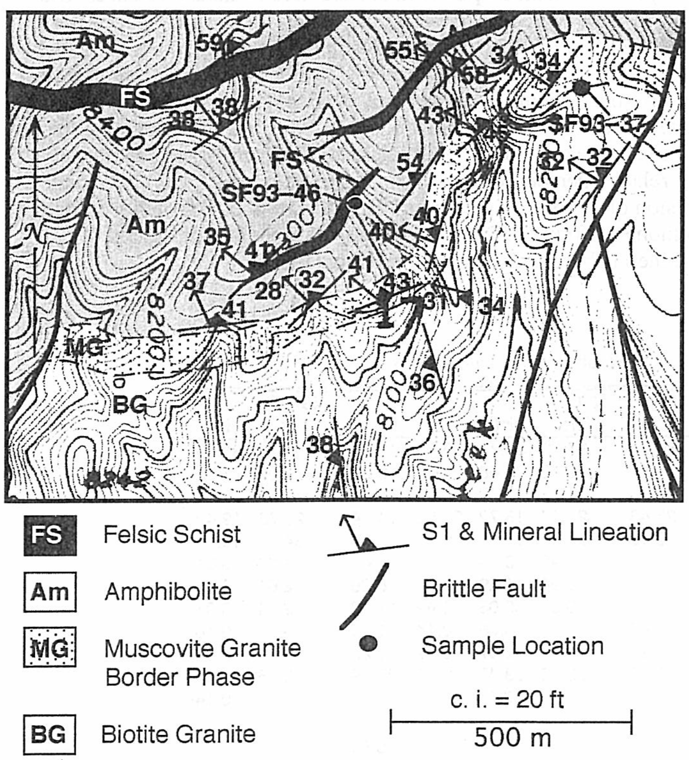

FIGURE 4. Detailed geologic map of the southeastern margin of the Thompson Peak metamorphic suite showing foliation and mineral lineations and sample locations for SF93–37 and SF93–46. Sample SF90–18 (not shown) is located approximately 1 km south.

