Magmatic arc asymmetry and distribution of anomalous plutonic belts in the batholiths of California: Effects of assimilation, crustal thickness, and depth of crystallization

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ABSTRACT

In order to better understand geologic factors controlling pronounced regional variations in whole-rock chemistry, mineralogy, and mineral chemistry in the batholiths of California, we calculate the magmatic intensive variables f_{HF}/f_{H_2O}, f_{HF}/f_{HCl}, and f_{O_2}. Regional-scale west-to-east increases in F/OH in mafic silicates, corresponding to the systematic I-WC to I-MC and I-SC progression, reflect orders-of-magnitude increase in f_{HF}/f_{H_2O} attending pluton crystallization. Low f_{HF}/f_{H_2O} of formation of western I-WC types is consistent with their derivation from low-fluorine source rocks in subducted oceanic slabs or the upper mantle. In contrast, higher f_{HF}/f_{H_2O} of crystallization of I-MC and I-SC types to the east implies the involvement of (1) progressively greater amounts of continental crustal source material such as biotite-bearing metamorphic rocks, their unweathered sedimentary derivatives retaining F-rich mafic minerals, or their fusion products and/or (2) source materials which become more F-rich toward the continental interior. The regional distribution of I-MC and I-SC types suggests that the Precambrian craton of western North America, or derivative sediments, may extend farther north in California and be morphologically more complex than previously thought. From seemingly out-of-place occurrences of I-WC plutons on the eastern slopes of the Sierra Nevada batholith, we infer the existence of regions where Precambrian basement was thin or absent in Mesozoic time, which prevented extensive cratonal contamination of subducted slab or upper mantle-derived magmas.

New methods for estimating T-f_{O_2} relations in the magmas demonstrate that I-SCR granites crystallize at oxygen fugacities as much as five orders of magnitude lower than those of I-WC, I-MC, and I-SC types under conditions at or below the maximum stability limit of graphite in equilibrium with a C-O-H-S gas phase. The local-scale formation of I-SCR granites in plutonic belts within specific wall-rock terranes containing highly reducing sediments or metasediments may occur by contamination of I-types with graphitic pelite or, in some cases, by the direct fusion of this reducing pelitic wall rock. The spatial distribution of I-SCR granite provinces therefore is controlled simply by wall-rock lithology.

Amphibole geobarometry demonstrates a general west-to-east decrease in crystallization pressure across the Sierra Nevada batholith. In contrast, the Peninsular Ranges batholith displays a west-to-east crystallization pressure increase. The bulk of the California batholiths crystallized at pressures less than 4–5 kb and depths less than about 15–19 km. In the southern Sierra Nevada batholith, the San Gabriels, and the eastern Peninsular Ranges, however, plutons crystallized at pressures exceeding 6 kb at deep crustal levels (>23 km). Reconstruction of the pre-erosion top of the batholith shows that in an east-west cross section, the central Sierra Nevada batholith was a horizontal tabular body with an aspect ratio of at least five to one.

INTRODUCTION

Magma sources, the extent of contamination involved in the generation of igneous rocks in continental magmatic arcs, and the depths of calc-alkaline magma production and crystallization have long remained as fundamental problems in petrology and tectonics (see Kistler and Peterman, 1973; DePaolo, 1981a; Farmer and DePaolo, 1983, 1984; Taylor, 1986; Saleeby and others, 1986). In Ague and Brimhall (1988), we address these issues by presenting new data on regional variations in whole-rock chemistry, mineralogy, and mafic and accessory mineral compositions in the Sierra Nevada batholith and White-Inyo Mountains (SNB), the northern Peninsular Ranges batholith (PRB), the San Bernardino fault block (SBB), and the San Gabriel fault block (SGB). Our results, obtained using a new technique of classifying granitic rocks (Table 1), reveal strong localized controls on magma chemistry by involvement of specific lithologic units within pre-batholithic terranes such as the Kings terrane of the SNB (Nokleberg, 1983) and more regional patterns due to variations in thickness and metamorphic grade of cratonal materials. We have therefore extended and refined conclusions reached previously on the basis of interpretation of isotopic data.

Critical to our interpretation of the pronounced regional-scale west-to-east increases in F/OH in mafic silicates corresponding to the I-WC to I-MC and I-SC type progression, and the belts of I-SCR granite plutons containing ferromagnesian phases with low Mg/Fe (Ague and Brimhall, 1987, 1988), is a quantitative understanding of f_{HF}/f_{H_2O} and oxygen fugacity regimes of crystallization of the plutons and the physicochemical properties of probable magmatic source components. The oxygen fugacities of crystallization of volcanic rocks are generally well understood (see Carmichael and others, 1974), but relatively little is known about the oxygen fugacities attending pluton crystallization, owing to the re-equilibration of magnetite during slow cooling (see Czamanske and others,

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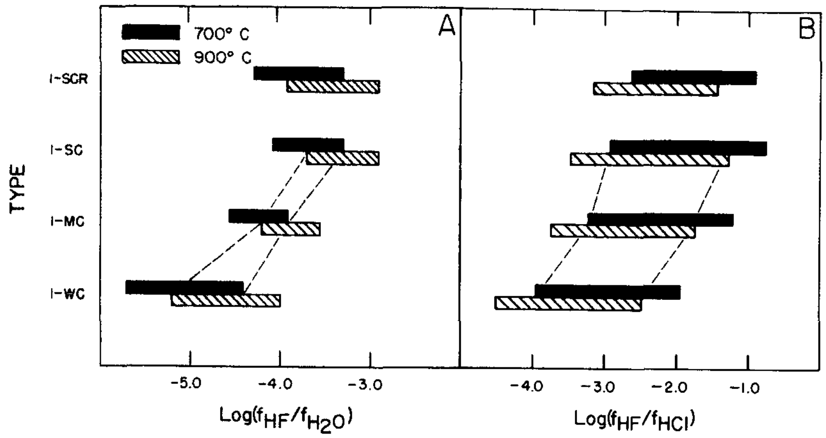

Figure 1. (A) Calculated log(f_{HF}/f_{H_2O}) and (B) log(f_{HF}/f_{HCl}) at 700 and 900 °C for plutonic rock types of the batholiths. Dashed lines indicate degree of overlap between fugacity ratios computed at each temperature.

1981) and the consequent interpretive problems of Fe-Ti oxide geothermometry and oxygen barometry. We therefore present new techniques utilizing equilibrium relations preserved between ilmenite, biotite, and potassium feldspar in order to provide a quantitative framework for interpreting T-f_{O_2} relations in the magmas before slow cooling in plutonic environments.

There are important advantages in studying the petrogenesis of plutons as opposed to their extrusive equivalents. The primary advantage is direct exposure of regions where chemically reactive pre-batholithic wall-rock terranes, such as highly reducing graphitic pelites, have interacted with rising subduction-related magmas via such processes as assimilation, partial melting, and magma mixing. This eliminates equivocal inferences regarding the petrologic character of magmatic source components based upon geochemical and isotopic evidence alone. Another advantage is the possibility of inferring the depths of emplacement of the plutons using the amphibole geobarometer of Hammarstrom and Zen (1986), which facilitates understanding of the intrusives from the sub-volcanic environment (Fiske and others, 1977) to the deep levels of batholithic root zones (see Ross, 1985) without having to rely on estimates of metamorphic grade in sparsely distributed roof pendants. Furthermore, interactions between magmas and wall rocks at various depths can be characterized.

THERMODYNAMIC RELATIONSHIPS

As a first step in obtaining a meaningful thermodynamic understanding of biotite compositions and regional variations in biotite chemistry, we address the relationships of X_F/X_{OH}, X_F/X_{Cl}, and X_{Mg}/X_{Fe} in biotites to fugacities of magmatic volatiles. In doing so, we clarify the chemical differences between I-WC–, I-MC–, I-SC–, and I-SCR–type plutons and the relationships between halogen species, magmatic water, and redox state. In addition, we examine the effects of Fe-F avoidance on our classification scheme.

f_{HF}/f_{H_2O}, f_{HF}/f_{HCl} and the I-WC, I-MC, I-SC, and I-SCR Classification Scheme

In order to quantify the fugacity regimes of crystallization of the pluton types, we may calculate log (f_{HF}/f_{H_2O}) and log (f_{HF}/f_{HCl}) utilizing the expressions presented by Munoz (1984) which relate biotite composition to temperature and hydrothermal fluid composition.

$$\log(f_{HF}/f_{H_2O}) = -2100/T - 1.523X_{Phl} - 0.416X_{Ann} - 0.2X_{Sid} + \log(X_F/X_{OH})_{Bio} \quad (1)$$

$$\log(f_{HF}/f_{HCl}) = 3051/T - 3.45X_{Phl} - 0.41X_{Ann} - 0.2X_{Sid} + \log(X_F/X_{Cl})_{Bio} - 5.01 \quad (2)$$

Mole fractions of the mica end-members phlogopite, annite, and siderophyllite in biotite were calculated following Gunow and others (1980).

Variations in log(f_{HF}/f_{H_2O}) and log(f_{HF}/f_{HCl}) at 700 and 900 °C are shown by pluton type in Figures 1A and 1B. At a given temperature, values of log(f_{HF}/f_{H_2O}) vary over 2 orders of magnitude between I-WC and I-SC types. I-SCR types have log(f_{HF}/f_{H_2O}) which ranges from values equivalent to the more F-rich I-MC types to ratios which are as high as the most F-enriched I-SC types. Although significant overlap between I-WC, I-MC, and I-SC types occurs in log(f_{HF}/f_{HCl}) (Fig. 1B) at a given temperature, calculated fugacity ratios vary over approximately 3 to 4 orders of magnitude and show a general increase from I-WC to I-SC types. Calculated log(f_{HF}/f_{HCl}) for I-SCR granites are similar to those of I-MC and I-SC types.

As has been observed by many workers, hydroxyl-bearing mafic minerals such as biotite with high Mg/Fe ratios tend to contain more F than do their iron-rich counterparts (see Ekstrom, 1972; Zaw and Clark, 1978; Gunow and others, 1980; Valley and Essene, 1980). In contrast, the Cl content of mafic silicates tends to be the greatest in Fe-rich minerals (see, for example, Munoz and Swenson, 1981). These effects are referred to as "Fe-F and Mg-Cl avoidance" (Munoz, 1984) and reflect the bond energies of metal cations in octahedral coordination with the halogens and OH.

We may investigate the effects of Fe-F avoidance on our classification scheme by utilizing equation 1. If ideality in the annite-phlogopite solid solution is assumed, isopleths of biotite composition at constant temperature and f_{HF}/f_{H_2O} evolve with a shallow slope of 0.6 in the log(X_F/X_{OH}) versus log(X_{Mg}/X_{Fe}) coordinate system which we use for biotite classification. This effect represents only very small increases in F/OH with increasing Mg in biotite. We conclude therefore that the approximately 2–orders-of-magnitude variation in log(X_F/X_{OH}) of I-WC–, I-MC–, and I-SC–type biotites, at essentially the same X_{Mg}/X_{Fe} (Ague and Brimhall, 1987, 1988), is a direct result of large differences in f_{HF}/f_{H_2O} attending pluton crystallization and does not reflect the operation of Fe-F avoidance to any significant degree.

Temperature-f_{O_2} Relations

Although estimates of temperature and oxygen fugacity place important constraints upon source materials responsible for pluton formation, such estimates are difficult to obtain owing to the widespread re-equilibration of magnetite and other minerals during slow cooling (see Whitney and Stormer, 1977; Czamanske and others, 1981; Noyes and others, 1983). We have utilized a new approach which involves biotite-ilmenite equilibria in granitic rocks to estimate T-f_{O_2} conditions, in conjunction with T-f_{O_2} estimates from one sample which has oxides retaining their primary composition, and garnet-biotite thermometry (Ferry and Spear, 1978) in rocks of suitable mineralogy.

Many authors (for example, Bowles, 1977; Anderson, 1980) have argued that ilmenites maintain a high-temperature composition and are thus indicative of magmatic oxygen fugaci-

TABLE 1. COMPARISON OF CLASSIFICATION SCHEMES

	I-WC	I-MC	I-SC	I-SCR
Rock type	Diorite-granodiorite	Granodiorite-granite	Granite	Granite
SiO_2	53–68	60–73	70–77	66–76
Molar $Al_2O_3/(K_2O + Na_2O + CaO)$	Generally ≤1	Generally ≤1	~1	0.94 to >1.1
Elements	High Ca, low Rb/Sr, generally high Ni, Cr, Cu	Intermediate Ca, intermediate Rb/Sr	Low Ca, high Rb/Sr	Low Ca, high Rb/Sr, in some cases high Cr
$Fe^{3+}/(Fe^{2+} + Fe^{3+})$	Moderate (?)	Moderate (?)	Moderate (?)	Low
Characteristic silicate phases	AMP + BIO ± PYX	AMP + BIO	BIO ± AMP	BIO ± MV ± GNT ± Tour ± AMP
Biotite log (X_{Mg}/X_{Fe})	> −0.21	> −0.21	> −0.21	< −0.21
Biotite log (X_F/X_{OH})	< −1.5	−1.5 to −1.0	> −1.0	−1.6 to −0.7
Characteristic accessory minerals	MT ± "oxidized" ILM ± SPH	MT ± SPH ± "oxidized" ILM	MT ± SPH ± "oxidized" ILM	"Reduced" ILM ± MT
Inclusions	AMP + BIO + PLAG mafic inclusions	AMP + BIO + PLAG mafic inclusions	Rare AMP + BIO + PLAG mafic inclusions	Rare BIO ± MV inclusions
Sr_i	<0.706	>0.706	>0.706	High (?)
$\delta^{18}O$	<10	7 to 12	7 to 12	High (?)
ϵ_{Nd}	> −6	< −6	< −6	Low (?)
Fugacities	f_{O_2} above graphite saturation, low f_{HF}/f_{H_2O}	f_{O_2} above graphite saturation, intermediate f_{HF}/f_{H_2O}	f_{O_2} above graphite saturation, high f_{HF}/f_{H_2O}	f_{O_2} at or below graphite saturation, variable f_{HF}/f_{H_2O}
Origins	West-to-east I-WC to I-MC and I-SC progression may be due to (1) increasing amounts of contamination of mafic magmas derived from upper mantle/subducted oceanic slab with high F/H_2O continental crustal source components and/or (2) regional variation in F/H_2O of source region. I-WC types of eastern Sierra probably due to intrusion of upper mantle magmas into zones of crustal thinning			(1) Contamination of I-types with reducing graphitic pelites in pre-batholithic roof-pendant terranes. (2) Fusion of graphitic pelites

