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Mineralogy of the La Posta pluton: Implications for the origin of zoned plutons in the eastern Peninsular Ranges batholith, southern and Baja California

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Abstract

The 94 Ma La Posta pluton is located in the eastern zone of the Peninsular Ranges batholith and is exposed over an area of approximately 1400 km². It is zoned from a sphene-hornblende-biotite tonalite rim inward to a core of muscovite-biotite granodiorite with internal contacts gradational over distances of several tens to hundreds of meters. This pluton is texturally distinct from the older synkinematic plutons of the western zone of the batholith in that it is undeformed and contains sharply euhedral mafic minerals.

Microprobe analyses indicate that hornblendes from the eastern side of the pluton have higher Al_T and lower Si than those from the western side. This variation in composition yields geologically unreasonable differences in hornblende geobarometry and reflects hornblende equilibration under different thermochemical conditions on either side of the pluton. Compositional variations within individual mineral suites are consistent with a general model involving inward crystallization of a static magma chamber. However, biotites in the interior facies are more oxidized and have abruptly higher Fe/(Fe + Mg) than those in the marginal facies. These data suggest that the muscovite-bearing core facies represents the tail of a diapir that intruded a ballooned magma chamber prior to its complete solidification. A longer residence time for the tail adjacent to a cratonal source resulted in its enrichment in, at least, Fe^{3+} and Fe/(Fe + Mg).

Introduction

The eastern side of the Peninsular Ranges batholith is dominated by a series of large, concentrically zoned plutons of intermediate composition that exhibit distinct similarities in age, rock type, and geochemistry (Walawender et al., 1989). The largest of these, the 94 Ma La Posta pluton, is located approximately 65 km east of San Diego, California, and straddles the international border (Fig. 1). Although the northern portion of this pluton and the section south of the international border have been mapped only in reconnaissance fashion, the approximately 750 km² that have been studied in detail (Kimzey, 1982; Sinfield, 1983; Clinkenbeard, 1987) reveal a more or less single magmatic pulse that crystallized inward to form a lithologic succession ranging from hornblende-biotite tonalite to muscovite-biotite granodiorite. Textural evidence indicates that this pluton experienced little subsolidus deformation or alteration and thus provides an excellent opportunity to examine compositional relationships between coexisting silicate minerals that have retained their primary magmatic character. This paper describes these compositional relationships and interprets them with respect to various parameters that affect cooling magmatic systems.

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Geologic setting

The Peninsular Ranges batholith is part of the circum-Pacific chain of Mesozoic batholiths and extends from Riverside, California, southward more than 1000 km to the lat 28°N in Baja California. It consists of hundreds of individual plutons that range in maximum dimension up to 45 km and in composition from gabbro to granite. The batholith, as a whole, is calcic in composition (Silver et al., 1979) and can be divided into western and eastern zones based on geochemical, lithologic, structural, and geophysical criteria.

The western zone is characterized by smaller plutons that range in composition from gabbro to monzogranite. They were emplaced into greenschist- to lower amphibolite-grade host rocks dominated by volcanic and volcanoclastic assemblages to the west and submarine fan deposits to the east (Todd et al., 1988). The eastern zone of the batholith is essentially devoid of gabbroic plutons and contains mainly large (hundreds of square kilometers) plutons of intermediate composition that were emplaced into locally migmatitic, sillimanite-bearing metasedimentary rocks. In addition, plutons in the eastern zone are undeformed and contrast with the synkinematically deformed plutons to the west (Todd and Shaw, 1979).

The boundary between these plutonic zones crudely coincides with a sharp gravity contrast that Oliver (1980) interpreted as the juxtaposition of a western oceanic crus-

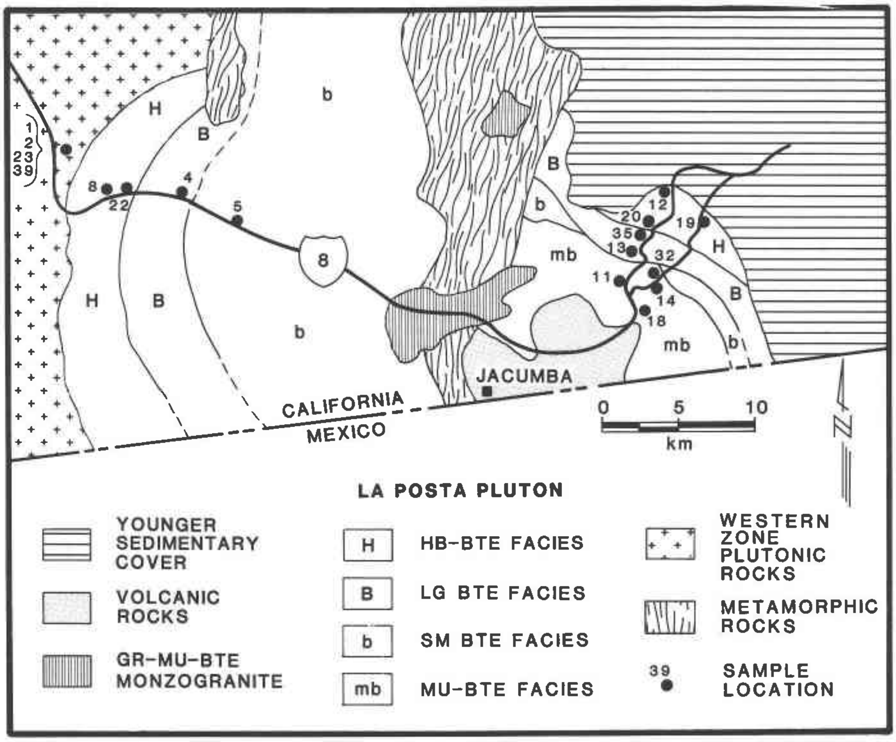

Fig. 1. Geologic map of the La Posta pluton (after Kimzey, 1982; Sinfield, 1983).

tal basement and an eastern continental basement. Silver et al. (1979) showed that this boundary also approximates a "step" in both the emplacement ages of the plutons and their oxygen-isotope character. Plutons in the western zone range in age from 120 Ma to 104 Ma with $\delta^{18}O$ less than 8.5‰, whereas those in the eastern zone are generally younger than 100 Ma and have $\delta^{18}O$ ranging from 9 to 12‰. Walawender et al. (1989) argued that although these regional patterns are generally valid, transitional plutons with characteristics of both zones are present in the vicinity of the age and isotopic "steps" and that this boundary represents a transition from mantle-derived melts to oceanic crust–derived melts.

Diamond et al. (1985) and Gastil et al. (1986) have shown that the plutons of the western zone contain magnetite and ilmenite as their primary opaque phases whereas those to the east are devoid of magnetite. This magnetite-ilmenite "line" approximates the lithologic, geochemical, and age "steps" described above. Gastil et al. (1989) have also considered it to reflect a transition from mantle-derived to oceanic crust–derived melts with the nature of the volatile phase released during anatexis controlling the presence or absence of magnetite.

