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PROTEROZOIC GEOLOGY OF THE CENTRAL SANTA FE RANGE, NORTHERN NEW MEXICO

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Abstract—Approximately 15 km^2 were mapped in the central Santa Fe Range, between the Pecos-Picuris and Borrego faults. Two major lithologic assemblages are present: (1) a south-dipping block of migmatitic supracrustal rocks which have volcanic and volcaniclastic protoliths; and (2) a suite of deformed calc-alkalic plutonic rocks ranging in composition from granite to quartz diorite. The boundaries separating these two assemblages are, at least in part, tectonic. The supracrustal rocks experienced a syn-kinematic episode of localized partial melting at metamorphic conditions of T = 650 to 730°C and 5.2 to 5.5 kbars. The calc-alkalic plutonic suite can be divided into an early felsic group and a later mafic group. Intrusion, solidification and deformation of the felsic group pre-dated the solidification of migmatite leucosomes. Intrusion of the mafic group may have been contemporaneous with the migmatization event. Whole-rock major and trace-element data for the calc-alkalic suite show fractionation trends similar to those seen in Phanerozoic arc-related plutonic rock suites. A younger group of alkali granites and associated epidote veins intruded most of the above mentioned lithologies.

INTRODUCTION

Recent work by Grambling et al. (1989) identified two metamorphic environments preserved within the Proterozoic rocks of northern New Mexico. The first is a regionally extensive, 75,000 km^2, terrane of supracrustal lithologies, interpreted as a sequence of metavolcanic and metasedimentary rocks, which record medium-grade metamorphic conditions near the aluminosilicate triple point (approximately 500°C; 4 kbars). The second environment is represented by isolated occurrences of high-grade felsic gneisses and amphibolites, which record metamorphic conditions of 700 to 800°C and 9 to 11 kbars. In two such areas, the northern Taos Range (Smith, 1988; Grambling et al., 1989) and the Cimarron Range (Grambling and Dallmeyer, 1990), high-grade rocks are separated from structurally overlying medium-grade rocks by low angle mylonitic shear zones.

A third high-grade terrane, present in the central Santa Fe Range, is composed of migmatitic supracrustal rocks and an associated suite of plutonic rocks. This paper reviews the geology and orogenic history of the central Santa Fe Range, and discusses the details of, and interrelationships among, plutonism, metamorphism and deformation.

GEOLOGICAL SETTING AND PREVIOUS WORK

Previous work within the Santa Fe Range includes that of Montgomery (Miller et al., 1963), Fulp (1982), Renshaw (1984) and Moench et al. (1988). The Santa Fe Range (Fig. 1) is bounded on the east by the Pecos-Picuris fault and on the west, north and south by depositional basins and structures associated with the Rio Grande rift. Two major fault zones occur within the range, the Garcia Ranch and Borrego faults, which are approximately parallel to the Pecos-Picuris fault. Medium-grade Proterozoic rocks east of the Pecos-Picuris fault include metavolcanic and metaplutonic rocks of the Pecos Complex and metasedimentary and metavolcanic rocks of the Hondo and Vadito Groups (stratigraphic nomenclature from Bauer and Williams, 1989).

Supracrustal rocks in the southern Santa Fe Range (Fig. 1) belong to the Dalton Canyon succession (Moench et al., 1988) and are characterized by mafic and felsic metavolcanics, micaceous quartz-feldspar phyllites and schists and quartzites. These rocks contain metamorphic mineral assemblages indicative of medium-grade metamorphism, including chlorite porphyroblasts, staurolite (±sillimanite), quartz + muscovite and cordierite. Renshaw (1984) estimated metamorphic conditions, using garnet-biotite exchange geothermometry combined with a petrogenetic grid, at 501 to 550°C and 3.3 to 4.8 kbars. The Dalton Canyon succession occurs as septa, collectively referred to as the McClure septa, lying within a pink biotite granite (Xgb of Moench et al., 1988). This biotite granite appears to grade into a quartz porphyry (Xqp of Moench et al., 1988) interpreted as hypabyssal intrusions within the Dalton Canyon succession (Fulp, 1982; Moench et al., 1988).

North of the McClure septa lies the Santa Fe Baldy batholith. Moench et al. (1988) mapped two plutonic units within the Santa Fe Baldy

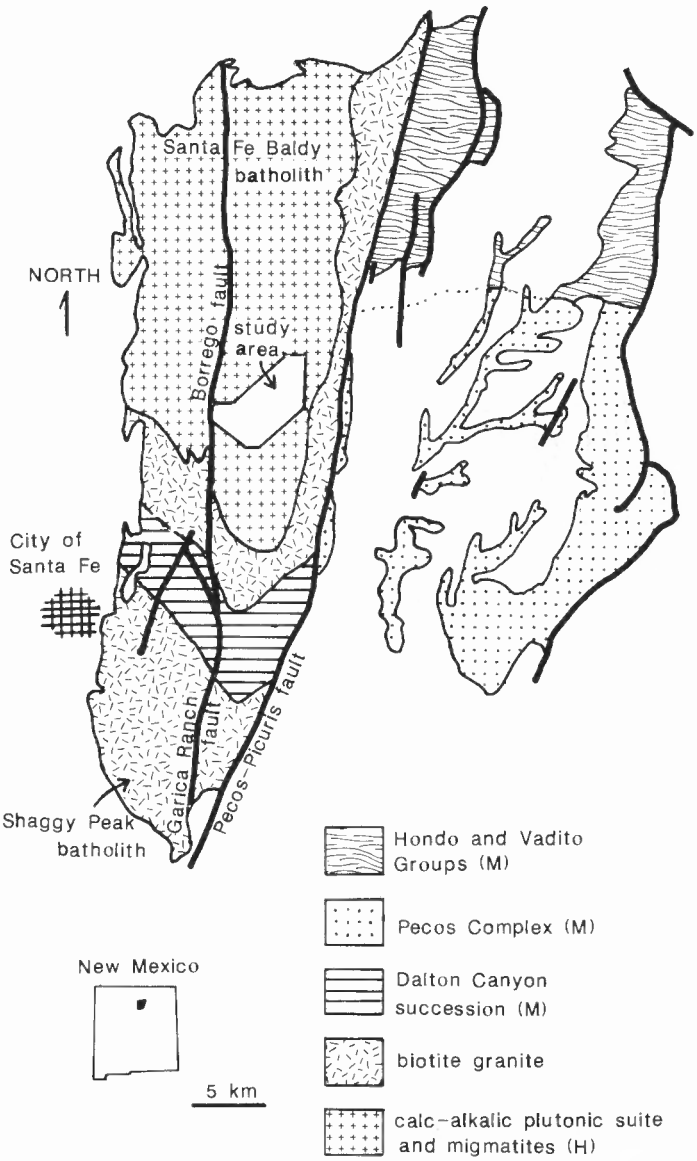


FIGURE 1. Generalized Proterozoic geology of the Santa Fe Range and adjacent areas, with the location of the study area shown in Figure 2. (M) denotes areas of medium-grade metamorphism and (H) denotes areas of high-grade metamorphism. Modified from Renshaw (1984) and Moench et al. (1988).

batholith, a quartz diorite (Xqd), which also included more felsic rock types, and the biotite granite unit mentioned above (Xgb). They believed the biotite granite to be intrusive into, and therefore younger than, the quartz diorite. The Santa Fe Baldy batholith is also characterized by a number of large blocks, covering tens of square kilometers, composed of metavolcanic and metasedimentary rocks, many of which are migmatitic in character. South of the McClure septa lies the Shaggy Peak batholith (Fig. 1), which is composed largely of the biotite-granite lithology (Xgb). Rocks of the Santa Fe Baldy and Shaggy Peak batholiths, and the supracrustal rocks of the McClure septa, were intruded by numerous small bodies of two-mica granite and associated granitic pegmatites (Ygt unit of Moench et al., 1988).

