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ORIGIN OF THE MAGNETITE BOUNDARY IN THE PENINSULAR RANGES BATHOLITH, SOUTHERN CALIFORNIA, U.S.A., AND BAJA CALIFORNIA, MEXICO

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ABSTRACT

In the Peninsular Ranges of southern California, U.S.A., and Baja California, Mexico, the Cretaceous granitic rocks to the southwest, nearly all of which contain magnetite, adjoin Cretaceous granitic rocks to the northeast, nearly all of which are magnetite-free, along a narrow northwest-trending zone called the "magnetite boundary." A few granitic plutons that straddle this boundary grade from magnetite-bearing (early) to magnetite-free (late).

To investigate the factors that cause variations in magnetite content traverses across representative plutons were examined for variation in whole-rock and mineral chemistry, iron-oxidation state, ammonium in biotite, and non-carbonate carbon in the rock. Texture, mineralogy, and chemistry are generally similar in the magnetite-bearing and magnetite-free tonalite and granodiorite located along and east of the magnetite boundary (La Posta-type plutons), but oxygen fugacity is generally higher in magnetite-bearing rocks. Oxygen fugacity differences in the larger plutons are not clearly related to either the abundance of ammonium in biotite or to non-carbonate carbon in the rock, but may be related to a greater abundance of iron relative to magnesium (in the melt), which could decrease oxygen fugacity and impede the crystallization of magnetite.

Key words: Magnetite boundary, Peninsular Ranges batholith, Baja California, Mexico, California, U.S.A.

RESUMEN

En las Sierras Peninsulares de California meridional, E.U.A., y de Baja California, México, las rocas graníticas cretácicas localizadas hacia el sudponiente, las cuales casi todas contienen magnetita, están junto a rocas graníticas cretácicas situadas al noreste, casi todas carentes totalmente de magnetita, a lo largo de una zona angosta alineada al norponiente, llamada la "frontera de magnetita". Algunos cuerpos plutónicos graníticos que están a lo largo de esta frontera muestran una gradación que varía desde con magnetita (tempranos), hasta libres de magnetita (tardíos).

Para investigar los factores que causan las variaciones en el contenido de magnetita, se examinó mediante recorridos a cuerpos plutónicos representativos, analizando la química, tanto de roca entera como de minerales de las rocas, el estado de oxidación del hierro, el contenido de amoníaco en la biotita, y el contenido del carbón no procedente de carbonatos. La textura, mineralogía y química son generalmente semejantes en la tonalita y la granodiorita, con o sin magnetita, localizadas tanto a lo largo como al oriente de la frontera de magnetita (cuerpos plutónicos de tipo La Posta), no obstante que la fugacidad de oxígeno es generalmente más alta en las rocas con magnetita. Las diferencias en la fugacidad de oxígeno en los cuerpos plutónicos más grandes no parecen estar claramente relacionadas ni con la abundancia del amoníaco en la biotita, ni tampoco con el carbón no procedente de carbonatos en la roca, pero pudieran estar relacionadas con una abundancia mayor de hierro en relación con el magnesio (en la mezcla fundida) que podría disminuir la fugacidad de oxígeno e impedir la cristalización de magnetita.

Palabras clave: Frontera de magnetita, batolito de las Sierras Peninsulares, Baja California, México, California, E.U.A.

INTRODUCTION

The recognition of regional zones of magnetite-bearing and magnetite-free granitic plutons (Ishihara, 1977), and of plutons which are magnetite-free in their margins contiguous with metasedimentary rocks, yet are magnetite-bearing elsewhere (Shimizu, 1986) is worldwide. These phenomena have been described for the Peninsular Ranges of southern California and Baja California by Gastil and others (1990), and Gastil (1990). In the Peninsular Ranges the presence or absence of magnetite can be ascribed to as many as four different phenomena. First, the contact effect of metasedimentary wallrock on adjacent granitic rock that lacks primary magnetite. Second, a contact phenomenon in which the primary magnetite was subsequently altered to ilmenite and hematite (Diamond and Frost, 1988). Third, zoned plutons in which the outer (earlier crystallized phase) bears magnetite and the inner (later crystallized phase) is free of magnetite. And fourth, a regional pattern in which plutons, of varied compositions are either magnetite-bearing or magnetite-free, depending on their geographic position.

In the Peninsular Ranges we can draw a line—called the magnetite boundary—parallel to the axis of the batholith, southwest of which nearly all granitic rocks are magnetite-

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bearing and northeast of which nearly all granitic rocks are magnetite-free (Figure 1). Exceptions are older,foliated, granitic rocks of Jurassic age that appear to be entirely magnetite-free. The magnetite boundary corresponds approximately with other geochemical and geophysical boundaries which have been used to divide the batholith (Todd and Shaw, 1979; Silver and Chappell, 1988; Gastil *et al.*, 1990).

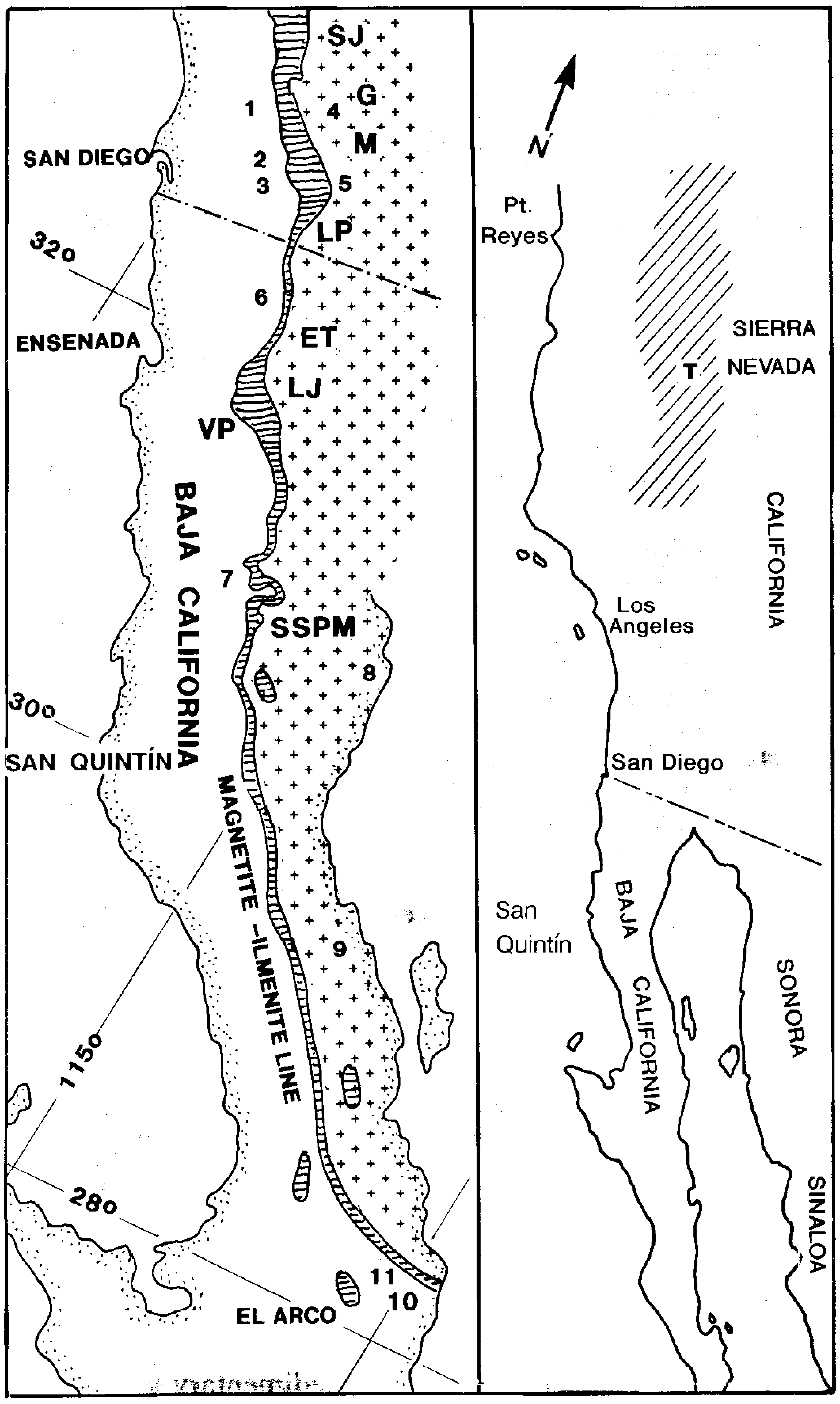

Figure 1.- Index map to peninsular California. Letter localities refer to Mount San Jacinto (SJ), Granite Mountain (G), Mason Valley (M), La Posta pluton (LP), El Topo pluton (ET), Laguna Juárez pluton (LJ), Valle Pedregoso pluton (VP), and Sierra San Pedro Mártir pluton (SSPM). Cross pattern is the magnetite-free eastern Peninsular Ranges batholith. Hash-patterned belt is transitional between the magnetite-bearing and magnetite-free zones. In the Sierra Nevada, T locates the Tuolomne transect. Numbers 1 to 11 refer to samples outside studied plutons (Table 1).

Elsewhere in the world the lack of magnetite has been associated with the oxidation state of iron (Ishihara and Terashima, 1985), and a reduced oxidation state has been attributed to the effect of organic carbon (graphite) incorporated from adjacent metasedimentary wall rock (Itihara and Aihara, 1987). Shimizu (1986) showed that in the 600 km^2 Tokuwa pluton of Japan magnetite is absent near contacts against metasedimentary rocks, but present near contacts against metavolcanic rocks; and Tainosho and others (1988) showed that rocks believed to be at least in part derived from the melting of metasedimentary rocks are largely magnetite-free and enriched in ammonium—believed to be organic in origin. However, a search for carbon of organic origin in the margins of magnetite-free plutons has not always supported this model (Ishihara, 1984; Ishihara *et al.*, 1985), and Bateman and others (1991) have not seen a correlation between carbon and magnetite in the central Sierra Nevada.

Since the plutons of the eastern Peninsular Ranges, U.S.A. and Mexico are similar in many ways, but differ in the presence or absence of magnetite, they present an opportunity to investigate what variables correspond to the presence or absence of magnetite.