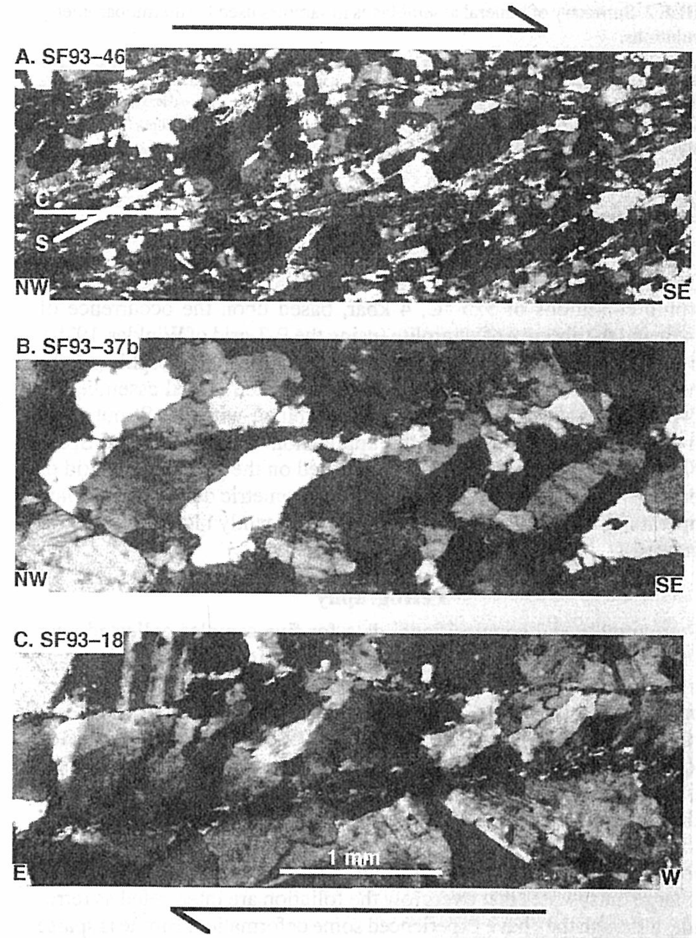

FIGURE 5. Composite video images from oriented samples showing top–to–west and southwest directed (reverse sense) movement. A, Sample SF93–46 from a felsic schist unit. B, sample SF93–37b, from the muscovite–rich border phase of the Shaggy Peak granite. C, Sample SF93–18, from the main phase of the Shaggy Peak granite. All three samples show S–C fabrics where muscovite or biotite define the C–plane and aligned quartz grains define the S–plane.

In the Thompson Peak–Glorieta Baldy area, the Picuris–Pecos and Garcia Ranch–Borrego fault zones are characterized by intense breccia-tion, cataclasis and alteration. Right-lateral movement across these fault zones is indicated by both map-scale offset of rock units and outcrop-scale deflections of layering. Locally, Paleozoic rocks are exposed within the fault zones, but they do not appear to be as intensely brecciated and deformed as the Proterozoic rocks. The smaller, northeast-trending Dalton fault (Fig. 2; Fulp, 1982; Renshaw, 1984) dips steeply to the southeast and shows minor right-slip, reverse displacement.

METAMORPHISM

No detailed metamorphic studies have been conducted in the Thompson Peak–Glorieta Baldy area. The earliest estimates of metamorphic

TABLE 2. Summary of mineral assemblages in samples used for thermobarometry calculations.

Sample	Ab	Bt	Chl	Ep	Grt	Hbl	Kfs	Ms	Pl	Qz	St	Oxides
SF90–17	X	X		X	X		X	X		X		$Ilm_{0.95}Hem_{0.05}$ + Rt
SF90–18	X	X			X		X	X		X		$Hem_{0.85}Ilm_{0.15}$ + Gahnite†
SF90–20		X	X*	X	X		X	X	X	X		no oxide analyzed
R90–2		X	X*		X	X			X	X		$Ilm_{0.95}$ $Hem_{0.05}$ + Spn
R90–8		X	X*		X			X		X	X	$Ilm_{0.97}Hem_{0.03}$ + Rt

*Retrograde, †Hercynite–Gahnite solid solution

temperatures and pressures are from Fulp (1982), who suggested metamorphic conditions of 525 °C, 4 kbar, based upon the occurrence of Grt+Bt and the absence of staurolite (using the P-T grid of Winkler, 1979). Subsequently, Renshaw (1984) estimated similar metamorphic conditions of 500–550°C and 3–5 kbar based upon the mineral assemblages Grt+Bt+St+Ms+Qtz, St+Sill+Ms+Qtz combined with the St-out reaction of Carmichael (1978) and the application of the Ferry and Spear (1978) Grt–Bt thermometer. However, based on the petrogenetic grid of Spear and Cheney (1989) and new thermobarometric data, metamorphic temperatures and pressures appear to be significantly higher than earlier estimated.

Petrography

Petrographic and compositional data for five samples collected near the northern margin of the Thompson Peak metamorphic suite are summarized in Tables 2 and 3. Samples SF90-17, SF90-18 and SF90-20 are from a felsic schist layer in a screen of supracrustal rock within the quartz porphyry (Fig. 2). These three samples are fine grained and dominated by quartz, K-feldspar, plagioclase and muscovite with minor oxides, garnet, biotite and rarely, gahnite (Zn-spinel). Muscovite shows a bimodal grain size with large muscovite grains (1–2 mm) abundant throughout the samples. Smaller (< 0.5 mm) muscovite grains are much less common, lie in the dominant foliation and are interpreted to be prograde. The large muscovites that overgrow the foliation are interpreted as retrograde, although they have experienced some deformation. Biotite is sparse and may be partially replaced by chlorite. Garnets in these samples range from 1–4 mm in diameter, and contain abundant quartz inclusions and less commonly, plagioclase, biotite and oxide inclusions. Some garnets preserve a euhedral shape, but most appear to be resorbed, with irregular grain boundaries and embayments.

