Regional variations in bulk chemistry, mineralogy, and the compositions of mafic and accessory minerals in the batholiths of California

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ABSTRACT

We define regional variations in mafic and accessory mineral assemblages and compositions and expand the current understanding of spatial variations in whole-rock geochemistry in the batholiths of California. In so doing, we gain new insights into the nature of magmatic source rocks and mechanisms of magma generation in volcano-plutonic arcs of active continental margins. Little-studied metaluminous to strongly peraluminous granites containing Fe-rich biotite with $\log(X_{Mg}/X_{Fe}) < -0.21$ (I-SCR type; strongly contaminated and reduced I-type) typically occur in north-northwest–striking belts within prebatholithic wall-rock terranes containing graphitic pelites in the western Sierra Nevada and Peninsular Ranges batholiths. The other pluton types (I-WC, I-MC, and I-SC; weakly, moderately, and strongly contaminated, but not reduced, I-types) range in composition from metaluminous to weakly peraluminous and form a general west-to-east progression across the batholiths defined by increasing F/OH in biotite. This correlates with the well-known petrologic sequence from quartz diorites and granodiorites on the west to quartz monzonites and granites to the east. I-WC types also occur in the central-eastern Sierra Nevada batholith, however, primarily in the vicinity of the Independence dike swarm.

F/OH and Mn in biotite and amphibole increase on a regional scale from western I-WC types to eastern I-MC and I-SC types, parallel to eastward increases in incompatible elements and decreases in compatible elements in the plutons. In contrast, the belts of western I-SCR granites and eastern I-WC quartz diorites and granodiorites disrupt the regional west-to-east systematics in both mineral and whole-rock geochemistry. Spatial variations in the Al content of amphibole are regional in scale and reflect pressures of pluton crystallization. We conclude that significant, previously unrecognized complexity exists in regional geochemical systematics in the California batholiths.

INTRODUCTION

The granitic batholiths of California have long been the focus of varied petrologic and isotopic research directed at interpreting geological factors which control the chemistry of melts generated and emplaced at plate margins where oceanic and continental crust interact by subduction. Pronounced transverse asymmetries with north-northwest longitudinal continuity have been recognized in the petrologic, geochemical, isotopic, and geochronologic character of the batholiths. Herein, in order to clarify spatial variations in magmatic source-region characteristics as well as mechanisms of magma–wall-rock interaction causing regional plutonic compositional trends, we present new data on common rock-forming and accessory mineral chemistry. Our approach, briefly outlined in Ague and Brimhall (1987) and developed here in greater detail, contributes to the further development and refinement of the regional geologic context of the California batholiths, particularly the controls on magma chemistry imposed by the localized occurrence of highly reducing, pre-batholithic wall-rock terranes and regional-scale variations in the thickness and metamorphic grade of cratonal basement. We focus on the spatial variation in complex solid-solution compositions and assemblages which reflect a number of factors in magmatic evolution such as redox effects and magmatic halogen content which have previously not received sufficient attention.

Lindgren (1915) was the first to document the fact that in general, the batholiths of western North America become increasingly felsic from west to east. Transverse variations in whole-rock chemistry exist in the central Sierra Nevada batholith which correlate with the west-to-east petrologic variations described by Lindgren (1915) (compare with Moore, 1959; Dickinson, 1970; Bateman and Dodge, 1970; Dodge, 1972). Stable- and radiogenic-isotope studies in both the Sierra Nevada and Peninsular Ranges batholiths (compare with Kistler and Peterman, 1973; Early and Silver, 1973; Taylor and Silver, 1978; DePaolo, 1981; Masi and others, 1981; Nelson and DePaolo, 1985) have broadly identified likely magmatic source components and processes of mixing and delineated the probable edge of the Precambrian craton of western North America. A geochronologic framework for these batholiths has been established (see Evernden and Kistler, 1970; Silver and others, 1979; Saleeby, 1981; Stern and others, 1981; Chen and Moore, 1982), detailing the intrusion of plutons in space and time. Systematic regional variations in the age and lithologic character of pre-batholithic wall-rock terranes (Nokleberg, 1983), as well as regional metallogenic patterns, have been documented (Albers, 1981).

Because a comprehensive petrologic framework exists for the California batholiths, this magmatic arc provides an ideal field region to apply new methods directed at further elucidating batholith formation processes at convergent plate boundaries. Our methods (Ague and Brimhall, 1987), involve the systematic study of

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Additional material for this article (appendices) may be obtained free of charge by requesting Supplementary Data 8813 from the GSA Documents Secretary.

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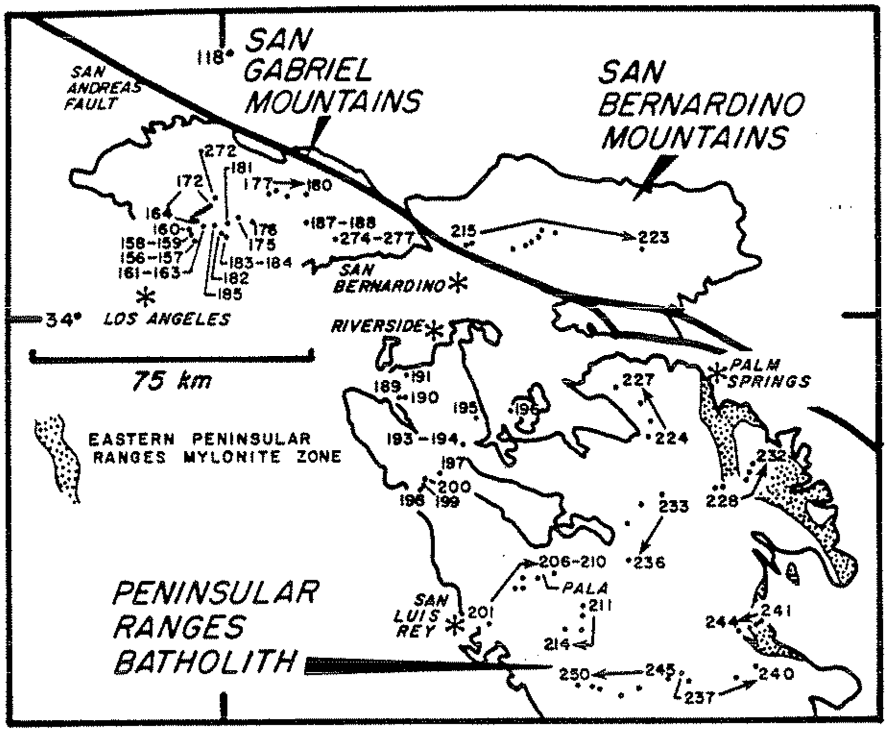

