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PROTEROZOIC PLUTONIC ROCKS OF THE CENTRAL SANTA FE RANGE: TRACE ELEMENT EVIDENCE OF SUBDUCTION ZONE MAGMATISM, NORTH–CENTRAL NEW MEXICO

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Abstract—Proterozoic plutonic rocks of the central Santa Fe Range exhibit a broad range of high-K calc-alkaline compositions from 51 to 73 weight percent SiO_2. From oldest to youngest, the suite can be divided into (1) a group of foliated felsic granitoid rocks, primarily granites, (2) a group of mafic granitoid rocks, including hornblende quartz diorite, hornblende biotite tonalite and biotite tonalite, and (3) a group of alkali granites and associated pegmatites. The plutonic rocks intrude a group of migmatitic supracrustal rocks. Field relationships demonstrate that pluton emplacement was broadly synchronous with deformation and upper amphibolite facies metamorphism within the supracrustal rocks. Incompatible trace element data from the plutonic rocks exhibit similarities to modern subduction zone magma systems, i.e, an enrichment in Rb, Ba, K, Sr and Th and a depletion in Nb and Ti. The plutonic rocks of the central Santa Fe Range most likely represent a batholith formed over a subduction zone as part of a Proterozoic continental arc system.

INTRODUCTION

Geochronologic and isotopic studies of Proterozoic rocks in Arizona, Wyoming, Colorado and New Mexico (Van Schmus and Bickford, 1981; Silver, 1984; Nelson and DePaolo, 1985; Bickford et al. 1989; Premo and Van Schmus, 1989) reveal 200 Ma of rapid growth of the North American continent from 1800 Ma to 1600 Ma (Karlstrom et al., 1987). Proterozoic magmatic rock ages become progressively younger from north to south across Wyoming, Colorado and northern New Mexico, and from northwest to southeast across Arizona. These patterns have led to models of continent growth by subduction zone magmatism. Tectonic models include the accretion of island-arc terranes developed outboard of the continent (Van Schmus and Bickford, 1981; Silver, 1984) and the direct addition of magmas in continental magmatic arcs, the latter accompanied by cycles of back-arc rifting (Condie, 1982; Robertson and Condie, 1989). Geochemical data supporting a subduction zone origin for Proterozoic magmatic rocks comes primarily from low-K tholeiites and calc-alkaline basaltic rocks in bimodal mafic-felsic metavolcanic assemblages (Condie, 1982, 1986; Condie and Shadel, 1984; Bickford and Boardman, 1984; Robertson and Condie, 1989). Considerably less geochemical data has been reported for Proterozoic plutonic suites or from compositionally expanded suites that characterize Phanerozoic arc systems.

A broad range of Proterozoic plutonic lithologies are exposed within the Santa Fe Range, northern New Mexico (Fig. 1). This paper evaluates the history of a suite of spatially-related plutonic rocks from the central portion of the Santa Fe Range. Field relationships are described and used to determine the timing of pluton emplacement with respect to regional deformation and metamorphism. New major and trace element geochemical data are reported and used to evaluate both the petrogenetic history of the plutonic suite and its possible origin in a subduction-related magmatic arc.

GEOLOGIC SETTING

The Santa Fe Range is bounded on the east by the Pecos-Picuris fault and on the west, south and north by depositional basins related to the Cenozoic Rio Grande rift (Fig. 1). The Santa Fe Baldy batholith, comprising calc-alkaline plutonic rocks ranging in composition from diorite to granite, occupies the central and northern portions of the range. Numerous large blocks and septa of upper amphibolite facies (T=650–730° C°, P=5.2 to 5.5 kilobars; Metcalf, 1990a,b) metasupracrustal rocks are present within the batholith (Fig. 1B). South of the batholith, middle amphibolite facies (T=500–550° C, P=3.3–4.8 kilobars; Renshaw, 1984) metasedimentary and metavolcanic rocks of the Dalton Canyon succession form several large septa. South of these septa is the Shaggy Peak batholith composed of pink biotite granite (Moench et al., 1988). This same biotite granite also crops out along the margins of the Santa Fe Baldy batholith (Fig. 1A). Proterozoic rocks east of the Pecos-Picuris fault consist of middle amphibolite facies metavolcanic and metasedimentary rocks of the Hondo and Vadito Groups (Grambling et al., 1989) and greenschist facies and middle amphibolite facies metavolcanic and metaplutonic rocks of the Pecos complex (Robertson and Condie, 1989).

Proterozoic rocks in the Santa Fe Range and adjacent areas vary between 1720 and 1465 Ma. 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). These authors also reported a date of 1650 Ma for a foliated quartz diorite in the Pecos complex near (east of) the Pecos-Picuris fault. A quartz porphyry that intrudes the Dalton Canyon succession was dated by Bowring at 1650 ± 10 Ma (reported in Fulp, 1982). Register and Brookins (1979) reported a Rb-Sr whole rock isochron age of 1465 ± 50 Ma for an undefined granite from the west side of the range, which may be part of the pink biotite granite unit. Supracrustal rocks of the Santa Fe Range correlate with lithologically similar rocks elsewhere in the region that are 1750–1700 Ma (Bauer and Williams, 1989; Metcalf, 1990a,b). Plutonic rocks of the Santa Fe Baldy batholith probably correlate with the 1650 Ma foliated quartz diorite in the Pecos complex and the 1650 Ma quartz porphyry body intruding the Dalton Canyon succession.