INVESTIGATIONS OF PLUTONS

To investigate the origin of magnetite presence in the Peninsular Ranges batholith whole rock and FeO/Fe$_2$O$_3$ analyses were carried out by J. Kimbrough, ammonium analyses and whole-rock carbon analyses by Tainosho, and microprobe analyses of the minerals by Shimizu. In this paper we also incorporate earlier work reported by Clinkenbeard (1987) and Chadwick (1987). As examples, we chose two small western (magnetite-bearing) plutons whose margin against metaclastic rocks is magnetite-free—Valle Pedregoso and Los Encinitos—(Figure 2); a 100 km^2 eastern, magnetite-free pluton which is reversely zoned—more mafic center, El Topo—(Figure 3); two symmetrical magnetite-free eastern plutons—La Posta, 1,400 km^2, and Laguna Juárez, 600 km^2—(Figures 4 and 5); and the asymmetrical 400 km^2 Sierra San Pedro Mártir pluton—SSPM—(Figure 6), which closely resembles the La Posta and Laguna Juárez plutons (Figures 7 and 8) except for the fact that most of the outer hornblende-biotite and biotite zones are magnetite-bearing. Superimposed on the magnetite-bearing facies of the SSPM is an outer rim in which primary magnetite has been replaced by ilmenite and ilmenite-hematite (Diamond, 1989). For comparison with another terrane, rocks of the Tuolomne Intrusive Suite of Yosemite National Park in the Sierra Nevada were plotted (Figures 1 and 9).

VALLE PEDREGOSO AND LOS ENCINITOS

Chadwick (1987) mapped several small plutons and enclosing metaclastic rocks along the magnetite boundary about 50 km southeast of Ensenada. Both the Valle Pedregoso and Los Encinitos plutons are on the magnetite-bearing (western) side of the magnetite boundary (Figure 1). Although they are hornblende tonalites, superficially similar to those further east in the peninsula, their older age, lower silica, higher mafic content, and lower strontium clearly place them with the west-

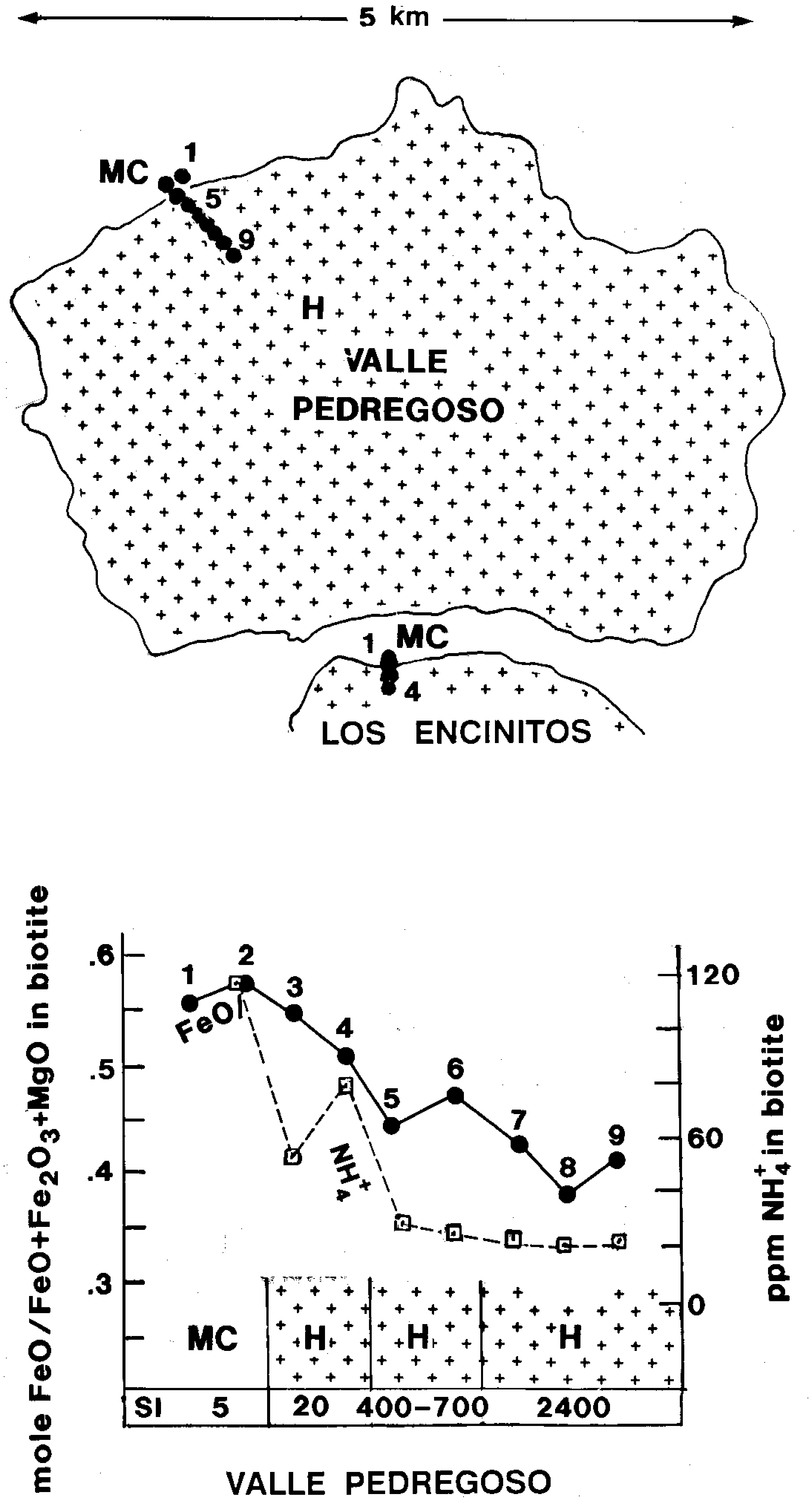

Figure 2.- Traverses across margins of Valle Pedregoso and Los Encinitos plutons. Both are hornblende-biotite tonalites (H) in contact with metaclastic schist and quartzite (MC); mapping after Chadwick (1987). Black spots indicate sample localities. SI indicates meter readings x 10^{-5} (k[SI] = 4πk[c·g·s]). Left scale on figures 2 through 7 is mole FeO / mole (FeO + Fe_2O_3 + MgO) in biotite.

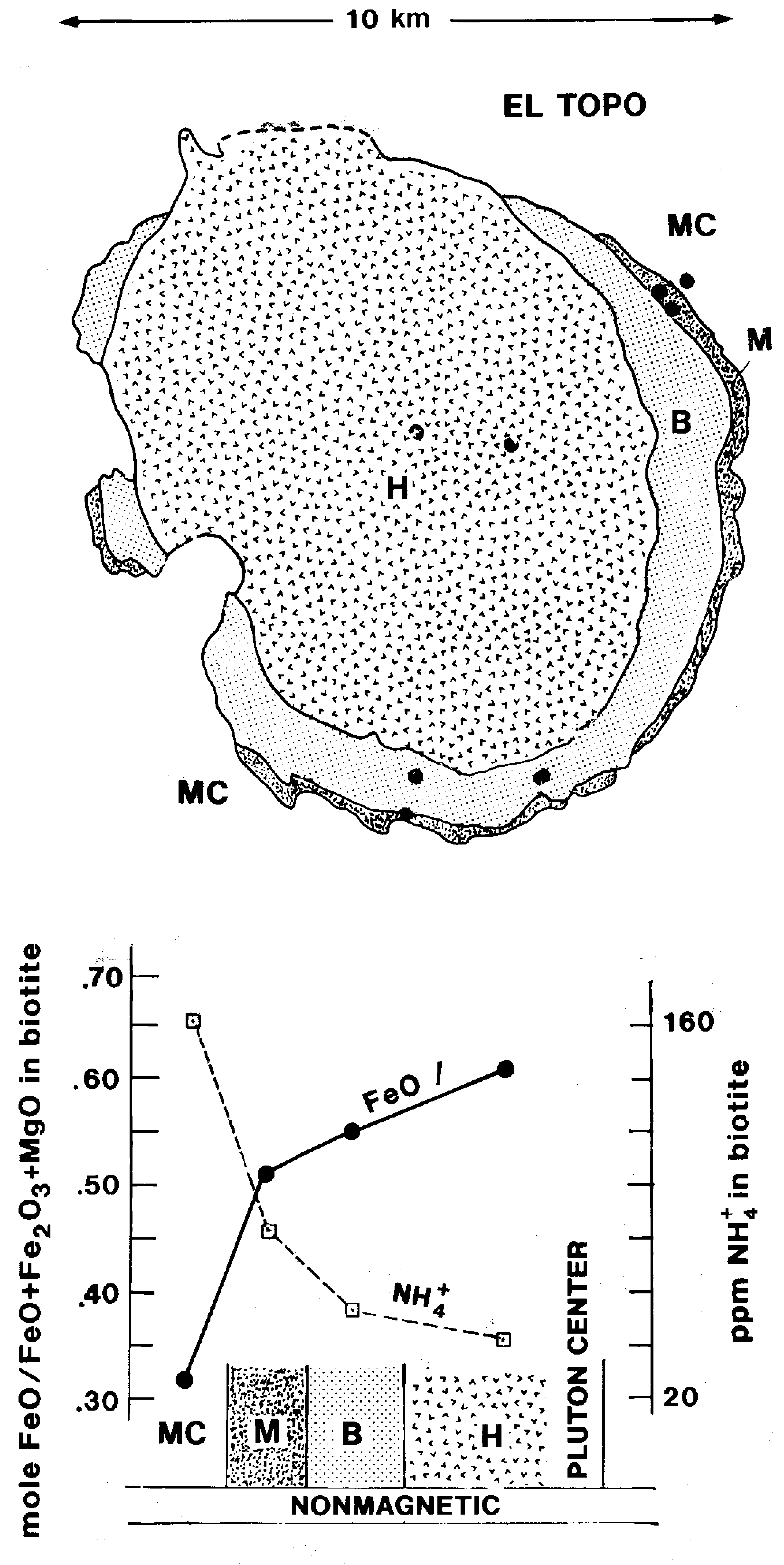

Figure 3.- The El Topo pluton has a central hornblende biotite tonalite facies (H), a biotite granodiorite facies (B), a locally garnetiferous, muscovite-bearing margin (M), and a metaclastic wall rock (MC). Mapping is after Wernicke (1987). The pluton is cut by garnetiferous granite dikes (see Table 1, R).

ern rocks. The Valle Pedregoso pluton measures about 3 km by 5 km, and the Los Encinitos pluton is of a similar size (Figure 2). Both are in contact with metaclastic rocks. At the contacts neither contains magnetite. The Valle Pedregoso rock increases from a magnetic susceptibility reading of 20 x 10^{-5} SI units—indicating an absence of magnetite—15 m within the pluton, to a reading of 3,000 x 10^{-5} SI units—0.9% magnetite by volume—200 m within the pluton. Los Encinitos—against a 0.4 km wide screen of metaclastic rock—increases from a reading of 18—no magnetite—at the contact to 2,000 x 10^{-5} SI units—0.6% volume magnetite—27 m within the pluton.