Note: data from Kistler and Peterman (1973, 1978), Chappell and White (1974), Ishihara (1977), Pitcher (1978, 1983), Silver and others (1979), Takahashi and others (1980), Czamanske and others (1981), DePaolo (1981a), Sillitoe (1981), Wyborn and others (1981), Collins and others (1982), Price (1983), White and Chappell (1983), White and others (1986).

ties even when coexisting magnetites have lost Ti at low temperatures. Support for this comes from the fact that ilmenites that we have analyzed from any given sample are all compositionally equivalent. Aside from possible differences in reaction kinetics, the rapid loss of Ti from magnetite may be due to the steep angle that isopleths of ulvospinel content make with common T-f_{O_2} paths taken by cooling igneous rocks (see Buddington and Lindsley, 1964; Carmichael and others, 1974). Herein, we employ a modification of the classical granite buffer of Wones and Eugster (1965), using the activity of the hematite component of ilmenite rather than of magnetite.

$$\underset{\text{in biotite}}{KFe_3AlSi_3O_{10}(OH)_2} + 0.75O_2 = \underset{\text{in K-fsp}}{KAlSi_3O_8} + \underset{\text{in ilm}}{1.5Fe_2O_3} + H_2O \quad (3)$$

We utilize an ideal model for the activity of annite in biotite [$a_{ann} = (K)(Fe/3)^3(Al^{IV})(Si/3)^3(OH/2)^2$] and set $a_{K\text{-feldspar}} = 0.9$. We have used the liquid standard state for H_2O and assume $a_{H_2O} = 1.0$. If it is assumed that the hematite component of ilmenite falls within the scope of Henry's law (Powell and Powell, 1977), the activity of hematite in ilmenite can be expressed as

$$a_{hm} = hX_{hm}, \quad (4)$$

where h is the Henry's law constant. An expression for h is given by Nakada (1983) and is of the temperature-dependent form

$$\log h = 1332/T - 1.124. \quad (5)$$

Log f_{O_2}'s calculated using equilibria involving this activity expression agree within less than 0.3 log units with other methods of estimation (Nakada, 1983). If we assume that the ilmenites retain a high-temperature signature that was once in equilibrium with titanium-rich magnetite, the point of intersection of the curves defined by equation 3 and the appropriate isopleth of ilmenite composition from Buddington and Lindsley (1964) gives a point in T-f_{O_2} space which presumably reflects the equilibration conditions of these phases. We have employed this technique only for rocks containing both magnetite and ilmenite because the isopleths of ilmenite hematite content from Buddington and Lindsley (1964) were determined with the ilmenite composition buffered by coexisting magnetite. We have determined that the average pressure of crystallization of the batholiths is 3 kb based upon amphibole chemistry (Hammarstrom and Zen, 1986; see below), and we have therefore carried out our calculations at this pressure. The original T-f_{O_2} curves of Buddington and Lindsley (1964) have been utilized instead of the calculated curves of Spencer and Lindsley (1981) in order to maintain consistency with published work on T-f_{O_2} conditions in volcanic rocks (compare with Carmichael and others, 1974).

It is important at this point to discuss the assumptions involved in the calculations and their possible effects. Although the presence of Fe^{3+} in biotite will tend to raise the oxygen fugacity buffer curves somewhat, approximately 0.25 log units maximum, if $a_{H_2O} < 1$, which is probably the general case for plutonic rocks, then this reduced water activity will lower them. Because H_2O and annite have the same stoichiometric coefficients in the reaction, these effects will tend to cancel. It is important to emphasize that the conclusions reached would remain essentially unchanged unless the a_{H_2O} in the I-WC, I-MC, and I-SC types was about 3 orders of magnitude less than the value of 1 used in our calculations. A more serious problem concerns the unknown effects of Mn on the activity of hematite in ilmenite, which we assume to be negligible but which in fact may not be. The T and f_{O_2} calculated from sample 1011-165, which contains oxides which have not re-equilibrated, using the method described above (T = 850 °C, log f_{O_2} = −12.9) agree well with estimates derived from the Buddington and Lindsley thermometer (T = 890 °C, log f_{O_2} = −12.3).

In addition, broad constraints may be placed upon oxygen fugacity regimes of crystallization for rocks containing only one Fe-Ti oxide phase. For samples containing no ilmenite, buffer curves may be generated using the standard granite buffer (Wones and Eugster, 1965) and taking magnetite to be pure Fe_3O_4. For ilmenite-bearing rocks, the biotite–ilmenite–K-feldspar–H_2O buffer described above may be utilized.

The results of the calculations are shown in Figure 2 along with common buffer curves at 3 kb pressure. The upper limit on the I-WC, I-MC, and I-SC field in Figure 2A is taken to be the highest f_{O_2} curve defined by samples containing only magnetite. In Figure 2A, it is immediately apparent that I-SCR types containing ilmenite and magnetite define a field in the temperature range of 700 to 850 °C at oxygen fugacities as much as 5 orders of magnitude lower than those for the I-WC, I-MC, and I-SC types. Although more overlap between the I-WC, I-MC, and I-SC T-f_{O_2} field and that of the I-SCR types is evident in Figure 2B for assemblages lacking magnetite, probably owing in large part to the fact that temperature cannot be determined for samples containing only ilmen-

TABLE 1. (*Continued*)

I	S	A	Magnetite series	Ilmenite series
Diorite-granite	Granite	Granite–alkalic granite	Diorite-granite	Diorite-granite
53–76	65–74	74–77	55–76	53–76
<1.1	>1.05	Variable	Variable	Variable
Variable Cr, variable Rb/Sr, Ni-Cr < S-types	Low Ca, high Rb/Sr, high Cr-Ni	Low Ca, high Rb/Sr, high Ga, Zr, Nb, REE, F, Cl	Predominantly "I-type" characteristics	Rocks may show "I-type" or "S-type" affinities
<0.45	<0.3	Variable	Typically >0.5	Typically <0.5
BIO ± AMP ± PYX	BIO + cordierite ± MV GNT ± Al_2SiO_5	BIO ± sodic amphibole	AMP + BIO ± PYX	BIO ± AMP ± MV ± GNT ± cordierite
> −0.2	~ −0.2	Low	Typically > −0.2	Typically < −0.2
Variable	Variable	High	Variable	Variable
MT ± ILM ± SPH	MT ± ILM ± monazite	MT, fluorite	MT ± ILM ± SPH	ILM ± SPH ± MT
AMP + BIO + PLAG mafic inclusions	Metasedimentary xenoliths	Cognate xenoliths, basic magma blebs	AMP + BIO + PLAG mafic inclusions	Variable
0.704 to 0.707	0.706 to 0.718	Variable	0.704 to 0.710	0.704 to 0.713
<10	>10	Variable	5.5 to 8	7.5 to 12.5
> −6	< −6	Variable	. .	. .
High f_{O_2}, f_{S_2}, low f_{HF}/f_{HCl}	Low to intermediate f_{O_2}, intermediate f_{HF}/f_{HCl}	Variable f_{O_2}, high f_{HF}, f_{HCl}	High f_{O_2}, high fugacities of oxidized S species	f_{O_2} below Ni–NiO
Partial melting of igneous source rocks	Partial melting of sedimentary or metasedimentary source rocks such as "graywacke" with a minor shale component	Partial melts of high-grade metamorphic rocks or I-types subjected to partial-melting events during late orogenic or anorogenic igneous activity	Predominant upper mantle source, melts chemically modified and oxidized within the crust	Low f_{O_2} inherited from lower crustal/upper mantle source or acquired through interaction with carbon-bearing sedimentary and metamorphic rocks

ite, the low oxygen fugacities of crystallization of the I-SCR types are still obvious.

Our computations show that the I-SCR types occupy a region in T-f_{O_2} diagrams which lies approximately at or below the maximum stability limit of graphite, coexisting with sulfides, in the C-O-H-S system (Ohmoto and Kerrick, 1977). On the basis of gas phase equilibria in the C-O-H-S system, the oxygen fugacity regime of crystallization of magmas derived from graphite-bearing source regions, such as those of "S-type" affinity and some ilmenite-series plutons, has long been suspected to lie below the QFM buffer astride the CO_2-CH_4 isofugacity line (Ohmoto and Kerrick, 1977; Burnham and Ohmoto, 1980), but our calculations displayed in Figure 2A represent the first T-f_{O_2} estimates from coexisting phase assemblages in reduced granitic rocks. The results of our calculations demonstrate that oxygen fugacities defined by the I-SCR types are consistent with buffering at low f_{O_2} by graphite-bearing wall rocks. In contrast, I-WC, I-MC, and I-SC types occupy a region in T-f_{O_2} diagrams generally above the maximum stability limit of graphite. This oxygen fugacity regime is consistent with that calculated using coexisting iron-titanium oxides in common intermediate and felsic volcanic rock types (see Carmichael and others, 1974).

Garnet-biotite Fe-Mg exchange thermometry (Ferry and Spear, 1978), using I-SCR samples 1011-303 and 1011-418 which contain garnets with reasonably low Mn and Ca contents, gives temperatures of 670 and 750 °C at 3 kb using the calibration of Hodges and Spear (1982). These results are broadly consistent with the temperature range defined by the biotite-ilmenite relations described above.

MAGMATIC SOURCE ROCKS

To interpret the origins of the geochemically distinct intrusive types which we have defined in the batholiths of California, it is necessary to consider hydrous minerals in probable magmatic source components and evaluate a complex array of isotopic and age data in conjunction with our results on regional variations in petrology, whole-rock geochemistry, mafic and accessory mineral assemblages and compositions, and fugacities of magmatic volatiles.

Hydrous Minerals in Magmatic Source Rocks

The nature and amounts of hydrous minerals in magmatic source rocks undergoing partial melting control the H_2O + halogen content and temperature of first-formed melts (Burnham, 1979, 1981; Burnham and Ohmoto, 1980; Brimhall and others, 1983). The hydrous minerals and source rocks thought to be important in the evolution of magmas responsible for porphyry mineralization and "calc-alkaline" magmatism in general are (1) amphibole in mafic amphibolites, (2) biotite in high-grade metamorphic rocks and residual melt-depleted igneous rocks, and (3) muscovite in pelitic schists (Burnham and Ohmoto, 1980; Burnham, 1981; Brimhall and others, 1983, 1985; Brimhall and Ague, 1988).

Amphibole-Bearing Source Rocks. Amphibole-rich source rocks such as mafic amphibolites in subducted oceanic slabs or hornblende gabbros of the continental crust melt at temperatures in excess of 1000 °C and give rise to liquids containing approximately 2.7 wt.% H_2O + halogens (Burnham, 1979, 1981). The melting of mafic amphibolite has often been proposed to explain the formation of the calc-alkaline batholiths of plutonic arcs (see Burnham, 1979, 1981; Wyllie, 1981; Ellis and Thompson, 1986). Mafic amphibolites and other metamorphosed mafic rock types are typically low in F (200–300 ppm), as are examples of nonphlogopitic rocks derived from the upper mantle (15–300 ppm F) (Koritnig, 1972). In addition, amphiboles in hydrothermally altered oceanic crust are consistently low in F but may be Cl rich, containing as much as approximately 3 wt.% Cl, probably owing to interaction of basalt with saline hydrothermal fluids (Vanko, 1986).

Biotite-Bearing Source Rocks. Micaceous biotite-bearing source rocks, such as deep crustal gneisses of tonalitic or granodioritic composition, fuse at significantly lower temperatures of 800–850 °C and yield melts containing about 3.3 wt.% H_2O + halogens (Burnham, 1981). Because hydrous minerals control to a large degree the volatile makeup of the melts, it is necessary to examine changes in biotite chemistry which occur during metamorphism and anatexis.

It is generally thought that increasing metamorphic grade results in the concentration of F (and sometimes Cl) into hydrous phases because progressive dehydration of the rock results in fewer and fewer hydrous minerals (see Dallmeyer, 1974; Kamineni and others, 1982; Guidotti, 1984). Partial melting events will also tend to increase the halogen content of whatever hydrous phases remain in the residue (Collins and others, 1982). Figure 3 shows biotite compositions of pelitic and quartzofeldspathic schists, gneisses, and migmatites ranging from garnet to "granulite" grade. It is clear that the highest grade metamorphic rocks contain the most F-rich biotites, with $\log(X_F/X_{OH})$ values comparable to those of the I-SC pluton types. In addition, the biotites from the highest grade metamorphic rocks show a trend of concurrent Mg and F enrichment which probably indicates that they are being stabilized at high temperatures by low-energy Mg-F bonds as fluorphlogopite is highly refractory.

Such high-F/OH silicates are likely to be quite common in the lower crust (see Fillipopov and others, 1974; Holloway and Ford, 1975; Holloway, 1977; Fountain and Salisbury, 1981; Manning and Pichavant, 1983; Christiansen and Lee, 1986). For example, Fountain and Salisbury (1981), in their summary of exposed cross sections through the continental lithosphere, observed that the primary variation through the crust with depth is in metamorphic grade, with the lower crust being dominated by upper amphibolite- and granulite-facies rocks. In this context, we note that biotite-bearing granulite xenoliths from the lower crust (17–43 km depth) occur in 10-m.y.-old volcanics in the central SNB (Dodge and others, 1986). In addition to examples of rocks from the Precambrian craton possessing hydrous phases with high halogen contents, such as the Silver Plume granite of Colorado (1,940 ppm F; see Koritnig, 1972). Precambrian high-grade aluminosilicate-topaz gneisses, such as those found in Colorado (Marsh and Sheridan, 1976), may also be F-rich, containing as much as 7.5 wt.% F.

Muscovite-Bearing Source Rocks. Muscovite-bearing pelitic rocks melt at the lowest temperatures (650–750 °C) and yield volatile-rich melts containing as much as 8.4 wt.% H_2O + halogens (Clemens and Wall, 1981; Burnham, 1981; Thompson, 1982; Grant, 1985). The F contents of pelitic sediments are variable (10–7,600 ppm) but are on average high (700–900 ppm) (Koritnig, 1972), as are their water contents which range from less than 1 to approximately 5 wt.% (Pettijohn, 1975).

It is important to note that because the right side of the reaction

$$C + H_2O = CH_4 + CO_2 \qquad (6)$$

is strongly favored by increasing temperature (Ohmoto and Kerrick, 1977), high-grade metamorphic rocks derived from graphitic pelites in general should not have the same reducing capabilities as their lower grade equivalents, owing to consumption of graphite during prograde metamorphism.