This study centers on an 18 km^2 area within the Santa Fe Baldy batholith between the Pecos-Picuris fault and the Borrego fault (Fig. 1). Two major lithologic assemblages are present in the study area; a suite of migmatitic supracrustal rocks and a suite of calc-alkaline plutonic rocks. The supracrustal rocks form a large south-dipping septum (Aspen Basin septum) in the center of the study area and also occur in numerous smaller blocks (Metcalf 1990a,b). The supracrustal rocks are divided into biotite gneiss, felsic gneiss and amphibolite gneiss map units. Anatectic migmatization of these rocks during upper amphibolite facies metamorphism resulted in the formation of leucosome magmas ranging in composition from granite to trondhjemite (Metcalf, 1990a,b). The dominant structural fabric in the supracrustal rocks is a combination of compositional layering and coplanar grain shape foliation. In places this fabric is folded into open to nearly isoclinal folds where foliations are either folded about fold axes or are reoriented into an axial plane foliation. The overall mesoscopic structure is regarded as a composite S1/S2 fabric. Post-S1/S2 leucosome dikes cross-cut the migmatite fabric. Meso- and microstructural relationships suggest the migmatization event was largely synkinematic with respect to deformation, but leucosome crystallization was late-to post-kinematic (Metcalf and Mawer, 1989; Metcalf, 1990a,b).

PLUTONIC ROCKS OF THE CENTRAL SANTA FE RANGE

The calc-alkaline plutonic rocks of the central Santa Fe Range can be divided into three main groups, (1) felsic granitoid rocks (granites), (2) mafic granitoid rocks (tonalite and diorite), and (3) alkali granite and pegmatite. The greatest volume of plutonic rocks belongs to the felsic

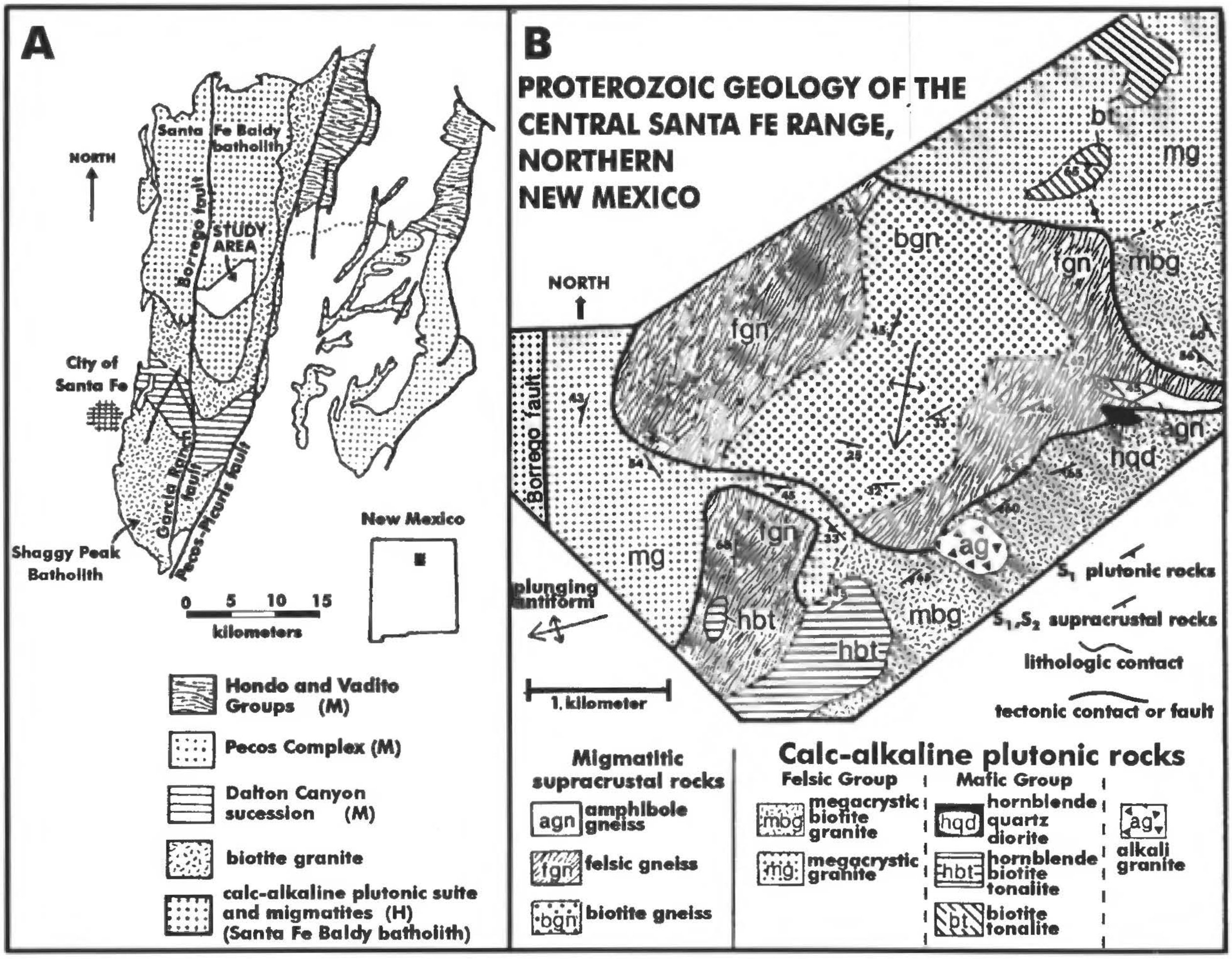

FIGURE 1. A, Geologic map of the Proterozoic geology of the Santa Fe Range and adjacent areas, northern New Mexico (M=medium grade, middle amphibolite facies metamorphism; H=high grade, upper amphibolite facies, metamorphism; modified from Renshaw, 1984). B, Geologic map showing the Proterozoic geology of a portion of the central Santa Fe Range. The large block of migmatitic supracrustal rocks in the center of the map is referred to as the Aspen Basin septum. Simplified from 1:12,000 scale map of Metcalf (1990b).

granitoid group. Each plutonic group is described in more detail in the following sections. More detailed petrographic descriptions and modal mineralogy data were presented by Metcalf (1990a,b).