Samples R90-2 and R90-8 were collected in the area of Thompson Peak. R90-2 (amphibolite) contains abundant blue-green hornblende and rare cummingtonite, large, euhedral plagioclase, and quartz with minor biotite and garnet. The garnets in this sample are relatively small (0.2–0.4 mm), euhedral, and have few inclusions. R90-8 (quartz-mica schist) preserves large (1–3 mm) garnet crystals coexisting with staurolite, biotite, muscovite and quartz. Garnets show embayments and irregular grain boundaries and preserve sigmoidal inclusion trails defined by quartz inclusions. Staurolites vary in size from 1 to 5 mm and show irregular to euhedral grain boundaries. Biotite is common and in one case appears to replace garnet (Fig. 6). Chlorite partially replaces garnet and biotite, and is interpreted to be retrograde. The absence of prograde chlorite in these rocks, the embayed garnet grains and the apparent replacement of garnet by biotite suggests that staurolite and biotite grew at the expense of chlorite and garnet.

Using the petrogenetic grid of Spear and Cheney (1989), the Grt+Bt+St assemblages documented in this study and by Renshaw (1984) suggest that temperatures were above the Grt+Chl = St+Bt reaction, approximately 550–560 °C (at 4 to 6 kbar; Fig. 7). The St+Bt+Sill assemblages reported by Renshaw (1984) suggest that temperatures were even higher, above the St+Chl = AS+Bt reaction, near 600 to 610 °C. No Al_2SiO_5+Kfs assemblages have been recognized and the reaction Qtz+Ms = Al_2SiO_5+Kfs places an upper limit of 700 to 750 °C for metamorphic temperatures. Based upon these mineral assemblages, metamorphic temperatures in the Thompson Peak suite are bracketed between 600 and 700 °C (Fig. 7). These assemblages do not provide good constraints for metamorphic pressures, which could range between 3 and 8 kbar.

Thermobarometry

Garnet-biotite temperatures were calculated with the calibration of Williams and Grambling (1990, 1992, model three, equation 13). This calibration is appropriate for Mn-rich garnets and accounts for ferric iron in biotite based upon the composition of coexisting ilmenite-hematite. The garnet-hornblende thermometer of Perchuck et al. (1985) was also applied to sample R90-2. Metamorphic pressures were calculated from three barometers including Grt+Bt+Pl+Ms (Ghent and Stout, 1981, equations 1b and 2a), Grt+Hbl+Pl (Kohn and Spear, 1993), and Grt+Bt+Pl+Qtz (Hoisch, 1990, reactions R1 and R2).

Analytical methods

Electron microprobe (EMP) analyses were performed with a JEOL 733 Superprobe at the Department of Earth and Planetary Sciences, University of New Mexico. Operating conditions were 15 kV acceleration potential and 20 nA beam current. Beam diameter was 1 μm for garnet analyses, ~5 μm for plagioclase and FeTi-oxides and 5-10 μm for micas. Compositional zoning in garnet and plagioclase was characterized by detailed traverses. Multiple spot analyses were used to determine mica and FeTi-oxide compositions. Precision of EMP analyses is estimated at ± 0.5 relative percent for all oxides except SiO_2, which has an estimated precision of ± 1.5 relative percent. Recalculation of FeTi-oxide mineral stoichiometry from EMP analyses followed the method of Rumble (1973). All mineral abbreviations are after Kretz (1983).

TABLE 3. Mineral compositions for samples used in thermobarometry calculations.