To conclude, it is clear that the halogen contents of likely source rocks considered herein vary widely and this has important implications for the observed west-to-east increases in the F/OH of mafic silicates in the batholiths. Hydrous minerals undergoing fusion control to a significant degree the volatile makeup of the resultant melt (compare with Burnham, 1981), and hydrous minerals which crystallize from this melt will then record the volatile composition of the magma via their hydroxyl sites. The F contents of mafic rocks are in general low, and therefore, the f_{HF}/f_{H_2O} of magmas formed from these rock types should also be low. On the other hand, high F/OH silicates in high-grade metamorphic rocks and residual melt-depleted igneous rocks should upon fusion yield magmas with elevated f_{HF}/f_{H_2O}. Melting of muscovite-rich pelites is likely to give rise to liquids with a range of f_{HF}/f_{H_2O}, owing to the variability of pelitic bulk compositions.

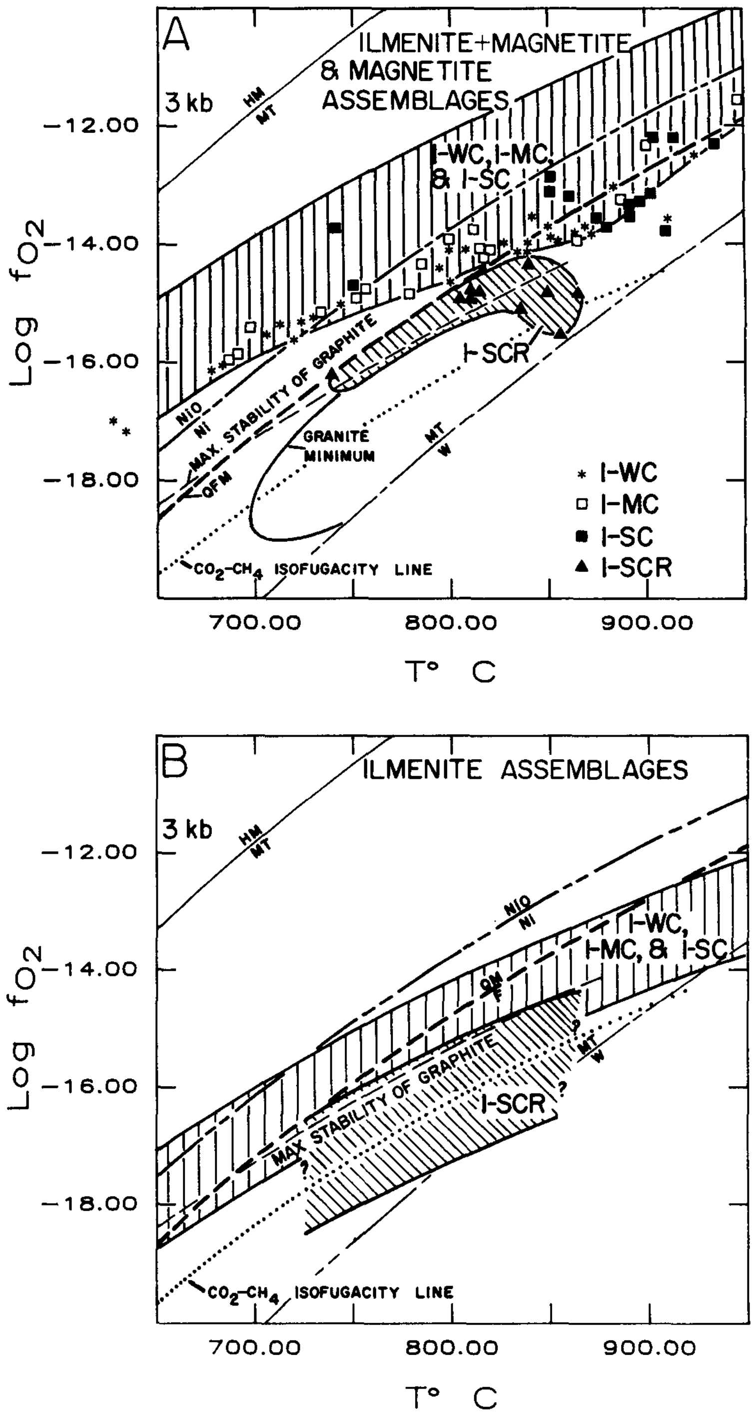

Figure 2. Oxygen fugacity regimes of crystallization, illustrating highly reduced nature of I-SCR types. Thermodynamic data from Ohmoto and Kerrick (1977) and Helgeson and others (1978). A. T-f_{O_2} points computed for samples containing magnetite and ilmenite. Upper f_{O_2} limit for I-WC, I-MC, and I-SC types defined by specimens containing magnetite without ilmenite. B. Broad regions in T-f_{O_2} space defined by samples containing only ilmenite.

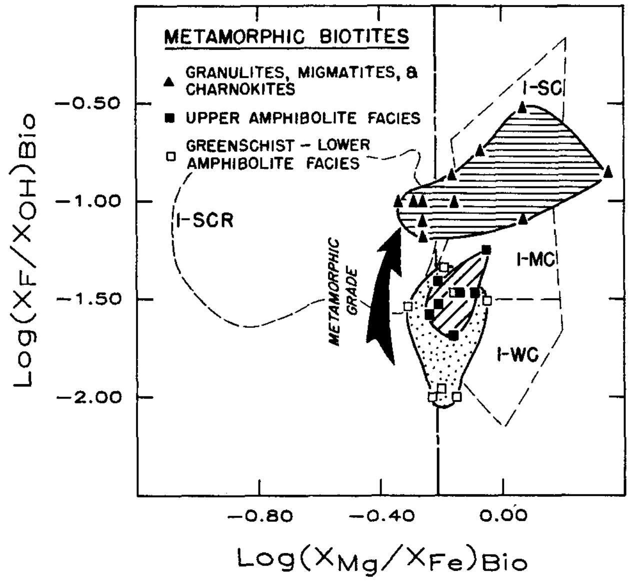

Figure 3. Evolution of biotite compositions with increasing metamorphic grade, illustrating pronounced increase in F/OH with increasing degrees of metamorphism. Stippled field: greenschist–lower amphibolite facies; diagonal-ruled field: upper amphibolite facies; horizontal-ruled field: granulites, migmatites, and charnockites. Data sources: Deer and others (1966), White (1966), Leelanandam (1969), Dallmeyer (1974), Yardley and others (1979), Olsen (1982), Pigage and Greenwood (1982), J. J. Ague (unpub. data on garnet-grade metapelites from central-western Spitsbergen).

Correlations with Radiogenic and Stable Isotope Variations

Regional variations in radiogenic and stable isotope systematics in the batholiths place important constraints upon the nature of magmatic source components and mixing processes. In examining our petrologic results in the light of published isotopic data, however, we must emphasize that the sampling systematics of our study allow for fairly fine resolution of regional geochemical detail whereas the isotope studies have to date relied upon fewer samples to define generalized large-scale regional trends. In particular, I-WC types of the eastern Sierra Nevada batholith and I-SCR granites appear to have been largely neglected in past sampling done for isotopic purposes.

Beginning with Kistler and Peterman (1973) and Early and Silver (1973), it has been recognized that the plutons of the SNB and PRB become increasingly radiogenic from west to east. Regional increases in initial strontium ratio (Sr_i) (Early and Silver, 1973; Kistler and Peterman, 1973, 1978) and decreases in ϵ_{Nd} (DePaolo, 1981a) are well-established trends. The west-to-east progression from I-WC to I-MC and I-SC types broadly parallels these isotopic contours. In the SNB, the $Sr_i = 0.706$ contour is thought to coincide roughly with the edge of the Precambrian craton of western North America or derivative sediments (Kistler and Peterman, 1973, 1978). The contours of $\delta^{18}O$ values of Taylor and Silver (1978) in the PRB show a pronounced west-to-east increase from less than +5.5 to +12 (SMOW), whereas the SNB patterns found by Masi and others (1981) are much less regular.

Comparison of published isotope systematics with our petrologic data allows us to make the following generalizations. I-WC types are typically the least radiogenic and have Sr_i less than 0.706 and ϵ_{Nd} greater than −6 with $\delta^{18}O$ being in general less than +10. I-MC and I-SC types, on the other hand, typically have Sr_i greater than 0.706 and ϵ_{Nd} less than −6. $\delta^{18}O$ ranges from approximately +7 to +12. The small amount of isotopic data which currently exists for plutons with I-SCR–type characteristics is discussed below in reference to contamination processes and the origins of I-SCR granites.

Age Variations

In the PRB and the Cretaceous part of the SNB, the ages of the plutons decrease from west to east. The transition is fairly gradual in the SNB and more abrupt across the 105-m.y. age step within the PRB. In the SNB, an Early Triassic to Jurassic magmatic arc is transected by the later main Cretaceous portion of the batholith (compare with Stern and others, 1981), whereas the PRB contains only Cretaceous plutons (Silver and others, 1979).

Using published age data (Silver and others, 1979; Stern and others, 1981; Chen and Moore, 1982), we find that I-WC, I-MC, and I-SC types range in age from Triassic to Cretaceous. I-SCR types may be as old as Triassic (Tungsten Hills quartz monzonite adjacent to the Pine Creek Mine, 203 m.y.), but most appear to be Cretaceous in age (for example, granite of Shuteye Peak, 101 m.y., and the Cactus Point pluton, less than 99 m.y.) (Stern and others, 1981; Chen and Moore, 1982).

In the Cretaceous portions of the SNB and PRB, the west-east decreases in pluton ages and ϵ_{Nd} and the increases in Sr_i are broadly mirrored by the progression from I-WC to I-MC and I-SC types. This is probably a reflection of some change in the subduction process which caused magmas to be generated farther inland with time during the Cretaceous (Chen and Moore, 1982), as has been observed in the modern Andes (McNutt and others, 1975; Pitcher, 1978). Both the most primitive I-WC types and the more evolved I-MC and I-SC types, however, crystallized throughout the Mesozoic, indicating that although the migration of the plutonic arc in space and time occurred, the nature of the magmas produced in any given geographic province was similar. This parallels observed regional trends in radiogenic isotope systematics, which also appear to be independent of pluton age (Kistler and Peterman, 1973, 1978).

In contrast to the west-to-east organization of the I-WC, I-MC, and I-SC belts, the I-SCR types are present mainly in the western SNB and PRB, although a few occurrences to the east have been recognized and are of Triassic to Cretaceous age. The processes which form I-SCR plutons therefore are not restricted to a particular time interval.

Origins of I-SCR Types

The localization of I-SCR types in prebatholithic wall-rock terranes containing graphite-bearing sediments strongly suggests that these reducing wall rocks are an essential source component for I-SCR melts. In addition to the petrologic evidence discussed above, consideration of Rb-Sr trace-element systematics and published isotopic data allows us to place further constraints on the origins of these reduced granites.

Because I-SCR granites are generally associated with I-WC types, it is important to evaluate whether assimilation of pelitic wall rocks by I-WC magmas, combined with concurrent fractional crystallization (AFC process; compare with Taylor, 1980; DePaolo, 1981b), is a mechanism compatible with the Rb-Sr trace-element systematics of I-SCR granites. We focus on Rb and Sr as examples of incompatible and compatible element behavior during crystallization. Figure 4 illustrates Rb-Sr element systematics for all rock types and shows that the I-SC and I-SCR types occupy well-defined fields on the diagram, with negative correlations between Rb and Sr. I-WC types have Rb-Sr element distributions distinct from the I-SC and I-SCR granites and display a weak positive correlation of Rb and Sr, which suggests that Sr may behave as an incompatible element in some cases (compare with DePaolo, 1981a). I-MC types show substantial overlap with the other rock types.

The results of the trace-element modeling are presented in Figure 5. Both AFC and simple fractional-crystallization calculations are shown. It is clear that the I-SCR Rb-Sr compositions could be derived from either fractionating I-WC intrusives or through the input of country rock into a crystallizing I-WC magma. In either case, the value of the bulk solid/liquid partition coefficient for Sr (D_{Sr}) must be relatively high (greater than ~1.5). The main difference between the two scenarios is that the AFC process causes faster crystallization and increases the proportions of late differentiates (Fig. 5A; Bowen, 1928). Fractional crystallization of I-WC magmas without assimilation, however, is almost certainly not the process by which I-SCR types form. This is because I-SCR granites are restricted to pre-batholithic terranes containing graphitic pelites which have been intruded by I-WC magmas and do not occur where I-WC types intrude other wall-rock terranes.

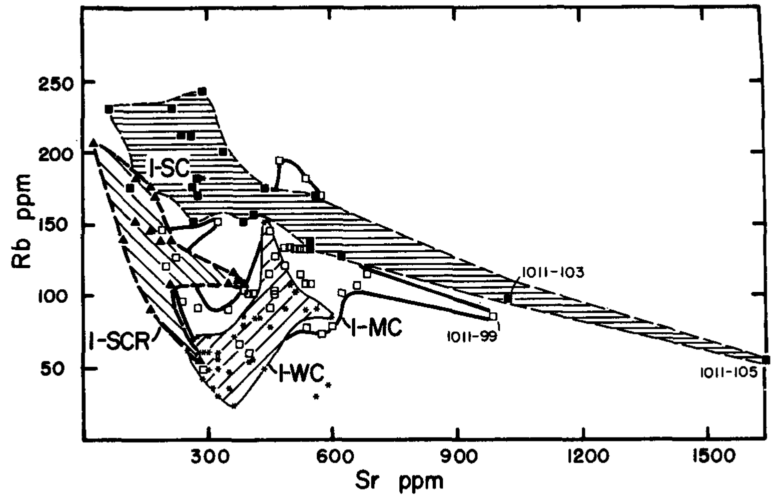

Figure 4. Rb and Sr trace-element systematics of pluton types. Note clear separation of I-SCR and I-SC granites from each other and I-WC types.

There is at present little isotopic evidence bearing on contamination processes and the origins of I-SCR granites, although the results of Moore and others (1979) and Hill and others (1986) provide important insights into the generation of strongly peraluminous garnet-aluminosilicate granites in the SNB and PRB. The SNB example occurs within the I-SCR belt and has extremely high $^{87}Sr/^{86}Sr$ of 0.7673 (Moore and others, 1979), which is comparable to values obtained from pelitic wall rocks in the northern PRB (Hill and Silver, 1983; Hill and others, 1986), strongly implying complete derivation of this granite from pendant material (Moore and others, 1979). The isotopic signature of the PRB granite (Sr_i = 0.712, $\delta^{18}O$ = +11.9), although interpreted by Hill and others (1986) to be the result of isotopic exchange with metamorphic waters, is also completely consistent with assimilation of local pelitic wall rock by tonalitic magma. In addition, in the southern SNB in the region occupied by the I-SCR belt, Masi and others (1981) found granitic rocks with $\delta^{18}O$ exceeding +10, which may indicate the involvement of sedimentary source materials in the generation of these magmas.