Felsic granitoid group

A megacrystic granite and a megacrystic biotite granite comprise the felsic group. The latter grades locally into a megacrystic biotite tonalite. These rocks are medium- to coarse-grained (0.5 to 18 mm) with hypidiomorphic, inequigranular, porphyritic textures. These felsic map units have similar mineral assemblages, with primary plagioclase, microcline, and quartz and accessory biotite, magnetite, apatite and zircon (+muscovite). Rocks of the biotite granite unit contain more biotite (>10%) than the granite unit. Muscovite is an important constituent (< 6%) in some samples of the megacrystic granite. Feldspar megacrysts are primarily microcline in the granite unit and plagioclase in the biotite granite unit. Rocks of the felsic granitoid group exhibit a pervasive S1 subsolidus foliation defined by the alignment of biotite mats and feldspar megacrysts and by millimeter-thick ductile shear bands (Metcalf, 1990a, fig. 3b, p. 182). This foliation is most strongly developed near contacts with septa and blocks of supracrustal rocks and is generally sub-parallel to such contacts (Fig. 1B). A lack of brittle deformation features in feldspar megacrysts suggests high-temperature deformation.

The megacrystic biotite granite crops out along the southeastern and northeastern margins of the Aspen Basin septum and the megacrystic granite along the southwest and to the north of the septum; contacts between these two granitoid units are gradational. The contact between the granitoid rocks and the Aspen Basin septum is a zone up to 100 m wide, where the granitoid rocks are interlayered with the migmatites on a scale of 0.5 to 5 m. Along the septum border, S1 in the felsic granitoid group is coplanar with S1/S2 in the migmatites; discordant leucosome bodies cross-cut both S1/S2 in the migmatites and S1 in the felsic granitoid rocks.

Mafic granitoid group

The mafic granitoid group occurs as several discrete plutons that cross-cut both the S1 foliation in the felsic granitoid group (see Stop 4, Metcalf, this volume) and contacts between the felsic group and the supracrustal rocks (Fig. 1B). A weak S1 foliation, confined to narrow north-northeast striking planar zones, can be observed in the mafic granitoid group at several locations. Three map units compose the mafic granitoid group: (1) a biotite tonalite present in two bodies north of the Aspen Basin septum, (2) a hornblende biotite tonalite present in two bodies south of the septum, and (3) a hornblende quartz diorite present in a single body intruding the eastern margin of the septum (Fig. 1B). Rocks of the mafic group are medium-grained (0.25 to 5 mm) with hypidomorphic, inequigranular seriate textures. Plagioclase occurs as randomly orientated subhedral, lath-shaped grains with euhedral internal zoning. These rocks generally lack an internal foliation but, where present, foliation is defined by a weak alignment of biotite and occurs in narrow, centimeter- to meter-scale planar zones. At most localities this alignment is accompanied by elongated quartz grains and appears to represent a subsolidus deformation fabric (see Stop 1, Metcalf, this volume). In at least one location, however, biotite alignment occurs in rocks with equant quartz grains and euhedral plagioclase and appears to represent a hypersolidus flow foliation (see Stop 2, Metcalf, this volume). The presence of a few flattened mafic microgranitoid enclaves contributes to a weak planar fabric in some areas of the southern hornblende biotite tonalite pluton.

The biotite tonalite unit consists primarily of plagioclase, quartz and biotite, with minor amounts of microcline and accessory zircon, magnetite, sphene and apatite. Plagioclase grains exhibit a coarse, patchy microcline antiperthite texture. The mineralogy of the hornblende biotite tonalite unit differs from the biotite tonalite unit by the addition of hornblende and by more abundant biotite and sphene. Both tonalite bodies are cut by planar aplite dikes up to a meter wide. The aplite is fine-grained with hypidiomorphic, equigranular textures and in places possesses a weak foliation. It is composed largely of plagioclase, microcline and quartz, with accessory biotite, muscovite, magnetite, zircon and apatite. The hornblende quartz diorite unit is composed largely of plagioclase and hornblende with minor amounts of quartz and biotite, with accessory sphene and microcline. A small portion of the body mapped as hornblende quartz diorite pluton is hornblende tonalite.

Alkali granites and pegmatites

Dikes and small stocks of alkali granite are present throughout much of the central Santa Fe Range and intrude every supracrustal and plutonic lithology. Most bodies are too numerous and small to map at a scale of 1:12,000, but one large body intrudes the southeastern margin of the Aspen Basin septum (Fig. 1B). The alkali granite is fine-grained (< 2 mm), with a simple alaskitic mineralogy with about 90% of the rock composed of quartz and feldspar. Secondary alteration products include sericite and epidote after plagioclase and almost complete alteration of biotite to chlorite. Although foliation is generally lacking in hand specimens, a tectonic foliation consisting of elongated quartz grains and shear bands can be seen in thin section.

Associated with the alkali granite are numerous simple pegmatite dikes of granitic composition. Many dikes are a composite of alkali granite and pegmatite. Alkali granite dikes and pegmatite dikes are abundantly exposed along the upper portion of New Mexico state highway 475 (NM-475), where they intrude all three supracrustal lithologies, the megacrystic granite unit and the hornblende biotite tonalite.