Uranium-lead zircon isotopic ages of 1720 Ma were reported for metavolcanic rocks and a foliated granodiorite pluton within the Pecos Complex by Bowring and Condie (1982). They also reported a date of 1650 Ma for a foliated quartz diorite in the Pecos Complex, near (east of) the Pecos-Picuris fault. The quartz porphyry (Xqp) which intrudes into the Dalton Canyon sequence has been dated at 1650 ± 10 Ma by S. A. Bowring (reported in Fulp, 1982). Register and Brookins (1979) reported a Rb-Sr whole rock isochron age of 1465 ± 50 Ma for an undefined granite along the northwestern edge of the range. This rock type may belong to the two-mica granite unit (Ygt).

MIGMATITE NOMENCLATURE

The migmatite literature is burdened with a confusing and often poorly understood nomenclature. In order to avoid confusion, the migmatite terminology used throughout this paper is briefly reviewed. Other terms are defined within the paper, as needed. For a more complete review, see Mehnert (1968).

Migmatite is a descriptive term and is defined as follows: a megascopically composite rock consisting of a geochemically mobile, igneous or igneous-like portion, and a less mobile metamorphic portion (modified from Dietrich and Mehnert, 1961; Mehnert, 1968). Four mechanisms can result in the production of migmatites: (1) anatexis (localized partial melting); (2) metamorphic (subsolidus) differentiation; (3) igneous injection; and (4) metasomatism.

Due to its light color, the igneous-like portion of the migmatite is called the leucosome, and is composed mostly of feldspar and quartz. Leucosomes are commonly spatially associated with melanosomes, which are dark colored mica-rich, schistose bodies that contribute, in part, to the metamorphic appearance of the migmatite. Leucosomes and melanosomes, which are newly formed during the migmatization process, are collectively referred to as the neosome. Also adding to the metamorphic appearance is the mesosome, which is generally gneissic in appearance. Mesosomes derive their name from the fact that they are usually intermediate in color between leucosomes and melanosomes (Johannes and Gupta, 1982). Mesosomes represent the portions of the migmatite that were relatively unchanged by the migmatization process.

LITHOLOGIC UNITS

The study area lies within the central Santa Fe Range (Fig. 1) and covers approximately 15 km^2. Figure 2 is a geologic map of the study area, simplified from geologic mapping carried out at a scale of 1:12,000 (Metcalf, 1990). Two major assemblages are present; one as a structural block consisting of migmatitic supracrustal lithologies, and the other in the surrounding suite of plutonic rocks.

The migmatitic supracrustal rocks are divided into three map units: biotite gneiss, felsic gneiss and amphibolite gneiss. These rocks have undergone some degree of migmatization and are named for the lithology of the mesosome. Four migmatite types were distinguishable at the mesoscopic scale, on the basis of mesosome lithology, mesoscopic structure, the amount of leucosome material present and leucosome composition.

In this study, the quartz-diorite unit of Moench et al. (1988) was subdivided into five map units, ranging in composition from granite to quartz diorite (Fig. 2). These rocks are collectively referred to as the calc-alkalic suite, which is divided into an older felsic group and a younger mafic group. Also present is an alkali granite mapped in the

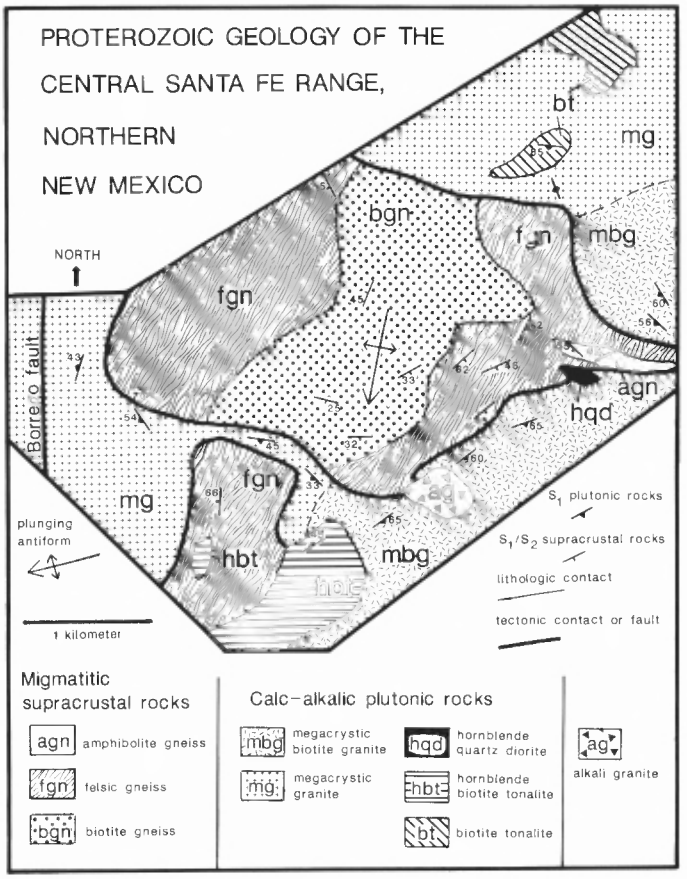


FIGURE 2. Generalized map showing the Proterozoic geology of a portion of the central Santa Fe Range. Modified from Metcalf (1990, plate 1).

southeastern portion of the area. The relationship of this lithologic unit to the calc-alkalic suite is unclear.

Migmatitic supracrustal rocks

Biotite gneiss unit

The biotite gneiss unit contains two migmatite types, which share a common mesosome lithology: a layered type with trondhjemitic leucosomes, and a schlieren type with granitic leucosomes. The layered migmatite (Fig. 3A) consists of leucosomes (1 cm to 1 m thick) concordantly interlayered with biotite gneiss mesosomes (1 cm to 0.5 m thick). Leucosomes are often mantled by mica-rich melanosome selvages ($\leq$10 cm thick). Leucosome dikes (1 cm to 1 m thick) crosscut the layered structure (Fig. 3A). Leucosome material comprises about 50% of outcrops of the layered migmatite.

In isolated outcrops of the schlieren migmatite, leucosome material comprises greater than 90% of the rock, with the remainder composed of streaky patches (schlieren) of melanosome and/or included blocks of layered migmatite. Where layered and schlieren migmatites occur together in single outcrops, schlieren leucosomes are broadly concordant with the surrounding layered structure, but can be locally discordant. Concordant leucosomes of the schlieren migmatite are generally 2 to 3 m in thickness. The biotite gneiss unit is heterogeneous, locally containing layers of migmatite characteristic of the felsic gneiss and amphibolite gneiss units.