Analyses for FeO/Fe_2O_3, carried out by the method of Fritz and Popp (1985), show that whereas the Valle Pedregoso tonalite is relatively enriched in FeO relative to Fe_2O_3 near the contact, this effect disappears after about 50 m into the body (Chadwick, 1987). A similar study on the biotites from both the Valle Pedregoso and Los Encinitos bodies gives similar results (Figure 2). The ammonium content in the biotite drops abruptly over the first 50 m into the Valle Pedregoso pluton and then flattens out. Organic carbon (total carbon less carbon-

Table 1.- Magnetic susceptibility, "organic" carbon content, and ammonium and iron oxide content of biotite.

Sample/Composition	Mag.S. [10^{-5}SI]	Biotite NH_4^+ [ppm]	FeO [wt%]	mole FeO/ mole FeO+ Fe_2O_3+MgO	"Organic" carbon [ppm]
LOS ENCINITOS					
LE-1 metacl.	20	95	-	0.56	609
LE-2 hybrid	18	45	19.3	0.53	110
LE-3 hbt	55	44	16.2	0.55	518
LE-4 hbt	2000	15	13.9	0.32	272
VALLE PEDREGOSO					
VP-1 metacl. MC**	5	-	17.1	0.55	1454
VP-2 metacl.	5	120	17.6	0.57	4176
VP-3 hbt	12	56	18.1	0.53	17
VP-4 hbt	20	82	18.8	0.50	116
VP-5 hbt H**	700	30	18.0	0.43	31
VP-6 hbt	440	27	18.6	0.48	123
VP-7 hbt	2400	-	14.6	0.42	69
VP-8 hbt	3000	22	13.2	0.36	45
VP-9 hbt	3000	21	13.8	0.40	66
SIERRA SAN PEDRO MÁRTIR					
VO-7 hbt GN	18	30 [41.5]	16.3	0.43 [0.45]	-
VO-6 hbt	20	53	22.1	0.47	-
26-8 hbt	900	33	15.9	0.42	8
26-7/8 hbt	500	12	16.3	0.31	-
26-4 hbt H	550	*3 [46.8]	15.5 [15.3]	0.41 [0.52]	-
26-6 hbt	700	93	14.6	0.40	149
24-2 hbt	325	81	18.5	0.41	686
24-3 hbt	325	15	11.2	0.28	151
25-7 bt	400	47	17.7	0.50	197
25-8 bt	300	15	17.7	0.52	39
26-3 bt B	30	10 [36.3]	17.2 [16.4]	0.58 [0.50]	-
26-2 bt	400	81	18.5	0.50	61
26-1 bt	25	29	11.0	0.38	209
25-4 mbgd	10	9	20.4	0.48	73
25-5 mbgd	5	12	19.7	0.50	-
CT-47 mbgd M	5	*56 [11.5]	24.3 [21.6]	0.69 [0.55]	112
Víbora mbgd	<10	7	21.0	0.61	-
Grulla mbgd	<10	17	22.8	0.56	-
Diablo rmbg R	4	-	21.9	0.61	-
EL TOPO					
ET-H hbt H	80	40.8 [43.7]	21.8 [23.6]	0.48 [0.61]	35
ET-3 hbt	19	46.6	25.4	0.74	-
ET-B bt B	14	71.5 [53.3]	22.3 [23.3]	0.64 [0.55]	113
ET-S bt	14	34.9	24.2	0.66	-
ET-4 rmbg	7	68.8	22.8	0.56	-
ET-C rmbg M	4	97.6 [83.2]	23.5 [20.8]	0.61 [0.51]	-
ET-7 rmbg	5	126.7	15.3	0.49	-
ET-1 dike R	10	78.0	21.4	0.28	-
ET-6 metacl. MC	24	163.1	15,2	0.32	-
LA POSTA					
LP-56 west hbt H	<10	17.8	19.2 [16.7]	0.51	-
LP-22 west hbt H	<10	-	14.3	-	52
LP-4A west lbgd B	<10	44.9	22.6	0.63	-
LP-16 west sbgd SB	<10	15.8	21.2	0.40	-

Table 1.- Magnetic susceptibility, "organic" carbon content, and ammonium and iron oxide content of biotite (*continued*).

Sample/Composition	Mag.S. [10^{-5}SI]	Biotite NH_4^+ [ppm]	FeO [wt%]	mole FeO/ mole FeO+ Fe_2O_3+MgO	"Organic" carbon [ppm]
LP-31 west mbgd M	<10	44.9	22.6	0.51	(204)
LP-14 east mbgd M	<10	75.7	-	-	-
LP-18a east mbgd M	<10	39.2	22.8	0.55	(478)
LP-35 east lbgd B	<10	10.2	21.8	0.44	(441)
LP-19 east hbt H	<10	9.0	21.8	0.41	251
LP-17 rmbg R	<10	46.7	20.6	0.51	(19)
LAGUNA JUÁREZ					
LJ-1 metacl. MC	12	71.8	14.2	0.28	-
LJ-2 hbt	24	7.7	-	-	-
LJ-H hbt	20	*43.2	17.2	0.45	315
LJ-3 hbt H	23	6.7 [9.3]	16.3 [17.3]	0.49 [0.46]	-
LJ-4 hbgd	10	13.6	18.3	0.44	-
LJ-5 bgd B	6	10.1 [18.7]	19.6	0.43 [0.46]	-
LJ-6 bgd	7	27.3	-	0.50	-
LJ-B mbg	8	51.0	19.2	0.57	42
LJ-M1 mbg M	7	15.0 [46.7]	18.5 [19.4]	0.56 [0.51]	78
LJ-M2 mbg	5	71.9	20.4	0.45	75
LJ-9 mbg FM	7	95.1	19.3	0.45	-
SJ-E rmbg	<10	134.8	22.5	0.56	-
SJ-391 rmbg	<10	44.4	28.9	0.57	-
TUOLOMNE					
kec hbt	1300	25.4	19.3	0.51	-
kec hbt	3000	18.0	21.0	0.43	173
kk hbgd	2250	11.6	16.9	0.45	88
khd hbgd	2250	18.2	15.3	0.41	333
khp hbgd	4250	34.4	14.6	0.37	168
kcp bgd	4250	37.1	13.7	0.35	63
SAMPLES OUTSIDE STUDIED PLUTONS^{xx}					
1 bg	1500	7.4	20.7	0.57	-
2 hbt	600	13.0	17.9	0.43	-
3 bgd	2000	18.9	17.9	0.47	-
4 mbg	10	106.4	14.2	0.31	-
5 mbg	<10	95.0	15.4	0.28	-
6 hbt	400	15.6	15.5	0.43	-
7 hbt	2400	13.5	12.8	0.37	-
8 hbt	15	-	15.5	0.45	-
9 hbt	15	25.8	15.5	0.43	104
10 bgd	250	34.8	15.7	0.42	66
11 hbt	1700	12.5	13.9	0.45	-

EXPLANATION

*	indicates an analysis omitted from average value
[ ]	average value for plutonic zone
( )	analysis from a different sample, same zone
t	tonalite
gd	granodiorite
g	granite
h	hornblende
b	biotite
m	muscovite
r	garnet
l	large
s	small
xx	located on Figure 1

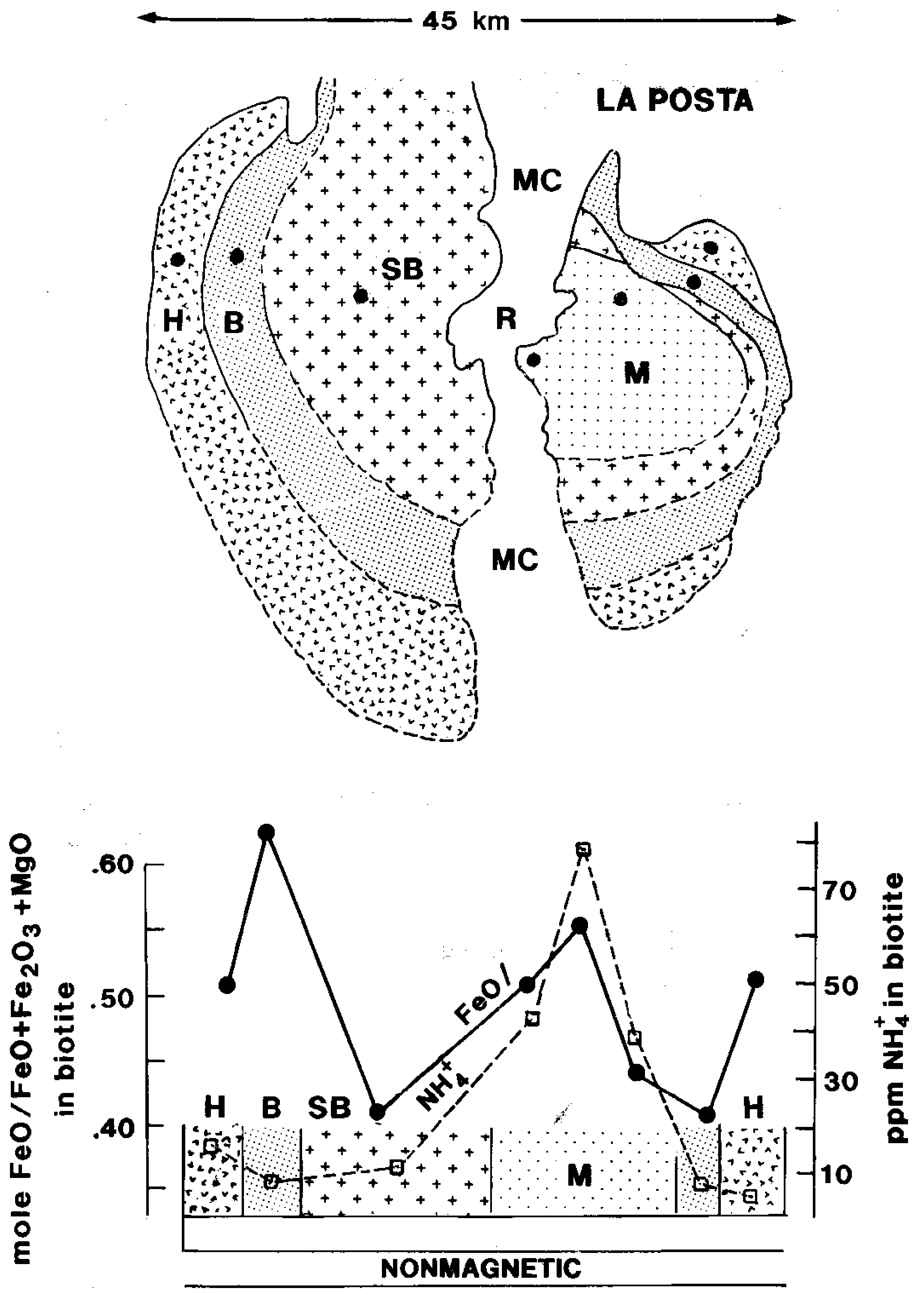

Figure 4.- In the La Posta pluton the authors have designated an additional small biotite facies (SB), and noted the location of a cross-cutting garnetiferous muscovite-biotite granite (R); other symbols as in previous figures. The La Posta pluton has been described by Kimzey (1982), Clinkenbeard (1987), and Walawender and others (1990). The southern half of the pluton (in Mexico) has only been mapped in reconnaissance.