In view of all available petrologic, geochemical, and isotopic evidence, we conclude that the production of I-SCR magmas requires reducing pelitic source components. This conclusion is supported by the following evidence. First, I-SCR granites, ranging in age from Triassic to Cretaceous, occur within pre-batholithic wall-rock terranes containing reducing graphitic pelites (Ague and Brimhall, 1988, Fig. 19). Second, the oxygen fugacities of I-SCR granite crystallization are at or below the maximum stability limit of graphite (Ohmoto and Kerrick, 1977), strongly implying involvement of graphitic sediments or metasediments. Third, the range in I-SCR granite compositions from metaluminous to strongly peraluminous suggests that varying amounts of contamination of I-type magmas with pelitic wall rock, or fusion of this wall rock, may give rise to I-SCR types. In addition, the occurrence of nonfractionated minimum-melt I-SCR granites may imply a local anatectic origin. Finally, the available isotopic evidence summarized above is consistent with formation of I-SCR types by assimilation of pelitic schist into I-type magmas or by the fusion of metasedimentary wall rock. Although the AFC Rb-Sr modeling is consistent with either AFC processes involving contamination of I-WC–type magma with pelitic metasediments or fractional crystallization of an I-WC intrusive, the operation of simple fractional crystallization alone is highly unlikely as I-SCR granites occur only where relatively mafic I-types intrude reducing pelitic wall-rock terranes. We predict, based upon the regional distribution of the I-SCR types which we have defined, that a zone of high Sr_i and $\delta^{18}O$ and low ϵ_{Nd} exists along the western margin of both the PRB and SNB, owing to the presence of I-SCR plutons.

Origins of I-WC, I-MC, and I-SC Types

In contrast to the localized occurrence of I-SCR granites within highly reactive reducing wall-rock terranes, I-WC, I-MC, and I-SC types form a regional-scale west-to-east sequence which parallels previously recognized petrologic, geochemical, isotopic, and age trends.

Evidence from isotope studies (Kistler and Peterman, 1973, 1978; Silver and others, 1979; DePaolo, 1981a; Hill and others, 1986; Kistler and others, 1986) indicates that the west-to-east increases in the radiogenic nature of the plutons reflect the interaction of at least two end-member components to produce the batholiths. One component, interpreted to be juvenile crust derived from the mantle in the Mesozoic, dominates the chemical signature of the more mafic (I-WC type) magmas of the western batholiths. The other, more-evolved component involved in the generation of the eastern batholiths is generally interpreted to be greater than 1-b.y.-old continental crust, or sediments derived therefrom, of the Precambrian craton of western North America. In addition, Hill and others (1986) and Taylor (1986) inferred that hydrothermally altered basalt and immature eugeoclinal sediments may have played an important role in the formation of the eastern PRB, not inclusive of the San Jacinto Mountains. The mechanisms by which mixing occurred are still matters of great controversy, with DePaolo (1981a) favoring AFC processes whereas Taylor (1980, 1986) and Hill and others (1986) have advocated mixing of source rocks or their fused equivalents in the source region and have emphasized lateral variations in the petrologic character of magmatic source regions.

Consideration of the volatile content of probable source components allows us to make further interpretations regarding the magmatic source components involved in producing the west-to-east I-WC to I-MC and I-SC progression. The low-F/OH silicates found in mafic I-WC types [$\log(X_F/X_{OH})$ less than −1.5] indicate crystallization at low f_{HF}/f_{H_2O}, which in

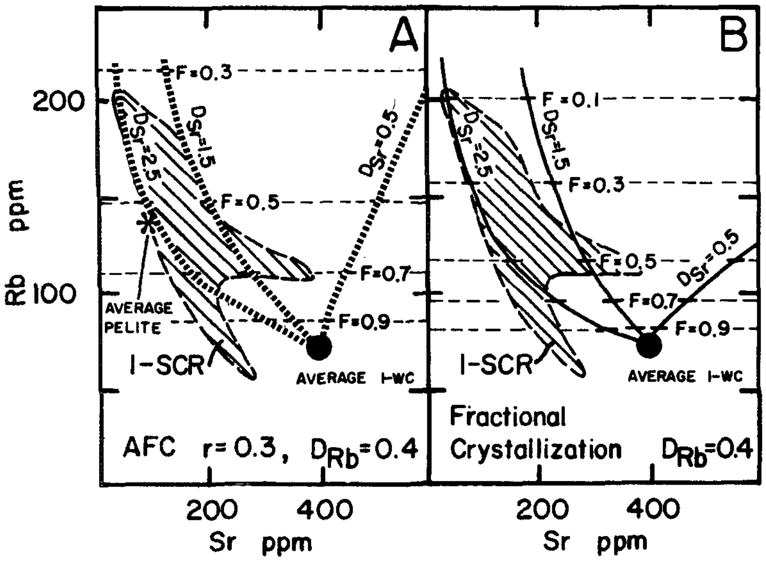

Figure 5. A. Assimilation–fractional crystallization (AFC) modeling. F is amount of liquid remaining, D_i is solid/liquid partition coefficient for element i, and r is ratio of assimilation to crystallization rate. D_{Rb} value of 0.4 calculated using mineral/liquid partition coefficients of Cox and others (1979) and assuming that the magma is crystallizing 63% plagioclase, 16% biotite, and 21% hornblende, corresponding to modal makeup of average I-WC type. D_{Sr} varies between 0.5 and 2.5. The r value of 0.3 is from Taylor (1980). Average I-WC–type Rb and Sr contents are taken to be initial magma composition. Rb and Sr values for assimilated pelite are from Haack and others (1984). The AFC model used is from DePaolo (1981b). B. Fractional crystallization calculations. Same as in Figure 5A except r = 0, equivalent to fractional crystallization without assimilation.

turn implies that the source components involved in producing the I-WC types were low-F mafic (or ultramafic) rocks such as mafic amphibolites. This interpretation is completely consistent with the low Sr_i and $\delta^{18}O$, high ϵ_{Nd}, and general mafic character of the western plutons of the batholiths, which suggests derivation from downgoing subducted slabs or the upper mantle during the Mesozoic (compare with DePaolo, 1981a; Hill and others, 1986).

The I-MC– and I-SC–type plutons to the east are generally richer in incompatible elements, have $Sr_i > 0.706$ and $\epsilon_{Nd} < -6$, and contain mafic silicates with $\log(X_F/X_{OH})$ greater than −1.5, indicating crystallization at values of f_{HF}/f_{H_2O} substantially higher than for the I-WC types. This implies the input of differentiated high–F/H_2O source materials in the formation of the I-MC and I-SC types. These source components are most likely high-grade metamorphic rocks and residual melt-depleted igneous rocks, or their fused equivalents, of the Precambrian craton of western North America. Immature sediments shed from the craton, in which the high F/OH mafic minerals have not been destroyed by weathering, could also be an important source component for the eastern plutons. The oxygen fugacities of crystallization of I-MC and I-SC types (above the maximum stability limit of graphite), however, rule out the possibility of fine-grained organic-rich sediments being important in the generation of the eastern magmas. We note that the extremely high Sr values (as much as ~1,600 ppm) in I-MC and I-SC types which intrude the carbonate-rich miogeoclinal sequences of the White-Inyo Mountains (Bear Creek quartz monzonite, samples 1011-99, -103, and -105; Fig. 4) are suggestive of contamination of magmas with marine carbonate-bearing wall rocks. In addition, high-Cl mafic minerals occur in I-MC and I-SC types of the eastern SNB and PRB, which suggests the involvement of a Cl-rich source, such as high-grade metamorphic rocks or basalt hydrothermally altered on the sea floor, in the formation of these magmas.

The available evidence indicates that two broad processes, or a combination of these processes, may have given rise to the observed I-WC to I-MC and I-SC progression. One possibility for generating this sequence is that mafic I-WC–type magmas became increasingly contaminated with continental crustal materials, through such mechanisms as assimilation combined with concurrent fractional crystallization or magma mixing, owing to the west-to-east increases in the thickness of continental crust (compare with Smith, 1978) and corresponding increases in the length scales of interaction of ascending mafic magmas with the Precambrian craton. The other possibility is that there were significant lateral variations in the petrologic character of source materials, such as west-to-east increases in metamorphic grade of the cratonal materials corresponding to west-to-east increases in crustal thickness and depth of melting or variations in the proportions of low–F/H_2O and high–F/H_2O source rocks in the source region.

Morphology of the Precambrian Basement

The assertion that cratonal material is important in the generation of I-MC and I-SC melts is strongly supported both by the general coincidence of the western I-WC–I-MC boundary and the isotopically defined edge of the Precambrian craton or derivative sediments in the SNB (Kistler and Peterman, 1973, 1978) and by the occurrence of I-MC types in the eastern PRB where a continental lithosphere component has been identified (Hill and others, 1986). The sample density of the isotope studies, however, is very low between lat 38° and 39° N. in the SNB (four samples of plutonic rocks; Kistler and Peterman, 1973), and we feel therefore that the isotopic contours are not directly comparable to our geochemical results in this region. In addition, significant isotopic heterogeneity exists such that rocks with $Sr_i < 0.706$ may occur on the high side of the 0.706 line and vice versa (Masi and others, 1981; Kistler and others, 1986). Although isotopic data are lacking in the literature, the SGB (San Gabriel fault block) has an over-all I-MC signature, and the SBB (San Bernardino fault block) is dominated by I-MC and I-SC types, completely consistent with the occurrence of Precambrian metamorphic and igneous wall rocks in these mountain ranges.

On the basis of these correlations, we feel that the westernmost occurrence of I-MC plutons reflects the edge of the Precambrian craton or the limit of quartzofeldspathic sediments shed westward from it. Our systematic sampling, however, shows that the basement edge may be morphologically more complex than inferred in the past, and this may reflect paleogeographic irregularities in the shape of the pre-batholithic continental margin (Fig. 6). In addition, owing to the occurrence of I-MC and I-SC types north of the sharp bend in the Sr_i = 0.706 contour in the SNB, we predict that the Precambrian basement or derivative sediments may extend farther north than thought previously on the basis of existing isotopic work (Fig. 6B).

In addition to the I-WC types of the western

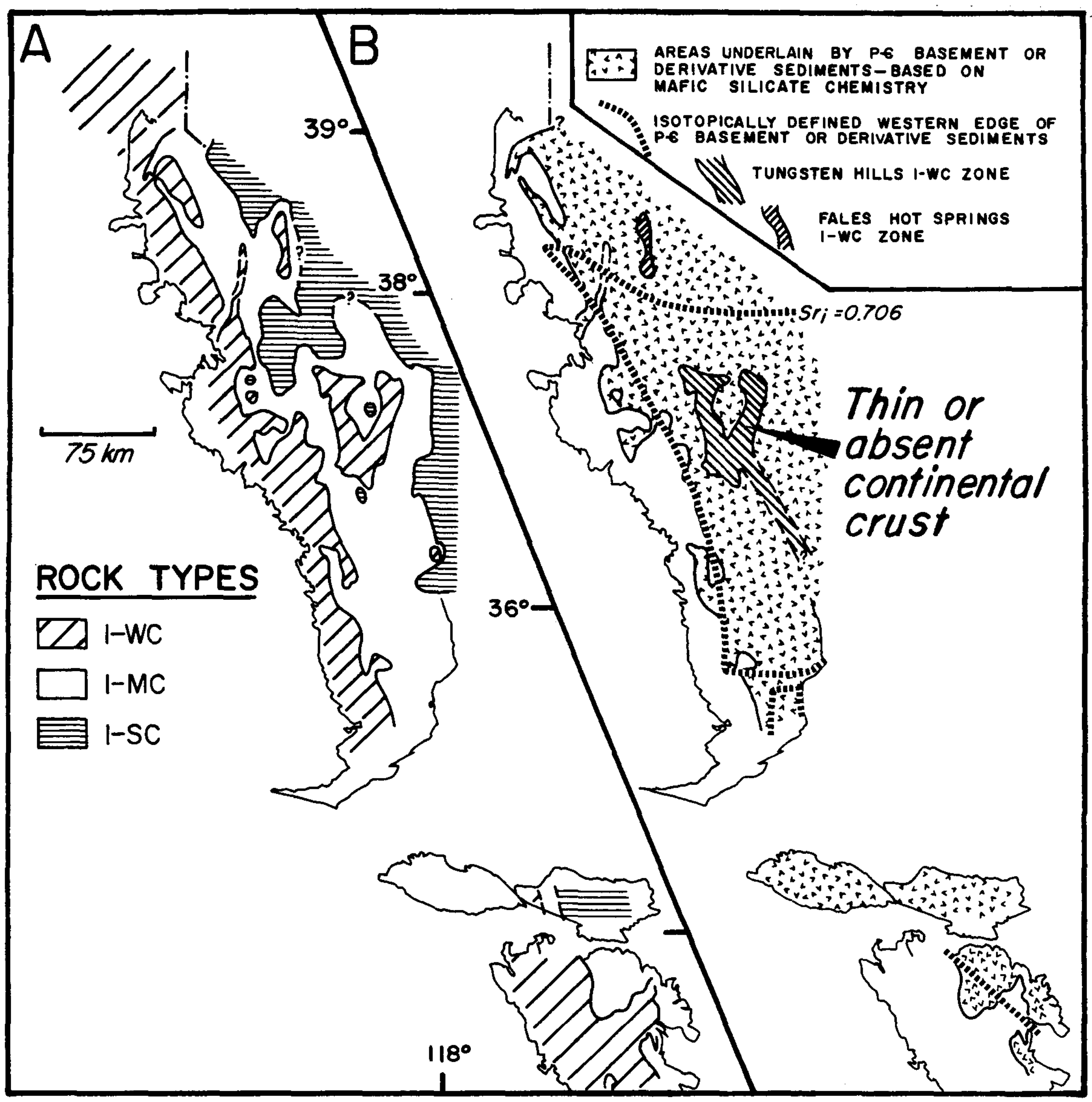

Figure 6. A. Distribution of I-WC, I-MC, and I-SC types. For clarity, I-SCR types are not shown. B. Western limit of the Precambrian craton of western North America or derivative sediments in the California batholiths as deduced from mineral chemistry and isotope systematics. Divergence of results on craton position between approximately lat 38° and 39° N. in the SNB may be due to low sample density of isotopic studies in this region. Note presence of Tungsten Hills I-WC zone magmatism in eastern SNB.

batholiths, I-WC intrusives which seem out of place occur in the eastern Sierra Nevada batholith in what we term the "Fales Hot Springs" and "Tungsten Hills" I-WC zones (Fig. 6B). In the vicinity of the Tungsten Hills I-WC zone, the presence of the Upper Jurassic Independence dike swarm (Moore and Hopson, 1961; Chen and Moore, 1979) indicates that extensional tectonic processes have operated in this region since at least as far back as Late Jurassic time (Chen and Moore, 1979). Basic intrusives of the eastern Sierra Nevada (see Ague and Brimhall, 1988, Fig. 20) correlate with the positions of both I-WC zones and the Independence dikes in the central-eastern portion of the batholith. In addition, anomalously low values of heat generation occur in the Tungsten Hills I-WC zone (Wollenberg and Smith, 1968; Bateman, 1979). Furthermore, alkalic magmatism, which may be associated with crustal rifting processes (Hollister, 1976; Chen and Moore, 1979), occurs in the White-Inyo Mountains, immediately to the east of the Tungsten Hills I-WC zone (Miller, 1978; Sylvester and others, 1978).