Sample	SF90–17		SF90–18		SF90–20				R90–2				R90–8	
Mineral	Grt	Bt	Grt	Bt	Grt	Bt	Ms	Pl	Grt	Bt	Pl	Hbl	Grt	Bt
SiO_2	37.56	37.12	36.90	34.96	37.10	34.36	45.15	60.04	37.22	35.71	58.71	43.20	37.17	34.79
TiO_2	0.04	2.23	0.03	2.76	0.01	1.81	0.27	---	0.05	1.68	---	0.26	0.02	1.62
Cr_2O_3	---	---	---	---	---	---	---	---	---	---	---	0.01	---	---
Al_2O_3	20.74	16.56	21.32	16.47	20.56	17.94	32.93	25.48	21.37	16.72	25.52	14.44	20.73	19.42
FeO	21.91	19.33	25.32	22.41	23.27	23.33	4.13	0.16	31.06	17.75	0.06	17.69	34.12	19.55
MnO	9.40	0.82	12.21	0.77	14.04	0.55	0.00	---	2.92	0.14	---	0.41	1.97	0.01
MgO	1.61	9.89	1.56	7.50	1.09	7.21	0.72	---	3.24	12.29	---	8.29	2.61	9.51
CaO	8.18	0.06	3.12	0.00	4.21	0.01	0.00	5.84	3.96	0.03	6.42	11.00	2.34	0.01
Na_2O	---	0.06	---	0.01	---	0.07	0.27	8.43	---	0.08	8.14	1.74	---	0.18
K_2O	---	9.25	---	9.37	---	9.73	10.87	0.21	---	9.07	0.17	0.25	---	9.31
Total	99.44	95.32	100.46	94.25	100.37	95.01	94.34	100.16	99.82	93.47	99.02	97.29	98.96	94.40
Fe^{3+}/Fe^{tot}		0.15		0.23		0.10				0.15				0.14
X_{T1Si}												0.619		
X_{T1Al}												0.381		
X_{Fe}	0.489	0.471	0.588	0.550	0.519	0.610		---	0.692	0.406	---	0.538	0.780	0.498
X_{Mn}	0.213	0.022	0.270	0.021	0.317	0.015		---	0.066	0.004	---	0.013	0.046	0.000
X_{Mg}	0.064	0.467	0.054	0.426	0.043	0.374		---	0.129	0.590	---	0.449	0.106	0.502
X_{Ca}	0.234	---	0.088	---	0.120	---		0.274	0.113	---	0.301	---	0.069	---

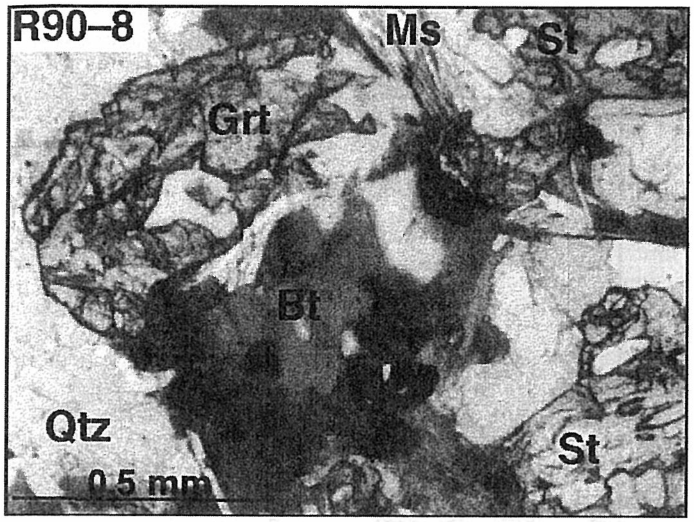

FIGURE 6. Composite video image showing the apparent replacement of garnet by biotite and surrounding staurolite.