The La Posta pluton is divided into two parts by a large metasedimentary screen (Fig. 1) that interrupts the continuity of the plutonic units. Sillimanite-bearing pelitic schists and migmatitic gneisses along with lesser amounts of marble, quartzite, and amphibolite make up the bulk of the metamorphic complex. The metamorphic complex and adjacent parts of the La Posta pluton are intruded by 89–93 Ma garnetiferous two-mica monzogranites. The western hornblende-biotite and small-biotite facies, and the eastern hornblende-biotite facies of the La Posta pluton have zircon U-Pb ages of 93, 94, and 95 Ma (±2 Ma), respectively, and indicate an emplacement age of approximately 94 Ma (Walawender et al., 1989). This U-Pb age is consistent with a four-point Rb-Sr isochron age of 92 ± 2.8 Ma for the western small-biotite facies. The continuity of ages across the pluton along with its map-unit symmetry and petrographic similarities suggest that the La Posta pluton was emplaced during a single intrusive event. In addition, the large-biotite facies occurs in identical pseudostratigraphic position on either side of the pluton. That particular facies has not been recognized as a map unit in any other La Posta–type pluton studied to date.

Petrography

The La Posta pluton is crudely circular and estimated to be approximately 1400 km² in total exposed area. Five lithologic facies (Fig. 1) have been recognized within the pluton (Kimzey, 1982). These, from the western contact inward, are the border, hornblende-biotite, large-biotite, small-biotite, and muscovite-biotite facies. The sequence is repeated in reverse order from the muscovite-bearing core eastward to the exposed edge of the pluton. Here, the pluton disappears beneath a cover of younger allu-

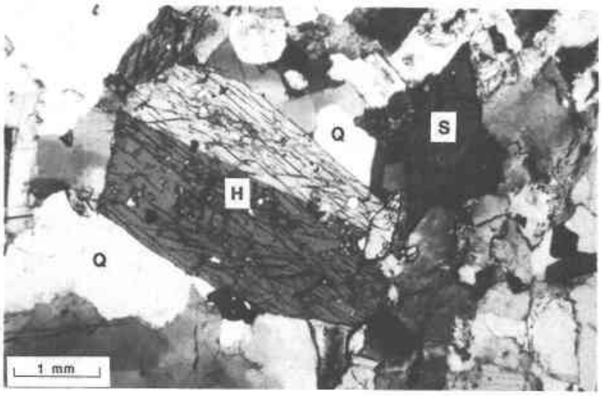

Fig. 2. Photomicrograph of sample 8 from the western hornblende-biotite facies. Q = quartz, H = hornblende, S = sphene. Idiomorphic hornblende boundaries against quartz indicate that hornblende growth had ceased by the time quartz began to nucleate.

vium such that neither the host rocks nor the border facies is exposed.

Border facies

The border facies, not shown in Figure 1, crops out in a narrow discontinuous band up to 100 m wide only where the La Posta pluton is in contact with the older igneous rocks of the western zone of the batholith. Where the pluton intrudes metasedimentary or metaigneous rocks, the border facies is absent, and the hornblende-biotite or large-biotite facies forms the outermost unit. The border facies changes inward from a banded marginal zone, through a gneissic, melanocratic biotite-hornblende diorite into weakly foliated and then nonfoliated hornblende-biotite facies rocks. All contacts are steep to vertical and subparallel to the margin of the pluton. This sequence is cut by narrow dikes of aplite and alkali feldspar megacrystic granite that form less than 10% of the exposures.

The banded marginal zone ranges up to 50 m in thickness and consists of alternating bands of plagioclase ± quartz and hornblende ± biotite, which range from a few centimeters to more than a meter in thickness. The mafic minerals are commonly aligned parallel to the banding but are typically subhedral to euhedral in form. The mafic diorites are in sharp contact with the banded zone but change laterally via an increase in plagioclase and a loss of gneissosity into unfoliated hornblende-biotite facies assemblages.

Hornblende-biotite facies

The hornblende-biotite facies is the main outer unit of both the eastern and western sides of the pluton. It is typically massive, but can exhibit a weak foliation near and parallel to the margin of the pluton. The dominant rock type is a sphene-hornblende-biotite tonalite that becomes progressively more enriched in alkali feldspar and depleted in hornblende inward.

The most obvious feature of this unit is the euhedral character of the hornblende, biotite, and sphene (Fig. 2), which occur as large discrete crystals up to 7 mm in length. Inclusions in the mafic minerals consist of ilmenite, apatite, zircon, and allanite (Clinkenbeard, 1987). This textural character is distinct from that of the hornblende and biotite in the older plutonic rocks to the west, which are commonly anhedral, charged with euhedral plagioclase inclusions, and intergrown with one another. Sphene in the older plutonic rocks is typically anhedral and intergrown with the biotite.

Plagioclase occurs as subhedral to euhedral crystals up to 10 mm in length that exhibit weak oscillatory or patchy zoning. They commonly have cores composed of two or more crystals joined in a synneusis relationship; the cores are mantled by less calcic rims. Alkali feldspar, where present, is interstitial and exhibits "gridiron" twinning. Locally, myrmekitic intergrowths occur at the contact between the two feldspars. Quartz exists as discrete or composite grains with weak undulatory extinction and moderately sutured boundaries.

Large-biotite facies

The sphene-hornblende-biotite tonalite of the hornblende-biotite facies grades inward into sphene-hornblende-biotite and sphene-biotite granodiorite of the large-biotite facies by loss of the large euhedral hornblende and an increase in both the size and abundance of the interstitial alkali feldspar. The presence of large (5–10 mm) pseudohexagonal books of biotite gives this rock a distinctive salt and pepper appearance. Small (1–3 mm) subhedral hornblende crystals are present in the outer portion of this facies but decrease in abundance toward the core of the pluton. Both biotite and hornblende are otherwise similar to those found in the hornblende-biotite facies.

Plagioclase occurs mainly as discrete subhedral crystals that average 3–4 mm in size but that may reach 10 mm. Oscillatory zoning is common. Quartz appears to be slightly coarser in this facies but is otherwise as described for the hornblende-biotite facies. Alkali feldspar is in greater abundance and tends to form oikocrysts up to 3 cm in size that enclose all of the above minerals. As in the hornblende-biotite facies, euhedral sphene is the main accessory mineral.

Small-biotite facies

Proceeding inward, the next zone of the La Posta pluton consists of biotite granodiorites that are texturally distinct from those in the large-biotite facies. The two facies have a gradational contact on the western side of the pluton, but this contact on the eastern side is at least in part intrusive (Sinfield, 1983).

The small-biotite facies is characterized by the presence of small (1–4 mm) euhedral to subhedral biotite crystals. Hornblende is scarce and, where present, occurs as minute inclusions in biotite or plagioclase. Plagioclase is present as 1- to 3-mm subhedral crystals, some of which

TABLE 1. Average modes of rocks in the study area

Mineral	W. H	W. LB	W. SB	MB	E. SB	E. LB	E. H	T
n	3	2	5	6	6	3	3	3
Quartz	25.1	29.4	31.5	36.1	34.5	35.8	29.8	26.3
Plagioclase	55.1	54.4	48.6	46.9	50.3	49.4	45.2	49.7
K-feldspar	2.7	4.2	7.6	8.0	4.6	3.2	0.8	0.2
Biotite	12.7	8.4	9.6	8.1	10.1	12.2	19.6	14.8
Hornblende	2.7	1.9	tr.	—	—	0.9	4.0	8.7
Muscovite	—	—	—	0.4	—	—	—	—
Sphene	0.4	0.6	0.1	—	tr.	0.8	0.9	tr.
Apatite	tr.	tr.	tr.	tr.	tr.	tr.	tr.	—
Zircon	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.
Allanite	tr.	tr.	tr.	—	—	tr.	tr.	—
Opaques	tr.	tr.	tr.	—	—	tr.	tr.	0.2
Myrmekite	0.4	0.4	0.4	tr.	tr.	0.1	—	—
Sericite	tr.	tr.	tr.	0.3	tr.	—	—	—
Chlorite	0.5	0.6	1.1	tr.	tr.	tr.	tr.	tr.
Epidote	tr.	tr.	tr.	—	tr.	tr.	tr.	tr.