Figure 2. Sample locations in the northern Peninsular Ranges batholith (PRB), San Bernardino Mountains (SBB), and the San Gabriel Mountains (SGB). Position of eastern Peninsular Ranges mylonite zone from Erskine (1985).

key mafic and accessory mineral compositions and assemblages, coupled with whole-rock geochemistry and regional distributions of geochemically distinct intrusive types, to refine interpretations of source materials involved in batholith generation and to provide new insight into the depth of exposure of the plutons. Our conclusions therefore bear directly upon such important problems as the generation of "S-type" granites in the western United States (Chappell and White, 1974; White and others, 1986), the petrologic regimes required to produce magnetite- and ilmenite-series plutons (Czamanske and others, 1981), the geochemical effects of contamination of mafic magmas with different types of crustal materials, and the magmatic processes operative in the crust as a function of depth.

In order to define regional geochemical trends accurately and in sufficient detail, we have carried out a regional-scale sampling program. We utilize a total of 393 samples of granitic rocks collected along numerous sampling traverses across 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) (Figs. 1, 2). The analysis of a large number of systematically collected samples has allowed us to generate a comprehensive geochemical data base with a high degree of internal consistency. A complete set of geochemical and mineralogical data for all samples and localities studied is available.[1]

Ague and Brimhall (1987) presented a classification scheme for granitic rocks of the batholiths using the composition of plutonic biotite as determined by electron microprobe. The rationale for choosing biotite is simple. Biotite is widely distributed in granitic magmatic and hydrothermal systems and has a complex crystal chemistry, with the metals Mg, Fe, Mn, Ti, and Al octahedrally coordinated to OH, F, and Cl. Biotite compositions, under the provision that other minerals enter into an array of useful equilibrium buffering relationships, thus relate directly to important magmatic and hydrothermal variables such as oxygen fugacity, water fugacity, f_{HF}/f_{H_2O}, and f_{HF}/f_{HCl} (Wones and Eugster, 1965; Brimhall and others, 1983, 1985; Munoz, 1984). Here, we have extended our study to plutonic amphiboles which provide critical data regarding the depths of emplacement of the plutons (Hammarstrom and Zen, 1986).

We utilize a $\log(X_F/X_{OH})$ versus $\log(X_{Mg}/X_{Fe})$ coordinate framework for biotite classification (Fig. 3A) because as part of ubiquitous buffer assemblages, these variables reflect the f_{O_2} and f_{HF}/f_{H_2O} conditions of biotite crystallization. In addition, in the biotite structure, F and OH are the primary substitutional anions in the hydroxyl site, whereas Mg and Fe are the predominant elements in octahedral sites. Rocks containing biotite with $\log(X_{Mg}/X_{Fe}) > -0.21$ are divided into three subgroups based upon increasing F/OH: (1) I-WC type (weakly contaminated I-type), (2) I-MC type (moderately contaminated I-type), and (3) I-SC type (strongly contaminated I-type). Reduced rocks containing biotite with $\log(X_{Mg}/X_{Fe}) < -0.21$ are classified as I-SCR type (strongly contaminated and reduced I-type). The term "contamination" is used here in a broad sense to refer to interactions of mafic "I-type" magmas derived from the upper mantle, deep crust, or subducted slabs with continental crustal source components, which may have spatially variable characteristics (compare with Farmer and DePaolo, 1983), by such processes as partial melting, magma mixing, and assimilation. We note in this context that mantle-derived rocks of "M-type," discussed first by White (1979) in abstract form, are here broadly classified as "I-type" for simplicity.

Figure 3B illustrates the spatial distributions of the rock types. The well-known petrologic sequence from western quartz diorites and granodiorites to eastern quartz monzonites and granites is broadly paralleled by the west-to-east progression from I-WC to I-SC types (Ague and Brimhall, 1987). Figure 3B, however, demonstrates that significant additional complexity exists in the regional distributions of I-SCR granites and I-WC types. The I-SCR granites occur primarily in narrow north-northwest–striking belts within pre-batholithic wall-rock terranes containing graphitic pelites in the western SNB and PRB, regions thought previously to be characterized by much more mafic intrusives (Ague and Brimhall, 1987). On the other hand, I-WC–type mafic quartz diorites and granodiorites are present in the eastern SNB in the vicinity of the Independence dike swarm (Chen and Moore, 1979) (immediately north of B′) and seem out of place there, given the regional petrologic systematics documented by Moore (1959). Although the eastward I-WC to I-MC and I-SC progression almost certainly requires the involvement of cratonal magmatic source components in the generation of the eastern batholiths (compare with Kistler and Peterman, 1973; Silver and others, 1979; DePaolo, 1981; Ague and Brimhall, 1987), the previously little-studied western I-SCR and eastern I-WC belts reflect the operation of distinct magmatic processes associated with intrusion of calc-alkaline magmas into reducing pelitic wall-rock terranes in the former case and regions of thin or perhaps absent continental crust in the latter.