Garnet zoning profiles

Three representative garnet zoning profiles are shown in Figure 8. Two samples from near Thompson Peak give contrasting zoning profiles. Sample R90-8 (Fig. 8) preserves a typical prograde zoning pattern with a bell-shaped Mn profile and decreasing Fe/(Fe+Mg) from core to near the rim, with reversals in both Mn and Fe/(Fe+Mg) approximately 200 μm from the rim. This zoning profile is interpreted to represent growth zoning with significant diffusional modification of the rim compositions (Florence and Spear, 1991; Spear, 1991). Garnet zoning in sample R90-2 (not shown) is characterized by relatively flat Mn and Fe/(Fe+Mg) profiles with X_{Mn} decreasing from 0.075 (core) to 0.060 (near rim) and then increasing to over 0.07 again at the rim. Fe/(Fe+Mg) shows a similar pattern and decreases from 0.86 (core) to 0.845 (near rim) and then increases to 0.855 at the rim. Given the small size of these garnets, the zoning profiles probably reflect diffusional modification of the original growth zoning. Compositional zoning in samples SF90-18 and SF90-20 (Fig. 8) is characterized by flat Mn and Fe/(Fe+Mg) zoning profiles with increasing Mn and Fe/(Fe+Mg) near the rim. These flat profiles are interpreted as diffusional zoning profiles (Florence and Spear, 1991; Spear, 1991). Garnet zoning profiles from SF90-17 show the same characteristics as SF90-18 and SF90-20.

These zoning profiles can be used as a qualitative assesment of temperatures between the samples. Given garnets of equal size, with similar growth zoning profiles, the garnet that experienced higher temperatures will show a greater relaxation or flattening of the Mn zoning than a garnet that experienced lower temperatures. Comparison of zoning profiles between the two areas suggests that the garnets in the northernmost three samples experienced higher temperatures than the garnets from the Thompson Peak area. The relatively large garnet in sample R90-8 still preserves zoning profiles characteristic of garnet growth (a "bell" shaped Mn zoning profile, Fig. 8) but also shows some diffusional modification of that zoning near the rims. However, in samples farther to the north, garnets of approximately the same size and even significantly larger ones (Fig. 8) show flat zoning profiles, suggesting that they experienced higher metamorphic temperatures. This comparison assumes that the garnets in the northern samples began with typical garnet growth zoning patterns.

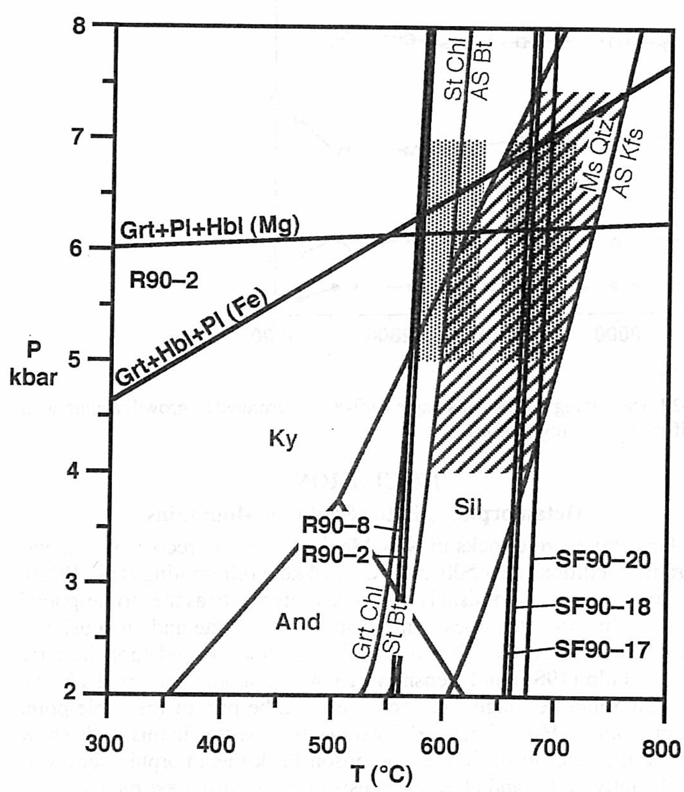

FIGURE 7. P-T estimates from both phase equilibria and thermobarometry (reactions from Spear and Cheney, 1989; Al_2SiO_5 phase relations from Holdaway and Mukhopadhyay, 1993). The diagonal lines represent P-T conditions based upon observed mineral assemblages. The dotted rectangles represent thermobarometric estimates. The overlap areas represent the best P-T estimates for both areas.