We interpret the zones of I-WC magmatism in the eastern Sierra Nevada batholith to reflect intrusion of low-F/H_2O upper mantle–derived magmas into regions of thin or perhaps completely absent continental crust in Mesozoic time. In the Tungsten Hills I-WC zone, crustal thinning may have been the result of extensional tectonism, evidence for which is provided by such geologic features as the Late Jurassic–age Independence dike swarm (Chen and Moore, 1979).

Belts of I-SC magmatism (Fig. 6A), on the other hand, may represent regions where the Precambrian crust thickened eastward in Mesozoic time, a factor which could have facilitated strong contamination of subduction-related magmas or the spatial distribution of crustal source components with greatly elevated F/H_2O. We note that I-SC types are absent from the eastern PRB, and this may be due to a lack of appropriate high-F/H_2O source components, insufficient contamination of mafic magmas with high-F/H_2O crustal sources, or perhaps removal by northward tectonic transport along the San Andreas fault.

COMPARISON WITH OTHER CLASSIFICATION SCHEMES

Having examined possible modes of origin for the pluton types that we have defined in the batholiths of California, it is instructive to compare our subdivisions, defined by differences in mafic silicate chemistry, to the existing I-, S-, and A-type classification scheme (Chappell and White, 1974; White and Chappell, 1983) and the magnetite and ilmenite series of Ishihara (1977) (Table 1).

I-, S-, and A-Types

Our classification scheme may be regarded as a subdivision of I-types (Chappell and White, 1974) which reflects the magmatic source components and possible contamination processes responsible for differences in petrology and geochemistry. S-types have recently been redefined by White and others (1986) as peraluminous plutons characterized by cordierite which have been derived solely from sedimentary or metasedimentary sources. We feel, however, that petrologic and isotopic evidence indicates that some nonfractionated "minimum melt" and strongly peraluminous I-SCR types may be "S-type" (that is, derived from sedimentary sources) even though they do not contain cordierite. A-types (Loiselle and Wones, 1979) are relatively alkaline granites thought to have formed through "anhydrous" melting of crustal source rocks in anorogenic, typically extensional environments (Collins and others, 1982; Clemens and others, 1986). Although A-types and cordierite-bearing S-types are important constituents of some magmatic arcs, these pluton types appear to be absent from the batholiths of California (compare with Collins and others, 1982; White and others, 1986).

Magnetite-Ilmenite Series

Representatives of both the magnetite and ilmenite series (Ishihara, 1977) are present in the California batholiths. Magnetite-series rocks are thought to originate in the upper mantle and may be further modified by interaction with the lower crust (Czamanske and others, 1981). Ilmenite-series rocks, on the other hand, are inferred to have crystallized under low f_{O_2} inherited from a lower crustal–upper mantle source or due to the incorporation of graphite from crustal sources into a magma. We have demonstrated, however, that in order to rigorously constrain the oxygen fugacity regimes of crystallization, information pertaining to the presence and abundance of Fe-Ti oxides must be coupled with compositional data on these oxides and coexisting mafic silicates. Therefore, although I-SCR granites and I-WC, I-MC, and I-SC types may be of the ilmenite series, our computations show that I-SCR types reflect crystallization at oxygen fugacities at or below the maximum stability limit of graphite whereas the I-WC, I-MC, and I-SC types typically crystallize at higher oxygen fugacities. More detail on these comparisons is given in Brimhall and Ague (1988).

PRESSURES OF PLUTON CRYSTALLIZATION

We turn finally to the problem of estimating the pressures of crystallization of the plutons and assessing regional variations in pressure with a particular focus on investigating processes by which I-SCR granites may form. We employ the Hammarstrom and Zen (1986) geobarometer, which is an empirical calibration of the variation in aluminum content of amphibole in calc-alkaline rocks with pressure.

$$P(kb) = 5.03Al(total) - 3.92 \pm 3kb \quad (7)$$

Hollister and others (1987) suggested that the error in estimated pressures may be on the order of ±1 kb in the pressure range 2–8 kb, much less than the ±3 kb originally proposed by Hammarstrom and Zen (1986). The barometer was calibrated using rocks containing K-feldspar, plagioclase, biotite, amphibole, sphene, quartz, and iron-titanium oxides.

The vast majority of our amphibole-bearing samples are similar to the ones used for calibration of the Hammarstrom and Zen (1986) geobarometer, but a number contain no sphene. Rocks lacking sphene give similar (±1 kb) pressure estimates to sphene-bearing rocks in the same regional location, however. We have therefore included pressure estimates from specimens lacking sphene in our data set. Because I-SCR granites crystallize at much lower f_{O_2}'s than do the rocks used to calibrate the geobarometer, they have been excluded from our contoured data set. Our conclusions regarding I-SCR genesis are therefore based on calculated pressures of crystallization in nearby I-WC, I-MC, and I-SC plutons. Regional variations in crystallization pressure are shown in Figure 7A, and sample locations, important localities, and structural features discussed below are illustrated in Figure 7B.

Regional Variations in Crystallization Pressure

Our amphibole geobarometry illustrates that there is a general west-to-east decrease in calculated pressures in the northern and south-central SNB from 3–5 kb to less than 1 kb (11–19 km to <4 km; crustal density of 2.7 g cm^{-3}). This gradient is in the same direction as expected due to west-to-east increases in the elevation of the plutons as sampled at the surface but greatly exceeds the effects due simply to differential elevations, as the maximum elevation difference between the western and eastern SNB is on the order of 3 km. Differences in sample elevation can therefore account only for about 0.8 kb of this pressure difference.

The eastern SNB is characterized by low computed pressures of crystallization. In the following discussion, major zones of crystallization pressure less than 1 kb are herein referred to as the "Donner Lake," "Bridgeport," "Independence," and "Owens Lake" low-pressure zones as shown in Figure 7A. Low pressures of crystallization in the northern SNB are evidenced by the occurrence of porphyry Cu mineralization in the northernmost SNB (Albers, 1981), slightly north of the Donner Lake low-pressure zone. This form of ore deposition typically occurs at shallow crustal depths of 2–3 km (Burnham, 1981). Low pressures of crystallization in the Bridgeport low-pressure zone are corroborated by the preservation of the Ritter Range caldera complex (Fiske and others, 1977; Saleeby and others, 1986), which occurs within Nokleberg's (1983) Jurassic-age metavolcanic Goddard terrane. The Independence and Owens Lake low-pressure zones are located in the vicinity of Mount Whitney in the southern portion of the Goddard terrane of Nokleberg (1983). The low δD values (less than −85) found by Masi and others (1981) in the intrusions of the northern and eastern SNB may be due to the interaction of these shallow plutons with heated meteoric waters (Taylor, 1974; Masi and others, 1981). The regions of highest calculated pressure in the eastern SNB (4–5 kb; 15–19 km) are present in the vicinity of the Benton Range horst associated with I-MC types. Evidence for higher pressures in the western SNB is scarce, but Saleeby (1987), on the basis of field relations, noted that in the western part of the southern SNB, plutons appear to have "ponded in the mid-crust" at deeper levels than did the eastern intrusions.

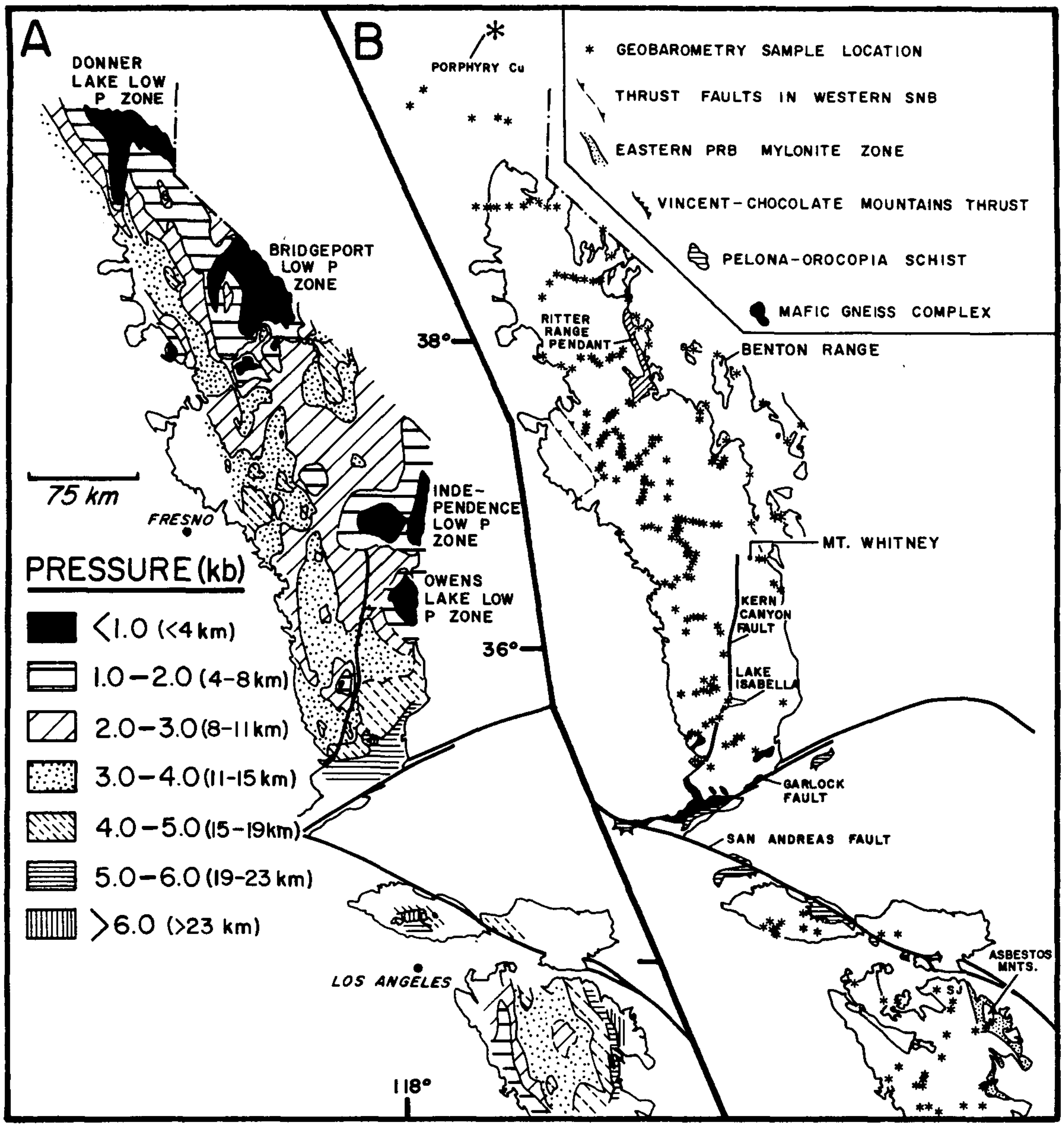

Figure 7. Pressures of crystallization. A. Regional variations in crystallization pressure in the batholiths of California quantified using amphibole barometry (Hammarstrom and Zen, 1986). Note regions of low pressure (<2 kb) in the northern and east-central SNB and in the western PRB and regions of high pressure (>6 kb) in the southern SNB, the San Gabriel Mountains, and the eastern PRB. Average values are shown in the SBB, owing to low sample density. B. Localities and structural features referenced in discussion of regional pressure variations in text. SJ: San Jacinto Mountains. Data sources: Haxel and Dillon (1978), Albers (1981), Bateman and others (1983), Nokleberg (1983), Erskine (1985), Ross (1985).

The major part of the southern portion of the batholith is characterized by pressures on the order of 3 kb (11 km) or more. This is consistent with Elan's (1985) work on the metamorphic grade of Lake Isabella roof pendants, which gives pressures of equilibration of about 3 kb. Furthermore, pressures of 3 kb or higher are consistent with the occurrence of plutonic muscovite in the I-SCR belt in the southern half of the SNB. Although most of the SNB is characterized by pressures of crystallization less than about 4–5 kb (15–19 km), in the southernmost portion of the batholith, calculated pressures are generally high and may reach 6 kb (23 km). This region is characterized by igneous and meta-igneous rocks inferred by a number of authors (see Sharry, 1981; Ross, 1985; Saleeby and others, 1986) to represent deep levels (as much as 30 km) of crustal exposure based primarily on metamorphic mineral thermometry and barometry. Sillimanite is the typical aluminosilicate polymorph in metamorphic wall rocks, indicating crystallization at both high pressures and temperatures, as opposed to andalusite, which predominates in the more northerly pendants (Ross, 1985).

In contrast to the calculated west-to-east pressure decreases in the SNB, our geobarometry indicates that pressures increase from west to east across the PRB from less than 2 kb to about 6.5 kb (<8 to 25 km). Independent pressure estimates are rare for the PRB, but Hill and others (1986), on the basis of metamorphic mineral assemblages in roof pendants, estimated pressures in the San Jacinto Mountains to be 3.2–4.3 kb; our pressure estimates based upon amphibole composition are in good agreement and are in the range of 4–4.4 kb (15–17 km). Schwarcz (1969) has discussed a west-to-east increase in the metamorphic grade of pelitic pendants in the northern PRB, and this is compatible with a west-to-east increase in the depth of exposure of the intrusives. Low-$\delta^{18}O$ rocks, interpreted by Taylor and Silver (1978) to represent interaction of the plutons with heated meteoric water, occur along the western margin of the PRB, and this is also the area where the lowest pressures of crystallization have been calculated.