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[1] Appendices A–F may be obtained free of charge by requesting Supplementary Data 8813 from the GSA Documents Secretary.

Whole-Rock XRF Analyses

Whole-rock major, minor, and trace elements were determined by energy-dispersive X-ray fluorescence (XRF) techniques (J. Hampel, analyst). Major- and minor-element analyses were performed on glass plates of fused rock samples, whereas trace elements were determined on pressed pills using a cellulose binder. Major and minor elements were determined using U.S. Geological Survey standards BCR-1 and W-1 and the following standards analyzed wet chemically by I.S.E. Carmichael: LHG, 780-K18, 867-311, and 913-8016. One additional standard, Napa glass, analyzed by M. S. Ghiorso, was also utilized. Trace elements were determined using U.S. Geological Survey standards G-2 and W-1. Precisions for all major and minor oxides except K_2O and Na_2O were better than 1%, whereas K_2O, Na_2O, and trace-element precisions were better than 5%.

WHOLE-ROCK CHEMISTRY

We have analyzed 44 samples of the SNB sample set for major and minor elements and 114 samples for trace elements in order to elucidate spatial variations in pluton geochemistry and to investigate relationships between mafic silicate chemistry, mineral assemblage, and whole-rock chemical composition. Representative analyses are given in Appendix 1.

Regional Variations

Strong west-to-east and north-to-south gradients in the compositions of plutonic rocks are an important geochemical feature of the California batholiths and the calc-alkaline magmatic arcs of continental margins in general (see Dickinson, 1970; Kistler and Peterman, 1973; Kistler, 1974b, p. 416). Although latitudinal variations in whole-rock chemistry across the SNB and PRB, such as the well-defined west-to-east increases in K_2O, have been documented previously (Bateman and Dodge, 1970; Silver and others, 1979), we present these variations in the context of mafic silicate geochemistry and, in addition, show the effect of the little-studied western I-SCR types and eastern I-WC types on regional profiles. The positions of our west-to-east geochemical traverses A–A′ and B–B′ are shown in Figure 3B.

In A–A′, which extends across the Yosemite Valley, the west-to-east increase in F/OH in biotite at this latitude discussed by Ague and Brimhall (1987) is immediately apparent (Fig. 4). Covarying with F/OH in biotite are whole-rock SiO_2, K_2O, Rb/Sr, and molar $Al_2O_3/(CaO + K_2O + Na_2O)$, whereas CaO and MgO show a pronounced west-to-east decrease. Although $\log(X_{Mg}/X_{Fe})$ in biotite remains more or less constant at a value of approximately 0.0 (equal mole fractions of Mg and Fe) from west to east, molar whole-rock $MgO/(MgO + FeO)$ shows a pronounced decrease in the I-SC types due to the presence of abundant accessory magnetite correlating with the eastward increase in Fe_2O_3 documented by Dodge (1972). Molar $MnO/(MnO + TiO_2 + FeO + MgO)$ shows a marked increase in the I-SC types, which correlates with increases in X_{Mn} in biotite (see below). Cr is most abundant in the least evolved western I-WC types.

In contrast to the relatively smooth, generally monotonic regional variations documented in traverse A–A′, traverse B–B′, which extends across the central SNB, is considerably more complex, owing to the presence of the I-SCR belt and eastern I-WC types (Figs. 3, 4). The geochemical characteristics associated with the west-to-east progression from I-WC to I-SC types are broadly similar to those in traverse A–A′, but in the central portion of B–B′, these trends are locally disrupted by the siliceous I-SCR granites. Note in particular the high values of $Al_2O_3/(CaO + K_2O + Na_2O)$, largely due to the presence of magmatic muscovite, and high K_2O due to abundant microcline. The values of $\log(X_{Mg}/X_{Fe})$ and $\log(X_F/X_{OH})$ (in biotite) and whole-rock molar $MgO/(MgO + FeO)$ and molar $MnO/(MnO + TiO_2 + FeO + MgO)$ also attain extremes in the I-SCR types. In addition to the western occurrences, traverse B–B′ illustrates that I-WC types may also be present in the eastern SNB (sample 1011-16; Fig. 4). Note in particular the high Cr content of 91 ppm in sample 1011-16.

Major-, Minor-, and Trace-Element Systematics

With the regional variations in pluton chemistry in mind, we now examine key whole-rock geochemical parameters in order both to characterize the various pluton types more fully and to compare the compositional systematics of the California batholiths with the Australian I-, S-, and A-types and the magnetite and ilmenite series of Japan.

A plot of CaO versus SiO_2 (Fig. 5A) shows a smooth linear trend which grades from I-WC to I-SC and I-SCR types with increasing silica and decreasing CaO. This type of linear array is characteristic of I-type plutons worldwide (Czamanske and others, 1981). The plot of K_2O versus SiO_2 (Fig. 5B), however, while showing a general positive correlation, displays considerable scatter, with the I-SC and I-SCR types in general having the highest K_2O content. Figure 5C shows molar $Al_2O_3/(CaO + K_2O + Na_2O)$ versus SiO_2, and here, it is apparent that I-WC, I-MC, and I-SC types range in composition from metaluminous to weakly peraluminous. I-SCR types, in contrast, range from metaluminous to strongly peraluminous granites with molar $Al_2O_3/(CaO + K_2O + Na_2O)$ greater than 1.05. This reflects the fact that the I-WC, I-MC, and I-SC samples contain biotite as the most peraluminous phase whereas muscovite is present in the most peraluminous of the analyzed I-SCR samples. Values of molar $Al_2O_3/(CaO + K_2O + Na_2O)$ greater than 1.05 are characteristic of the S-types of Australia (White and Chappell, 1983). Na_2O shows no distinct variation between types (Fig. 5D), and it is important to note that none of the analyzed samples display the low Na_2O characteristic of the Australian S-types and most contain more Na_2O than does the average Australian I-type (White and Chappell, 1983).