Note: Facies designation as follows: H = hornblende-biotite, LB = large-biotite, SB = small-biotite, MB = muscovite-biotite, and T = western-zone tonalite. E. and W. represent the eastern and western sides of the pluton, respectively; *n* = number of analyses; tr. = trace.

are joined in a synneusis relationship. Weak oscillatory zoning is present, but the patchy zoning observed in the plagioclase of the hornblende-biotite and large-biotite facies is missing. Quartz is texturally similar to that found in the other facies but exhibits stronger undulatory extinction. Alkali feldspar typically forms oikocrysts up to several centimeters in size that have well developed "gridiron" twinning.

Muscovite-biotite facies

This facies is mainly found in the eastern portion of the La Posta pluton where it grades into the eastern small-biotite facies. Locally, however, muscovite-bearing granodiorite also occurs just west of the large metasedimentary screen (Fig. 1) in the central part of the study area. The main rock type is a muscovite-biotite granodiorite that is similar to the small-biotite facies except for the presence of 1- to 3-mm subhedral muscovite crystals and the absence of sphene. Based on the textural criteria of Miller et al. (1981), the muscovite is considered to be primary, i.e., magmatic in origin. Secondary muscovite (sericite) is present in trace amounts in the plagioclase.

Analytical methods

Chemical analyses of minerals in polished thin sections were made using the three-channel CAMECA MBX electron microprobe at the Scripps Institute of Oceanography. Operating conditions were as follows: accelerating potential = 15 kV, sample current = 15 nA on brass, spot size = 2 to 10 μm. Standards used for calibration were well-characterized silicates and oxides. Data reduction was performed on-line using the program CORREX, which is part of the MBXCOR software package. Mineral formulas for biotite, muscovite, plagioclase, alkali feldspar, and ilmenite were calculated using the program GEO, also part of the MBXCOR package. Amphibole formulas were calculated by using an electronic spreadsheet program in the manner suggested by Leake (1978). Their ferrous/ferric ratios were varied until the sum of the cations exclusive of Ca, Na, and K totaled 13. The ferrous/ferric ratios of selected biotite separates were determined with the technique of Fritz and Popp (1985).

Mineralogy

Amphibole

Amphibole is found only in the outer zones of the La Posta pluton. It occurs in significant amounts in the hornblende-biotite and large-biotite facies but decreases inward to trace amounts in the innermost portion of the large-biotite and throughout the small-biotite facies (Table 1). Hornblende is absent in all muscovite-bearing rocks.

Analyses of amphiboles from seven samples within the La Posta pluton and four samples in tonalitic rocks immediately west of the pluton (Fig. 1) are reported in Table 2. All samples plot close to the boundary between the magnesio- and ferro-hornblende fields (Fig. 3), but differences between the western and eastern sides of the pluton are apparent. Amphibole from the western hornblende-biotite and large-biotite facies have Si > 7.0, whereas those from the eastern equivalents have Si < 6.8. This difference is also observed in the lower Al_T of the amphiboles in the western half of the pluton (Table 2) and indicates that at the time of amphibole nucleation in the melt, conditions of lower a_{SiO_2} and higher $a_{Al_2O_3}$ existed in what is now the eastern side of the pluton.

Hammarstrom and Zen (1986) and Hollister et al. (1987) have defined a geobarometer based on the Al content of hornblende. Constraints on the use of this geobarometer were summarized by Hollister et al. (1987) and include the presence of magnetite among the opaque phases; a magmatic assemblage of hornblende, biotite, plagioclase, alkali feldspar, and quartz; and plagioclase rim compositions between An_{25} and An_{35}. The hornblende-bearing rocks of the La Posta pluton have plagioclase rim compositions between An_{27} and An_{37} and the required mineral paragenesis with the exception of mag-

TABLE 2. Average hornblende compositions of rocks in the study area

Unit:	W. H	W. H	W. LB	E. LB	E. H	E. H	E. H	T	T	T	T
Sample:	8	22	4	35	12	19	20	23	1	2	39
n:	6	4	7	4	5	5	4	7	7	8	4
SiO_2	47.62	47.30	47.76	45.54	43.81	44.46	44.25	44.82	44.68	42.93	46.42
TiO_2	1.01	1.06	1.01	1.11	1.22	1.08	1.02	1.12	1.21	1.23	1.29
Al_2O_3	6.74	7.13	6.46	8.85	10.24	10.20	10.68	9.64	9.20	10.17	8.81
Cr_2O_3	—	0.05	0.02	0.05	0.02	0.01	0.02	0.02	0.02	0.02	0.04
Fe_2O_3	—	—	—	—	—	—	—	—	—	—	—
FeO	18.34	18.49	18.69	18.01	18.80	18.20	18.53	17.18	17.70	18.78	16.43
MnO	0.60	0.64	0.59	0.55	0.47	0.44	0.45	0.41	0.43	0.43	0.39
MgO	10.52	10.22	10.48	9.73	9.19	9.24	9.06	10.76	10.52	9.60	12.01
CaO	11.91	11.73	12.02	11.88	12.15	11.78	12.00	12.09	12.06	12.18	11.47
Na_2O	0.98	1.02	0.93	1.04	1.16	1.15	1.15	1.06	1.11	1.18	1.16
K_2O	0.51	0.60	0.57	0.86	0.97	0.89	1.01	0.71	0.68	1.10	0.41
NiO	0.02	0.05	0.02	0.04	—	0.03	0.02	0.01	0.01	0.02	0.02
P_2O_5	0.10	0.10	0.09	0.10	0.11	0.10	0.10	0.10	0.10	0.11	0.11
Total	98.35	98.39	98.64	97.76	98.13	97.59	98.29	97.92	97.72	97.75	98.56
Fe/(Fe + Mg)	0.64	0.64	0.64	0.65	0.67	0.67	0.67	0.61	0.63	0.66	0.58
Si	7.05	7.00	7.06	6.81	6.57	6.67	6.61	6.64	6.65	6.47	6.72
Al	0.95	1.00	0.94	1.19	1.43	1.33	1.39	1.36	1.35	1.53	1.28
Sum	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al	0.22	0.24	0.19	0.37	0.38	0.47	0.49	0.32	0.46	0.28	0.22
Fe^{3+}	0.30	0.34	0.28	0.25	0.28	0.27	0.25	0.47	0.46	0.42	0.76
Cr	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01
Ni	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.11	0.12	0.11	0.13	0.14	0.12	0.11	0.13	0.14	0.14	0.14
Mg	2.32	2.25	2.31	2.17	2.06	2.07	2.02	2.37	2.33	2.16	2.59
Fe^{2+}	1.97	1.95	2.03	2.00	2.08	2.01	2.06	1.66	1.74	1.94	1.23
Mn	0.08	0.08	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.06	0.05
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	5.00	5.00	5.00	5.01	5.01	5.00	5.00	5.01	4.99	5.01	5.00
Fe^{2+}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	1.89	1.86	1.90	1.90	1.95	1.89	1.92	1.92	1.92	1.97	1.78
Na	0.11	0.14	0.09	0.10	0.05	0.11	0.08	0.08	0.08	0.03	0.22
Sum	2.00	2.00	1.99	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Na	0.17	0.15	0.18	0.20	0.29	0.22	0.25	0.22	0.24	0.31	0.11
K	0.10	0.11	0.11	0.16	0.19	0.17	0.19	0.13	0.13	0.21	0.08
Sum	0.27	0.26	0.29	0.36	0.48	0.39	0.44	0.35	0.37	0.52	0.19