The SGB gives the highest over-all pressure signature (about 5.5 kb on average) of all the batholiths. Metamorphic rocks of Sierra Pelona yield calculated pressures of 6 to 7.5 kb (Graham and England, 1976). Amphibole pressure estimates from plutonic rocks in the San Gabriels are consistent with this and are typically in the range of 5–7.5 kb (19–28 km). Plutonic epidote is present in the central part of the range.

The geobarometric data presented above indicate that I-WC and I-MC types may crystallize at pressures ranging from less than 1 kb to over 6 kb (<4 km to >23 km). I-SC granites of the eastern SNB, on the other hand, generally crystallize at pressures less than about 3 kb, which corresponds to depths of emplacement of less than 11 km. The I-SCR granites are restricted to crystallization pressures greater than approximately 2.5 kb, indicating that they are never emplaced at depths shallower than about 9 km in the crust.

Discussion of Regional Pressure Trends

The west-to-east decrease in crystallization pressures of plutons in the SNB documented herein is a consistent trend which extends from the northern portion of the batholith to latitudes slightly south of Mount Whitney. Although resolution is limited by sample density and the accuracy of the Hammarstrom and Zen (1986) geobarometer, it is tempting to suggest that in detail, a pressure maximum is present in the western SNB, extending from approximately lat 38° N. south-southeast to the Kern Canyon fault (Figs. 7A, 7B). Although it is possible that high pressures along the western margin of the southern SNB are an artificial effect reflecting increased activity of aluminum in I-WC or I-MC melts due to very small amounts of assimilation of pelite in the Kings terrane, this is unlikely because the west-to-east trend of decreasing pressure also extends well to the north of the Kings terrane and the I-SCR belt.

Structural evidence for differential uplift of the SNB giving rise to deeper levels of exposure on the west side is extremely rare. We note, however, that deformation associated with thrust faults of the western metamorphic foothills belt, such as the Melones fault, may also extend into the plutonic rocks of the batholith (Bateman and others, 1983; Nokleberg, 1983). Although the cause of the west-to-east pressure decrease is at present indeterminate, this sense of "tilting" must have been established prior to Miocene or Pliocene uplift of the eastern portions of the batholith (compare with Bateman and Wahrhaftig, 1966; Christensen, 1966; Chase and Wallace, 1986) since late Cenozoic uplift should expose relatively deep portions of the batholith in the east.

The regions of highest calculated pressure in the southern SNB and in the SGB (>6 kb; >23 km) are spatially associated with exposure of the Vincent-Chocolate Mountain thrust system and related metamorphic rocks of the Pelona-Orocopia schist (see Haxel and Dillon, 1978). Although the tectonic regime of formation and direction of thrusting are presently poorly understood (see Haxel and Dillon, 1978; Burchfiel and Davis, 1981), geologic evidence is consistent with its interpretation as a site of subduction, active approximately 60 to 80 m.y. ago (Burchfiel and Davis, 1981; Ehlig, 1981). Rocks of the southern SNB and the SGB mountains are indicative of deep levels of crustal exposure, consistent with the interpretation that the thrust system is a deep-seated feature.

The southern SNB began to be uplifted at approximately 80 Ma and was subsequently covered by Eocene marine sediments (Saleeby, 1988). The maximum pressures estimated for the southern SNB rocks (~6 kb) indicate that rates of erosion were high (on the order of 0.4–0.7 mm/yr). Similarly, given that metamorphic rocks of the Vincent-Chocolate Mountain thrust were exposed about 15 m.y. ago in the SGB, and assuming that uplift began about 60 m.y. ago (Ehlig, 1981), rapid erosion rates on the order of 0.5 mm/yr are also computed for this region. Saleeby (1986) has speculated that uplift in the southern Sierra, termination of magmatic activity, and the beginning of Kern Canyon faulting may be genetically related events, perhaps caused by northward underthrusting of Pelona-Orocopia–type schist. Alternatively, deep sections of the crust may have been uplifted by the generation of transpressive stresses along the Garlock and San Andreas strike-slip fault zones (compare with Haxel and Dillon, 1978).

The PRB displays west-to-east pressure increases which are opposite in sense to the west-to-east pressure decreases calculated for the SNB. The highest pressures in the PRB are calculated for rocks located within and to the east of the eastern Peninsular Ranges mylonite zone (shown by a stippled pattern in Fig. 7B), a major westward-directed overthrust system active in middle to Late Cretaceous time (compare with Erskine, 1985). It is probable that the west-to-east "tilt" of the PRB is due either to middle to Late Cretaceous deformation associated with the formation of the eastern Peninsular Ranges mylonite zone or to later transpression along the San Andreas fault.

Crystallization Pressure and Constraints on the Origins of I-SCR Granites

I-SCR intrusives are not found at crustal levels shallower than about 9 km in the Sierra Nevada and Peninsular Ranges batholiths, based upon pressure estimates from adjacent amphibole-bearing I-WC and I-MC types which are always greater than about 2.5 kb. This fact is consistent with the interpretation that I-SCR magmas require pelitic rocks as a magmatic source component for the following reasons. Contamination of calc-alkaline magmas by assimilation of H_2O-rich muscovite-bearing pelitic rocks will speed crystallization of the resultant melt. This will tend to prevent I-SCR magmas from reaching the shallow levels of the crust necessary for eruption. In addition, H_2O-rich magmas derived entirely from pelitic sources should be unable to attain depths in the crust shallower than about 6 km (Burnham, 1981). We note in this context that intermediate to felsic volcanic rocks which crystallize at the low oxygen fugacity conditions of I-SCR granites are apparently very rare (compare with Carmichael and others, 1974).

DISCUSSION AND CONCLUSIONS

By utilizing a petrologic approach focusing on interpretation of regional variations in whole-rock geochemistry, mineralogy, and mafic and accessory mineral compositions, it is possible to make unique inferences about the generation of batholiths in the calc-alkaline magmatic arcs of continental margins. In so doing, we demonstrate a heretofore unrecognized complexity in reconstructions of the North American cratonal mar-

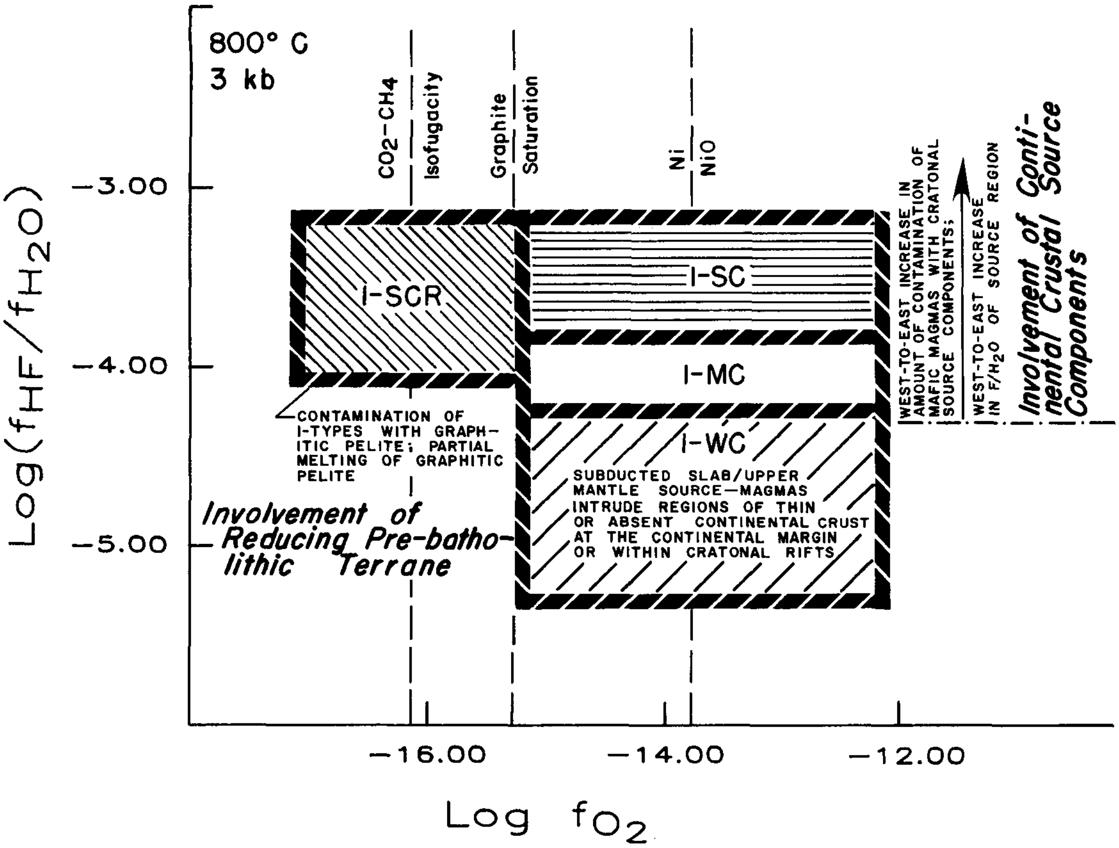

Figure 8. f_{HF}/f_{H_2O} **and** f_{O_2} **regimes of crystallization of the pluton types, showing inferred origins of I-WC, I-MC, I-SC, and I-SCR intrusives.**

gin and identify two major plutonic belts which would otherwise seem out of place: a belt of generally peraluminous granites on the west side of the Sierra Nevada and Peninsular Ranges batholiths and an easterly belt of quartz diorites and granodiorites in the Sierra Nevada batholith. Analysis of a complex array of petrologic and geochemical data demonstrates that regional trends and discontinuities in mineral chemistry can be directly linked to fundamentally important controls such as the position of geochemically distinct source regions, the pressures of crystallization of the plutons, and possibly the location of fragmented cratonal blocks near the continental margin.

Owing to the strong controls imposed by magmatic source component chemistry on fugacities of intensive variables in the magmas, the origins of I-WC, I-MC, I-SC, and I-SCR types may be visualized by consideration of both f_{HF}/f_{H_2O} and f_{O_2} regimes of crystallization. We depict the crystallization conditions of the rock types in a $\log(f_{HF}/f_{H_2O})$ versus $\log f_{O_2}$ coordinate framework at representative conditions of 800 °C and 3 kb in Figure 8.

The diverse geologic controls on magmatic chemistry may be further appreciated by consideration of a regional traverse across the central SNB (Fig. 9). This traverse (A–A′) extends from the western SNB, 30 km north of Fresno, northeastward through Bishop to the eastern slopes of the White Mountains (Fig. 9). Figure 9A shows the reconstructed top of the SNB, on the basis of computed depths of crystallization derived from our pressure estimates, in relation to the present structure of the batholith as determined by geologic mapping and regional seismic, gravity, and magnetic studies (Bateman and Eaton, 1967; Oliver, 1977; Bateman, 1979; Mavko and Thompson, 1983). The broad west-to-east decrease in crystallization pressures discussed above is evidenced in Figure 9A by eastwardly decreasing amounts of eroded overburden, averaging approximately 15 km in the west and 10 km in the east. It is tempting to suggest that undulations in the reconstructed batholith top represent paleotopography, but care must be taken not to overinterpret the details of the pre-erosion surface given the accuracy of the Hammarstrom and Zen (1986) barometer (±1 kb at best). In the Sierra Nevada batholith west of Owens Valley, the reconstructed top of the batholith lies subparallel to the 6.4 to 6.9 km s^{-1} seismic P-wave velocity boundary, which suggests that prior to erosion, the granitic batholith was relatively uniform in thickness, averaging about 30–35 km, and tabular in shape as are other batholiths (Lynn and others, 1981). Because the individual plutons range in age from Triassic to Cretaceous, the relatively flat nature of the reconstructed top of the SNB, essentially parallel to the base of the batholith, implies that major uplift and erosion of the batholith commenced after the Cretaceous-age intrusives had crystallized.

The 6.0 to 6.4 km s^{-1} P-wave velocity boundary lies at a pre-erosion depth of approximately 23 km, roughly equivalent to the deep levels of crystallization exposed in the southern SNB. It is possible that this transition to higher P-wave velocities of the order of 6.4 km s^{-1} reflects a lithologic transition from typical granitic rocks (density = 2.67 g cm^{-3}) to rocks analogous to those presently exposed in the southern SNB, such as the mafic gneiss complex of Ross (1985).

The 6.4 to 6.9 km s^{-1} velocity transition at the base of the granitic batholith may reflect a major contrast in acoustic impedance (product of velocity and density) between the batholith and underlying rocks, as in the Black Rock Desert of northwestern Nevada (Lynn and others, 1981). Existing interpretations of the sub-batholithic reflectors are underplated gabbro and cumulate layers, the latter being favored.