RELATIVE TIMING OF PLUTON EMPLACEMENT, METAMORPHISM AND DEFORMATION

Plutonic rocks in the central Santa Fe Range were emplaced in three stages. Magmas related to the felsic granitoid group (megacrystic granite and megacrystic biotite granite units) were emplaced during the first stage. The coplanar nature of S1 in the felsic granitoid group and S1/S2 in the migmatites, suggests that these plutonic rocks and the supracrustal rocks were deformed in the same deformation event. This relationship indicates that the first emplacement stage was a pre- to synkinematic event with respect to both deformation and peak metamorphism within the supracrustal blocks. The lack of brittle deformation features in K-feldspar megacrysts indicates that deformation was at elevated temperature, which supports a synmetamorphic timing of deformation within the felsic group. Plutons of the mafic granitoid group (diorite and tonalite units) cross-cut S1 in the felsic group and S1/S2 in the migmatites, indicating a second emplacement stage. Deformation fabrics in the mafic group rocks are restricted to planar shear zones. Some of these fabrics are subsolidus and other hypersolidus fabrics, suggesting that this second emplacement stage was late- to post-kinematic. At one location on NM-475, (Stop 4, Metcalf, this volume) a tonalite of the mafic group appears to commingle with granitic leucosome magmas of the migmatitic supracrustal rocks. This relationship suggests that the second emplacement stage was synchronous with the metamorphic thermal peak. The alkali granite unit and related pegmatite dikes intrude all of the other units in the study area and represent the third stage of emplacement.

GEOCHEMISTRY OF THE PLUTONIC ROCKS

Eighteen plutonic rock samples were analyzed for major and selected trace elements by x-ray fluorescence spectrometry (XRF). Additional trace element data were collected on 12 of these samples by instrumental neutron activation analysis (INAA). XRF analyses were performed either at the University of New Mexico or at the University of Nevada, Las Vegas, using Rigaku automated XRF spectrometers. INAA analyses were performed either at the Phoenix Memorial Laboratory at the University of Michigan or at Sul Ross State University. Geochemical data are presented in Table 1.

TABLE 1. Geochemical data for plutonic rocks of the central Santa Fe Range

Sample	837-66	857-21	918-9	9110-5	8310-2	8310-3	918-10	838-62	838-57	8310-7	838-48	848-11	9110-1	857-18	858-11	838-63	846-8	846-6
Unit**	HD	HD	HD	HD	HBT	HBT	HBT	BT	BT	AP	AP	MBG	MBG	MBG	MG	MG	AG	AG
XRF(wt%)																		
SiO2	51.04	51.04	54.2	57.4	58.7	59.54	63.9	61.1	64.83	73.22	70.75	69.1	66.1	65.96	72.45	72.51	72.83	72.02
TiO2	0.82	0.91	0.94	1.43	0.96	0.94	1.03	1.16	0.82	0.24	0.24	0.66	0.77	0.88	0.24	0.17	0.1	0.15
Al2O3	15.64	14.75	16.7	15.4	16.21	16.24	14.6	16.22	15.23	14.92	14.78	15.23	13.5	15.39	14.19	14.13	14.12	14.1
FeO*	9.83	10.48	7.4	7.6	8.3	7.59	5.8	8.7	7.94	2.8	2.78	5.41	5.5	6.57	2.42	2.15	2.07	2.1
MgO	8.94	9.47	6.6	3.6	3.59	3.55	2.1	1.84	1.52	0.4	0.39	0.99	1.3	1.34	0.44	0.34	0.18	0.35
CaO	8.28	7.86	8.6	6.1	5.23	5.18	4.3	4.3	3.89	1.7	1.64	2.58	2.9	3.14	1.33	1.16	1.08	0.85
Na2O	2.61	2.53	2.6	2.4	3.43	3.42	2.7	3.37	3.14	3.89	3.66	3.84	2.8	3.33	3.97	3.49	3.02	2.9
K2O	1.17	1.41	1.7	2.6	2.25	2.22	2.7	2.65	1.59	3.64	3.93	2.71	2.5	2.92	3.86	4.26	5.38	5.76
P2O5	0.12	0.23	0.32	0.44	0.25	0.24	0.3	0.37	0.21	0.04	0.04	0.25	0.3	0.12	0.04	0.03	0.03	0.07
MnO	0.15	0.14	0.14	0.14	0.12	0.12	0.09	0.15	0.11	0.06	0.06	0.11	0.12	0.12	0.07	0.13	0.06	0.06
Total	98.45	98.68	99.06	96.97	98.92	98.92	97.43	99.71	99.17	100.85	98.21	100.77	95.67	99.65	98.94	98.24	98.81	98.3
XRF(ppm)																		
Ba	500		686	1099	595	1082	1351	1540		987	1466		1174	1610	819	1336	1185	
Rb	65	64	104	95	132	133	59	134	84	167	169	168	138	142	207	195	159	169
Sr	458	435	308	413	340	333	482	432	297	214	217	196	249	267	121	110	131	124
Nb	9	10	16.7	13.9	21	21	8.6	19	18	13	14	17	12.8	18	15	18	12	17
Zr	134	323	259	271	169	167	166	344	343	148	155	230	298	290	118	96	122	148
Y	26	28	42	67	54	53	30	62	54	30	31	56	33	49	52	52	40	39
Ni	197	235			87	74		43	38	28	29			35	29	29	29	29
INAA(ppm)																		
La	18.32		30.62	87.96	41.43	38.49	56.85	41.9		31.35			56.1	68.5	44.97		48.92	
Ce	31.91		75.43	209	93	98	85.47	97.3		51			132	127	111		85.41	
Nd	15.92		27.31	63.23	55.95	24.9	33.88	53.3		18.85			41.62	59.5	29.96		35.24	
Sm	4.19		6.6	12.44	10.11	5.25	8	10.1		3.07			7.93	9.7	6.23		6.33	
Eu	1.12		1.66	2.92	1.74	0.98	2.09	2.9		0.61			2.02	2.3	1.28		0.6	
Tb	0.38		0.8	1.43	1.82	0.56	0.92	2		0.25			0.95	1.7	0.99		0.89	
Yb	1.88		2.62	4.25	4.34	0.82	2.95	6.5		0.56			2.49	3.1	3.64		2.05	
Lu	0.305		0.416	0.666	0.57	0.123	0.425	0.91		0.07			0.333	0.46	0.553		0.3	
Hf	2.56		3.31	9.9	5.55	4.27	8.74	9.96		3.83			9.81	9.04	4.94		3.59	
Sc	27.43		24.23	19.77	20.14	2.77	14.14	17.09		2.62			11.59	14.32	7.18		2.78	
Th	2.72		4.4	22.57	12.6	13.81	5.89	4.76		15.44			6.43	7.53	15.95		19.52	