Felsic gneiss unit

Migmatites of the felsic gneiss unit have granitic leucosomes, and commonly exhibit a nebulitic structure, i.e., one in which it is difficult to distinguish leucosome from mesosome. In some occurrences these migmatites exhibit a weak compositional layering, and it is here that mesosomes and leucosomes are most readily distinguished, due to dif-

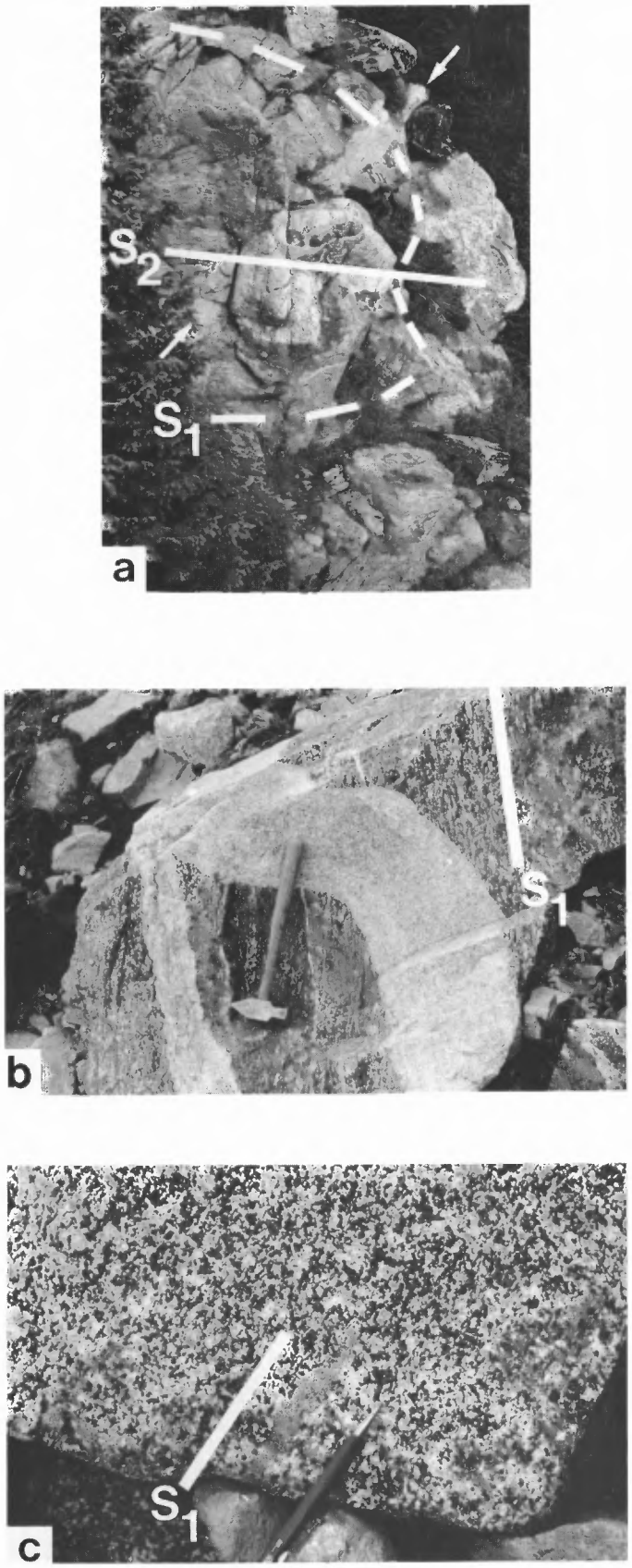


FIGURE 3. A, Outcrop of the layered migmatite from the biotite gneiss map unit. Note S_1/S_2 fabrics cut by a leucosome dike (arrows). B, Field photograph of the megacrystic biotite granite showing leucosome of the nebulitic migmatite crosscutting S_1 fabric. C, Field photograph of the hornblende-biotite tonalite with a flattened mafic enclave which defines a weak S_1 fabric.

ferences in textures and mineral modes. Melanosomes are rare, but where present occur either as selvages or schlieren. Many smaller outcrops lack a significant non-leucosome component (homophanous structure). Although it is difficult to estimate, the percentage of leucosome present in the felsic gneiss unit is high (>60%). The felsic gneiss unit is heterogeneous, locally containing layers of migmatite characteristic of the biotite gneiss and amphibolite units.

Amphibolite gneiss unit

This unit is composed primarily of amphibolite gneiss mesosomes (≤1 m thick), with leucosomes contributing only 5 to 10% of outcrops. Leuco-tonalite leucosomes (1 to 5 cm thick) occur as concordant layers, discordant dikes and rarely as ptygmatic veins. Melanosomes are only rarely observed, but where present occur as selvages on concordant leucosome layers. Migmatites within the amphibolite gneiss unit are collectively referred to as veined migmatites.

Calc-alkalic plutonic suite

Felsic group

Two map units comprise the felsic group: a megacrystic granite and a megacrystic biotite granite, with the latter grading locally into a megacrystic biotite tonalite. This biotite granite is not the same as that shown in Figure 1. The megacrystic biotite granite unit crops out along the southeastern and northeastern margins of the supracrustal block. The megacrystic granite unit crops out to the southwest and to the north of the block. Contacts between these units are gradational and were only approximately located. All rocks in this group exhibit a strong pervasive foliation defined by mica grainshape, and contain conspicuous feldspar megacrysts which lie in the plane of foliation (Fig. 3B).

Mafic group

Three map units comprise the mafic group: a biotite tonalite, a hornblende-biotite tonalite and a hornblende-quartz diorite. All occur as distinct plutonic bodies displaying sharp, mappable contacts. Mafic microgranitoid enclaves are present along the margins of the biotite tonalite and hornblende-biotite tonalite bodies. Where contacts are exposed, margins of the mafic plutons are discordant to foliations within the felsic plutonic group. The hornblende-biotite tonalite body contains a large block (about 10 m^2) of megacrystic biotite granite from the felsic group believed to be an inclusion, although it is not well exposed. Rocks of the mafic group generally lack observable foliations, but locally exhibit a weak foliation-defined hornblende and biotite grainshapes and/or flattened mafic enclaves (Fig. 3C). The hornblende-biotite tonalite body contains a few planar zones, 1 to 2 m thick, which exhibit a strong foliation defined by mica alignment and, in one case, quartz and feldspar ribbons. Both tonalite units are cut by numerous granitic aplite dikes.

Alkali granite

In addition to the mapped body of alkali granite (Fig. 2), there are many small, unmapped bodies and dikes of this lithology throughout the area. These are particularly abundant along the ski basin road (NM-475) south of the study area, where they intrude the hornblende-biotite tonalite. The contacts of the mapped body of alkali granite are not well exposed, but small bodies along the ski-basin road have tectonized borders characterized by slickensides. Associated with this lithology are numerous simple granitic pegmatite dikes and veins of epidote, some containing microlitic cavities. The alkali granite is probably the same lithology that Moench et al. (1988) designated as two mica granite (Ygt).

PETROGRAPHY

Migmatic supracrustal rocks

Textures and microstructures are similar in all the migmatite types. Mesosomes generally are fine-grained (0.2 to 1 mm), exhibiting granoblastic-polygonal textures and internal grainshape foliations defined by the alignment of mica and/or hornblende. Leucosomes are coarse-grained

(2 to 10 mm) and lack both granoblastic-polygonal textures and significant internal foliations, but serrated grain boundaries are common. Leucosome plagioclase feldspars are typically lath-shaped and exhibit subhedral to euhedral morphology (Fig. 4A). Plagioclase grains with internal euhedral zoning cores have been observed in a few leucosome samples. Melanosomes are coarse-grained (1 to 20 mm) and display a strong grainshape foliation defined by the alignment of micas and oxides (ilmenite), and where present, sillimanite and disk-shaped garnets.

Quartz in all migmatite-rock types shows undulose extinction, and in some samples, the development of subgrains. Most leucosome samples contain bent albite twins in plagioclase and bent mica grains showing undulose extinction. Secondary alteration products include epidote and minor chlorite associated with ferromagnesian minerals and sericite after plagioclase. The latter is best developed in the granitic leucosomes and in mesosomes and leucosomes in the veined migmatites. Representative modal analyses for migmatite leucosomes are shown in Table 1.