ate carbon) averages 2,800 ppm for the two metasedimentary wall rock samples, and drops precipitously at the contact to an average value of 68 ppm suggesting that very little carbon was ingested into the pluton. The four measurements of carbon across the margin of the Los Encinitos contact do not present a clear picture. Microscopic study fails to reveal any reason to believe that the opaque oxides within the outer margin of these small plutons are not primary. Therefore, it is concluded that there was a marginal effect that influenced the primary crystallization, producing only a relatively reduced iron-bearing oxide (ilmenite). The higher ammonium content in the outer margin of the tonalite as well as in the adjacent wall rock suggests that it may have acted as a sediment-derived reducing agent, but the role, if any, for graphite is ambiguous (Table 1, Figure 10).

EL TOPO

The El Topo pluton was studied by Wernicke (1987). Unlike the other large plutons of the eastern Peninsular Ranges this 100 km^2 body (Figure 3) is reversely zoned, grading from hornblende tonalite in the central portion, through biotite granodiorite to two-mica monzogranite, locally bearing garnets, at the rim (Table 1). Strontium initials and oxygen isotope studies (unpublished data by J. Kimbrough) suggest that the composition of the narrow outer margin has been strongly influenced by the metaclastic wallrock (Figure 3). And, indeed FeO/Fe$_2$O$_3$ on biotite climbs steeply from the wall rock to the hornblende-bearing center, whereas the ppm ammonium in biotite drops sharply. On the other hand, the two analyses for organic carbon (Table 1) show more carbon in the central

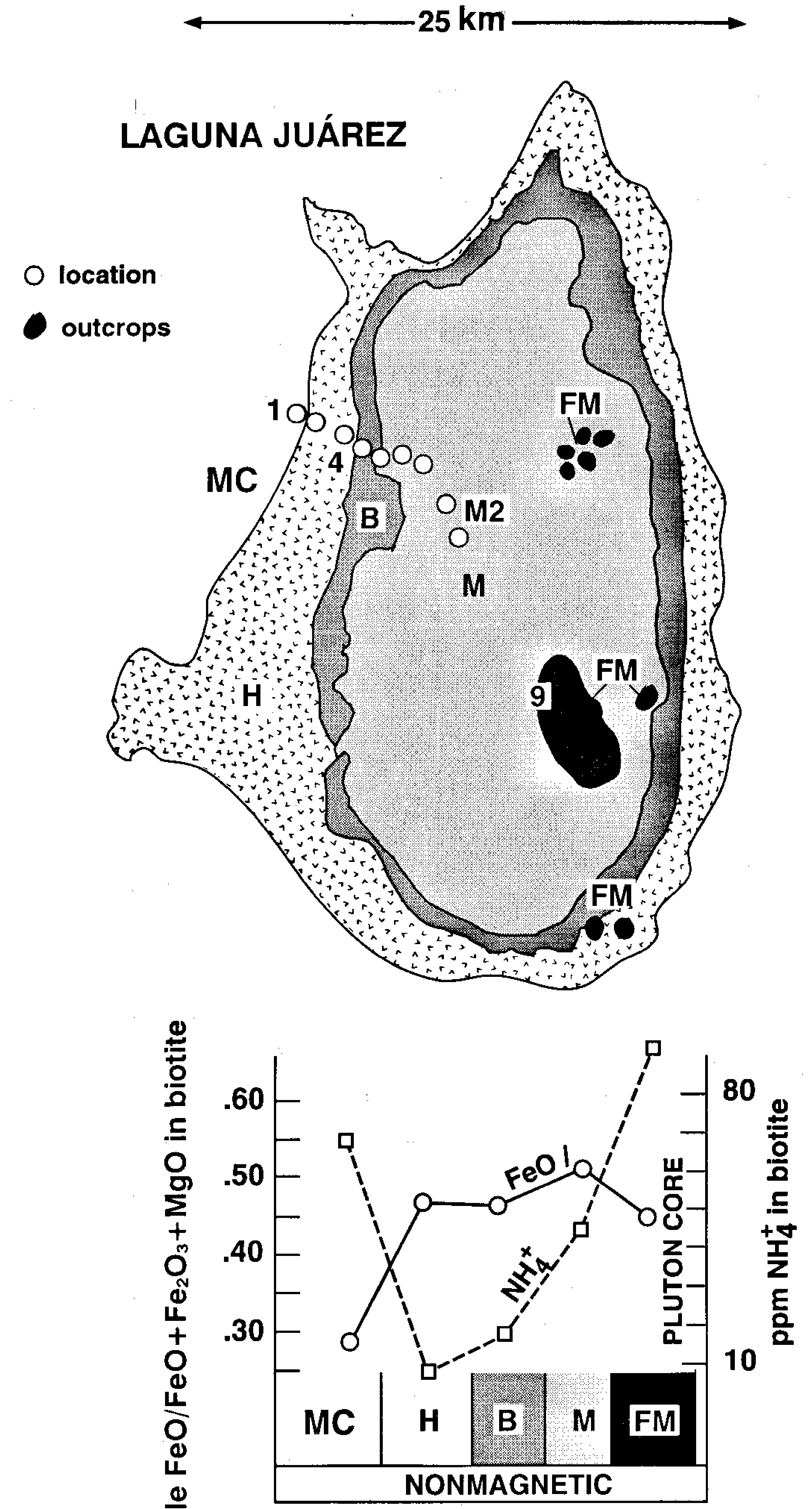

Figure 5.- In the Laguna Juárez pluton, an additional fine-grained cross-cutting phase of the muscovite-biotite granite (FM) is recognized. Other symbols have been explained for the previous figures; mapping from Gunn (1985).

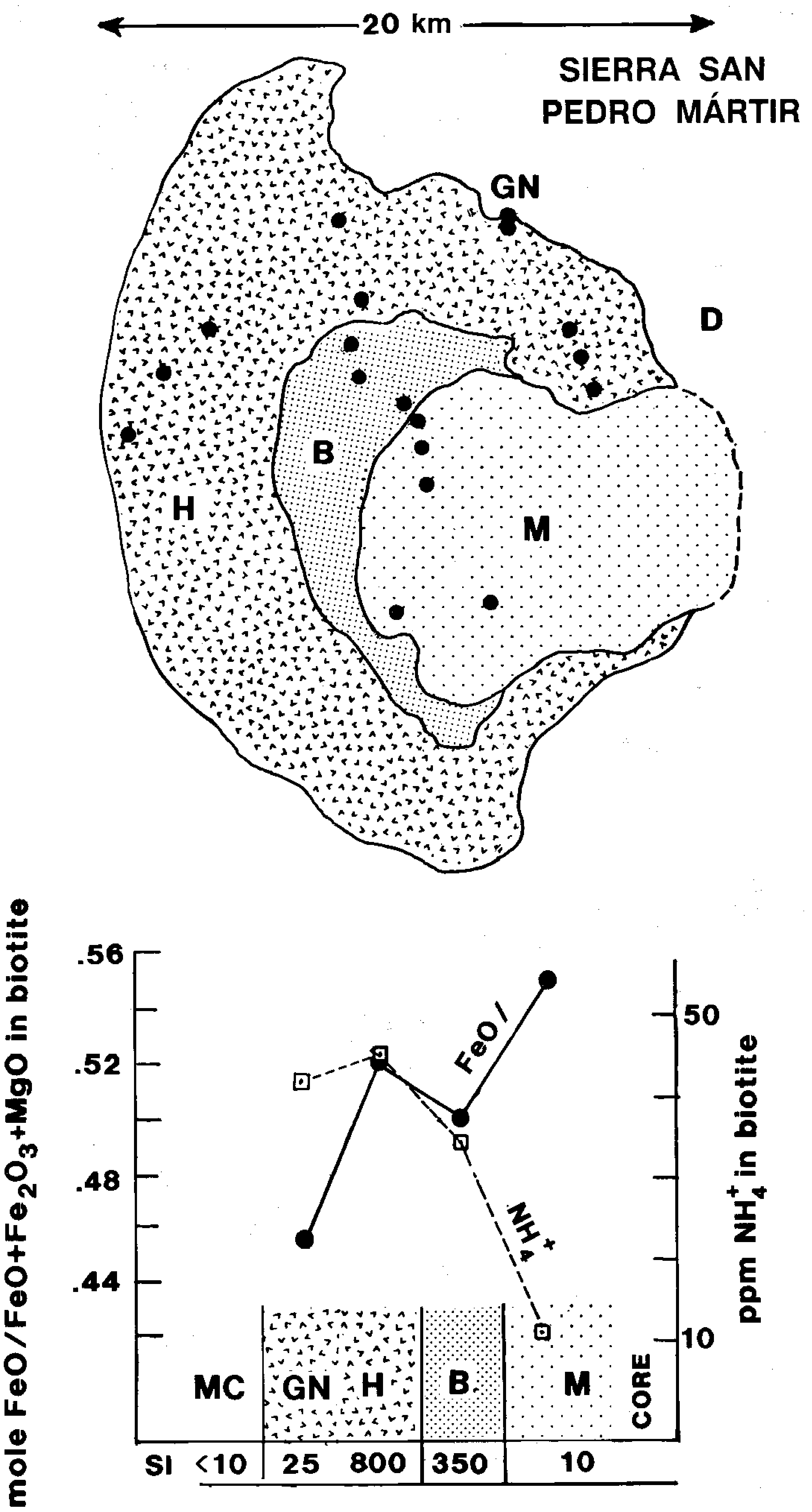

Figure 6.- Sierra San Pedro Mártir zoned pluton. In addition to symbols in previous figures, (GN) indicates the foliated marginal hornblende-biotite tonalite facies; mapping after McCormick (1986), and Eastman (1986).

hornblende facies than in the outer biotite facies, which is difficult to understand. Except for the carbon data, this appears to be a clear cut example of a pluton that interacted at its margin with metaclastic rock reducing the iron, and incorporating ammonium.