Relationships between whole-rock MgO, FeO, MnO, and TiO_2 are important in the context of mafic silicate chemical systematics in that Mg, Fe, Mn, and Ti substitute into the octahedral sites of ferromagnesian minerals. Figure 5E illustrates that on average, the I-SCR types are the most magnesium poor although some I-SC granites are equally iron rich. The I-SC and I-SCR fields overlap, owing to the fact that we show all Fe as FeO. The I-SC types contain MgO-rich silicates and substantial magnetite (App. 2). The I-SCR types, on the other hand, generally contain minor ilmenite with Fe^{2+} being concentrated in the mafic phases. We note that values for average molar $MgO/(MgO + FeO)$ for Australian I- and S-types, 0.46 and 0.45, respectively, are comparable to those for I-WC, I-MC, and some I-SC types but are much higher than those of the I-SCR granites.

Although MnO decreases with SiO_2 content (App. 1), Figure 5F shows that molar $MnO/(MnO + TiO_2 + FeO + MgO)$ increases as silica increases, with the I-SC and I-SCR types displaying the highest degrees of relative Mn enrichment. This is consistent with available evidence regarding the behavior of Mn in magmatic systems. As pointed out by Goldschmidt (1954), magmas tend to have increasing $Mn/(Mg + Fe)$ with increasing differentiation, owing to the large ionic radius of Mn^{2+} and its consequent behavior as a relatively incompatible element. In addition, Hildreth (1979) has suggested that Mn may be concentrated in silicic magmas through some as yet poorly understood process of liquid-state differentiation. As Mn, Ti, Mg, and Fe are the primary substitutional metals in mafic mineral octahedral sites, this relationship indicates that the I-SC and I-SCR silicates should contain more Mn than those found in