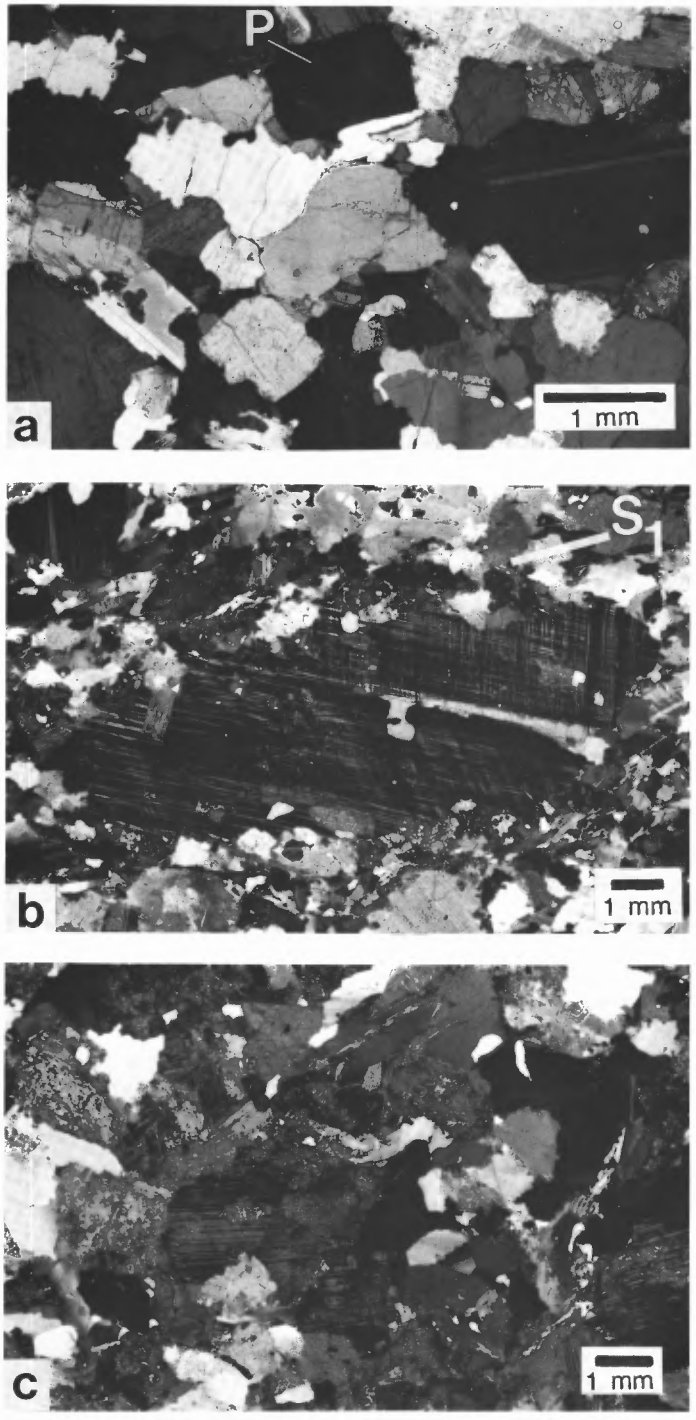


FIGURE 4. Photomicrographs of (A) leucosome from the layered migmatite, note euhedral plagioclase grain (P); (B) megacrystic biotite granite showing S_1 subsolidus fabric (note deformed microcline megacryst); and (C) hornblende-biotite tonalite.

Biotite gneiss unit

Mesosomes in the biotite gneiss unit are composed of plagioclase, quartz and biotite, +magnetite, +zircon, ±garnet and ±muscovite. Leucosomes in the layered migmatite are composed of plagioclase, quartz and muscovite, ±biotite, ±oxides, ±microcline, ±zircon, ±apatite and ±sillimanite. A considerable amount of modal variation exists in these leucosomes, with muscovite + quartz increasing at the expense of plagioclase (Table 1). Melanosomes in the layered migmatite are composed of muscovite, biotite, and oxides, +zircon, ±garnet, ±sillimanite, ±quartz and ±apatite. It should be noted that sillimanite and K-feldspar do not coexist, even when combined leucosomes and melanosomes are considered. Leucosomes in the schlieren migmatites are composed of subequal amounts of microcline, plagioclase and quartz, +biotite, +muscovite, +zircon, ±garnet and ±apatite. Melanosomes in the schlieren migmatite are composed of muscovite, biotite, and oxides, +zircon, ±garnet, ±quartz and ±apatite.

Felsic gneiss unit

Mesosomes in the felsic gneiss unit are composed of plagioclase, microcline and quartz, +biotite, +muscovite, +oxides and +apatite. Leucosomes are composed of plagioclase, microcline and quartz, +biotite, +muscovite, +oxides, and ±zircon. Mesosomes differ from leucosomes by having less microcline than plagioclase and more mica. Melanosomes, where present are composed of biotite, muscovite and oxides.

Amphibolite gneiss unit

Mesosomes in this unit are composed of hornblende, biotite and plagioclase, +quartz, +oxides, +sphene, +oxides, ±apatite and ±zircon. Leucosomes are composed almost entirely of plagioclase and quartz, +biotite, +apatite, ±sphene and ±microcline. Melanosomes, where present, are composed of biotite, oxides and quartz.

Calc-alkalic plutonic suite

Table 2 contains representative modal analyses for each plutonic map unit, as well as the aplite dikes. Subgrain development in quartz, bent albite twins in plagioclase and bent mica grains are ubiquitous features in these rocks. Secondary alteration products include sericite after plagioclase and minor amounts of chlorite after biotite. Secondary alteration is most strongly developed in the hornblende-biotite tonalite and hornblende-quartz-diorite units, where abundant secondary epidote is associated with plagioclase and biotite.

TABLE 1. Modal analyses of representative samples of migmatite leucosomes. (np = not present; tr = trace amount)

Sample type	846-55 layered	836-32 layered	846-28 schlieren	837-61 nebulitic	838-41 veined
counts	(512)	(531)	(655)	(425)	(335)
Qtz	40.0	44.8	32.5	27.7	51.6
Pl	53.0	26.7	28.7	36.6	44.2
Kfs	np	tr	25.3	28.7	np
Ms	4.1	24.9	11.1	1.6	np
Bt	1.4	1.9	tr	5.9	3.0
oxides	1.4	1.1	tr	3.0	0.2
Grt	np	np	tr	np	np
Zrn	tr	tr	tr	tr	np
Ap	np	np	tr	tr	1.0
Spn	np	np	np	np	tr
other	tr	tr	2.3	1.0	tr

TABLE 2. Modal analyses for representative samples of the plutonic lithologies. Lithologic designations are the same as used in Figure 2. (np = not present; tr = trace amount)

Sample	837-66	8310-2	838-57	8310-7	848-11	838-63	846-8
type	hqd	hbt	bt	ap	mbg	mg	ag
counts	(579)	(547)	(656)	(585)	(603)	(624)	(533)
Qtz	2.4	24.7	40.1	26.8	35.1	32.4	31.1
Pl	31.6	40.0	43.4	38.6	32.3	25.2	17.5
Ksp	np	0.5	1.5	27.0	19.7	30.9	41.0
Ms	np	np	tr	1.2	1.3	6.6	4.3
Bt	7.9	19.5	11.4	3.6	10.0	0.3	1.0
Hbl	56.8	4.2	np	np	np	np	np
oxides	0.9	0.4	0.4	0.2	1.0	tr	0.2
Grt	np	np	np	tr	np	tr	np
Zrn	tr	tr	tr	tr	tr	tr	np
Ap	tr	tr	tr	tr	tr	tr	tr
Spn	tr	1.6	tr	np	np	np	np
other	0.4	9.3	3.1	1.5	0.5	4.7	3.2

Felsic group

Rocks of the felsic group are medium- to coarse-grained (0.5 to 18 mm), with hypidiomorphic, inequigranular, porphyritic textures. Foliations are defined by isolated mats of aligned mica and by coplanar shear bands ($\leq$1 mm thick), which exhibit dynamic recrystallization textures. Feldspar megacrysts are lath-shaped and subhedral but have undergone deformation where they abut the shear bands (Fig. 4B).