Note: Unit abbreviations as in Table 1. Formulas based on 23(O,OH); *n* = number of analyses.

netite. However, the data used to establish the high-pressure end of the geobarometer are from the magnetite-free Ecstall pluton (Hammarstrom and Zen, 1986) and raise some question as to the importance of magnetite as a requirement. Pressure estimates of synchronous (93 Ma) and spatially associated garnet-muscovite-biotite monzogranites (Fig. 1) range between 2.7 and 3.0 kbar (Clinkenbeard, 1987) and indicate that the La Posta pluton was emplaced above the 2-kbar minimum pressure required by the geobarometer. Hollister et al. (1987) argued that only rim compositions of the hornblende crystals should be used because these are likely to have formed from the late stages of the melt and therefore in a narrow range of temperatures. Our analyses, part of a larger study, were completed prior to the publication of the above restrictions. Grain traverses and random spot analyses (both rim and core as seen in thin section) showed little compositional variation within individual grains or from grain to grain in single samples. The data are reported as sample averages in Table 2 with the average value of Al_T for each sample applied to the geobarometer (Table 3).

The lack of compositional zoning and constant composition of hornblende with respect to changing rock (melt?) chemistry (Clinkenbeard, 1987) suggest that hornblende equilibrated with an intermediate rather than a late stage of the La Posta melt. On the basis of textural criteria, Clinkenbeard (1987) also argued that hornblende nucleated early in the cooling history of the melt and that its growth had effectively ceased before the appearance of quartz and orthoclase. In addition, the low abundance of alkali feldspar in the hornblende-bearing rocks (Table 1) and its interstitial character may indicate that the hornblende grains were not in contact with an alkali feldspar–saturated melt. Thus, amphibole may not have equilibrated under the thermal and compositional restrictions of the geobarometer.

Despite this complicating and unknown factor, a plot of $^{[4]}Al$ versus Al_T (Fig. 4) for the La Posta pluton overlaps the data shown by Hammarstrom and Zen (1986) for several plutons from different pressure regimes. Their data indicate that hornblende from high-pressure (epidote-bearing) plutons have $Al_T > 1.8$. Three of four analyses

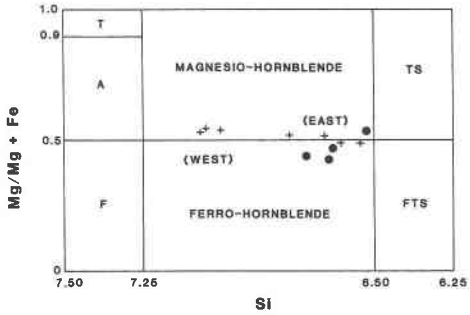

Fig. 3. Hornblende classification after Leake (1978). Crosses represent hornblendes from the western and eastern facies of the La Posta pluton. Solid circles represent hornblendes from an older tonalite body adjacent to the western margin of the pluton. Remaining fields are T = tremolitic hornblende, A = actinolitic hornblende, F = ferro-actinolitic hornblende, TS = tschermakitic hornblende, and FTS = ferro-tschermakitic hornblende.

Table 3. Calculated *P-T* conditions

Sample no.	Unit	P_T (kbar)	Average P_T (kbar)	T (°C)	Average T (°C)
22	W. H	2.3		742	
8	W. H	1.9	1.9	738	740
4	W. LB	1.6		739	
12	E. H	5.5		777	
19	E. H	5.4		757	
20	E. H	5.8	5.2	761	763
35	E. LB	4.0		756	
1	T	4.3		789	
2	T	5.4		805	
23	T	4.7	4.5	783	791
39	T	3.7		787	
11	MB	—		480	
18	MB	—		570	

Note: Unit abbreviations as in Table 1. P_T was calculated from the algorithm of Hollister et al. (1987); average value for Al_T for each sample was used in the calculation. Error range based on multiple analyses in each sample is 0.7 kbar. Temperatures for the hornblende-bearing rocks were calculated using the algorithm of Nabelek and Lindsley (1985) and utilized the calculated P_T for each sample. Temperatures for the muscovite-bearing rocks are from the plagioclase-muscovite geothermometer of Green and Usdansky (1986) and are based on the rim compositions of plagioclase.

from the eastern side of the La Posta pluton have $Al_T > 1.8$, whereas those from the western side have $Al_T < 1.8$. Epidote occurs as an accessory mineral throughout the La Posta pluton except in the innermost muscovite-bearing facies. It is typically granular and mantles allanite where the latter was in contact with biotite. We interpret this relationship to indicate that epidote is not a primary magmatic mineral and that its presence does not imply crystallization under high (8 kbar?) pressure.

Results of the hornblende geobarometer (Hollister et al., 1987) are listed in Table 3 and appear to indicate that the western side of the La Posta pluton was emplaced at considerably shallower levels (1.9 kbar) than the eastern side (5.2 kbar) and the older tonalitic pluton to the west (4.5 kbar). This suggested relationship implies that major structural discontinuities exist at the western edge of the pluton and at an unknown central location within the pluton. Field relationships and radiometric ages (Walawender et al., 1989), however, do not support such an interpretation. The contact with the older tonalitic pluton is clearly intrusive, and evidence to support a major structural feature in either the metasedimentary screen or the interior of the pluton is lacking.

Temperature estimates of the La Posta pluton were based on the $^{[4]}Al$ content of the amphibole in the hornblende-biotite and large-biotite facies. This geothermometer (Nabelek and Lindsley, 1985) is designed for use with amphiboles in equilibrium with intermediate composition plagioclase (An_{40}–An_{65}). Amphiboles in this study coexist with weakly zoned plagioclase whose compositions fall just below this range (Table 5). The results are given in Table 3 and indicate that the plagioclase-amphibole equilibration occurred at lower average temperature (740 °C) on the western side of the pluton than on the eastern side (763 °C). The lower temperature can be correlated to the coarsely bracketed lower limit of amphibole stability in a granodiorite system at 2 kbar (Naney, 1983) and appears to reflect near-solidus equilibration. Data for the same system at 8 kbar indicate that this limit would migrate to lower temperatures, i.e., show a negative correlation between equilibration temperature and pressure. The higher pressure and temperature estimates for the eastern side of the pluton (763 °C, 5.2 kbar), therefore, are in direct conflict with the experimental data. The plagioclase-muscovite geothermometer of Green and Usdansky (1986) was used to calculate temperatures for the muscovite-bearing rocks and gave subsolidus conditions (Table 3).