RESULTS

Calculated temperatures and pressures are shown in Figure 7 and summarized in Table 4. Temperatures and pressures calculated for R90-2 used the minimum Fe/(Fe+Mg) garnet composition (just before the reversal) and an average matrix biotite composition or an average hornblende rim composition (Table 3) and plagioclase rim compositions. Plagioclase in sample R90-2 shows only minor zoning, with $X_{Ca} \approx 0.30$ in the core and ≈ 0.33 at the rim. Calculated temperatures are 575 °C for Grt+Bt and 595 °C for Grt+Hbl. Pressures determined from Grt+Hbl+Pl equilibria are 6.4 kbar (Mg-end member) and 6.1 kbar (Fe-end member). Pressures determined from Grt+Bt+Pl+Qtz equilibria give higher pressures of 7.7 kbar for both the Fe and Mg end members.

The temperatures calculated from these samples coincide with the Grt+Chl = St+Bt reaction (Fig. 8). Given the apparent diffusional modification of the growth zoning in these two samples, the calculated temperatures probably underestimate the peak metamorphic temperatures (Florence and Spear, 1991; Spear, 1991). It is most likely that peak metamorphic temperatures were closer to 600 to 620 °C. These temperatures would be consistent with the St+Chl = AS+Bt reaction inferred from petrologic data. The Grt+Hbl+Pl pressure estimates of ~6 kbar are favored because the reactions show relatively little temperature dependence and the higher Grt+Bt+Pl+Qtz pressures fall in the kyanite field. No prograde kyanite has yet been recognized in the Thompson Peak area. For temperatures of 600–620 °C, the 6 kbar pressure falls just inside the sillimanite stability field and may represent an upper limit of estimated pressures. The best estimate for the temperatures and pressure of metamorphism in the Thompson Peak area is 600–620 °C, and 5–6 kbar, consistent with the occurrence of sillimanite and the absence of kyanite in these rocks (Fig. 8).

Temperatures for samples SF90-17, SF90-18 and SF90-20 were determined from garnet compositions measured just before the Fe/(Fe+Mg)

TABLE 4. Summary of calculated temperatures and pressures.

Sample	Temperature* (°C) Grt+Bt	Grt+Hbl	Pressure (kbar) Grt+Pl+Hbl	Grt+Pl+Ms+Bt	Grt+Pl+Bt+Qtz
SF 90–17	670			----	
SF 90–18	675			-----	
SF 90–20	690			5.6 (Fe) 4.1 (Mg)	9.4 (Fe) 8.8 (Mg)
R90–2	575	595	6.1 (Fe) 6.4 (Mg)		7.7 (Fe) 7.7 (Mg)
R90–8	570			-----	