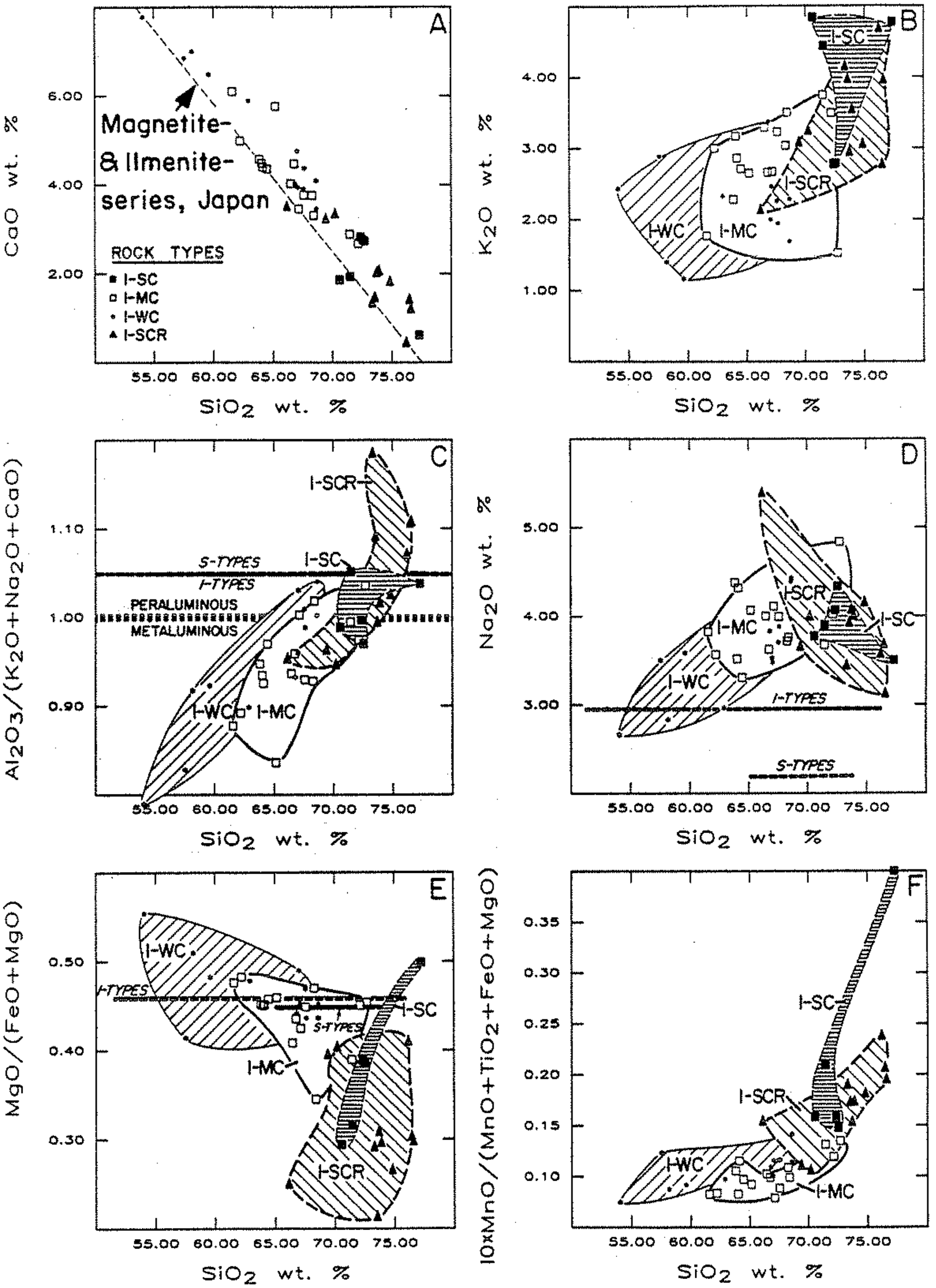


Figure 5. Whole-rock geochemical systematics based on XRF analyses of 44 samples. A. CaO versus SiO_2. Note similarity to trend defined by Japanese magnetite- and ilmenite-series plutons. B. K_2O versus SiO_2. C. Molar $Al_2O_3/(CaO + Na_2O + K_2O)$ versus SiO_2. Only I-SCR types display the "S-type" characteristic of $Al_2O_3/(CaO + Na_2O + K_2O) > 1.05$. D. Na_2O versus SiO_2. The California batholiths are generally more Na_2O rich than are both average Australian I-types ($Na_2O = 2.95$) and S-types ($Na_2O = 2.2$). E. Molar MgO/(MgO + FeO) versus SiO_2. Note that I-SCR types are in general the most Mg poor, with MgO/(MgO + FeO) lower than in both average Australian I-types and S-types [MgO/(MgO + FeO) = 0.46 and 0.45, respectively]. F. 10 × MnO/(MnO + FeO + MgO + TiO_2) (moles) versus SiO_2. I-SC and I-SCR types are in general more Mn enriched, relative to Fe, Ti, and Mg, than are I-WC and I-MC types. Data for the magnetite and ilmenite series are from Czamanske and others (1981); data for I-types and S-types are from White and Chappell (1983).

and low Al_2O_3 characteristic of minimum melts (White and Chappell, 1977) (App. 1, sample 12), possibly indicating a local anatectic origin. The high values of Cr in the more mafic I-WC and I-MC types reflect the compatible nature of this element, whereas high Cr in some I-SCR granites (as much as 60 ppm) may indicate the involvement of marine sedimentary source materials as Cr may be concentrated into clays during weathering (White and Chappell, 1983). The compatible element Ni is concentrated into the more mafic I-WC and I-MC samples, however, and shows no enrichment in the I-SCR types, in contrast to the high Ni values (average 17 ppm) reported for the Australian S-types

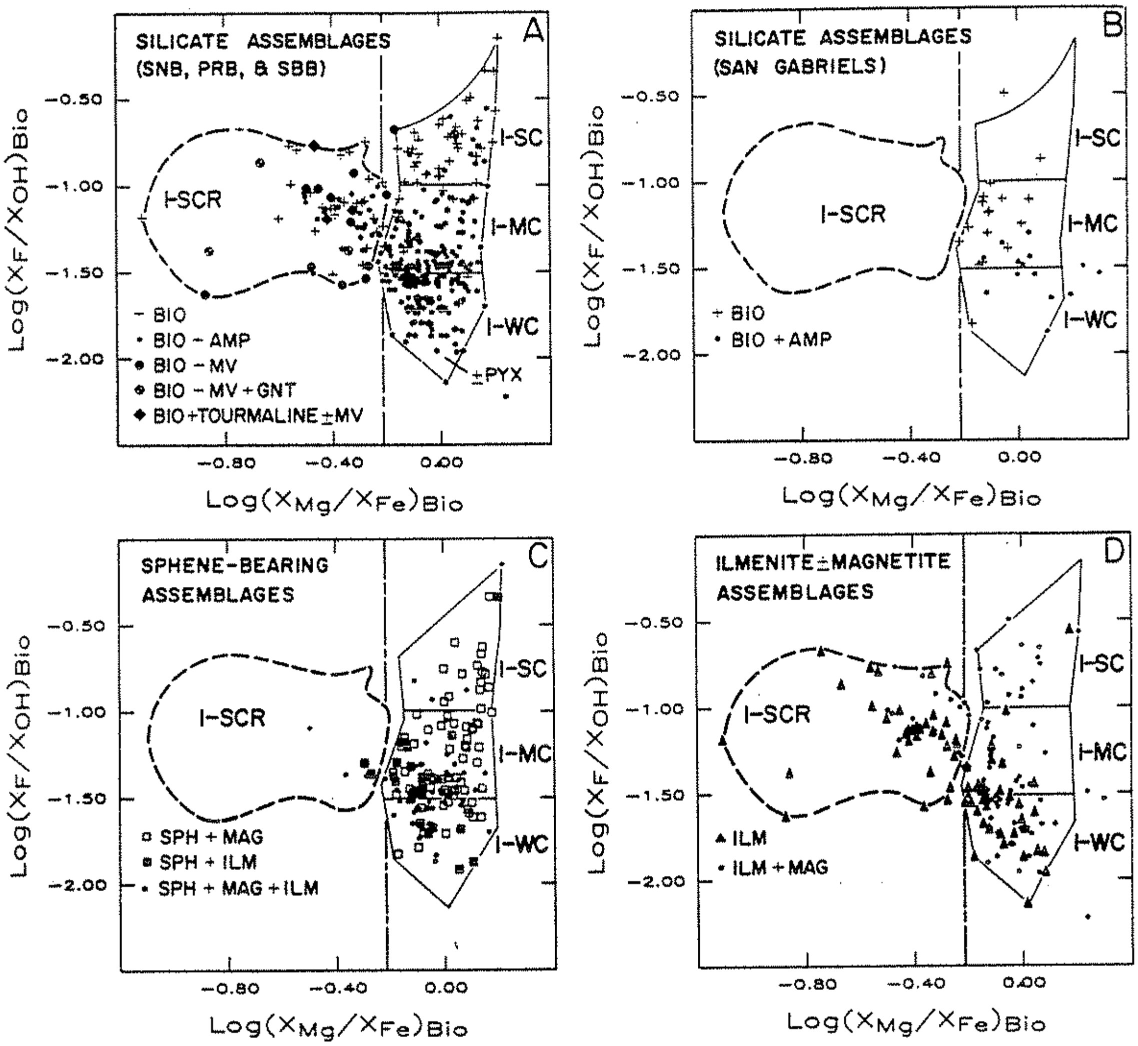


Figure 8. Coexisting mineral assemblages in relation to biotite chemistry. A. Biotite compositions for the SNB, PRB, and SBB. Note abundance of aluminous minerals in the I-SCR group. B. Biotite compositions for the SGB. Note absence of I-SCR types. C. Primary sphene-bearing assemblages for all batholiths. Sphene only rarely coexists with I-SCR–type biotites. D. Ilmenite + magnetite assemblages.

lesser degree, I-MC and I-SC types belong to the ilmenite series (Figs. 8C, 8D).