FeO*=total Fe; **HD=hornblende diorite; HBT=hornblende diorite tonalite; BT=biotite tonalite; AP=aplite; MBG=megacrystic biotite granite; MG=megacrystic granite

Variation diagrams

Rocks of the mafic and felsic groups form generally well-defined compositional trends for both the major and trace elements (Figs. 2, 3). Rock compositions are fairly continuous, i.e. lacking compositional gaps, over a broad range of SiO_2 compositions (51–73 wt%). The most mafic rocks in the sample suite (hornblende quartz diorite samples 837–66, 857–21, 918–9) have low SiO_2 (51–54 wt%) and high MgO (6.6–9.5 wt%), FeO (7.4–10.5 wt%), CaO (7.4–8.6 wt%) and Ni (197–235 ppm). The most felsic rocks (megacrystic granite samples 858–11, 838–63; alkali granite samples 846–6, 846–8) have high SiO_2 (72–73 wt%) and low MgO (0.2–0.2 wt%), FeO (2.1–2.4 weight percent) and CaO (0.9–1.3 wt%). The two alkali granite samples plot with the felsic group on most variation diagrams (Fig. 2), with the exception of higher alkali contents, in particular K_2O (Fig.3). The plutonic rocks plot as a subalkaline suite on an SiO_2 vs. total alkali diagram (Fig. 3A) and primarily in the calc-alkaline field on a (Na_2O+K_2O)-FeO-MgO (AFM) ternary plot, although there is some overlap with the tholeiitic field (Fig. 3C). A K_2O-SiO_2 plot indicates this is a high-K suite (Fig. 3B).

At present there is insufficient data to clearly define compositional trends within individual map units. The existing data does suggest compositional trends may differ among the various units. For example, with increasing SiO_2, TiO_2 increases in the hornblende quartz diorite unit, remains relatively constant in the hornblende biotite tonalite unit and decreases in the biotite tonalite unit (Fig. 2A). Differences can also be seen on the FeO, P_2O_5 and La plots (Fig. 2C,E,G). Another example are the aplite dikes, which clearly are related in the field to the tonalite bodies and are presumably differentiates of the tonalite magmas. The REE patterns of the aplites differ markedly from the REE patterns of other felsic rocks in the central Santa Fe Range, suggesting unique REE differentation trends for the tonalite magmas.

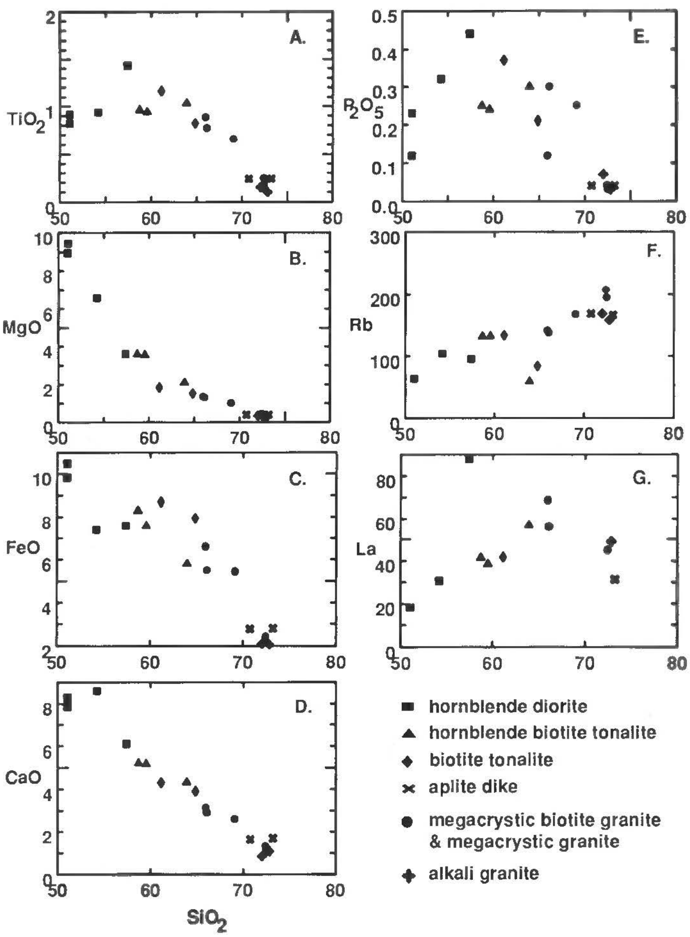

FIGURE 2. Harker variation diagrams for selected major and trace element data. Oxide values are in weight percent, trace element values are in parts per million.