Although their modes are different, rocks of the megacrystic granite and megacrystic biotite-granite units have nearly identical mineral assemblages, characterized by plagioclase, microcline, and quartz, + biotite, + magnetite, + apatite, + zircon and ± muscovite. In the granite unit, feldspar megacrysts are microcline, whereas in the biotite granite unit, megacrysts are microcline and/or plagioclase. Rocks of the biotite granite unit contain more biotite ($\geq$10%) than the granite unit.

Muscovite is an important constituent (up to 6%) in some samples from the megacrystic granite unit. Because of the tectonic recrystallization which produced the mica foliations, it is difficult to determine if muscovite was a primary crystallization phase. Some of the muscovite is clearly secondary, but other grains have a morphology similar to that of biotite and may represent primary grains recrystallized during deformation.

Mafic group

The tonalites and the quartz diorite of the mafic suite are medium-grained (0.25 to 5 mm) with hypidiomorphic, inequigranular seriate textures (Fig. 4C). Where present, foliations are defined by the weak alignment of isolated mats of biotite and, in some cases, particularly in the biotite tonalite, shear bands displaying dynamic recrystallization textures. Plagioclase occurs as subhedral, lath-shaped grains, which show apparent random orientations.

The biotite tonalite unit is composed of plagioclase, quartz and biotite, + microcline, + zircon, + magnetite, + sphene and + apatite. Plagioclase grains exhibit a coarse, patchy microcline antiperthite texture. Accessory muscovite is present within biotite mats, and is comparable in size and morphology to that of biotite, raising the possibility that some of the muscovite is primary. The hornblende-biotite tonalite unit is similar to the biotite tonalite, but with accessory hornblende, a greater abundance of biotite and sphene and no muscovite (Fig. 4C). The presence of sphene distinguishes tonalites of the mafic group from tonalites present locally in the megacrystic biotite-granite unit.

Rocks of the hornblende-quartz-diorite unit are composed largely of plagioclase and hornblende with accessory quartz and biotite. Trace amounts of sphene and microcline are also present. The aplite dikes are fine-grained with hypidiomorphic, equigranular textures and lack foliations. These rocks are composed largely of plagioclase, microcline and quartz, + biotite, + muscovite, + magnetite, + zircon, + apatite and ± garnet.

Alkali granite

Samples from the alkali granite body are fine-grained (<2 mm) with a simple alaskitic mineralogy, and about 90% of the rock composed of quartz and feldspar (Table 2). Secondary alteration products include sericite and epidote after plagioclase and almost complete alteration of biotite to chlorite. Although foliation is generally lacking in hand specimen, a tectonic foliation can be seen in thin-section. This is characterized by an elongation of quartz grains, which show the development of subgrains, and by shear bands exhibiting dynamic recrystallization textures.

STRUCTURES

Migmatite structures

Structural relationships at the mesoscopic scale are best understood within the layered migmatites of the biotite-gneiss unit. Here, the dominant texture consists of three planar structural fabrics: (1) a compositional layering composed of interlayered neosomes and mesosomes; (2) mica-grainshape foliations in mesosomes; and (3) mica-grainshape foliations in melanosome selvages. In most outcrops, these elements are coplanar. In some outcrops, compositional layering has been folded into tight to isoclinal, intrafolial folds (Fig. 3A). In some of these, mica foliations in mesosomes and melanosomes wrap around fold hinges, where in others, mesosomes and melanosomes exhibit foliations coplanar with the axial surface of the intrafolial folds. Also present are a few, rare refolded folds of compositional layering, where melanosome and mesosome mica grainshape foliations are coplanar with F_2 axial surfaces. Based on these relationships, the dominant planar fabric seen at outcrop scale is regarded as a composite S_1/S_2 fabric. Migmatites in the amphibolite and felsic gneiss units also show a compositional layering and a parallel mica grainshape foliation. These are parallel to S_1/S_2 in the layered migmatites. Discordant leucosomes, which crosscut the S_1/S_2 foliation and contain inclusions of migmatite (neosome + mesosome) exhibiting translation and rotation of S_1/S_2, are present in migmatites from both the biotite gneiss and felsic gneiss units.

The biotite gneiss unit forms the core of a large map-scale antiform (Fig. 2). The effects of topography on the lithologic contacts separating the biotite gneiss and felsic gneiss units suggest that the eastern contact dips eastward and the western contact westward. These contacts are roughly parallel to the S_1/S_2 structural fabric. A few parasitic S-folds have been observed on the western limb of the fold, with hinges plunging approximately south (20°—>190°). Although there is a considerable amount of scatter, a plot of poles to S_1/S_2 fabrics in the migmatites (Fig. 5), also indicates a southerly plunge.

Plutonic rocks and the border zone

The block of supracrustal rocks is bordered on all sides by calc-alkalic plutonic rocks belonging to the felsic group (Fig. 2). These plutonic rocks exhibit a single S_1 foliation, defined by the alignment of biotite and feldspar megacrysts (Figs. 3B, 4B), which are more strongly developed near the border. The border zone is best exposed along the southeastern contact where the megacrystic biotite granite is in contact with migmatites of the felsic gneiss unit. Here, the border is characterized by an interlayering of felsic gneiss and megacrystic biotite granite, where S_1 in the plutonic rocks and S_1/S_2 in the supracrustal rocks are coplanar with the interlayering. Individual layers of megacrystic biotite granite range in thickness from a few centimeters to several meters. The contact of the hornblende-quartz-diorite pluton, and probably that of the alkali granite, crosscuts the border contact (Fig. 2).

Although not as well exposed, similar relationships to those described above exist along other segments of the border zone. All contacts which comprise the border zone, and all structural fabrics within the border zone, dip in a southerly direction (Fig. 2). This can be seen in Figure 6, a plot of poles to S_1 planes in the plutonic rocks (the mafic plutonic group) and S_1/S_2 in interlayered supracrustal rocks along the border zone. The block of supracrustal rocks, therefore, would seem to represent a south-dipping sheet. It can be seen in Figure 6 that three predominant strike directions are present, at approximately 015° (which is nearly parallel to the Pecos-Picuris and Borrego faults), at 075° and at 325°. The latter two directions are roughly coincidental with borders of the supracrustal block (Fig. 2).

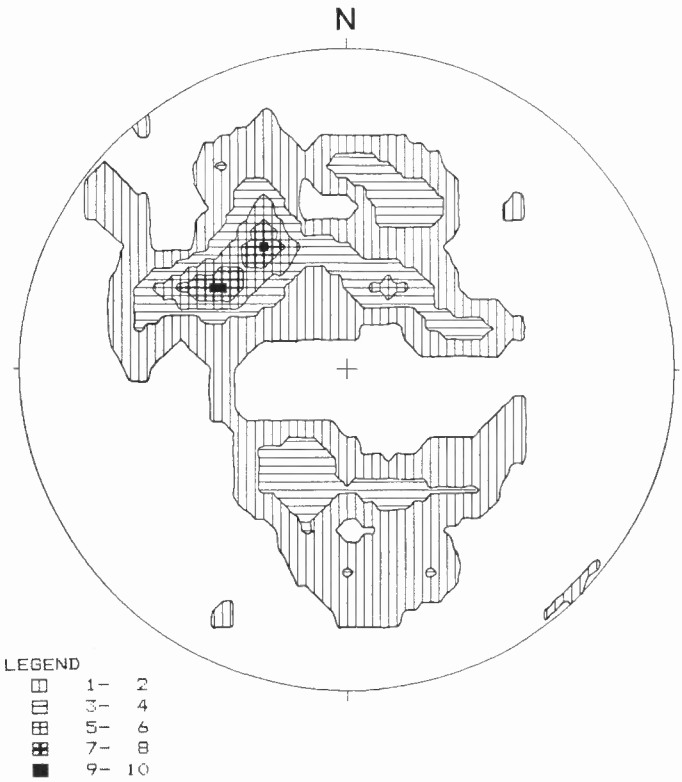


FIGURE 5. Contoured stereonet plot of poles to S_1/S_2 planes within the migmatitic supracrustal block (n = 64 points). Contour interval is 2% points per 1% area.