LA POSTA

The 1,400 km^2 La Posta pluton (Figure 4) is the largest of the eastern plutons. It is normally zoned and symmetrical in that, starting in the west, you can traverse through the hornblende to the muscovite-bearing facies, pass through the core of the pluton and continuing east, repeating the facies in reverse order (Figure 4). The pluton was mapped by Kimzey (1982) and samples of both rock and mineral were analyzed by Clinkenbeard (1987) and interpreted by Clinkenbeard and Walawender (1987). It is bounded to the west only by older plutons, to the east by alluvial desert floor, and through the midsection by a large screen of metaclastic rocks and a small body of younger granite. The large portion of this body lying south of the international border has not been carefully mapped.

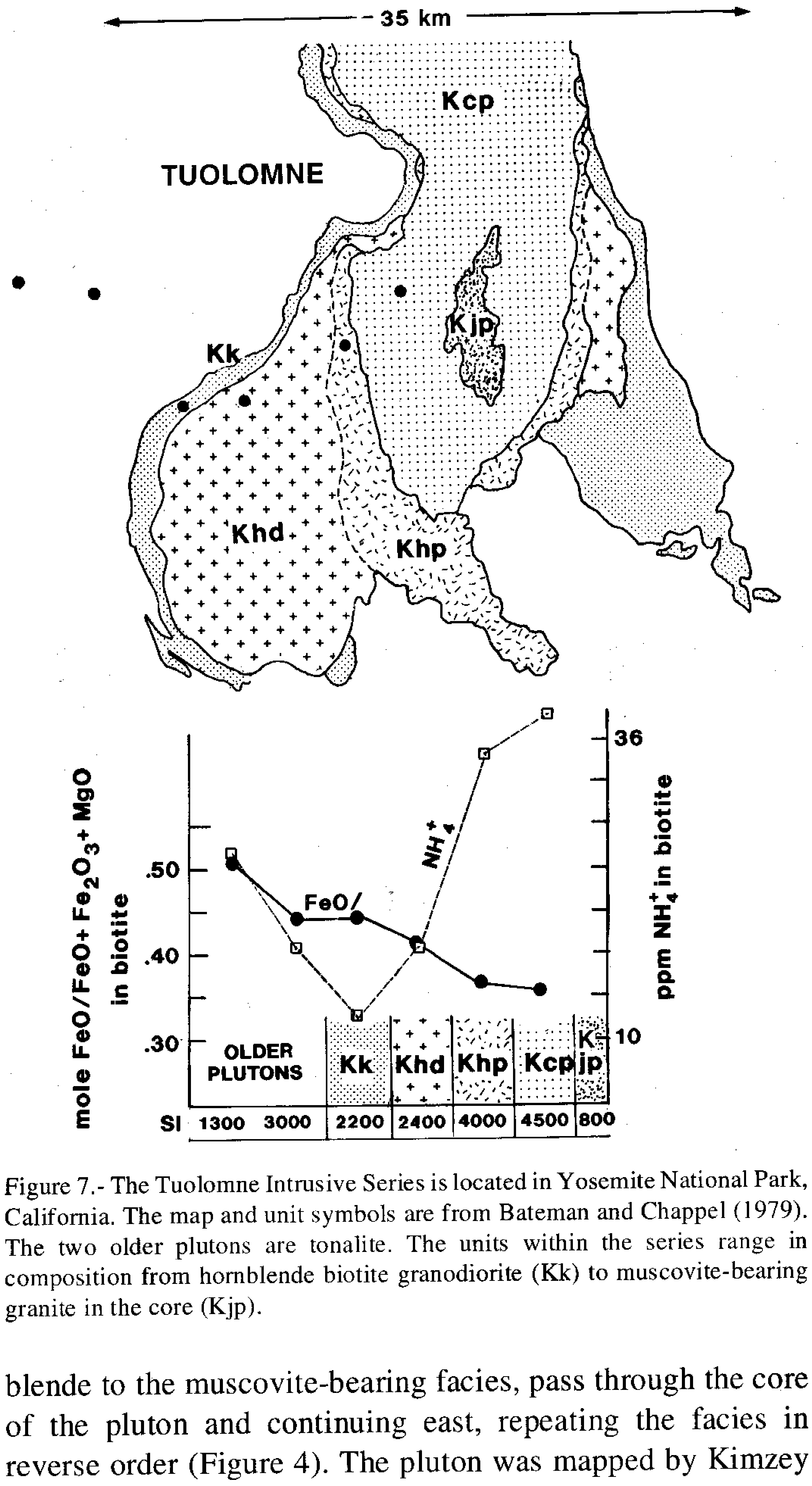

Figure 7.- The Tuolomne Intrusive Series is located in Yosemite National Park, California. The map and unit symbols are from Bateman and Chappel (1979). The two older plutons are tonalite. The units within the series range in composition from hornblende biotite granodiorite (Kk) to muscovite-bearing granite in the core (Kjp).

Both the proportion of mole FeO / sum (FeO + Fe_2O_3 + MgO) and the amount in ppm of ammonium in biotite are symmetric relative to the muscovite-bearing core of the pluton, where they are the highest. The seven analyses for carbon seem to show no pattern. None of the facies contain magnetite. If the presence of ammonium and the reduced state of iron were caused by interaction with metasedimentary rock, the muscovite-bearing core of the pluton might retain this signature from a preemplacement contact at depth.

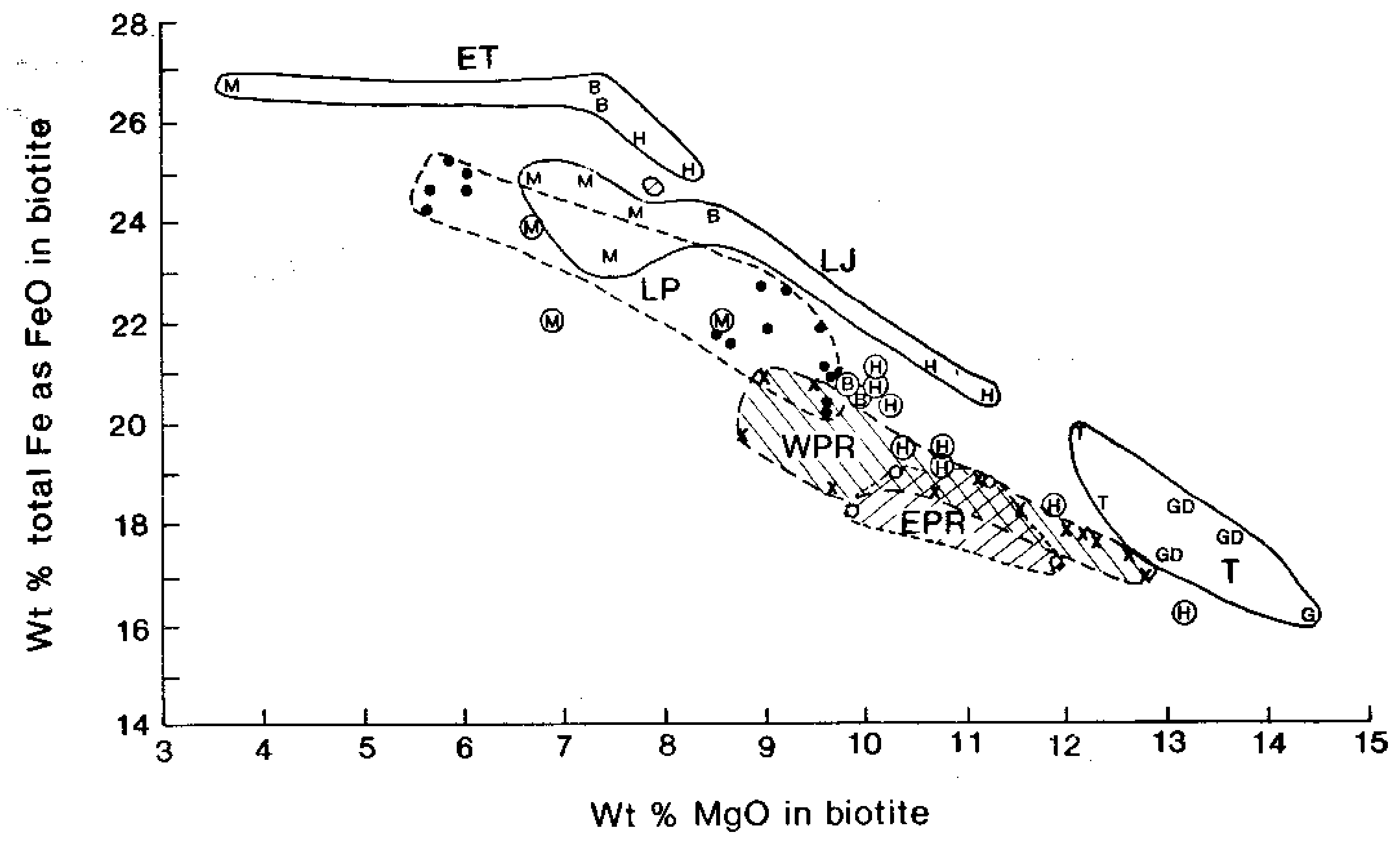

Figure 8.- Weight percent total iron as FeO in biotite plotted against weight percent MgO in biotite. The samples are from El Topo (ET), Laguna Juárez (LJ), La Posta (LP), Tuolomne (U), the western Peninsular Ranges (WPR), eastern Peninsular Ranges (along the Gulf of California) (EPR). Muscovite facies rocks (M), biotite facies rocks (B), hornblende-biotite facies rocks (H), (T) tonalite, (GD) granodiorite, (G) granite. Circled letters are samples from the Sierra San Pedro Mártir pluton.

LAGUNA JUÁREZ

The 600 km^2 Laguna Juárez pluton (Figure 5) was mapped by Gunn (1985). In many ways it is similar to the La Posta pluton. The outer margin is largely emplaced against older plutons, and it grades inward from hornblende tonalite to muscovite-bearing granite. But there are several contrasts. First, there is no metaclastic screen through the center. Second, the bulk of the exposed body is granite, and in large part K-feldspar megacrystic granite. The last melt to crystallize was a fine-grained two-mica granite which has intrusive contacts and occurs as several small bodies within the pluton. The three carbon analyses from the muscovite-bearing facies are lower than that from the hornblende facies.