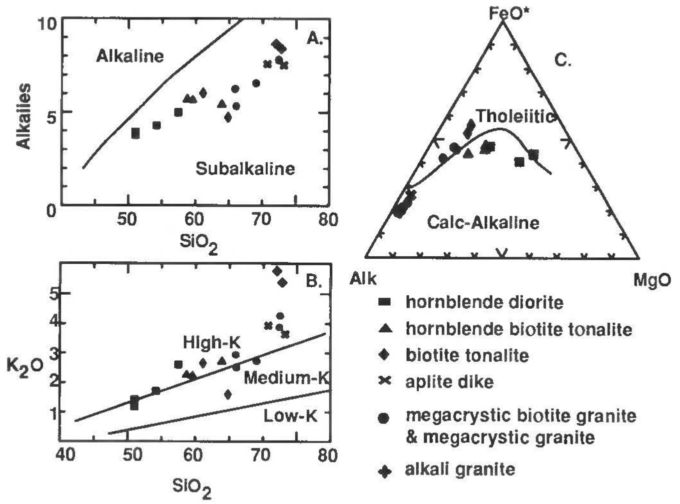

FIGURE 3. A, Total alkali (Na_2O+K_2O) vs. SiO_2 plot showing alkaline and subalkaline fields. B, K_2O vs. SiO_2 plot showing low-K, medium-K and high-K fields. C, AFM plot (Alkali-FeO-MgO) showing calc-alkaline and tholeiitic fields.

Normalized plots

The plutonic rocks are plotted on chondrite-normalized rare earth element (REE) diagrams in three groups, hornblende quartz diorite (Fig. 4A), tonalites (Fig. 4B) and felsic rocks including the alkali granite (Fig. 4C). An aplite dike is also plotted with the tonalites (Fig. 4B). All of the samples, with the exception of the aplite dike, show similar moderate light REE enrichment patterns. The aplite dike shows heavy REE depletion. Europium anomalies are largely absent except for small negative anomalies in some of the less mafic rocks (one tonalite and some of the granites, Figs. 4B,C). The alkali granite shows the largest negative Eu anomaly (Fig. 4C).

Selected samples are plotted on primitive mantle-normalized spider diagrams in Figure 5. The most mafic rock in the suite (hornblende quartz diorite, sample 837–66, Fig. 5A) is enriched in the highly incompatible elements (Rb-K) and in Sr, and shows negative spikes for Nb, P and Ti. Two tonalite samples (Fig. 5B) exhibit a pattern similar to the hornblende quartz diorite but are more enriched in most trace elements. A megacrystic granite and an alkali granite (Fig. 5C) share similar patterns and concentrations. Relative to the hornblende quartz diorite, these granites are depleted in P, Sr and Ti, have similar Nb and Zr and are enriched in the more incompatible elements (Rb-Ce)

DISCUSSION

The similar patterns exhibited on REE plots and trace element spider diagrams (Figs. 4, 5) suggest a similar petrogenetic history for plutonic rocks of the central Santa Fe Range. The relative age assignments discussed earlier, however, preclude the derivation of older felsic group magmas by differentiation directly from younger mafic group magmas. In addition, independent compositional trends within some of the lithologies suggested by the limited data set, indicate separate differentiation histories for some of the units. A single quantitative cogenetic model for the entire suite, therefore, seems unlikely. However, the similarities exhibited among the trace element patterns of the various units could be explained with a more general model in which the plutonic rocks are related by broadly similar processes. Specifically, the plutonic suite may represent different stages in a series of repeated independent differentiation cycles operating on parental magmas derived from a similar source region. Each differentiation cycle would differ somewhat in the kind and proportions of fractionating minerals, and on whether open-system mixing of migmatite leucosome magmas occured. Preliminary major and trace element modeling has shown that such differentiation processes are capable of producing many of the observed variations.

The similarity of parental magma sources can be tested by examining an incompatible trace element ratio plotted against a differentiation monitor. The Nb/Y ratio is a sensitive monitor of differences in magma source

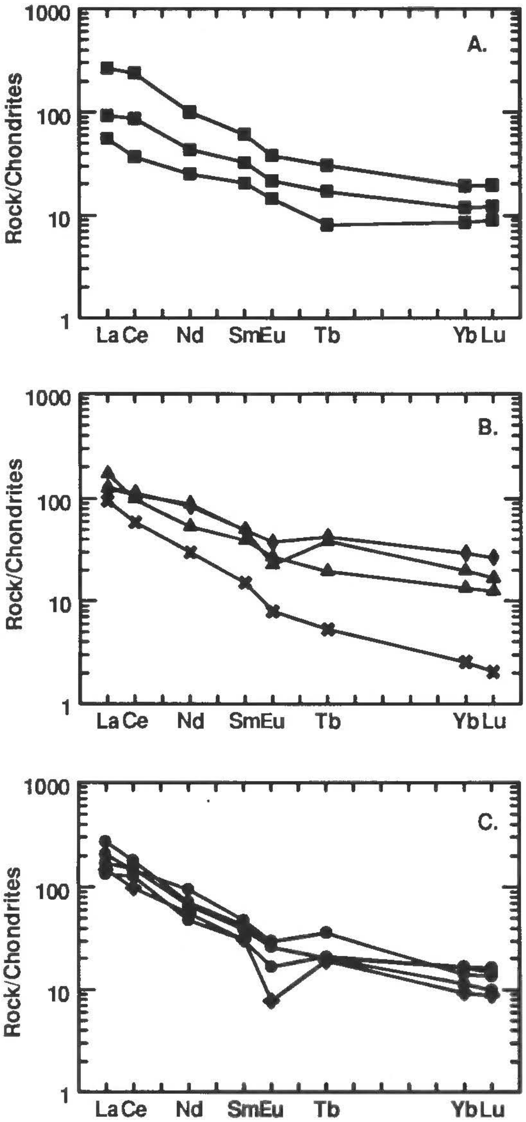

FIGURE 4. Chondrite-normalized rare earth element plots; normalization values from Sun and McDonough (1989). Symbols are the same as in Figures 2 and 3. A, Hornblende quartz diorite samples; B, hornblende biotite tonalite, biotite tonalite and aplite samples; C, megacrystic biotite granite, megacrystic granite and alkali granite samples.