I-SCR types comprise a wide variety of assemblages and mineralogically are typically true granites with low color indices ranging from 2 to 16. The majority of I-SCR types contain microcline, quartz, plagioclase, biotite, and ilmenite, with or without magnetite. Other minerals which may occur include amphibole, garnet, muscovite, and tourmaline (Fig. 8A). Cordierite has not been found in any of the studied samples. Amphibole is present in only 30% of the specimens and never coexists with muscovite, garnet, or tourmaline. Allanite crystals may be associated with mafic phases and can attain 3 mm in length. Anhedral to subhedral zircon, and to a lesser degree monzonite, is commonly included within biotites and may represent refractory material inherited from sedimentary protoliths (compare with Sawka and others, 1986). Ilmenite alone or with magnetite is the predominant accessory assemblage, with primary sphene being extremely rare (Figs. 8C, 8D). Petrographic observations indicate that the bulk of the I-SCR types parallel Ishihara's (1977) ilmenite series, first defined for Japanese granitoids on the basis of iron-titanium oxide content and assemblages.

Sulfides are rare in the plutonic rocks of the batholiths; pyrrhotite, pyrite, and chalcopyrite have been observed either as anhedral, interstitial crystals or as inclusions within amphibole or magnetite. The occurrence of magnetite alone is not restricted to any particular rock type, although only 13% of the I-SCR types contain this assemblage.

Mafic inclusions, composed of plagioclase, amphibole, and biotite with or without K-feldspar, magnetite, ilmenite, and sphene, are common in the I-WC and I-MC types but are rare in I-SC granites. Microscopically, they are texturally distinctive in that late-formed microcline and biotite poikilitically enclose early-formed minerals such as plagioclase. In contrast, I-SCR types rarely contain mafic inclusions of any kind. The inclusions which do occur are typically small (on the order of 1 cm) aggregates of biotite or, less commonly, muscovite, biotite, and accessory phases.

Although biotite is present in nearly all of the unaltered specimens studied, monzonites from the Joshua flat pluton of the White-Inyo Mountains (Sylvester and others, 1978), the granodiorites of the Strawberry W Mine of the SNB (Nokleberg, 1981), and uncommon mafic and intermediate rocks from the SGB and western SNB and PRB lack biotite but contain amphibole with or without pyroxene, magnetite, sphene, and ilmenite.

I-SCR types may occur as discrete plutons (for example, granite of Shuteye Peak; Stern and others, 1981) or as granite facies of compositionally variable plutons such as the Bonsall Tonalite described by Larsen (1948). In general, plutons which are compositionally variable, such as the Mount Givens granodiorite (Stern and others, 1981), which ranges from I-MC to I-SC type, may comprise more than one rock type as defined herein on the basis of biotite chemistry.