Like the La Posta pluton both the mole FeO/sum (FeO + Fe_2O_3 + MgO) in biotite and ppm ammonium in biotite increase from the hornblende facies to the muscovite-bearing facies, and as in other plutons the ammonium is higher in the metaclastic wall rock than in the hornblende facies rock.

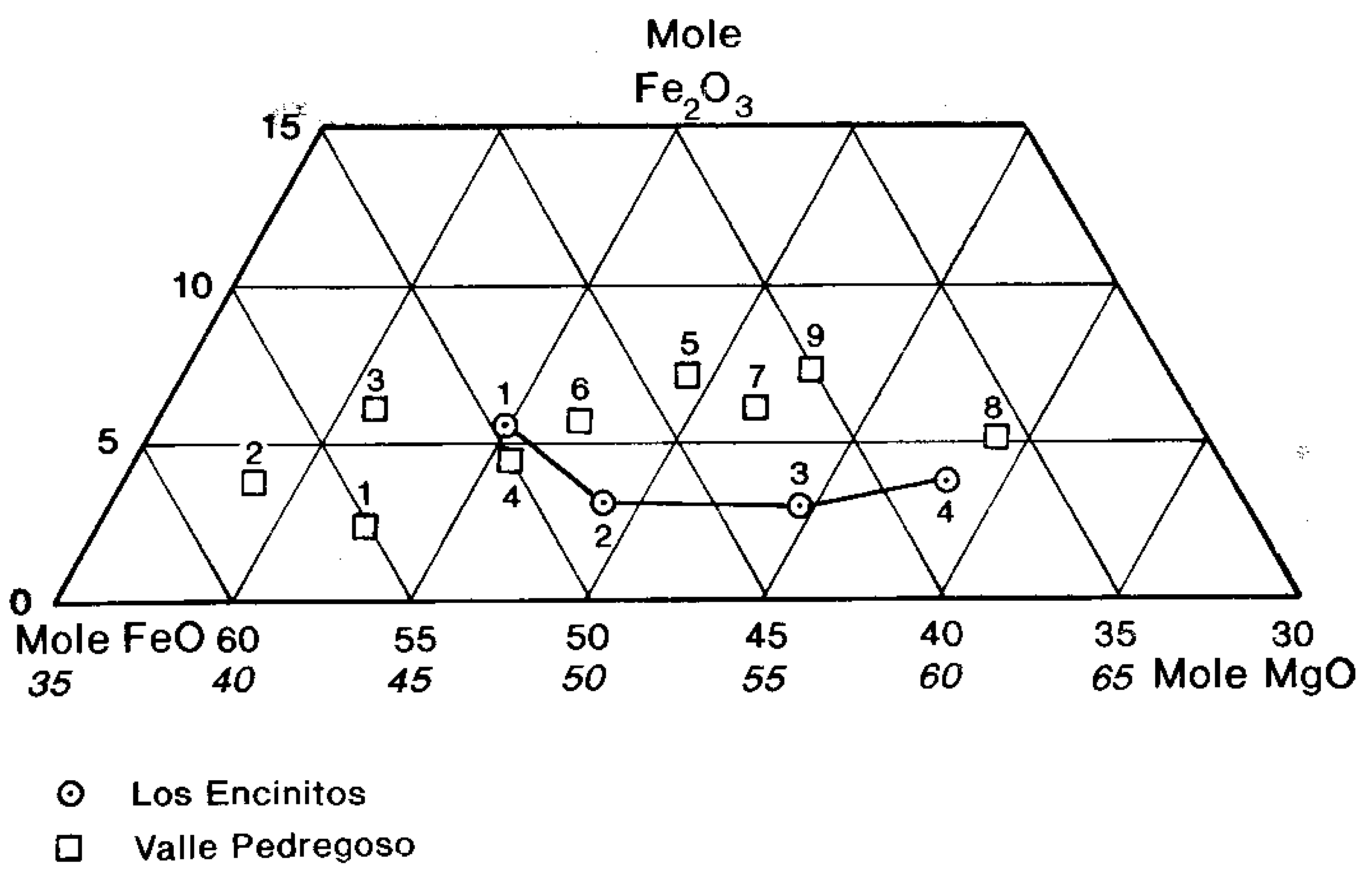

Figure 9.- Moles FeO^{++} - Fe^{+++} - MgO in biotite from the Valle Pedregoso and Los Encinitos pluton margins (Figure 2).

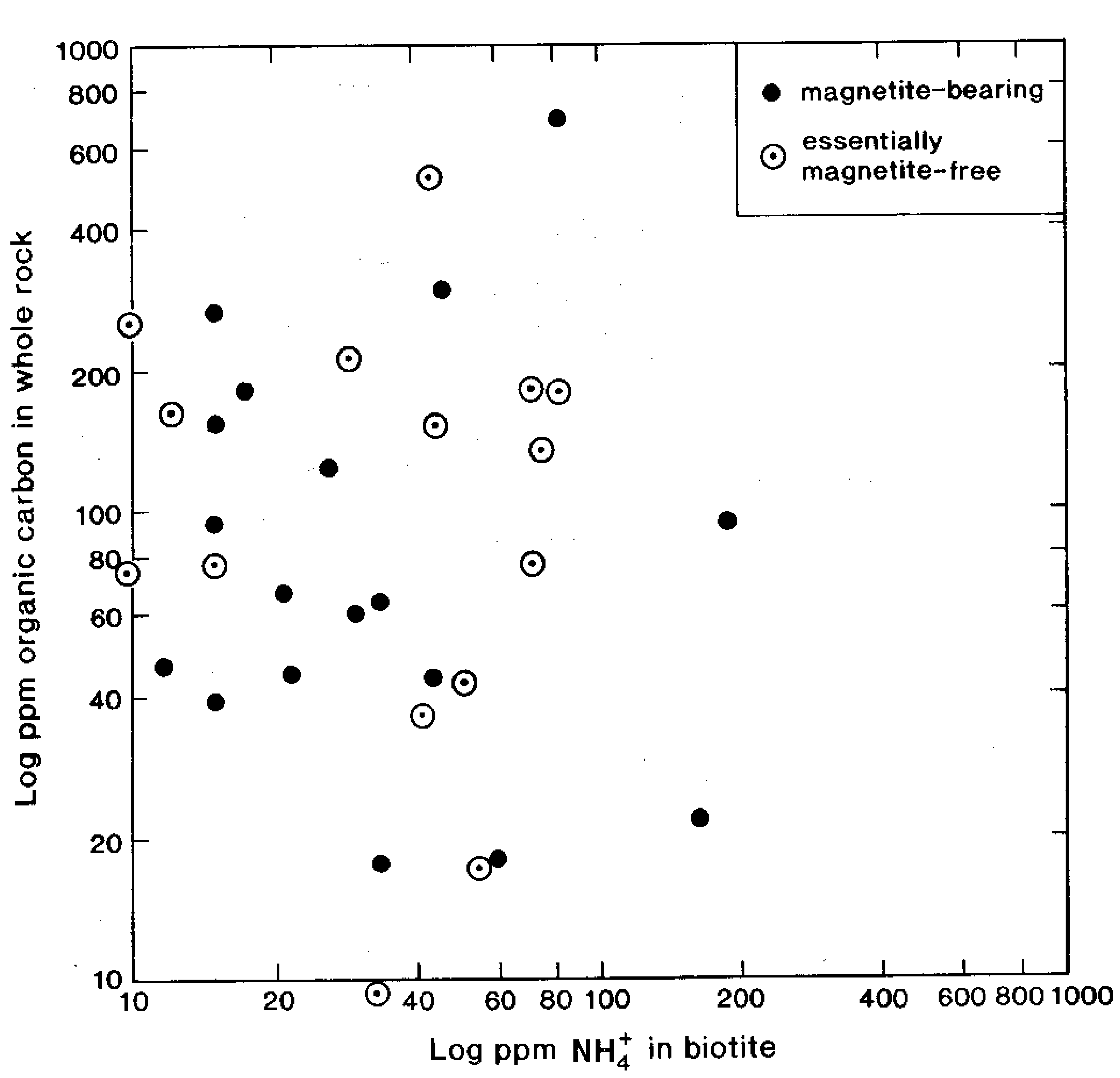

Figure 10.- Log ppm non-carbonate carbon in rock plotted against NH4$^+$ in biotite for granitic rocks of the Peninsular Ranges batholith.

SIERRA SAN PEDRO MÁRTIR

This 600 km^2 pluton (Figure 6) was mapped and analyzed by Eastman (1986) and McCormick (1986). It has subsequently been sampled, analyzed, and mapped in greater detail by the authors of this paper. Although the facies, hand specimens, and even the chemical analyses of this body bear many resemblances to the La Posta and Laguna Juárez plutons, there are some critical differences. The asymmetry of the body, along with the internal structure, and metamorphic grades of the wallrock strongly suggest that the present erosional exposure is that of a pluton turned on edge so that it can be viewed from the roof to the root (Gastil *et al.*, 1991). But most important, a large portion of the hornblende and biotite facies is magnetite-bearing, not in the multi-thousand x 10^{-5} SI unit range indicated for parts of Valle Pedregoso, Los Encinitos, and Tuolomne plutons, but very clearly endowed with appreciable primary magnetite—commonly up to 900 x 10^{-5} SI units, or 0.2 to 0.3% by volume. The 18 ammonium and iron oxidation measurements are summarized in Figure 6 according to facies. The contact rock (GN Figure 6) is a highly deformed marginal tonalite against migmatitic sillimanite-bearing metaclastic rock.

From Table 1 it can be seen that the values plotted for the respective facies are averages of all of the samples located within that facies and that some of these averages combine values that vary widely. Like the La Posta and Laguna Juárez plutons the mole FeO/sum for biotite rises in the muscovite-bearing facies. However, unlike these plutons, ammonium is lowest in the muscovite-bearing facies. There is no clear pattern to the analyses for carbon. The average value of 92 ppm

C for the muscovite-bearing facies is lower than the average value of 169 ppm for the entire pluton. These analyses fail to indicate why the SSPM contains magnetite whereas the other La Posta-type plutons are magnetite-free.