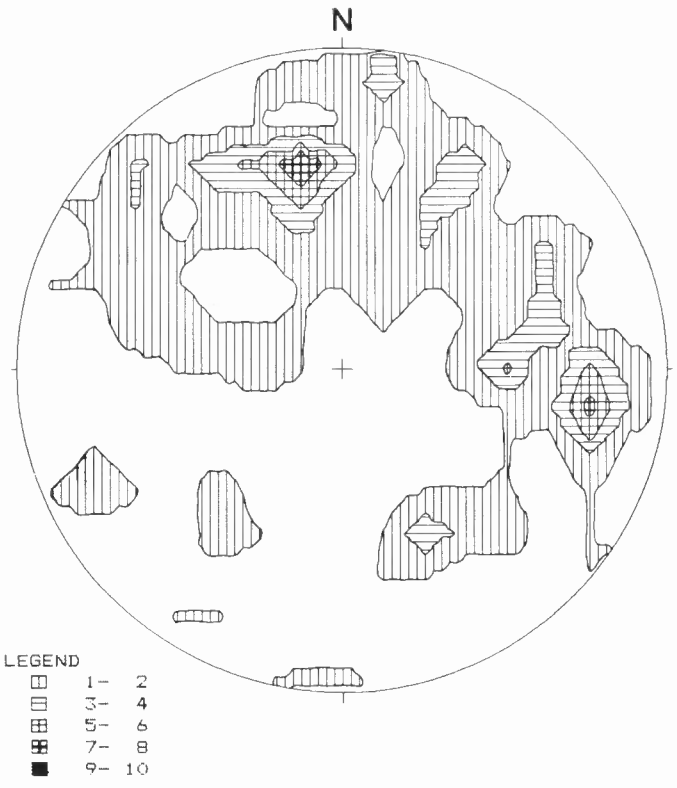


FIGURE 6. Contoured stereonet plot of poles to S_1 planes in the plutonic rocks and poles to S_1/S_2 in interlayered supracrustal rocks from the border zone separating (n = 91). Contour interval is 2% points per 1% area.

Within the border zones, where the plutonic and supracrustal rocks are interlayered, migmatite leucosomes crosscut S_1 fabrics in the plutonic rocks (Fig. 3B), as well as S_1/S_2 in the migmatites. Inclusions of plutonic rocks have been observed within the leucosomes, which show apparent translation and rotation of S_1.

CHEMISTRY OF THE PLUTONIC ROCKS

Two samples of each plutonic rock lithology, including the aplite dikes, were analyzed for major and selected trace elements using a Rigaku 3064M automated x-ray fluorescence analyzer, housed at the University of New Mexico. These data are presented in Harker variation diagrams (Figs. 7, 8), in an AFM plot (Fig. 9) and in a CaO-Na_2O-K_2O plot (Fig. 10). Data tables can be found in Metcalf (1990) or are available from the author upon request. For comparison purposes, Figure 10 also shows compositional fields defined by whole rock chemical analyses of migmatite leucosomes (Metcalf, 1990).

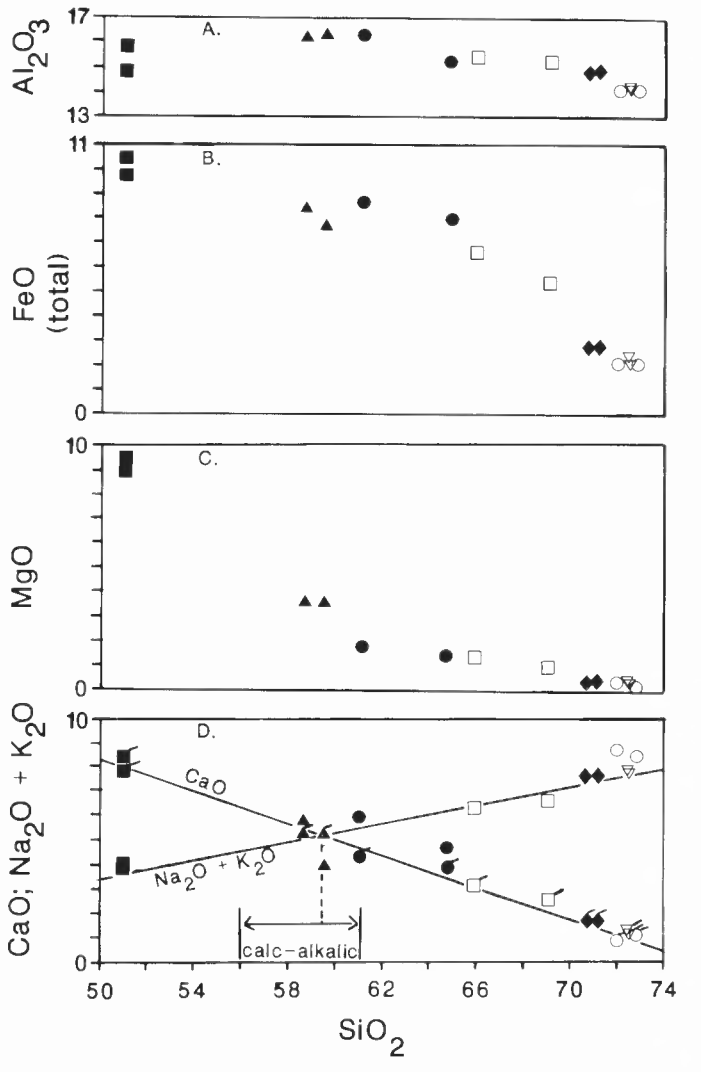


FIGURE 7. Harker variation diagrams showing SiO_2 vs. major element oxides in the plutonic rocks. In Figure 7D, CaO values are distinguished from Na_2O + K_2O values with tick marks. Also plotted on Figure 7D are linear regression lines calculated using the twelve samples of the calc-alkalic suite (exclusive of the two alkali granite samples).

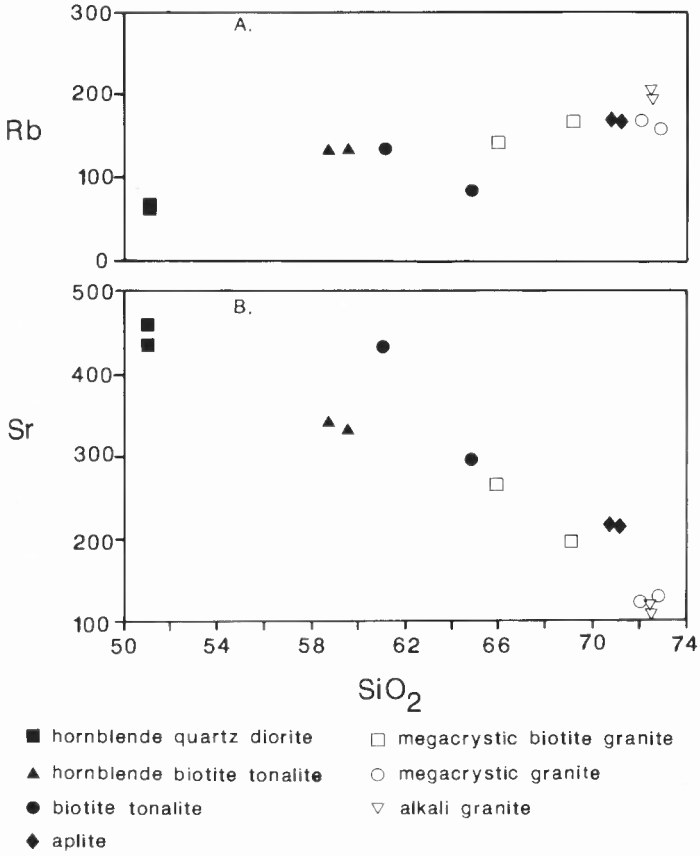


FIGURE 8. Harker variation diagrams showing SiO_2 vs. Rb and Sr in the plutonic rocks.