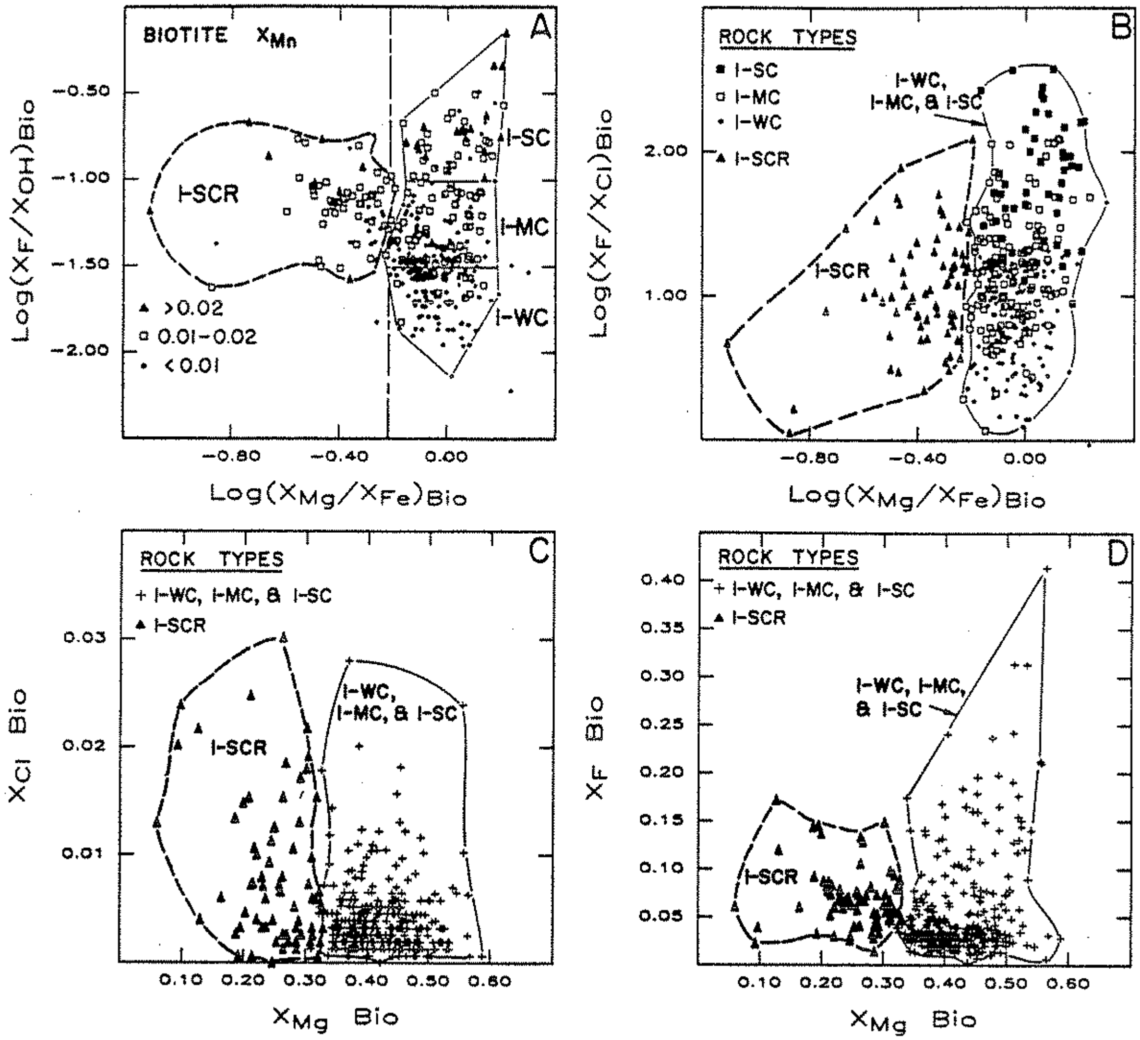


Figure 10. Biotite com- sitional systematics. A. $_{Mn}$ in biotite. In general, SC- and I-SCR-type iotites are the most Mn ch. B. $\log(X_F/X_{Cl})$ ver- s $\log(X_{Mg}/X_{Fe})$. C. X_{Cl} ersus X_{Mg}. D. X_F ver- s X_{Mg}.

phibole in the form of sphene or rutile has t been observed in any of the studied samples, d it is therefore probable that unlike biotite, amphibole compositions record a high- nperature magmatic signature for Ti.

Elemental Partitioning between Mafic Phases

It is important to evaluate geochemical interrelationships between coexisting amphiboles and biotites in order to ascertain the preservation of equilibrium and the possible temperature dependency of elemental partitioning between these phases.

Figure 12A shows $\log(X_{Mg}/X_{Fe_{total}})$ for coexisting amphiboles and biotites from the batho-

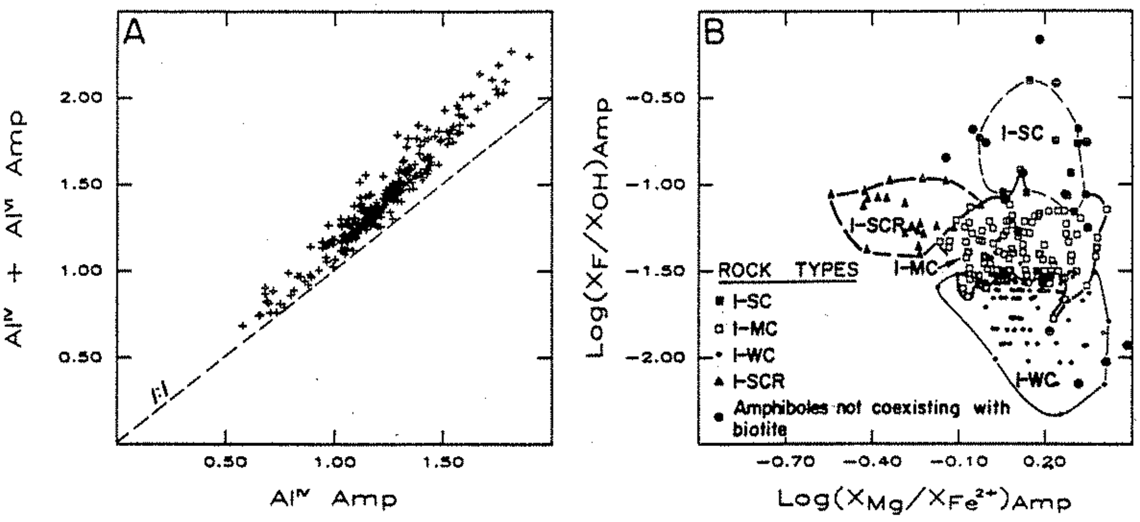


Figure 11. Amphibole mpositional systematics. . Total Al versus Al^{IV} ll rock types). Note co- riation of Al^{VI} and ^{IV}. B. $\log(X_F/X_{OH})$ rsus $\log(X_{Mg}/X_{Fe^{2+}})$. mphiboles from I-WC, MC, I-SC, and I-SCR pes occupy distinct mpositional fields with ly minor overlap.

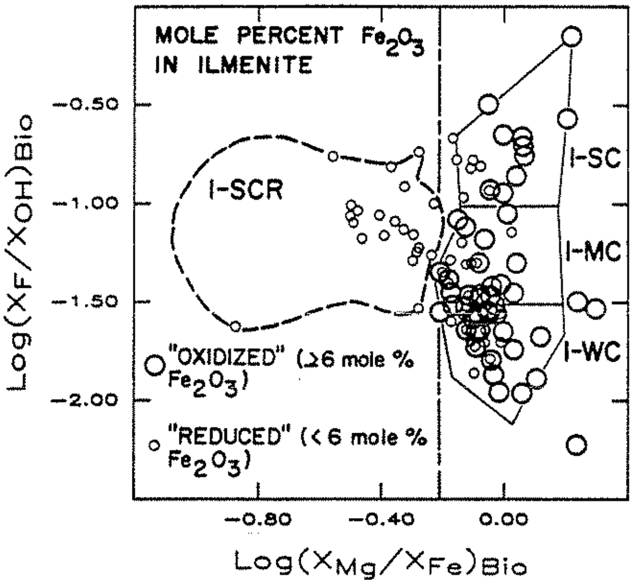


Figure 13. Ilmenite Fe_2O_3 mole percent plotted in terms of coexisting biotite composition. Note that "reduced" ilmenites with $Fe_2O_3 < 6$ mole percent are present in I-SCR types. "Oxidized" ilmenites containing 6 mole percent or more Fe_2O_3 are common in the I-WC, I-MC, and I-SC types.