Figure 9B illustrates regional biotite $\log(X_F/X_{OH})$ systematics for I-WC, I-MC, and I-SC types. The regional-scale west-to-east increases in F/OH, related to the position of Precambrian basement or derivative sediments, are imme-

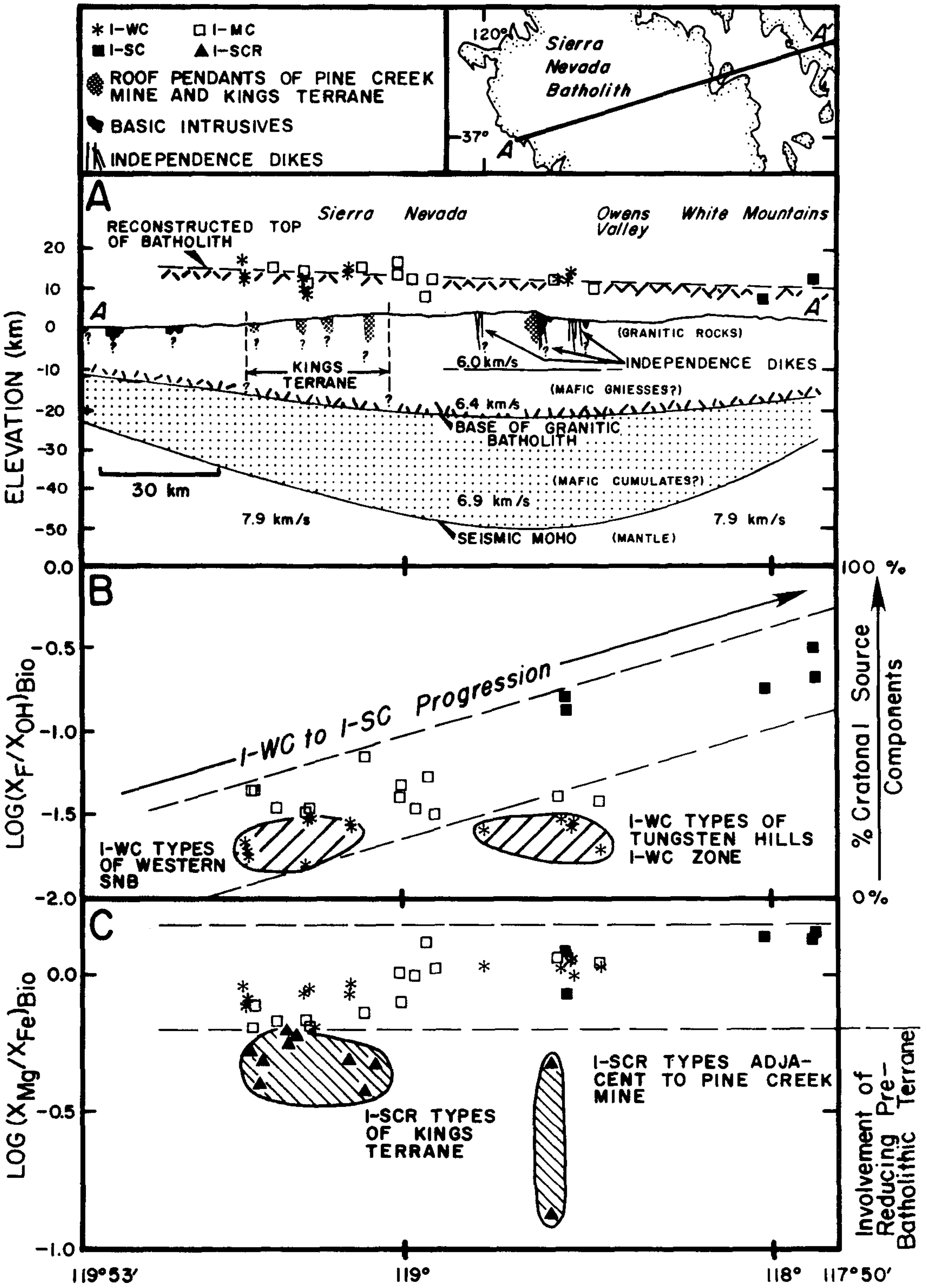

Figure 9. Regional profiles across the central SNB. Geology from Bateman (1979) and Nokleberg (1983). Sample data 15 km on either side of A–A′ has been projected onto cross section. A. Present structure of the SNB and reconstructed top of batholith based on amphibole crystallization pressures. Note west-to-east decrease in amount of eroded overburden. For clarity, geologic features 8 km on either side of A–A′ have been projected onto cross section. B. Biotite $\log(X_F/X_{OH})$ illustrating regional-scale eastward progression from I-WC to I-SC types. Tungsten Hills I-WC zone of eastern Sierra Nevada batholith disrupts the I-WC-to-I-SC progression. C. Biotite $\log(X_{Mg}/X_{Fe})$ illustrating occurrence of I-SCR types in the Kings terrane (Nokleberg, 1983) and in the eastern Sierra adjacent to the Pine Creek pendant.

diately apparent. I-WC types, however, also occur in the eastern Sierra Nevada, as exemplified by the Tungsten Hills I-WC zone, which is spatially associated with basic intrusives and the Independence dike swarm (Figs. 9A, 9B). The eastern I-WC intrusives disrupt the regional west-to-east F/OH increases and probably reflect the intrusion of upper mantle–derived magmas into a region of thin or absent continental crust in Mesozoic time. On the basis of biotite $\log(X_F/X_{OH})$ values of about 0.0 for intra-cratonal granites interpreted by Brimhall and Ague (1988) to be derived completely from Precambrian crust, it is apparent that granites of the eastern SNB have a strong crustal component.

Figure 9C demonstrates that biotite $\log(X_{Mg}/X_{Fe})$ for I-WC, I-MC, and I-SC types stays approximately constant at a value of about 0. Regions of $\log(X_{Mg}/X_{Fe}) < -0.21$ correspond to the I-SCR intrusives, which in the western SNB, occur in the pre-batholithic Kings Terrane (Nokleberg, 1983) and, in the eastern SNB, are associated with pelitic hornfels of the Pine Creek roof pendant (Figs. 9A, 9C). The low f_{O_2} of I-SCR granite crystallization, due to generation of I-SCR types by contamination of calc-alkaline intrusives with graphitic pelites or fusion of reducing pelitic lithologies, results in low Mg/Fe biotites which are distinct from the biotites of the I-WC-to-I-SC spectrum which have subequal X_{Mg} and X_{Fe}.

The petrologic approach to understanding the formation of the granitic batholiths of California described herein and in Ague and Brimhall (1987, 1988) is straightforward in its application and has general applicability to problems relating to calc-alkaline magmatism and ore deposition (Brimhall and Ague, 1988) at convergent plate boundaries worldwide. We have demonstrated that an integrative interpretation of regional variations in whole-rock geochemistry, mineralogy, mineral chemistry, and values of critical magmatic intensive variables, in addition to isotopic data, is essential in order to understand more completely magma production in active continental margins.

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REFERENCES CITED

Ague, J. J., and Brimhall, G. H., 1987, Granites of the batholiths of California: Products of local assimilation and regional scale contamination: Geology, v. 15, p. 63–66.

——1988, Regional variations in bulk chemistry, mineralogy, and the compositions of mafic and accessory minerals in the batholiths of California: Geological Society of America Bulletin, v. 100, p. 891–911 (this issue).

Albers, J. P., 1981, A lithologic-tectonic framework for the metallogenic provinces of California: Economic Geology, v. 76, p. 765–790.

Anderson, A. T., 1980, Mineral equilibria and crystallization conditions in the late Precambrian Wolf River rapakivi massif, Wisconsin: American Journal of Science, v. 280, p. 298–332.

Bateman, P. C., 1979, Cross section of the Sierra Nevada from Madera to the White Mountains: Geological Society of America Map and Chart Series MC-28E.

Bateman, P. C., and Eaton, J. P., 1967, Sierra Nevada batholith: Science, v. 158, p. 1407–1417.

Bateman, P. C., and Wahrhaftig, C., 1966, Geology of the Sierra Nevada, *in* Bailey, E. H., ed., Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 107–172.

Bateman, P. C., Busacca, A. J., and Sawka, W. N., 1983, Cretaceous deformation in the western foothills of the Sierra Nevada, California: Geological Society of America Bulletin, v. 94, p. 30–42.

Bowen, N. L., 1928, The evolution of the igneous rocks: Princeton, New Jersey, Princeton University Press, 332 p.

Bowles, J.F.W., 1977, A method of tracing the temperature and oxygen-fugacity histories of complex magnetite-ilmenite grains: Mineralogical Magazine, v. 41, p. 103–109.

Brimhall, G. H., and Ague, J. J., 1988, Granitic systems, *in* Barnes, H. L., and Ohmoto, H., eds., Hydrothermal processes—Applications to ore genesis: Dordrecht, Holland, Reidel (in press).

Brimhall, G. H., Jr., Gilzean, M., and Burnham, C. W., 1983, Magmatic source region, protoliths, and controls on metallogenesis: Mica halogen chemistry [abs.]: EOS (American Geophysical Union Transactions), v. 64, p. 884.

Brimhall, G. H., Jr., Agee, C., and Stoffregen, R., 1985, The hydrothermal conversion of hornblende to biotite: Canadian Mineralogist, v. 23, p. 369–379.

Buddington, A. F., and Lindsley, D. H., 1964, Iron-titanium minerals and synthetic equivalents: Journal of Petrology, v. 5, p. 310–357.

Burchfiel, B. C., and Davis, G. A., 1981, Mojave desert and environs, *in* Ernst, W. G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 217–252.

Burnham, C. W., 1979, Magmas and hydrothermal fluids, *in* Barnes, H. L., ed., Geochemistry of hydrothermal ore deposits (2nd edition): New York, John Wiley, p. 71–136.

——1981, Physicochemical constraints on porphyry mineralization, *in* Dickinson, W. R., and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 71–77.

Burnham, C. W., and Ohmoto, H., 1980, Late-stage processes of felsic magmatism: Mining Geology Special Issue 8, p. 1–11.

Carmichael, I.S.E., Turner, F. J., and Verhoogen, J., 1974, Igneous petrology: New York, McGraw-Hill, 739 p.

Chappell, B. W., and White, A.J.R., 1974, Two contrasting granite types: Pacific Geology, v. 8, p. 173–174.

Chase, C. G., and Wallace, T. C., 1986, Uplift of the Sierra Nevada of California: Geology, v. 14, p. 730–733.

Chen, J. H., and Moore, J. G., 1979, The Late Jurassic Independence dike swarm in eastern California: Geology, v. 7, p. 129–133.

——1982, Uranium-lead isotopic ages from the Sierra Nevada batholith, California: Journal of Geophysical Research, v. 87, p. 4761–4784.

Christensen, M. N., 1966, Late Cenozoic crustal movements in the Sierra Nevada of California: Geological Society of America Bulletin, v. 77, p. 163–182.

Christiansen, E. H., and Lee, D. E., 1986, Fluorine and chlorine in granitoids from the Basin and Range province, western United States: Economic Geology, v. 81, p. 484–494.

Clemens, J. D., and Wall, V. J., 1981, Origin and crystallization of some peraluminous (S-type) granitic magmas: Canadian Mineralogist, v. 19, p. 111–131.

Clemens, J. D., Holloway, J. R., White, A.J.R., 1986, Origin of an A-type granite: Experimental constraints: American Mineralogist, v. 71, p. 317–324.

Collins, W. J., Beams, S. D., White, A.J.R., and Chappell, B. W., 1982, Nature and origin of A-type granites with particular reference to southeastern Australia: Contributions to Mineralogy and Petrology, v. 80, p. 189–200.

Cox, K. G., Bell, J. D., and Pankhurst, R. J., 1979, The interpretation of igneous rocks: Boston, Massachusetts, Allen and Unwin, 450 p.

Czamanske, G. K., Ishihara, S., and Atkin, S. A., 1981, Chemistry of rock-forming minerals of the Cretaceous-Paleocene batholith in southwestern Japan and implications for magma genesis: Journal of Geophysical Research, v. 86, p. 10431–10469.

Dallmeyer, R. D., 1974, Metamorphic history of the northeastern Reading Prong, New York and northern New Jersey: Journal of Petrology, v. 15, p. 325–359.

Deer, W. A., Howie, R. A., and Zussman, J., 1966, An introduction to the rock-forming minerals: London, United Kingdom, Longman, 528 p.

DePaolo, D. J., 1981a, A neodymium and strontium isotopic study of Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular Ranges, California: Journal of Geophysical Research, v. 86, p. 10470–10488.

——1981b, Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization: Earth and Planetary Science Letters, v. 53, p. 189–202.

Dodge, F.C.W., Calk, L. C., and Kistler, R. W., 1986, Lower crustal xenoliths, Chinese Peak lava flow, central Sierra Nevada: Journal of Petrology, v. 27, p. 1277–1304.

Early, T. O., and Silver, L. T., 1973, Rb-Sr isotopic systematics in the Peninsular Ranges batholith of southern and Baja California [abs.]: EOS (American Geophysical Union Transactions), v. 54, p. 494.

Ehlig, P. L., 1981, Origin and tectonic history of the basement terrane of the San Gabriel Mountains, central Transverse Ranges, *in* Ernst, W. G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 253–283.

Ekstrom, T. K., 1972, The distribution of fluorine among some coexisting minerals: Contributions to Mineralogy and Petrology, v. 34, p. 192–200.

Elan, R., 1985, High grade contact metamorphism at the Lake Isabella north shore roof pendant, southern Sierra Nevada, California [M.S. thesis]: University of Southern California, 202 p.

Ellis, D. J., and Thompson, A. B., 1986, Subsolidus and partial melting reactions in the quartz-excess CaO + MgO + Al_2O_3 + SiO_2 + H_2O system under water-excess and water-deficient conditions to 10 kb: Some implications for the origin of peraluminous melts from mafic rocks: Journal of Petrology, v. 27, p. 91–121.

Erskine, B. G., 1985, Mylonitic deformation and associated low-angle faulting in the Santa Rosa mylonite zone, southern California [Ph.D. thesis]: University of California, Berkeley, 247 p.

Farmer, G. L., and DePaolo, D. J., 1983, Origin of Mesozoic and Tertiary granite in the western United States and implications for pre-Mesozoic crustal structure 1. Nd and Sr isotopic studies in the geocline of the northern Great Basin: Journal of Geophysical Research, v. 88, p. 3379–3401.

——1984, Origin of Mesozoic and Tertiary granite in the western United States and implications for pre-Mesozoic crustal structure 2. Nd and Sr isotopic studies of unmineralized and Cu- and Mo-mineralized granite in the Precambrian craton: Journal of Geophysical Research, v. 89, p. 10141–10160.

Ferry, J. M., and Spear, F. S., 1978, Experimental calibration of the partitioning of Fe and Mg between biotite and garnet: Contributions to Mineralogy and Petrology, v. 66, p. 113–117.

Fillipopov, L. U., Savimova, Y. N., Kapitonova, T. A., and Andreveda, T. D., 1974, Fluorine in Mg-Fe micas from granitoids of various magmatic formations in the folded belt of central Asia: Geochemistry International, v. 11, p. 185–194.

Fiske, R. S., Tobisch, O. T., Kistler, R. W., Stern, T. W., and Tatsumoto, M., 1977, Minarets caldera: A Cretaceous volcanic center in the Ritter Range pendant, central Sierra Nevada, California: Geological Society of America Abstracts with Programs, v. 9, p. 975.

Fountain, D. M., and Salisbury, M. H., 1981, Exposed cross-sections through the continental crust: Implications for crustal structure, petrology, and evolution: Earth and Planetary Science Letters, v. 56, p. 263–277.

Graham, C. M., and England, P. C., 1976, Thermal regimes and regional metamorphism in the vicinity of an overthrust fault—An example of shear heating and inverted metamorphic zonation from southern California: Earth and Planetary Science Letters, v. 31, p. 142–152.

Grant, J. A., 1985, Phase equilibria in low-pressure partial melting of pelitic rocks: American Journal of Science, v. 285, p. 409–435.

Guidotti, C. V., 1984, Micas in metamorphic rocks, *in* Bailey, S. W., ed., Micas: Reviews in Mineralogy, v. 13, p. 357–468.

Gunow, A. J., Ludington, S., and Munoz, J. L., 1980, Fluorine in micas from the Henderson molybdenite deposit, Colorado: Economic Geology, v. 75, p. 1127–1137.

Haack, U., Heinrichs, H., Bone, B. M., and Schneider, A., 1984, Loss of metals from pelites during regional metamorphism: Contributions to Mineralogy and Petrology, v. 85, p. 116–132.