TUOLOMNE TRANSECT

Because the leucocratic, inclusion-poor, normally zoned tonalite, granodiorite, and granite of the Tuolomne intrusive series (Bateman and Chappell, 1979) in some ways resemble rocks of the La Posta type plutons in the Peninsular Ranges, a few samples for comparison were collected. However, although idiomorphic hornblende, biotite, and sphene-bearing rocks resemble those of the outer La Posta zones and the K-feldspar megacrystic rock resembles that of the Laguna Juárez granite facies, the suite is fundamentally different: the Tuolomne rocks (Figure 7) are magnetite-abundant with even the core muscovite-bearing Johnson Creek granite containing appreciable magnetite. The Tuolomne is the only suite that was studied in which the proportion of mole FeO/(FeO + Fe_2O_3 + MgO) decreased with differentiation (Figure 7). Like in the La Posta, Laguna Juárez, and SSPM, ammonium was highest in the central portion of the sequence, where it would appear to be isolated from metasedimentary wallrock. The carbon content trend appears reverse to that of ammonium.

OTHER AREAS

Although the SSPM has only been cited as an example of a "La Posta type" pluton, where the hornblende and biotite facies contain magnetite, there are others. On Figure 1 locality 3 is the 25 km^2 Long Potrero pluton (Hoppler, 1983; Rector, 1994), where the rocks grade inward from magnetite-rich hornblende tonalite to magnetite-free muscovite-bearing rock. In locality 6 (Figure 1), just west of the magnetite boundary, El Pinal pluton (Duffield, 1968) strongly resembles the La Posta-type rocks, but contains moderate magnetite throughout. Just north of the 28th parallel (localities 10 and 11, Figure 1) La Posta-type rocks are magnetite-rich.

DISCUSSION

Previous efforts to identify the regional controls on magnetite-bearing and magnetite-free plutonic rocks have concerned the degree to which magnetite series and ilmenite series rocks conform to magnetite content, terms introduced by Ishihara (1977). Looking at terranes around the circum-Pacific, Takahashi and others (1980) concluded that while there were similarities between the two discriminations, there were many contradictions. For example, Tainosho and others (1988), studying the Lachlan fold belt of southeastern Australia, showed that whereas nearly all S-type granitoids are magnetite-free there are also important I-type terranes which are magnetite-free.

The eastern Peninsular Ranges regional magnetite deficiency is the first reported area in which the contrast is found between nearly contemporaneous rocks, all of which are I-type (Gastil, 1990; Gastil *et al.*, 1990).

In an attempt to learn the origin of the magnetite present/absent discrimination examples such as the Valle Pedregoso and Los Encinitos seem easy to ascribe to a metaclastic wallrock exchange, even if we do not know just what the reducing agent was or how it penetrated the tonalite magma. In the case of El Topo, there appears to be a sedimentary rock marginal reduction superimposed on an eastern type (magnetite-free) pluton. This results in the appearance of both muscovite and garnet in the contact margin. For the La Posta, Laguna Juárez, and many other totally magnetite-free plutons located east of the magnetite boundary (Figure 1), there is no clear relation to wallrock, and it is difficult to see why these plutons totally lack magnetite, whereas plutons such as Long Potrero, El Pinal (localities 6 and 7, Figure 1), Sierra San Pedro Mártir, and those east of El Arco (localities 10 and 11, Figure 1) contain varying proportions.

The unanswered question is divided into two parts: first, can properties other than magnetite content which discriminate magnetite-bearing from magnetite-free rocks be identified? And second, having discovered such properties, can these properties help to identify a common factor which allowed or prevented primary magnetite crystallization? Comparison of the major and minor element chemistry of the magnetite-bearing with the magnetite-free rocks of the plutons mentioned above show that there is a great deal of compositional overlap (Walawender *et al.*, 1990). And additional unpublished data further confirms this conclusion (Chadwick, 1987; Rector, 1994; J. Kimbrough, unpublished).

Biotite is a mineral common to nearly all of the rocks of the batholith, certainly to all of the rocks of La Posta affinity, both magnetite-bearing and magnetite-free. In Figure 8, wt % total Fe as FeO against wt % MgO in biotite was plotted and it is seen that there is not only a systematic difference between the facies within each pluton, the less differentiated facies being relatively richer in MgO, but there is a systematic compositional positioning of the various plutons. The magnetite-rich Tuolomne rocks are relatively richer in MgO, along with rocks from the western part of the Peninsular Ranges batholith. The magnetite-free La Posta, Laguna Juárez, and El Topo plutons are distinctly richer in biotite iron. The composition of biotite in the SSPM —circled letters—overlaps the boundary between the magnetite-bearing and magnetite-free plutons. Thus, it can be concluded that the presence or absence of magnetite, although apparently not corresponding to the whole-rock chemistry (Walawender *et al.*, 1990) does correspond to Fe/Mg variation in biotite.

In Figure 9, the proportions of mole FeO, Fe_2O_3 and MgO in biotite for rocks of the Valle Pedregoso and Los Encinitos traverses are plotted. For Los Encinitos the sequence is straightforward from the metaclastic (locality 1, Figure 2) to the highly magnetic tonalite (locality 4). In the Valle Pedregoso traverse from metaclastic rocks (localities 1 and 2) to the highly magnetic interior of the pluton (localities 8 and 9) there is some scatter in the data, but the conclusion is the same: magnetite content corresponds to iron oxidation state, more magnetite with the higher oxidation—greater oxygen fugacity in the magma. In Figure 11, analyses of biotite from the various hornblende-bearing La Posta-type rocks are plotted, and there is a correspondence: nearly all of the magnetite-free rocks are located closer to the FeO-MgO side of the diagram, whereas the magnetite-bearing rocks are positioned closer to the Fe_2O_3-MgO side of the diagram.

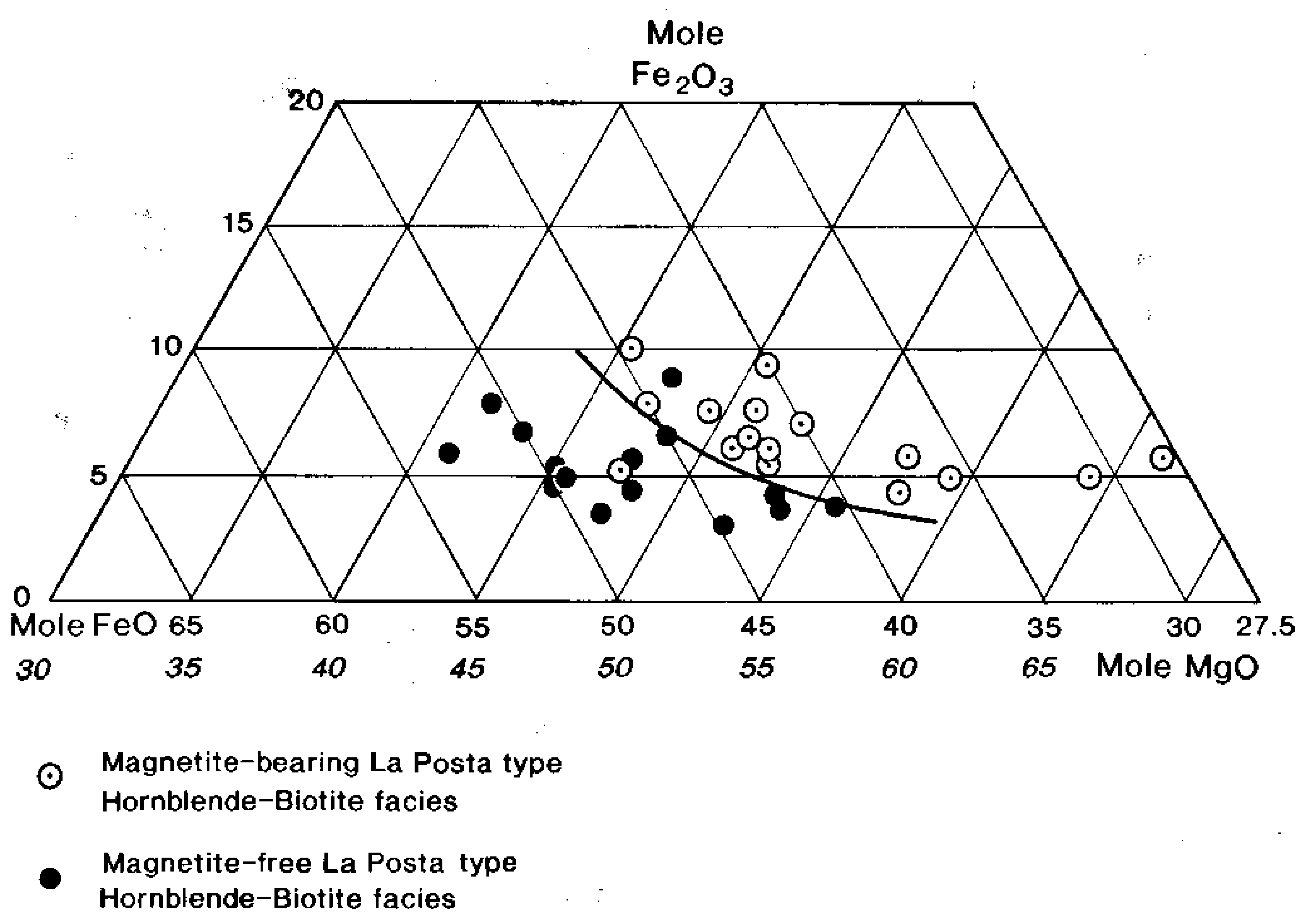

Figure 11.- Moles FeO^{++} - Fe^{+++} - MgO in biotite for all hornblende-biotite tonalites from the La Posta-type plutons: rocks represented by solid dots are magnetite-bearing, rocks represented by open circles are magnetite-free. The line is drawn to emphasize the separation of the magnetite-bearing and magnetite-free rocks.

Since iron substitutes for both magnesium and aluminium in hornblende, and since magnetite in La Posta-type rocks commonly crystallizes within hornblende crystals, these three end members for tonalite and granodiorite hornblendes (Figure 12) have been compared and it can be seen that magnetite-free and magnetite-poor (SI unit reading <350 x 10^{-5}, <0.15% magnetite) fall on the iron-rich side of the diagram. So, in Figure 13, the following question is asked: does relative iron abundance in amphibole correspond to relative iron abundance in the rock? And several relations are discovered. First, there is little or no magnetite in any tonalite in which there is more than 18.75 weight percent iron as FeO in the amphibole. Second, a line can be drawn separating La Posta-type hornblende tonalites and granodiorites from non-La Posta types. Third, rocks plotting above this discrimination line bear appreciable magnetite, except for two rocks from the metaclastic wallrock contact of a magnetite-bearing pluton. Below the discrimination line La Posta-type rocks with 4.9 or more weight percent Fe as FeO have SI unit readings less than 350 x 10^{-5}. Finally, there is a surprising lack of correspondence between iron abundance in the rock and in the amphibole.