*Temperatures calculated at P = 6 kbar

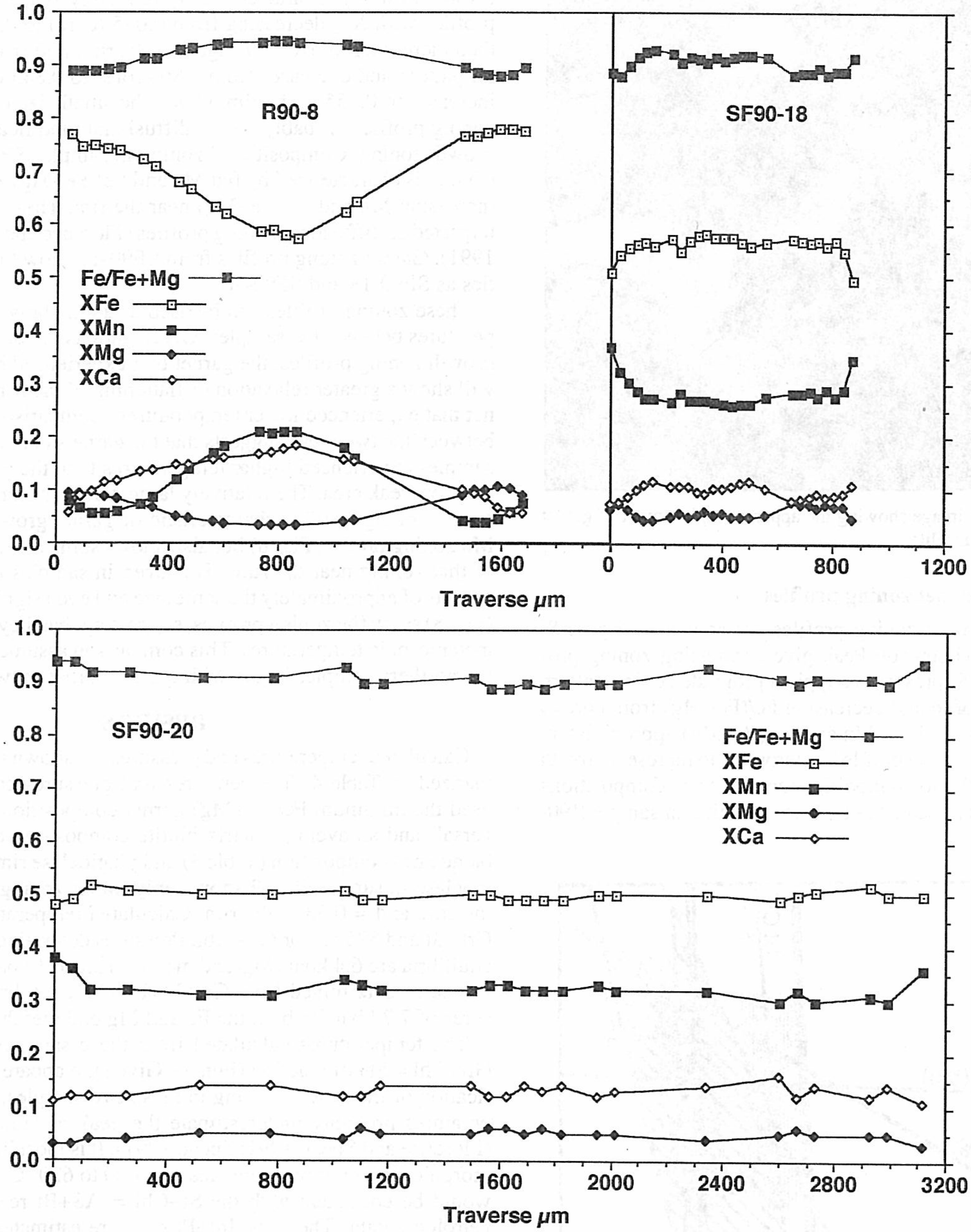

FIGURE 8. Representative garnet zoning profiles for samples R90–8, SF90–18 and SF90–20. The zoning profile for sample R90–8 is interpreted as growth zoning with diffusional modification near the rim. Samples SF90–18 and SF90–20 are interpreted as diffusional zoning profiles.

increase near the rim and an average matrix biotite composition (Table 3). The calculated temperatures for these samples cluster near 680 °C. These temperatures are significantly higher than the previous two samples from the Thompson Peak area, but are consistent with the greater amount of diffusional modification observed in the garnets from these samples. Pressures calculated for SF90-20 are based upon the same garnet and biotite analyses combined with plagioclase rim analyses and an average of matrix muscovite compositions. Grt+Bt+Ms+Pl pressures range from 4.1 kbar (Mg-end member) to 5.6 kbar (Fe-end member). However, pressures calculated from Grt+Bt+Pl+Qtz are 8.8 kbar (Mg-end member) and 9.4 (Fe-end member). The Grt+Bt+Ms+Pl pressure estimates are consistent with observed mineral assemblages and the average of ~5 kbar is relatively consistent with the ~6 kbar estimate from R90-2. However, the Grt+Bt+Pl+Qtz pressure estimates fall in the kyanite stability field and probably greatly overestimate the pressure. Until more detailed work can be done to better understand the reaction histories of these rocks, and more specifically the relationship between plagioclase and garnet, the temperatures and pressures presented here should be considered as general estimates.