Hammarstrom, J. M., and Zen, E-An, 1986, Aluminum in hornblende: An empirical igneous geobarometer: American Mineralogist, v. 71, p. 1297–1313.

Haxel, G., and Dillon, J., 1978, The Pelona-Orocopia schist and Vincent-Chocolate Mountain thrust system, southern California, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium, 2nd, p. 453–469.

Helgeson, H. C., Delany, J. M., Nesbitt, H. W., and Bird, D. K., 1978, Summary and critique of the thermodynamic properties of rock-forming minerals: American Journal of Science, v. 278A, 229 p.

Hill, R. I., and Silver, L. T., 1983, Contrasting west-east strontium isotope properties of wall-rocks, No. Peninsular Ranges batholith, California: Geological Society of America Abstracts with Programs, v. 15, p. 439.

Hill, R. I., Silver, L. T., and Taylor, H. P., Jr., 1986, Coupled Sr-O isotope variations as an indicator of source heterogeneity for the northern Peninsular Ranges batholith: Contributions to Mineralogy and Petrology, v. 92, p. 351–361.

Hodges, K. V., and Spear, F. S., 1982, Geothermometry, geobarometry, and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire: American Mineralogist, v. 67, p. 1118–1134.

Hollister, L. S., Grissom, G. C., Peters, E. K., Stowell, H. H., and Sisson, V. B., 1987, Confirmation of the empirical correlation of Al in hornblende with pressure of solidification of calc-alkaline plutons: American Mineralogist, v. 72, p. 231–239.

Hollister, V. F., 1976, Porphyry copper province of northern Cordilleran orogen—Summary, *in* Halbouty, M. T., Maher, J. C., and Lian, H. M., eds., Circum-Pacific energy and mineral resources: American Association of Petroleum Geologists Memoir 25.

Holloway, J. R., 1977, The effect of fluorine on dehydration equilibria: Geological Society of America Abstracts with Programs, v. 9, p. 1021.

Holloway, J. R., and Ford, C. E., 1975, Fluid-absent melting of the fluor-hydroxyl amphibole pargasite to 35 kilobars: Earth and Planetary Science Letters, v. 24, p. 44–48.

Ishihara, S., 1977, The magnetite-series and ilmenite-series granitic rocks: Mining Geology, v. 27, p. 293–305.

Kamineni, D. C., Bonardi, M., and Rao, A. T., 1982, Halogen-bearing minerals from Airport Hill, Visakhapatnam, India: American Mineralogist, v. 67, p. 1001–1004.

Kistler, R. W., and Peterman, Z. E., 1973, Variations in Sr, Rb, K, Na and initial $^{87}Sr/^{86}Sr$ in Mesozoic granitic rocks and intruded wallrocks in central California: Geological Society of America Bulletin, v. 84, p. 3489–3512.

——1978, Reconstruction of crustal blocks of California on the basis of initial strontium isotopic composition of Mesozoic granitic rocks: U.S. Geological Survey Professional Paper 1071, 17 p.

Kistler, R. W., Chappell, B. W., Peck, D. L., and Bateman, P. C., 1986, Isotopic variation in the Tuolumne intrusive suite, central Sierra Nevada, California: Contributions to Mineralogy and Petrology, v. 94, p. 205–220.

Koritnig, S., 1972, Fluorine, *in* Wedepohl, K. H., exec. ed., Handbook of geochemistry, Volume 11/3: New York, Springer-Verlag, p. 9-B-1-9-O-4.

Leelanandam, C., 1969, H_2O+, F, and Cl in the charnockitic biotites from Kondapalli, India: Neues Jahrbuch für Mineralogie Monatshefte, v. 10, p. 461–468.

Loiselle, M. C., and Wones, D. R., 1979, Characteristics and origin of anorogenic granites: Geological Society of America Abstracts with Programs, v. 11, p. 468.

Lynn, H. B., Hale, L. D., and Thompson, G. A., 1981, Seismic reflections from the basal contacts of batholiths: Journal of Geophysical Research, v. 86, p. 10633–10638.

Manning, D.A.C., and Pichavant, M., 1983, The role of fluorine and boron in the generation of granitic melts, *in* Atherton, M. P., and Gribble, C. D.,

eds., Migmatites, melting, and metamorphism: Cheshire, United Kingdom, Shiva, p. 95–109.
Marsh, S. P., and Sheridan, D. M., 1976, Rutile in Precambrian sillimanite-quartz gneiss and related rocks, east-central Front Range, Colorado: U.S. Geological Survey Professional Paper 959-G, 17 p.
Masi, U., O'Neil, J. R., and Kistler, R. W., 1981, Stable isotope systematics in Mesozoic granites of central and northern California and southwestern Oregon: Contributions to Mineralogy and Petrology, v. 76, p. 116–126.
Mavko, B. B., and Thompson, G. A., 1983, Crustal and upper mantle structure of the northern and central Sierra Nevada: Journal of Geophysical Research, v. 88, p. 5874–5892.
McNutt, R. H., Crocket, J. H., Clarck, A. H., Caelles, J. C., Farrar, E., Haynes, S. J., and Zentilli, M., 1975, Initial $^{87}Sr/^{86}Sr$ ratios of plutonic and volcanic rocks of the central Andes between latitudes 26° and 29° south: Earth and Planetary Science Letters, v. 27, p. 305–313.
Miller, C. F., 1978, An early Mesozoic alkalic magmatic belt in western North America, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium, 2nd, p. 163–174.
Moore, J. G., and Hopson, C. A., 1961, The Independence dike swarm in eastern California: American Journal of Science, v. 259, p. 241–259.
Moore, J. G., Nokleberg, W. J., Chen, J. H., Girty, G. H., and Saleeby, J. B., 1979, Geologic guide to the Kings Canyon highway, central Sierra Nevada, California: Geological Society of America, Annual Meeting, 75th, San Jose, California, Guidebook, 33 p.
Munoz, J. L., 1984, F-OH and Cl-OH exchange in micas with applications to hydrothermal ore deposits, *in* Bailey, S. W., ed., Micas: Reviews in Mineralogy, v. 13, p. 469–494.
Munoz, J. L., and Swenson, A., 1981, Chloride-hydroxyl exchange in biotite and estimation of relative HCl/HF activities in hydrothermal fluids: Economic Geology, v. 76, p. 2212–2221.
Nakada, S., 1983, Zoned magma chamber of the Osuzuyama acid rocks, southwest Japan: Journal of Petrology, v. 24, p. 471–494.
Nokleberg, W. J., 1983, Wallrocks of the central Sierra Nevada batholith, California: A collage of accreted tectono-stratigraphic terranes: U.S. Geological Survey Professional Paper 1255, 28 p.
Noyes, H. J., Wones, D. R., and Frey, F. A., 1983, A tale of two plutons: Petrologic and mineralogic constraints on the petrogenesis of the Red Lake and Eagle Peak plutons, central Sierra Nevada, California: Journal of Geology, v. 91, p. 353–379.
Ohmoto, H., and Kerrick, D., 1977, Devolatilization equilibria in graphitic systems: American Journal of Science, v. 277, p. 1013–1044.
Oliver, H. W., 1977, Gravity and magnetic investigations of the Sierra Nevada batholith, California: Geological Society of America Bulletin, v. 88, p. 445–461.
Olsen, S. N., 1982, Open- and closed-system migmatites in the Front Range, Colorado: American Journal of Science, v. 282, p. 1596–1622.
Pettijohn, F. J., 1975, Sedimentary rocks: New York, Harper and Row, 628 p.
Pigage, L. C., and Greenwood, H. J., 1982, Internally consistent estimates of pressure and temperature: The staurolite problem: American Journal of Science, v. 282, p. 943–969.
Pitcher, W. S., 1978, The anatomy of a batholith: Geological Society of London Journal, v. 135, p. 157–182.
——— 1983, Granite type and tectonic environment, *in* Hsü, K. J., ed., Mountain building processes: London, Academic Press, p. 19–40.
Powell, R., and Powell, M., 1977, Geothermometry and oxygen barometry using coexisting iron-titanium oxides: A reappraisal: Mineralogical Magazine, v. 41, p. 257–263.
Price, R. C., 1983, Geochemistry of a peraluminous granitoid suite from north-eastern Victoria, south-eastern Australia: Geochimica et Cosmochimica Acta, v. 47, p. 31–42.
Ross, D. C., 1985, Mafic gneissic complex (batholithic root?) in the southernmost Sierra Nevada, California: Geology, v. 13, p. 288–291.
Saleeby, J. B., 1987, Structural relations in the Cretaceous southern Sierra Nevada batholith and some implications on petrogenetic phenomena: Geological Society of America Abstracts with Programs, v. 19, p. 446.
——— 1988, A down-structure view of the Sierra Nevada batholith—From resurgent caldera to granulitic levels, *in* Ernst, W. G., ed., Metamorphic and crustal evolution of the western U.S. (Rubey volume 7): Englewood Cliffs, New Jersey, Prentice-Hall (in press).
Saleeby, J. B., Sams, D. S., and Tobisch, O. T., 1986, A down-plunge view of the Sierra Nevada batholith from resurgent caldera to ultrametamorphic levels: Geological Society of America Abstracts with Programs, v. 18, p. 179.
Schwarcz, H. P., 1969, Pre-Cretaceous sedimentation and metamorphism in the Winchester area, northern Peninsular Ranges, California: Geological Society of America Special Paper 100, 61 p.
Sharry, J., 1981, The geology of the western Tehachapi mountains, California [Ph.D. thesis]: Cambridge, Massachusetts, Massachusetts Institute of Technology, 215 p.
Sillitoe, R. H., 1981, Ore deposits in Cordilleran and island-arc settings, *in* Dickinson, W. R., and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 49–69.
Silver, L. T., Taylor, H. P., Jr., and Chappell, B. W., 1979, Some petrological, geochemical, and geochronological observations of the Peninsular Ranges batholith near the international border of the U.S.A. and Mexico, *in* Abbot, P. L., and Todd, V. R., eds., Mesozoic crystalline rocks: Geological Society of America Annual Meeting, Guidebook, p. 83–110.
Smith, R. B., 1978, Seismicity, crustal structure and intraplate tectonics of the interior of the western Cordillera: Geological Society of America Memoir 152, p. 111–144.
Spencer, K. J., and Lindsley, D. H., 1981, A solution model for coexisting iron-titanium oxides: American Mineralogist, v. 66, p. 1189–1201.
Stern, T. W., Bateman, P. C., Morgan, B. A., Newell, M. F., and Peck, D. L., 1981, Isotopic U-Pb ages of zircon from the granitoids of the central Sierra Nevada, California: U.S. Geological Survey Professional Paper 1185, 17 p.
Sylvester, A. G., Miller, C. F., and Nelson, C. A., 1978, Monzonites of the White-Inyo range, California, and their relation to the calc-alkaline Sierra Nevada batholith: Geological Society of America Bulletin, v. 89, p. 1677–1687.
Takahashi, M., Aramaki, S., and Ishihara, S., 1980, Magnetite-series/ilmenite-series vs. I-type/S-type granitoids: Mining Geology Special Issue 8, p. 13–28.
Taylor, H. P., Jr., 1974, The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore deposition: Economic Geology, v. 69, p. 843–883.
——— 1980, The effects of assimilation of country rocks by magmas on $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ systematics in igneous rocks: Earth and Planetary Science Letters, v. 47, p. 243–254.
——— 1986, Igneous rocks II. Isotopic case studies of circumPacific magmatism, *in* Valley, J. W., Taylor, H. P., Jr., and O'Neil, J. R., eds., Stable isotopes in high temperature geological processes: Reviews in Mineralogy, v. 16, p. 273–317.
Taylor, H. P., Jr., and Silver, L. T., 1978, Oxygen isotope relationships in plutonic igneous rocks of the Peninsular Ranges batholith, southern and Baja California, *in* Zartman, R. E., ed., Short papers of the 4th International Conference on Geochronology, Cosmochronology, and Isotope Geology: U.S. Geological Survey Open-File Report 78-701, 423–426.
Thompson, A. B., 1982, Dehydration melting of pelitic rocks and the generation of H_2O-undersaturated granitic liquids: American Journal of Science, v. 282, p. 1567–1595.
Valley, J. W., and Essene, E. J., 1980, Calc-silicate reactions in Adirondak marbles: The role of fluids and solid solutions: Summary: Geological Society of America Bulletin, Part I, v. 91, p. 114–117; Part II, v. 91, p. 720–815.
Vanko, D. A., 1986, High-chlorine amphiboles from oceanic rocks: Product of highly saline hydrothermal fluids?: American Mineralogist, v. 71, p. 51–59.
White, A.J.R., 1966, Genesis of migmatites from the Palmer region of south Australia: Chemical Geology, v. 1, p. 165–200.
White, A.J.R., and Chappell, B. W., 1983, Granitoid types and their distribution in the Lachlan fold belt, southeastern Australia, *in* Roddick, J. A., ed., Circum-Pacific plutonic terranes: Geological Society of America Memoir 159, p. 21–34.
White, A.J.R., Clemens, J. D., Holloway, J. R., Silver, L. T., Chappell, B. W., and Wall, V. J., 1986, S-type granites and their probable absence in southwestern North America: Geology, v. 14, p. 115–118.
Whitney, J. A., and Stormer, J. C., Jr., 1977, Geothermometry and geobarometry in epizonal granite intrusions: A comparison of iron-titanium oxides and coexisting feldspars: American Mineralogist, v. 61, p. 751–761.
Wollenberg, H. A., and Smith, A. R., 1968, Radiogenic studies in the central part of the Sierra Nevada batholith, California: Journal of Geophysical Research, v. 73, p. 1481–1495.
Wones, D. R., and Eugster, H. P., 1965, Stability of biotite: Experiment, theory, and application: American Mineralogist, v. 50, p. 1228–1272.
Wyborn, D., Chappell, B. W., and Johnston, R. M., 1981, Three S-type volcanic suites from the Lachlan fold belt, southeast Australia: Journal of Geophysical Research, v. 86, p. 10335–10348.
Wyllie, P. J., 1981, Magma sources in Cordilleran settings, *in* Dickinson, W. R., and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 39–47.
Yardley, B.W.D., Leake, B. E., and Farrow, C. M., 1979, The metamorphism of Fe-rich pelites from Connemara, Ireland: Journal of Petrology, v. 21, p. 365–399.
Zaw, U. K., and Clark, A. H., 1978, Fluorine-hydroxyl ratios of skarn silicates, Cantung E-zone scheelite orebody, Tungsten, Northwest Territories: Canadian Mineralogist, v. 16, p. 207–221.

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