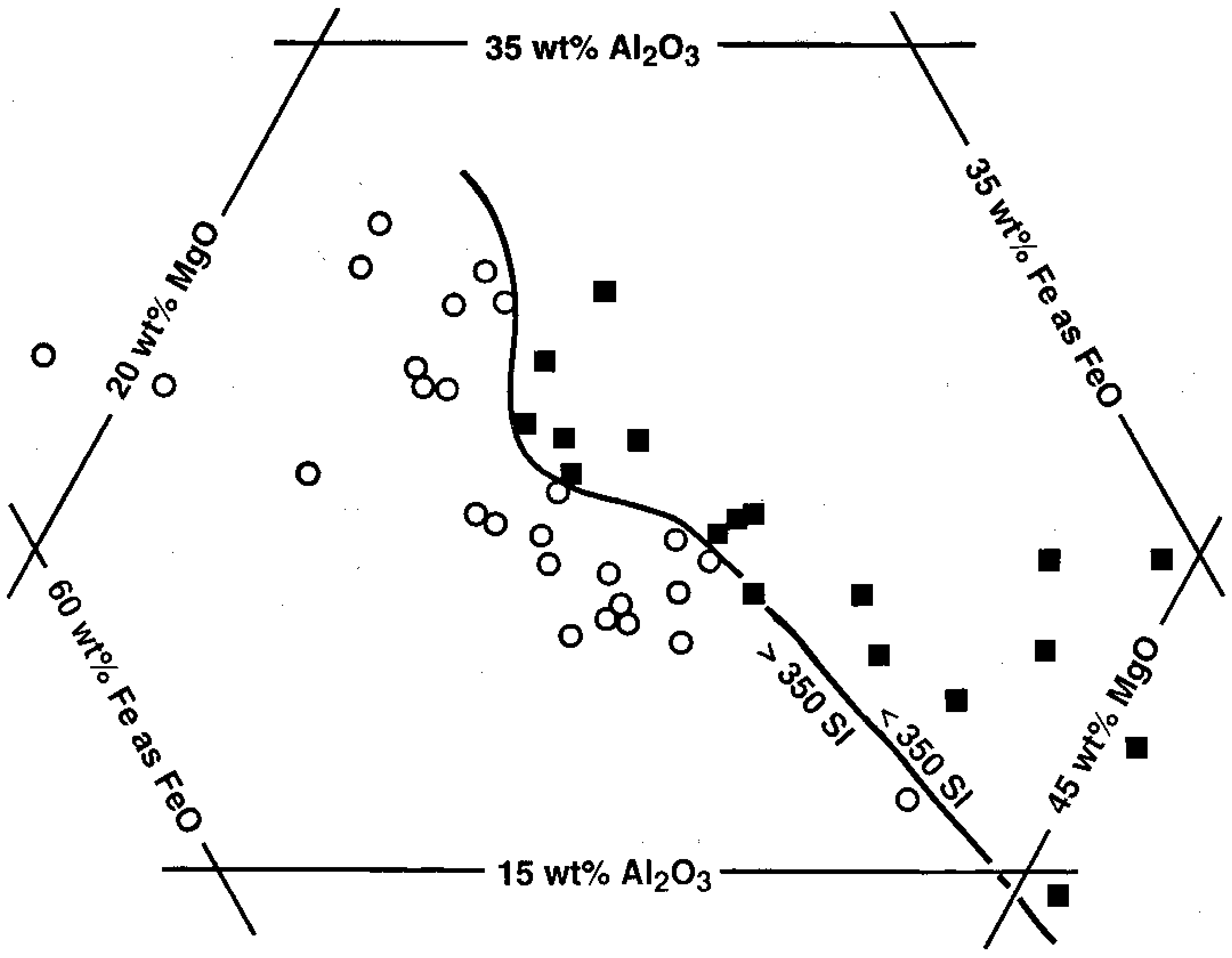

Figure 12.- Total Fe as FeO, MgO, and Al_2O_3 as weight percentages of combined iron, magnesium, and aluminium oxides in hornblendes in tonalite and granodiorite of the Peninsular Ranges. Solid squares indicate rocks measuring >350 SI x 10^{-5}, open circles indicate rocks measuring <350 SIx10^{-5}.

REGIONAL PICTURE

In the Peninsular Ranges batholith special attention has been paid to those bodies where both the magnetite-bearing and magnetite-free rocks exist, because it is here that might be found the answers to the discrimination. However, the great proportion of these bodies is either magnetite-bearing throughout or magnetite-free throughout. Rocks with marginal amounts of magnetite are the exception. This geographic consistency lead to conclude that the discriminating factor is not a variable, or a set of variables, that can be applied pluton by pluton, but rather is a fundamental variation in the generation of magma beneath arcs, and relates to the depth and pressure and rock composition in the domain of melting.

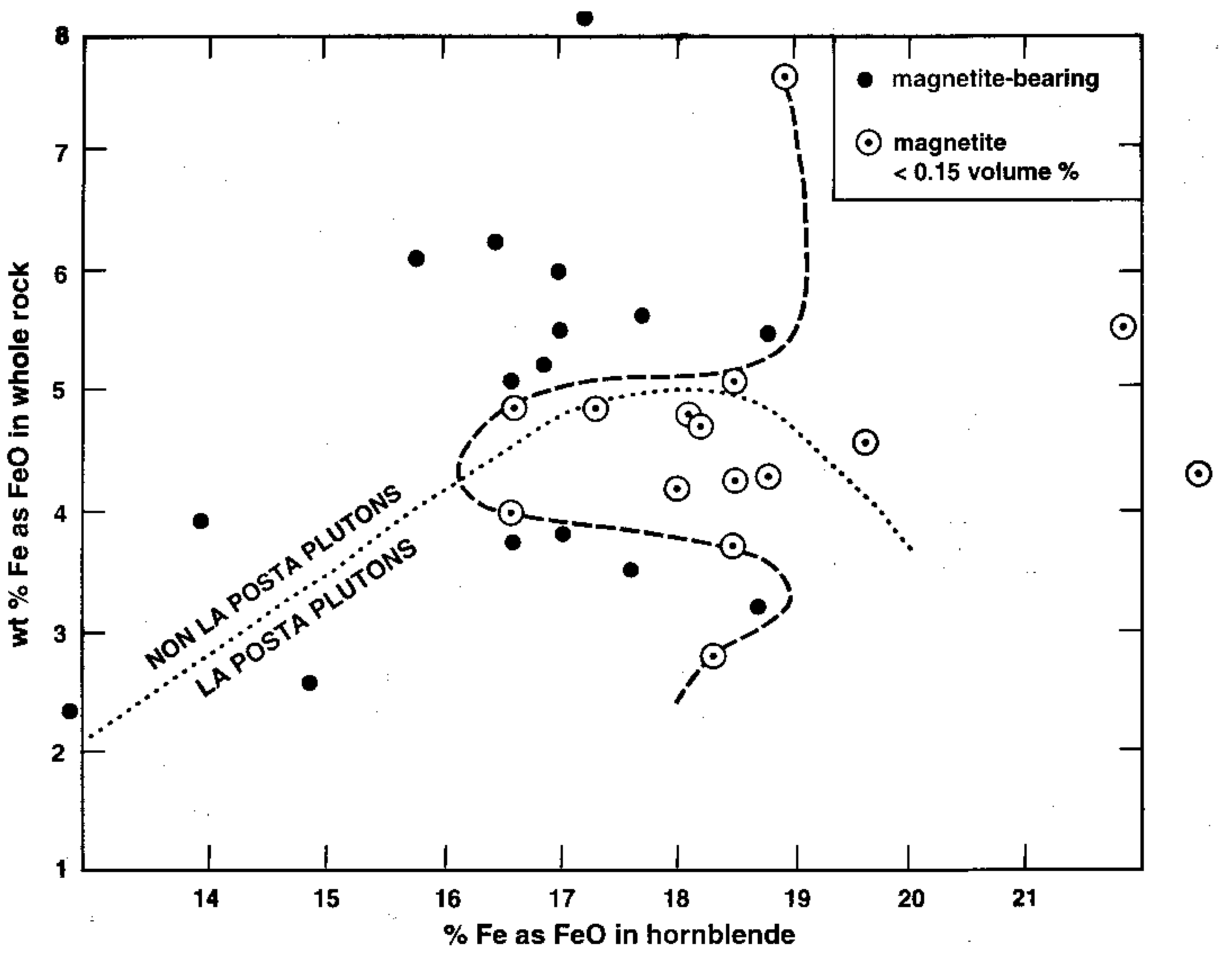

Figure 13.- Weight percent total Fe as FeO in rock plotted against weight percent Fe as FeO in amphibole. Solid dots indicate magnetite-bearing rock, open dots indicate rock with <0.15 volume percent magnetite.

CONCLUSIONS

The observations in the Valle Pedregoso, Los Encinitos, and El Topo plutons may well correspond to the finding of Ishihara and others (1985) in the Miyaki pluton, and of Shimizu in the Tokuwa pluton (1986). And the magma contamination in the outer margin of the El Topo pluton may correspond to the observation that granites generated at least in part from the melting of sedimentary rocks are magnetite-free and ammonium enriched (Tainosho *et al.*, 1988; Tainosho and Itihara, 1988). In this study the non-carbonate carbon content of the granitic rocks seems to have little bearing on magnetite content (Figure 10).

Comparing the La Posta-type hornblende tonalites and granodiorites across the entire eastern half of the Peninsular Ranges batholith, the presence or absence of magnetite appears to correspond to two variables: oxygen fugacity as expressed in iron oxidation state in biotite (Figure 11), and the relative abundance of iron in amphibole (Figures 12 and 13) and in biotite (Figure 8). It may appear contradictory that the absence of magnetite in the rock corresponds to relative iron abundance (Figure 12), and that the absence or poverty of magnetite corresponds to the partitioning of iron into amphibole in iron-poorer rocks (Figure 13).

Why should iron abundance favor a paucity of magnetite? Except for substitution for the hydroxyl ion, each amphibole will contain the same number of oxygen atoms, yet the preferential incorporation of iron atoms will deplete the melt in oxygen faster than the incorporation of magnesium atoms because some proportion of the iron will crystallize trivalent. It is suggested that during the subduction process and the gradual motion of the melt-critical subduction depth across the arc, there is a progressive enrichment in iron relative to magnesium, and to a lesser extent aluminium, in the magmas created, and that it is this iron enrichment which decreases oxygen fugacity and impedes the crystallization of magnetite.

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