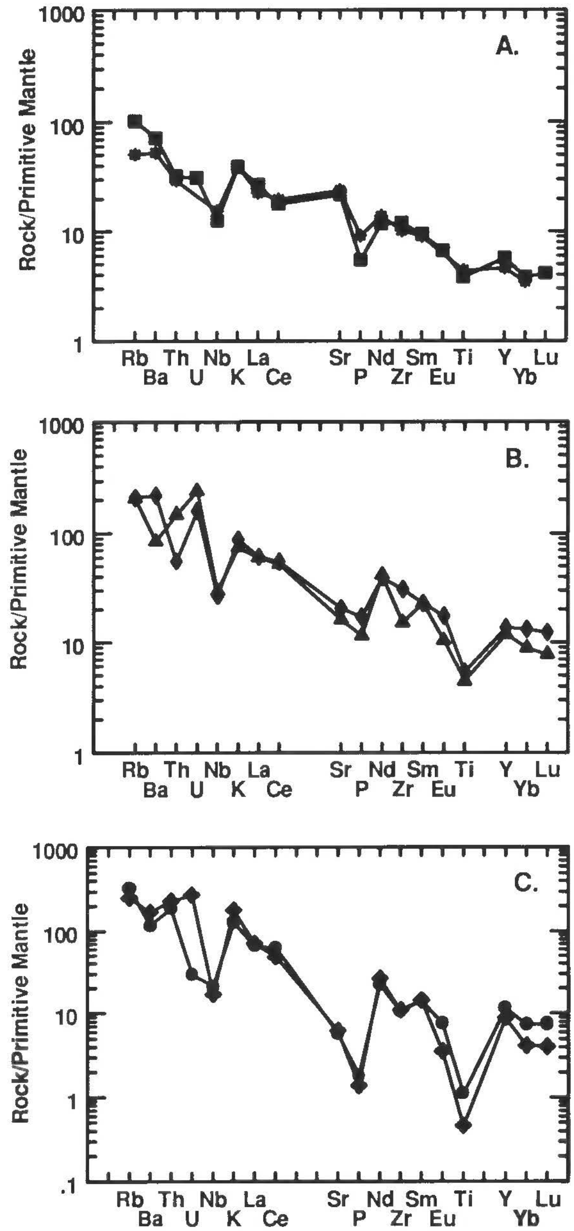

FIGURE 5. Primitive mantle-normalized incompatible trace element spider diagrams; normalization values from Sun and McDonough (1989). Elements are arranged with increasing incompatibility from right to left; symbols are the same as in Figures 2 and 3. A, hornblende quartz diorite (square) compared to a sample of Cenozoic high-K basalt (star) from the Peruvian Andes (data from Thorpe et al., 1984); B, hornblende biotite tonalite and biotite tonalite samples; C, megacrystic granite and alkali granite samples.

regions but insensitive to fractional crystallization in the crust. Rocks produced by fractional crystallization of parental magmas derived from the same source should have similar Nb/Y ratios. The range of Nb/Y ratios exhibited by the entire plutonic suite is relatively small and is no more than that within a single map unit (Fig. 6). The observed variations in Nb/Y may result from small amounts of contamination by migmatite leucosome magmas.

Several lines of evidence point to a subduction origin for the plutonic rocks of the central Santa Fe Range. First, the broadly calc-alkaline compositional trends (Fig. 3) are typical of those found in Phanerozoic subduction-related magmatic arcs. Second, the mineralogy of these rocks is similar to that found in subduction-related Phanerozoic batholiths formed above subduction zones, most notably hornblende as the dominate ferromagnesian mineral and sphene as a major accessory mineral. Finally, the incompatible trace element signature of the mafic group is similar to that found in mafic rocks from Cenozoic arc systems. This latter point is discussed in more detail below.

Basaltic rocks from subduction-related magmatic arcs typically exhibit a enrichment in large ion lithophile elements (LILE) particularly Ba, Rb, K, Sr and Th, and a depletion in high field strength elements (HFSE) such as Nb and Ti. The origin of these trace element signatures in arc rocks continues to be a matter of considerable debate (e.g. Yogodzinski et al. 1994). Magma generation is thought to occur primarily in the mantle wedge overlying the subducting slab. LILE enrichment in subduction zone magmas is thought to result from the transfer of LILE to the overlying mantle wedge, either by aqueous fluids released from the subduction slab (Tatsumi, 1982; Stern et al. 1991) or by water-rich melts formed by low degrees of partial melting of the slab (Yogodzinski et al. 1994). Depletion of HFSE is thought to result from stabilization of minor accessory phases (e.g., rutile or other Ti-rich phase), which concentrate HFSE either within the mantle wedge (fluid model) or within the downgoing slab (slab melt model) (Pearce, 1982; Yogodzinski et al. 1994). The trace element pattern and concentrations of the hornblende quartz diorite are almost identical to a high-K calc-