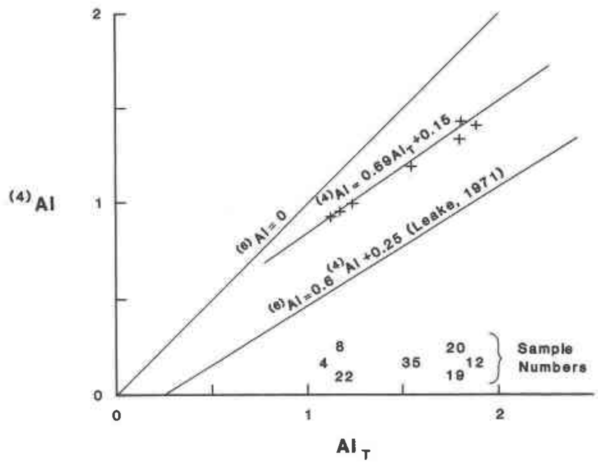

Fig. 4. $^{[4]}Al$ versus Al_T for hornblende in the La Posta pluton. The upper line represents the limiting condition of $^{[4]}Al = 0$ whereas the lower line is the lower limit of igneous amphiboles as defined by Leake (1971). The middle line represents the regression curve of Hammarstrom and Zen (1986) and closely approximates the data from this study. Our data yielded a regression fit of $^{[4]}Al = 0.64\ Al_T + 0.23$ and a correlation coefficient of 0.991.

Table 4. Average compositons of biotite and muscovite

	Biotite						
Unit:	W. H	W. H	W. LB	W. SB	MB	MB	MB
Sample:	8	22	4	5	11	14	18
n:	4	5	5	5	3	4	5
SiO_2	35.78	34.85	35.61	35.80	34.28	33.55	33.81
TiO_2	3.59	3.64	3.70	4.18	3.15	3.39	3.50
Al_2O_3	15.52	14.88	15.23	14.74	18.66	17.40	18.72
Cr_2O_3	0.02	0.02	0.04	0.02	0.02	0.01	0.04
Fe_2O_3	n.d.	0.46	2.56	n.d.	10.19	6.57	2.64
FeO	21.84	21.32	20.28	22.63	15.91	18.85	21.72
MnO	0.33	0.35	0.31	0.40	0.35	0.34	0.41
MgO	9.50	8.97	9.20	8.88	5.72	5.98	5.65
CaO	0.01	0.28	0.02	0.03	0.01	0.01	0.04
Na_2O	0.10	0.09	0.09	0.14	0.07	0.08	0.07
K_2O	9.07	9.04	9.55	9.36	9.69	8.91	8.93
NiO	0.01	0.03	0.02	0.01	0.01	0.02	0.02
P_2O_5	0.01	—	0.09	0.10	0.11	0.01	0.01
Total	95.78	93.93	96.70	96.29	98.17	96.12	95.56
Fe/(Fe + Mg)	0.70	0.71	0.72	0.72	0.83	0.81	0.81
Si	5.50	5.49	5.48	5.51	5.29	5.31	5.29
Al	2.50	2.51	2.52	2.49	2.71	2.69	2.71
Sum	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al	0.32	0.26	0.24	0.19	0.68	0.56	0.73
Fe^{3+}	0.00	0.05	0.29	0.00	1.15	0.77	0.31
Cr	0.01	0.01	0.01	0.01	0.01	0.00	0.01
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.42	0.43	0.43	0.48	0.37	0.40	0.41
Mg	2.18	2.11	2.11	2.04	1.32	1.41	1.32
Fe^{2+}	2.81	2.81	2.59	2.92	2.00	2.46	2.82
Mn	0.04	0.05	0.04	0.05	0.05	0.05	0.05
Sum	5.78	5.72	5.71	5.69	5.57	5.65	5.65
Ca	0.00	0.05	0.00	0.01	0.00	0.00	0.00
Na	0.03	0.03	0.03	0.04	0.02	0.03	0.03
K	1.78	1.82	1.87	1.84	1.91	1.80	1.78
Sum	1.81	1.90	1.90	1.89	1.93	1.83	1.81

	Biotite					
Unit:	MB	E. LB	E. LB	E. H	E. H	E. H
Sample:	32	13	35	12	19	20
n:	4	6	5	4	7	4
SiO_2	34.32	35.06	35.33	35.86	34.74	35.66
TiO_2	3.33	3.00	2.82	3.26	3.09	3.31
Al_2O_3	18.19	16.56	16.49	16.30	16.10	16.59
Cr_2O_3	0.01	0.02	0.02	0.04	0.03	0.02
Fe_2O_3	n.d.	n.d.	2.23	n.d.	0.70	4.81
FeO	24.50	21.53	19.06	20.96	19.83	15.95
MnO	0.27	0.33	0.32	0.28	0.26	0.27
MgO	5.94	8.77	9.54	9.72	9.60	9.67
CaO	0.01	—	0.01	—	0.15	0.01
Na_2O	0.08	0.09	0.09	0.28	0.07	0.09
K_2O	9.04	9.04	8.94	9.06	8.93	9.11
NiO	0.03	0.03	0.01	0.03	0.02	0.01
P_2O_5	0.02	0.01	0.01	0.01	0.01	0.02
Total	95.64	94.44	94.87	95.80	93.53	95.51
Fe/(Fe + Mg)	0.80	0.71	0.69	0.68	0.68	0.69
Si	5.33	5.46	5.47	5.48	5.45	5.48
Al	2.67	2.54	2.53	2.52	2.55	2.52
Sum	8.00	8.00	8.00	8.00	8.00	8.00
Al	0.68	0.50	0.48	0.42	0.43	0.48
Fe^{3+}	0.00	0.00	0.26	0.00	0.08	0.55
Cr	0.00	0.01	0.01	0.01	0.01	0.01
Ni	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.39	0.35	0.33	0.38	0.37	0.38
Mg	1.38	2.04	2.20	2.22	2.25	2.21
Fe^{2+}	3.19	2.81	2.46	2.68	2.60	2.02
Mn	0.04	0.04	0.04	0.04	0.04	0.04
Sum	5.68	5.75	5.78	5.75	5.78	5.69
Ca	0.00	0.00	0.00	0.00	0.02	0.00
Na	0.02	0.03	0.03	0.08	0.02	0.03
K	1.80	1.80	1.77	1.77	1.79	1.79
Sum	1.82	1.83	1.80	1.85	1.83	1.82

Note: Unit abbreviations as in Table 1. Formulas are based on 22(O,OH); *n* = number of analyses.

Micas

Biotite is the most common mafic mineral in all facies of the La Posta pluton. It nucleated after hornblende and typically formed discrete subhedral to euhedral crystals. Lack of fine-grained biotite along rims of the hornblende grains indicates that reaction of hornblende with melt to produce biotite did not play a role in the evolution of the melt system.

Smith and Walawender (1987) reported the presence of significant quantities (up to 67%) of vermiculite within biotite separates from the La Posta pluton. However, the data from that report cannot be either reconciled with the analyses reported in this study or replicated in our laboratory. The sample-preparation techniques employed in that earlier study appear to favor concentration of vermiculite relative to biotite in the -10-μm fraction and led to strongly biased results.