Within the calc-alkalic suite, SiO_2 concentrations range from 51 to 74 weight percent. Major oxides, MgO, FeO* (total Fe), Al_2O_3, CaO and $Na_2O + K_2O$ vary systematically and show good correlation with SiO_2 (Fig. 7). Similar relationships exist between SiO_2 and the trace elements, Rb and Sr (Fig. 8). It should be noted that there is a significant compositional gap between the hornblende-quartz diorite and the hornblende-biotite tonalite (Figs. 7, 8, 9 and 10). The suite is defined as calc-alkalic based in part on Peacock's (1931) alkali-lime index (Fig. 8D) and the trends seen in the AFM plot (Fig. 9).

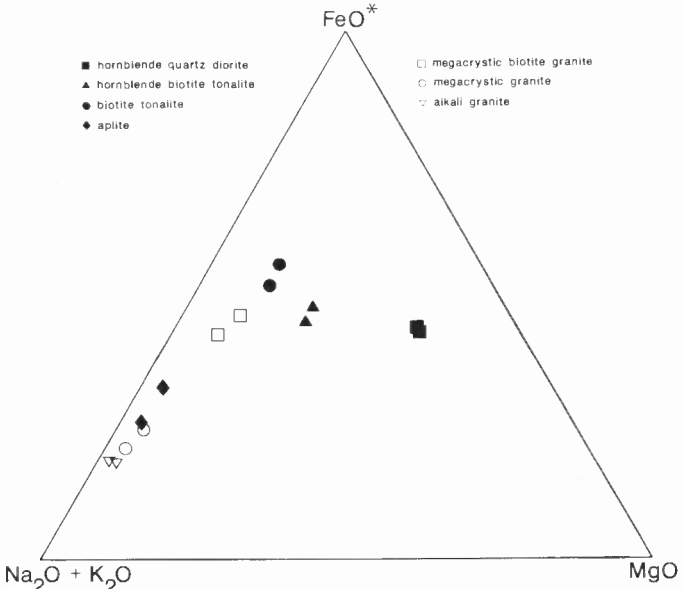


FIGURE 9. AFM plot for the plutonic rocks.

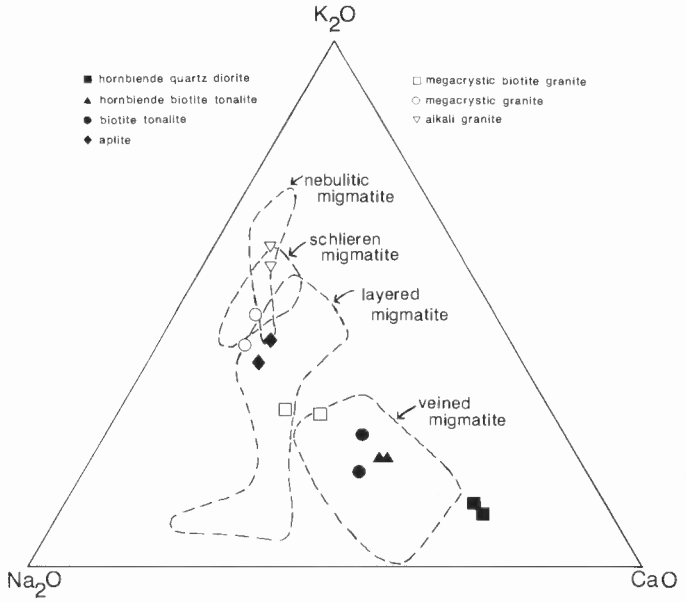


FIGURE 10. CaO-Na_2O-K_2O plot for the plutonic rocks. Also shown are fields defined by whole rock chemical data from migmatite leucosomes (after Metcalf, 1990).

The alkali granite is chemically similar in most respects to the megacrystic granite (Fig. 7, 8B and 9). However, the alkali granite is slightly richer in Rb (Fig. 8A) and in K_2O relative to CaO and Na_2O (Fig. 10).

PETROGENESIS

The supracrustal rocks are thought to represent a series of mafic metavolcanic rocks (amphibolite gneiss), felsic metavolcanic rocks (felsic gneiss) and metavolcaniclastic rocks (biotite gneiss). A sedimentary protolith is inferred for the biotite-gneiss unit because of its apparent compositional heterogeneity and the abundance of aluminous minerals, in particular muscovite. There is no evidence suggesting that the compositional layering is of sedimentary origin.

Of the four mechanisms capable of forming migmatites, only anatexis produces internally derived, magmatic leucosomes. Two lines of evidence suggest that migmatite leucosomes in the Santa Fe Range are the products of magmatic crystallization. First, it has been generally considered that plagioclase grains exhibiting lath-shape, subhedral to euhedral external morphologies and internal euhedral compositional zoning, can grow only in an isotropic medium, such as a melt (Ashworth and McLellen, 1985; Metcalf, 1990). Second, discordant leucosomes and leucosomes with translated and rotated inclusions suggest a magmatic origin. It is still possible that the magmatic leucosomes are the result of igneous injection. However, rocks of the mafic group are too rich in ferromagnesian components and too poor in silica to have served as an injection source for any of the migmatite leucosomes (compare Tables 1 and 2). In addition, the relative CaO-Na_2O-K_2O values of leucosomes from the layered and the veined migmatites are far more variable than those of the plutonic rocks (Fig. 10). The granitic leucosomes of the schlieren and nebulitic migmatites are similar in composition to the megacrystic granite and the alkali granite, but, the relative age relationships discussed below would seem to rule out the megacrystic granite as a potential injection source. Furthermore, there is a clear correlation between mesosome and leucosome compositions, suggesting the latter were generated internally.

Leucosomes in the schlieren and nebulitic migmatites formed by water saturated melting of plagioclase + K-feldspar + quartz and have compositions near the granite eutectic (Metcalf, 1986, 1990). Leucosomes in the layered migmatites and veined migmatites formed by water saturated-melting of plagioclase + quartz, with solidus temperatures lowered slightly by the dissolution of muscovite and biotite, respectively (Metcalf, 1990).

Metamorphic temperatures and pressures were estimated using the KNASH petrogenetic grid (Thompson and Tracy, 1979). Pressures and temperatures are constrained by the granite solidus, the presence of quartz + muscovite + plagioclase and rare sillimanite, and the absence of coexisting sillimanite and K-feldspar. This yields a possible range of T = 630 to 725°C and P = 3.5 to 7.5 kbars. Temperatures of 650 to 730°C and pressures of 5.2 to 5.5 kbars were calculated from mineral chemistries in the layered migmatites by Metcalf (1990), using the garnet-biotite geothermometer (calibration of Ferry and Spear, 1978; non-ideal mixing models from Ganguly and Saxena, 1984; Heckler and Wood, 1989; Williams and Grambling, 1990) and the garnet-plagioclase-sillimanite-quartz geobarometer (Newton and Haselton, 1981; Koziol and Newton, 1988).