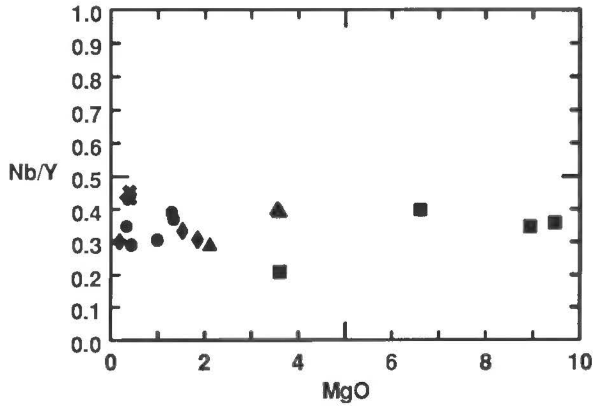

FIGURE 6. Plot of MgO (weight percent) vs. the incompatible trace element ratio Nb/Y. Symbols are the same as in Figures 2 and 3. The narrow range of Nb/Y ratios over such a large range of MgO compositions suggests that these rocks are related to mafic parental magmas derived from a similar source region.

alkaline basalt from the Cenozoic central volcanic zone of the Peruvian Andes (Fig. 5), except for slightly elevated Ba and Rb concentrations in the Santa Fe sample. These similarities suggest that the mafic rocks of the central Santa Fe Range had an origin similar to that of Andean basaltic magmas, i.e. generated over a subduction zone. As an additional test, diorite and tonalite samples from the Santa Fe Baldy batholith are plotted on Pearce and Cann (1973) trace element tectonic discrimination diagrams (Fig. 7) and fall primarily within the subduction-related calc-alkaline basalt field.

The data presented here supports the interpretation that the plutonic rocks of the central Santa Fe Range represent a portion of a batholith formed above a Proterozoic subduction zone. In general, this supports the model of Proterozoic continental growth via subduction zone magmatism discussed in the introduction. However, the geochemical data does not distinguish between an island arc setting and a continental arc setting. Two pieces of evidence, however, favor a continental arc setting. First, the high proportion of felsic rocks (felsic group and alkali granite) relative to mafic and intermediate rocks (diorites and tonalites of the mafic group) within the plutonic suite is more typical of continental arcs (Wilson, 1989). Second, the timing of plutonism is broadly correlative with the timing of deformation and the thermal peak metamorphism, suggesting that this represents an episode of synorogenic plutonism that is entirely consistent with a continental arc.

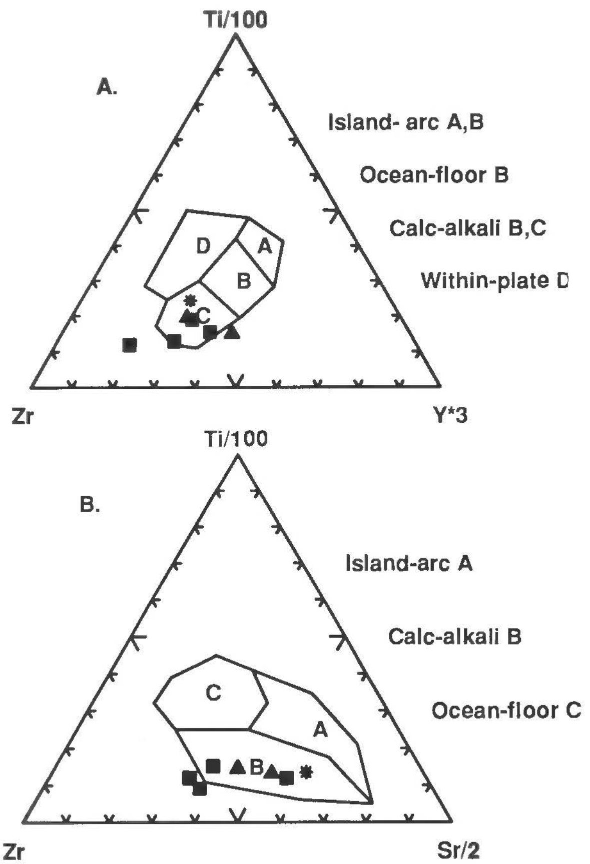

FIGURE 7. Tectonic discrimination diagrams of Pearce and Cann (1973). Samples of hornblende quartz diorite, hornblende biotite tonalite and biotite tonalite are plotted. Symbols are the same as in Figures 2 and 3; star represents a sample of Cenozoic high-K basalt from the Peruvian Andes.

CONCLUSIONS

The main conclusions of this paper are as follows.

1. The main groups of plutonic rocks present in the central Santa Fe Range, in order of decreasing relative age, are felsic granitoid rocks (granites), mafic granitoid rocks (diorite and tonalites), and alkali granite and associated pegmatite.

2. The granitoid rocks intruded a suite of migmatitic supracrustal rocks. The plutonic rocks can be considered synorogenic in that their emplacement was broadly synchronous with ductile deformation and peak metamorphism within the supracrustal rocks. Although no isotopic ages are available for these rocks, their emplacement is thought to be ca 1650 Ma based on regional correlations.

3. Incompatible trace element data suggest that the plutonic rocks represent a composite batholith formed over a Proterozoic subduction zone. Compositional variability within the batholith was apparently the result of multiple cycles of fractional crystallization.

4. The relatively high proportion of felsic rock types suggests a continental arc rather than an island arc setting for the plutonic suite. This supports a model of crustal growth by direct addition of mantle-derived magmas to the edge of the Proterozoic craton.

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