Biotite compositions from 13 samples of the La Posta pluton and from 4 samples of the adjacent tonalitic unit (Fig. 1) are listed in Table 4. Biotites coexisting with amphibole, including those from the older tonalite to the west, form a tight cluster near the center of the phlogopite-annite-eastonite-siderophyllite quadrilateral (Fig. 5). Biotites coexisting with muscovite, however, form a distinct group with higher $^{[4]}Al$ and Fe/(Fe + Mg). The higher Al content of biotite from the eastern versus western side of the pluton is apparent in Figure 6, which depicts a threefold grouping that is both geographic (west versus east) and lithologic (muscovite-bearing versus hornblende-bearing). Similar differences have also been reported by de Albuquerque (1973) for a series of discrete biotite and biotite-muscovite granodiorite plutons in the Aregos region of Portugal and by Speer (1981) for biotite and biotite-cordierite assemblages in the Cloud Creek pluton, South Carolina. The latter, however, showed no significant change in Fe/(Fe + Mg) and has considerable $^{[4]}Al$ overlap between the two assemblages whereas the Portugal study documents a continuum in terms of Fe/(Fe + Mg) rather than distinct jumps.

Wones and Eugster (1965) argued that the Fe/(Fe + Mg) of biotites should increase during differentiation. This ratio increases slightly (0.68–0.72, Table 4) from the hornblende-bearing rocks on each margin of the pluton inward but jumps to 0.81 in the muscovite-bearing core. This abrupt change is not consistent with in situ fractional crystallization and implies that a compositional discontinuity exists between the core zone of the pluton and its marginal facies.

TABLE 4—*Continued*

Biotite				Muscovite	
T 1 4	T 2 4	T 39 4	T 23 5	MB 11 9	MB 18 8
35.06	35.33	35.86	34.74	45.40	45.11
3.00	2.82	3.26	3.09	0.79	0.89
16.56	16.49	16.30	16.10	34.87	34.22
0.02	0.02	0.04	0.03	—	—
3.08	—	2.73	—	—	—
16.97	20.84	16.13	19.33	2.23	2.27
0.33	0.32	0.28	0.26	0.02	0.01
8.77	9.54	9.72	9.60	0.81	0.87
0.27	0.01	0.02	0.01	0.01	0.01
0.13	0.09	0.19	0.15	0.39	0.37
9.13	9.10	8.82	9.12	11.08	10.86
0.03	0.01	0.03	0.02	—	—
0.01	0.01	0.01	0.01	—	—
93.06	95.78	93.39	92.46	95.60	94.60
0.70	0.69	0.66	0.67		
5.46	5.48	5.53	5.49	6.08	6.11
2.54	2.52	2.47	2.51	1.92	1.89
8.00	8.00	8.00	8.00	8.00	8.00
0.50	0.49	0.49	0.48	3.59	3.56
0.36	—	0.32	—	—	—
0.01	0.01	0.01	0.01	—	—
0.00	0.00	0.00	0.00	—	—
0.35	0.33	0.38	0.37	0.08	0.09
2.05	2.20	2.24	2.26	0.16	0.18
2.21	2.70	2.08	2.55	0.25	0.26
0.04	0.04	0.04	0.03	0.00	0.00
5.52	5.77	5.56	5.70	4.08	4.09
0.05	0.00	0.00	0.00	0.00	0.00
0.04	0.03	0.06	0.05	0.10	0.10
1.82	1.80	1.74	1.84	1.89	1.88
1.91	1.83	1.80	1.89	1.99	1.98

Biotite was separated from eight samples of the La Posta pluton and two samples of the older tonalite adjacent to its western margin (Fig. 1). From the microprobe-derived FeO (total Fe) analyses, FeO and Fe_2O_3 were determined by using the technique of Fritz and Popp (1985). The results are listed in Table 4. Wones and Eugster (1965) determined that biotites crystallizing from a common parental magma under oxygen-buffered conditions should plot on a trend with significant increases in Fe/(Fe + Mg) but only modest increases in the ferrous/ferric ratio. Data from the La Posta pluton are plotted on the Fe^{2+}-Fe^{3+}-Mg ternary diagram (Fig. 7a) along with the trends for several oxygen-buffered systems (Wones and Eugster, 1965). The data are again clearly separated into two groups representing biotite coexisting with hornblende and biotite coexisting with muscovite. Both groups, however, have subparallel trends that cut across the trends of oxygen-buffered systems; the most pronounced increase in Fe^{3+} occurs in biotites from the muscovite-biotite facies in the core of the pluton. These data are not consistent with crystallization under buffered conditions. They suggest that a source more oxidized than the parental melt contributed to the system and that this contribution is greater in the core of the pluton than in its outer facies. The data

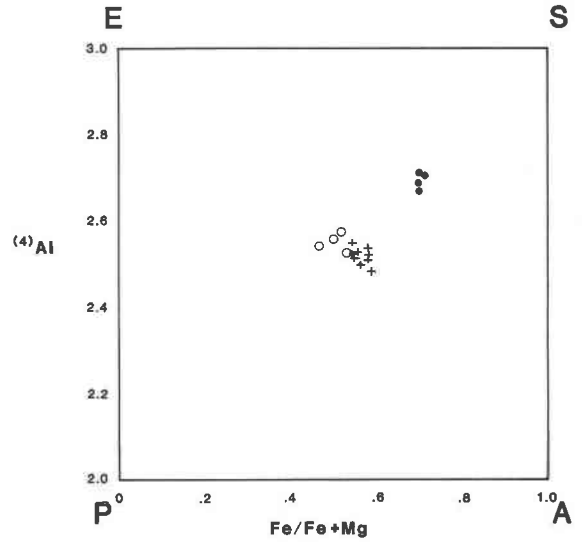

Fig. 5. Ideal biotite compositional plane modified from Deer et al. (1963). Crosses and solid dots represent biotites from the La Posta pluton that coexist with hornblende and muscovite, respectively. Open circles are analyses of biotites that coexist with hornblende from the adjacent older tonalite. End-members are E = eastonite, S = siderophyllite, P = phlogopite, and A = annite.

also suggest that the parental melt for the magnetite-free La Posta pluton was more reduced than the fayalite-quartz-magnetite buffer. In contrast, the data for biotite from two samples of the older western tonalite and five biotite analyses from other plutons in the western zone of the batholith (Larsen and Draisen, 1950) cluster above the Ni-NiO buffer (Fig. 7b) and further emphasize the differences between the older plutons in the western zone of the batholith and the younger La Posta–type plutons.

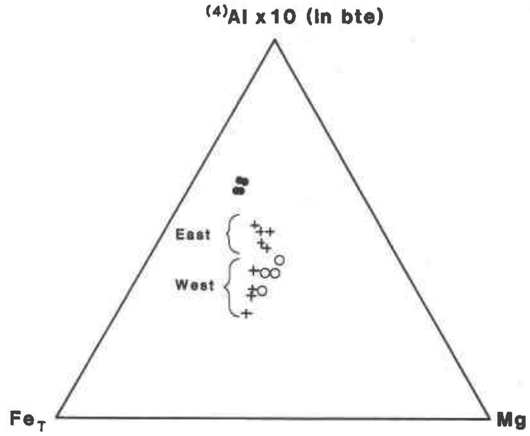

Fig. 6. Fe_T–($^{[4]}Al$ × 10)–Mg ternary diagram for biotite. Symbols as in Fig. 5. Brackets depict samples from the western and eastern sides of the pluton and emphasize their differences in $^{[6]}Al$.