DISCUSSION

Metamorphism in the Santa Fe Mountains

Many Proterozoic rocks in New Mexico appear to record peak metamorphic conditions near 500–540 °C and 4 kbar (Grambling et al., 1989). This regional metamorphism is commonly referred to as the "triple-point" metamorphism for the coexisting kyanite, sillimanite and andalusite in many of the rocks (Grambling and Williams, 1986). Based upon the early work of Fulp (1982) and Renshaw (1984) the supracrustal rocks in the southern Santa Fe range were considered to be part of the triple-point metamorphism. However, the P–T estimates presented in this study show that the metamorphism in the Thompson Peak metamorphic suite was significantly hotter and at higher pressures than earlier estimated.

The relatively high temperatures in the Thompson Peak suite may be the result of heat from the large granitic plutons exposed both north and south of the complex. The biotite granite along the northern margin of the Thompson Peak suite and the Shaggy Peak granite are likely contemporaneous and heat from these two large plutonic bodies is probably responsible for the elevated temperatures in the Santa Fe Mountains. This model predicts that temperatures would be highest along the margins and decrease toward the middle of the Thompson Peak suite. The higher temperatures (~680°C) documented in the northernmost exposures of the Thompson Peak suite and lower temperatures (~600°C) observed farther south are consistent with this model. Metamorphism in the southern Santa Fe Mountains appears to be similar to the pluton-enhanced regional metamorphism proposed for Arizona by Williams (1991).

Timing of deformation and metamorphism

The timing of Proterozoic orogenesis in New Mexico is not well understood. However, several studies (Bauer et al., 1993; Karlstrom and Daniel, 1993; Bauer and Williams, 1994) suggest that the regional metamorphism and deformation took place from ~1650 to 1600 Ma (the Mazatzal orogeny; Karlstrom and Bowring, 1988; 1993; Karlstrom and Daniel, 1993). The deformed quartz porphyry that intrudes the Thompson Peak metamorphic suite places an upper limit of ~1655 Ma for the absolute timing of deformation in the southern Santa Fe Mountains. The gradational contact between the quartz porphyry and biotite granite suggests that they are related and that the biotite granite is likely a deeper level of the same plutonic complex. If this inference is correct and the model of pluton-enhanced metamorphism is correct, the metamorphism, deformation and plutonism are roughly coeval and took place at ~1650 Ma.

SUMMARY

Supracrustal rocks in the Thompson Peak metamorphic suite are bounded by large granitic plutons to the north and south. The southern margin of the Thompson Peak suite appears to be a sheared intrusive contact and juxtaposes the Shaggy Peak granite against amphibolites and schists. To the north, supracrustal rocks are intruded by a strongly deformed, ~1655 Ma quartz porphyry body and the contact is interpreted as a sheared intrusive contact. Deformation in these rocks clearly postdates ~1655 Ma but the lower bounding age is not yet known. A reevaluation of mineral assemblages and new thermobarometry data from the Thompson Peak suite show that metamorphic temperatures are significantly higher than previously documented (Fulp, 1982; Renshaw, 1984) and range from ~600 to 680 °C with pressures of 5–6 kbar. Metamorphism is probably related to heat from ~1650 Ma plutons and a model of coeval deformation, metamorphism and plutonism is suggested for the rocks in the southern Santa Fe Mountains.

The immature quartzofeldspathic sedimentary, volcaniclastic and volcanic protoliths inferred for the Thompson Peak suite are part of the ~1660 Ma Mazatzal crustal province. The metamorphism and deformation of these rocks is interpreted to reflect the accretion of these rocks to the older, continental margin (1700 Ma, Yavapai crustal province) during the Mazatzal orogeny (Karlstrom and Bowring, 1988;1993; Bowring and Karlstom, 1990; Karlstrom and Daniel, 1993).

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