Anatectic migmatization involves a progressive sequence of melting, segregation and melt crystallization occurring over a limited portion of the metamorphic P-T-time path. Because the melanosome selvages did not exist until segregation had occurred, the deformation event(s) D_1/D_2 that produced the composite S_1/S_2 fabric exhibited by these melanosomes did not occur until P/T conditions had reached those necessary for melting, i.e., not until the temperature exceeded about 630°C. It is unclear whether the layered structure and mesosome foliations formed at this time or were formed earlier, although the preferred interpretation is that these fabrics pre-date melting. (Johannes and Gupta [1982] have concluded that layered structures in migmatites generally mimic pre-migmatization tectonic layering.) The relationships between the leucosome dikes and the S_1/S_2 fabrics, including fabrics developed in the melanosomes, indicate that leucosome melt crystallization post-dated the D_1/D_2 deformational event(s).

The feldspar megacrysts present in the felsic calc-alkalic plutonic group are thought to represent original phenocrysts, rather than porphyroblasts (see discussion on this topic by Vernon, 1986). Observations consistent with this interpretation are: (1) the morphology of the megacrysts; (2) the lack of megacrysts in spatially associated supracrustal lithologies; and (3) the fact that plagioclase forms megacrysts only in the more mafic, biotite-rich portion of the felsic group (megacrystic biotite granite), whereas K-feldspar forms the majority of megacrysts in the less mafic, biotite-poor portion of the group (megacrystic granite). Microstructures in these rocks indicate that S_1 is a tectonic fabric, rather than a flow foliation, and developed after solidification. The relationships described from the border zone indicate that the S_1/S_2 fabric in the supracrustal rocks is coeval, at least in part, with the development of S_1 fabrics in the felsic plutonic group. Furthermore, the relationships between S_1 fabrics in the felsic group, and crosscutting migmatite leucosomes, indicate that leucosome crystallization post-dated S_1. It is unclear whether the border zone is purely a tectonic feature or an original intrusive contact modified by subsequent tectonism.

The margins of the mafic plutonic bodies in the calc-alkalic suite represent original intrusive contacts. This interpretation is supported by the sharp nature of these contacts and the presence of mafic enclaves, which are often concentrated near intrusive contacts (Pitcher and Berger, 1972). The mafic plutons are intrusive into, and therefore younger than, the felsic group. Intrusion of the hornblende-quartz-diorite body apparently post-dated tectonism of the border zone separating the supracrustal block and the felsic group. The possibility that intrusion of the mafic group was contemporaneous with the migmatization event cannot be ruled out.

The alkali granite is younger than the mafic plutons as indicated by relationships described from south of the area shown in Figure 2. The intrusion of these bodies is clearly related to extensive epidote veining in the area and perhaps to secondary epidote growth in mafic rocks of the calc-alkalic suite. The presence of miarolitic cavities within these epidote veins indicates that vein production, and presumably intrusion of the alkali granite, occurred at relatively shallow depths.

Mineral assemblages and compositional variations displayed by the calc-alkalic suite are similar to Phanerozoic arc-related plutonic suites (see for example: Erikson, 1977; Atherton and Sanderson, 1985). The relative age relationships discussed above rule out the possibility that the mafic and felsic groups of the calc-alkalic suite are related by a single fractionation event. However, close correlations seen in Figures 7–10 suggest that the suite is genetically related in some fashion. The preferred interpretation is that the central Santa Fe Range was a site of prolonged calc-alkalic magmatism which produced several similar fractionation sequences. In this interpretation, the felsic group represents the latter stages of an earlier fractionation event, whereas the mafic group represents the early stages of a second, younger fractionation event. The biotite granite map unit (Xbg) of Moench et al. (1988) shown in Figure 1 may represent the felsic portion of this second fractionation event.

SUMMARY AND CONCLUSIONS

The Proterozoic geologic history of the central Santa Fe Range can be summarized as follows:

1. A sequence of mafic and felsic volcanic rocks and associated volcaniclastic sedimentary rocks accumulated. A reasonable estimate for the age of this event would be between 1765 and 1700 Ma, the time of formation of most bimodal mafic/felsic volcanic rock suites in northern New Mexico (see Bauer and Williams, 1989).

2. After burial of the supracrustal rocks, tectonic layering and mica foliations now preserved in mesosomes developed. This event was followed by folding which produced the map-scale antiform. It should be noted that the timing of these events, relative to other events in the Santa Fe Range, is not well constrained.

3. Intrusion and solidification of the felsic portions of the calc-alkalic suite preceded peak metamorphic (anatectic) conditions. This event most likely occurred before 1650 Ma (the age of the younger biotite granite unit, Xbg).

4. With attainment of peak metamorphic conditions (T = 604 to 680°C; P = 5.2 to 5.5 kbars) anatexis and leucosome-melanosome segregation took place. Tectonism contemporaneous with this event produced S_1/S_2 neosome fabrics and S_1 in the felsic group and modified the former intrusive contacts between the felsic group and the supracrustal block. The retention of large amounts of leucosome magmas within the supracrustal block would suggest that this deformational event was primarily a compressive one.

5. Later during the deformation event the mafic group was intruded, solidified and acquired its weak S_1 fabrics.

6. Migration of leucosome magmas occurred after the S_1/S_2 supracrustal rock fabrics and the S_1 plutonic rock fabrics were acquired. This migration suggests at least a relaxation of compressional stresses, and perhaps a change from compression to extension, prior to solidification of the leucosome magmas.

7. Intrusion of the alkali granite and associated epidote veining took place after solidification of the mafic plutons and after a significant reduction in pressure so as to allow for the formation of miarolitic cavities. This event probably occurred at about 1465 Ma.

8. The deformation which produced subgrains in quartz and related fabrics throughout the area must have occurred at sufficiently low temperature so that annealing of these fabrics could not occur.

The results of this study raise several interesting questions. First, what is the relationship between the medium-grade metamorphic rocks in the McClure speta to the high-grade migmatitic rocks in the central portion of the range? There are three possible answers: (1) a tectonic boundary, similar to those described by Grambling et al. (1989), separates the two areas; (2) there is a gradational change in metamorphic grade between the two areas; or (3) the two areas are the result of two separate metamorphic events and are separated by an unconformity with the rocks of the central Santa Fe Range serving as basement to the rocks of the McClure septa. Second, are the elevated temperatures in the migmatites due to heat transported by the mafic plutonic suite? This question arises because the pressure estimates in the migmatites, although not well constrained, are not as high as pressure estimates from the other high-grade metamorphic terranes elsewhere in northern New Mexico. Third, was tectonism along the borders of the supracrustal block related to motion on precursor structures to the Pecos-Picuris and Borrego faults? This question arises because the angular relationships

between these faults and the border zones (and their associated fabrics) are appropriate for the latter to represent Riedel shear features associated with these two fault zones (see Tchalenko, 1970, fig. 1, p. 1626).

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Traveling in high style during the late 'teens, this entourage (whose identity is lost to history) hit all the major attractions between Taos and Dawson, New Mexico. Stops included the pueblos, Red River, U.S. Hill (where this lunchtime stop for suds and sandwich was made), Elizabethtown, Eagle Nest dam, Ute Park and the "Palisades." Many of the sights were recorded, apparently, on 16mm film (the camera is proudly displayed in other views of the series). The excursion was obviously well financed—this lovely Packard touring car sold for nearly $4000 when new in 1914—the equivalent of road logging today in a Rolls Royce! Collier Collection, album #31994; courtesy of New Mexico State Records Center and Archives.