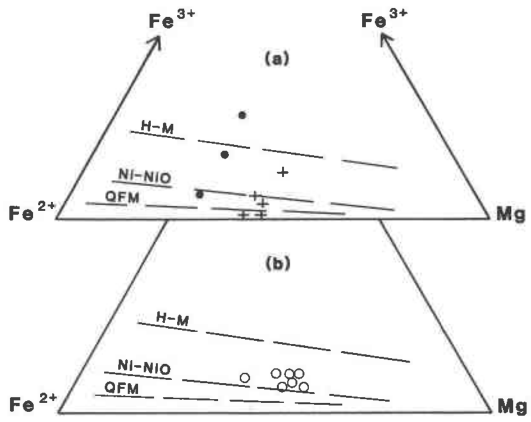

Fig. 7. Fe^{2+}-Fe^{3+}-Mg ternary diagram for biotite after Wones and Eugster (1965). Dashed lines represent compositional trends under buffered conditions; QFM = quartz-fayalite-magnetite, Ni-NiO = nickel–nickel oxide, and HM = hematite-magnetite. Symbols as in Fig. 5. (**a**) Data from the La Posta pluton. (**b**) Data from plutons in the western zone of the batholith (see text).

Table 5. Average analyses of feldspars in the study area

			Plagioclase		
Unit	W. H	W. H	W. LB	W. SB	MB
Sample	8	22	4	5	11
Ab	67.0(3.7)	63.9(7.5)	66.9(4.2)	61.8(3.1)	72.4(2.0)
Or	1.2(0.3)	1.5(0.3)	1.4(0.5)	1.0(0.2)	1.2(0.2)
An	32.2(4.0)	34.6(7.7)	31.8(4.6)	37.2(3.3)	26.4(2.2)
			Plagioclase		
Unit	MB	MB	MB	E. LB	E. LB
Sample	14	18	32	13	35
Ab	72.0(1.1)	74.1(1.0)	73.4(1.1)	67.1(3.7)	65.9(2.3)
Or	1.3(0.3)	1.1(0.2)	1.7(0.2)	1.5(0.2)	1.2(0.3)
An	26.9(0.5)	24.7(1.4)	25.1(1.3)	31.4(3.7)	33.0(2.4)
			Plagioclase		
Unit	E. H	E. H	E. H	T	T
Sample	12	19	20	2	23
Ab	62.9(1.5)	62.4(1.7)	65.2(2.2)	59.5(1.6)	53.9(1.1)
Or	1.1(0.2)	1.2(0.3)	1.1(0.2)	1.4(0.2)	1.0(0.1)
An	36.0(1.6)	36.3(1.8)	33.7(2.2)	39.1(1.7)	45.1(1.1)
			Plagioclase and alkali feldspar		
Unit	T	W. LB	W. SB	MB	MB
Sample	39	4	6	11	18
Ab	61.1(2.5)	7.0(2.6)	8.0(2.4)	9.6(2.0)	7.9(0.8)
Or	0.6(0.1)	93.0(2.7)	91.9(2.5)	90.3(2.0)	92.1(0.8)
An	38.3(2.5)	0.0(0.0)	0.1(0.0)	0.1(0.0)	0.0(0.0)

Note: Unit abbreviations as in Table 1. Number in parentheses is one standard deviation. All plagioclase values were calculated from three analyses each of grain center and rim. All alkali feldspars were calculated from an average of five analyses per sample.

Miller et al. (1981) summarized textural and geochemical criteria for the recognition of primary versus secondary muscovite. Both types occur in the muscovite-biotite facies of the pluton, but only those meeting the textural criteria for primary (magmatic) origin were analyzed in this study. The results are listed in Table 4 and are in close agreement with the "typical" primary muscovite of Miller et al. (1981) in terms of their higher Al_2O_3 and TiO_2 and lower MgO contents.

Feldspars

Plagioclase feldspar is the most abundant mineral in the La Posta pluton. It occurs as subhedral to euhedral grains with moderate normal to weak oscillatory zoning and formed throughout the crystallization history of the pluton. In contrast, alkali feldspar is typically found only in the three interior facies of the pluton and occurs as interstitial fillings or equidimensional poikilitic patches up to 4 cm in diameter. Calculated end-member fractions are given in Table 5.

Figure 8 shows the variation in plagioclase composition across the pluton. Plagioclase compositions for the hornblende-biotite, large-biotite, and small-biotite facies average approximately An_{35} and are essentially identical on either side of the pluton. Plagioclase in the muscovite-biotite facies, however, shows a rather abrupt decrease in average composition to approximately An_{25}. Core and rim compositions are plotted against Fe/(Fe + Mg) for coexisting biotite (Fig. 9) and indicate that a compositional gap exists for both minerals. Alkali feldspar compositions vary little between the three innermost facies of the pluton.

Opaque minerals

Because of the scarcity of opaque minerals in the rocks of this study, they were quantitatively analyzed in only three samples. These samples were from the two outermost facies on the west side of the pluton and the adjacent older tonalite. The results are given in Table 6. Opaque minerals that were encountered in the course of analyzing other minerals were examined semiquantitatively with the energy-dispersive spectrometer (EDS) on the microprobe. All of the opaque grains analyzed in samples from the La Posta pluton, including those examined by the EDS, were found to be ilmenite. The sample from the western zone tonalite was found to contain mostly ilmenite, but one grain of the six analyzed was found to be magnetite. This is consistent with the findings of Gastil et al. (1989) that the magnetite-ilmenite line in the Peninsular Ranges batholith coincides with the western boundary of the La Posta pluton.

Conclusions

Equilibration of hornblende with plagioclase of similar compositions on both sides of the pluton at different but geologically reasonable temperatures suggests differences in the cooling histories of opposite sides of the pluton. Naney and Swanson (1980) pointed out that undercooling of intermediate-composition melts leads to a more rapid nucleation of mafic minerals such as hornblende and biotite relative to feldspar and quartz. The presence of mafic mineral–rich rocks in the banded part of the border facies suggests that the western margin may have undergone more severe undercooling relative to the eastern margin. Whether this process is responsible for the lower mafic mineral content in the western hornblende-

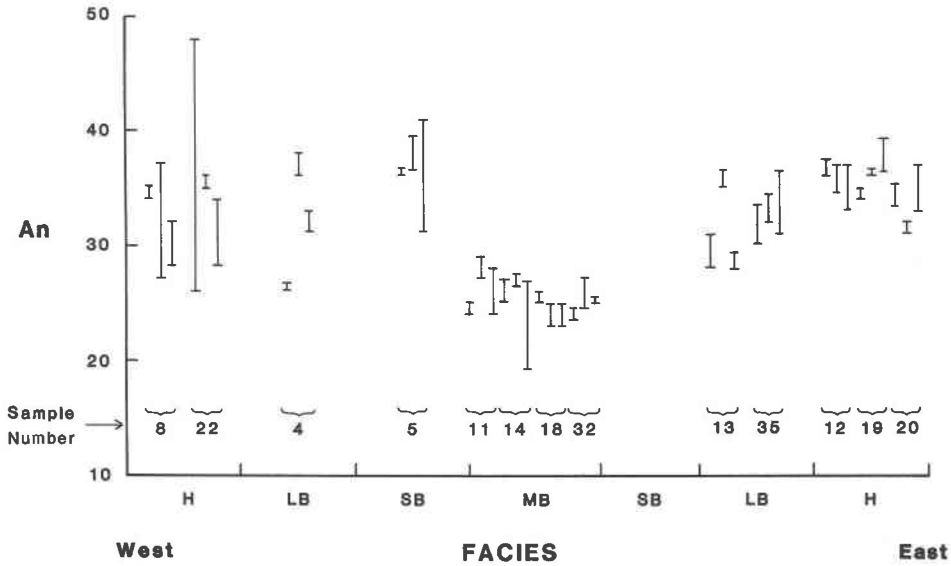

Fig. 8. Schematic variation in plagioclase composition from west to east across the pluton. Three rim and core analyses (Table 5) are shown for each sample. Facies symbols are H = hornblende-biotite, LB = large-biotite, SB = small-biotite, and MB = muscovite-biotite.

biotite facies (Table 1) is speculative but cannot be ruled out.

The hornblende geobarometry for the two sides of the La Posta pluton and the older tonalitic body adjacent to the western contact (Table 3) overlaps with somewhat less precise estimates of P_T (2–5 kbar) for the medial zone of the batholith (Walawender and Smith, 1980; Berggreen and Walawender, 1977; Detterman, 1984; Eaton, 1982; Diercks, 1981) that were based on coexisting mineral assemblages in both the metamorphic and plutonic rocks. Other geobarometric techniques have yielded more precise results. Taylor et al. (1979) calculated that a pressure of 2.1 kbar was required to correct fluid-inclusion closure temperatures in pegmatites north of the study area to temperatures consistent with those calculated from their oxygen-isotope data. London (1986) estimated an emplacement depth between 2.4 and 2.8 kbar for the same pegmatite system on the basis of phase equilibria for the pocket minerals. Clinkenbeard (1987) used the Ca-exchange geobarometer of Ghent and Stout (1981) on the 93 Ma garnet-bearing monzogranite near the center of the study area (Fig. 1) and calculated P_T between 2.7 and 3.0 ± 0.5 kbar. K. E. Parrish (unpublished data) reported P_T of 2.5 ± 0.5 kbar for a similar garnet-bearing monzogranite located near the northern end of the central metamorphic screen (Fig. 1). Although the hornblende geobarometry reported in this study brackets these latter figures, the difference between the western and eastern sides of the La Posta pluton does not fall within the error estimates of Hollister et al. (1987). We also argue that the variation in emplacement depths (P_T) calculated from the hornblende geobarometer is not consistent with either the known field and age relationships, experimentally determined variation in solidus temperature with pressure,

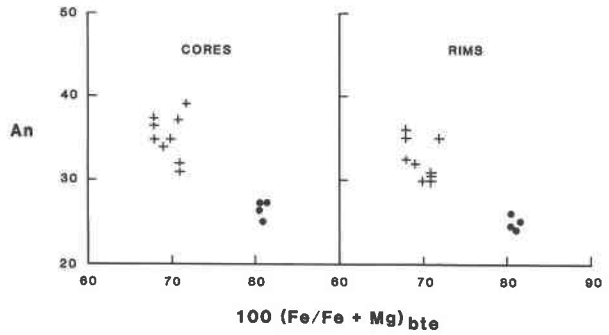

Fig. 9. Average rim and core compositions for plagioclase versus 100 Fe/(Fe + Mg) in coexisting biotite. Symbols as in Fig. 5.

Table 6. Average analyses of opaque minerals

Unit:	W. LB	W. H	T	T
Sample:	4	8	39	39
n:	6	4	5	1
FeO	43.20	45.41	51.30	93.30
MgO	0.13	0.05	0.15	—
TiO_2	51.23	50.29	42.54	0.02
MnO	2.75	2.04	1.56	—
Total	97.31	97.79	95.55	93.32
Fe^{2+}	1.846	1.857	1.591	8.004
Fe^{3+}	0.024	0.101	0.654	15.990
Mg	0.010	0.004	0.012	—
Ti	1.994	1.949	1.672	0.005
Mn	0.136	0.089	0.069	—
Sum	4.009	4.000	3.998	23.999

Note: Unit abbreviations as in Table 1. Mineral formulas are based on 6 oxygens for ilmenite and 32 oxygens for magnetite; *n* = number of analyses.

or other geobarometers based on mineral chemistries. This discrepancy could be due to equilibration of hornblende with an intermediate stage of the La Posta melt rather than with the alkali feldspar–saturated stage required by Hollister et al. (1987). Under this condition, the Al_T content of amphibole would not reflect a simple pressure control but would depend upon other variables in the melt system such as the temperature of hornblende equilibration. Thus, local perturbations in cooling histories may also be important in terms of controlling hornblende compositions.

Unlike hornblende, biotite is found in all facies of the La Posta pluton so that its compositional variations reflect the entire range of melt compositions during crystallization. Modest but identical increases in Fe/(Fe + Mg) from the marginal hornblende-biotite facies inward through the large-biotite and small-biotite facies are consistent with in situ fractional crystallization. However, the jump in that ratio (Table 4) combined with a sharp decrease in plagioclase composition (Fig. 8, Table 5) across a gradational contact into the muscovite-biotite facies reflects a compositional discontinuity between the outer facies and the muscovite-bearing core.

In addition, the ferrous/ferric ratios of biotite vary considerably, with the greater degree of variation found in the muscovite-bearing core of the pluton (Fig. 7a). The data form subparallel, quasi-linear arrays that we interpret to represent mixing of two components with different ferrous/ferric ratios. The parental magma is considered to be the most reduced component since no evidence of a reducing mechanism, e.g., inclusions of C-bearing metasedimentary material, has been observed. As such, the parental magma would have had original oxygen fugacities more reducing than the QFM buffer (Fig. 7a). The remaining component in this mixing relationship is more problematic.

Walawender et al. (1989) described anomalous isotopic patterns (higher $\delta^{18}O$ in quartz, excess radiogenic Sr, and higher contents of inherited zircon) in the muscovite-bearing cores of several La Posta–type plutons in southern and Baja California and concluded that they represent mixing of a parental melt, which was derived primarily from subducted oceanic crust, and a continental component with an average age of approximately 1300 Ma. We would add oxidizing capabilities greater than the Ni-NiO buffer and relatively high Fe/(Fe + Mg) to the aforementioned characteristics of this continental component. The parental La Posta melt rose between the older western zone of the batholith and the leading edge of the North American craton (Gastil, 1975). We suggest that during ascent, the portion of the rising diapir adjacent to the deeper (granulite facies?) segments of the craton reacted with crustal materials, whereas the remainder of the diapir rose and expanded into the overlying metasedimentary apron. Inward crystallization produced the marginal facies, but prior to the solidification of the small-biotite facies, the isotopically enriched and more oxidized tail of the diapir entered the magma chamber and mixed with the derivative liquid. The resulting hybrid melt could only undergo limited mixing and diffusion with the already partly solidified outer zones of the pluton and cooled in situ to form the muscovite-bearing core with its gradational contacts. We would extend this model to include all of the zoned and lithologically similar La Posta–type plutons in southern and Baja California.

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