Ilmenite Chemistry

Ilmenite occurs in rocks of all types studied and varies substantially in Fe_2O_3 and MnO. Figure 13 shows that calculated maximum mole percent Fe_2O_3 for I-WC, I-MC, and I-SC types may exceed 6 mole % (reaching a maximum of 20 mole %), whereas ilmenites from I-SCR types have less than 6 mole % hematite. As in biotites and amphiboles, Mn content is highest in the ilmenites from I-SC and I-SCR types. I-SCR ilmenites are generally homogeneous in reflected light, but I-WC, I-MC, and I-SC ilmenites may display micron-scale exsolution features. Grains with significant exsolution were analyzed with a wide (10 μ) microprobe beam. In contrast to Czamanske and others (1981), separate ilmenites from a single sample do not show significant compositional variation.

REGIONAL VARIATIONS

We now examine in detail previously unrecognized spatial variations in mineral assemblages and mafic mineral chemistry in the California batholiths. These variations are of central importance in understanding geologic factors controlling intrusive chemistry and the evolution of batholiths at convergent plate boundaries where magmas derived from downgoing subducted slabs, the upper mantle, or crust may interact with a diverse array of geochemically distinct pre-batholithic terranes.

Mineral Assemblages

One of the most useful petrologic distinctions between I-SC and I-SCR granites and the more mafic I-WC and I-MC types is the general absence of amphibole in the I-SC and I-SCR types. Although the assemblage biotite + amphibole is widespread, granitic rocks with biotite but no amphibole are prevalent in the eastern SNB and SBB and in narrow northwest-trending belts in the western SNB and PRB (Fig. 14). The eastern "biotite only" assemblages correspond in general to I-SC plutons, whereas the northwest-trending belts in the SNB and PRB are defined by I-SCR types. Also shown are the occurrences of the aluminous minerals muscovite, garnet, and tourmaline, and here, it is clear that these minerals typically occur in the I-SCR belts. The rocks of the SGB in many cases lack amphibole; here, however, the rocks are of I-MC or I-SC affinity. The SGB has been subjected to a complicated series of tectonic and metamorphic events (Ehlig, 1981), and it is therefore probable that the compositions of phases from the SGB may not always be directly comparable with those from the rest of the batholiths.

The regional distributions of accessory mineral assemblages define systematic variations which correlate with rock type and silicate character (Figs. 15A, 15B). The assemblages ilmenite or ilmenite + magnetite in both the SNB and PRB occur almost exclusively in the western portions of the batholiths, generally in rocks of I-SCR, I-WC, and I-MC type. These assemblages also occur within isolated I-SCR types from the eastern SNB and PRB, in I-SC types in the vicinity of the Strawberry W Mine, and in I-SC types of the SBB. The magnetite + ilmenite + sphene assemblage is found south of 38° N. latitude in the SNB, the western SBB, and throughout the PRB, generally within I-WC and I-MC types, although rare I-SC and I-SCR granites also contain this assemblage. The highly oxidized assemblage magnetite + sphene occurs in the northern and eastern SNB and eastern PRB, whereas the relatively uncommon assemblage ilmenite + sphene is present in the eastern PRB and sporadically in the SNB. We should emphasize at this point that the ilmenites in the I-SCR types define local-scale compositional discontinuities in regional ilmenite composi-

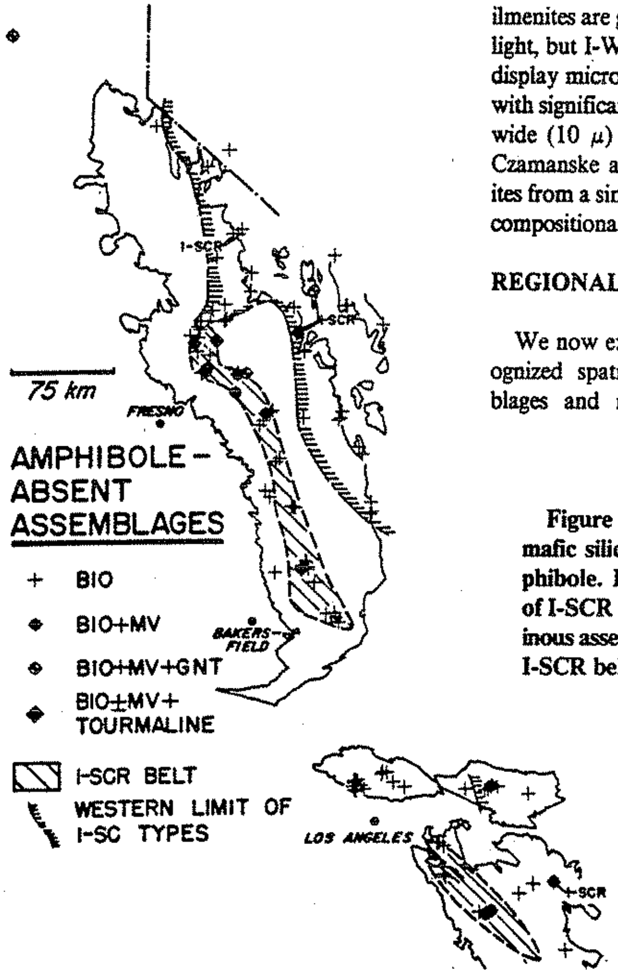
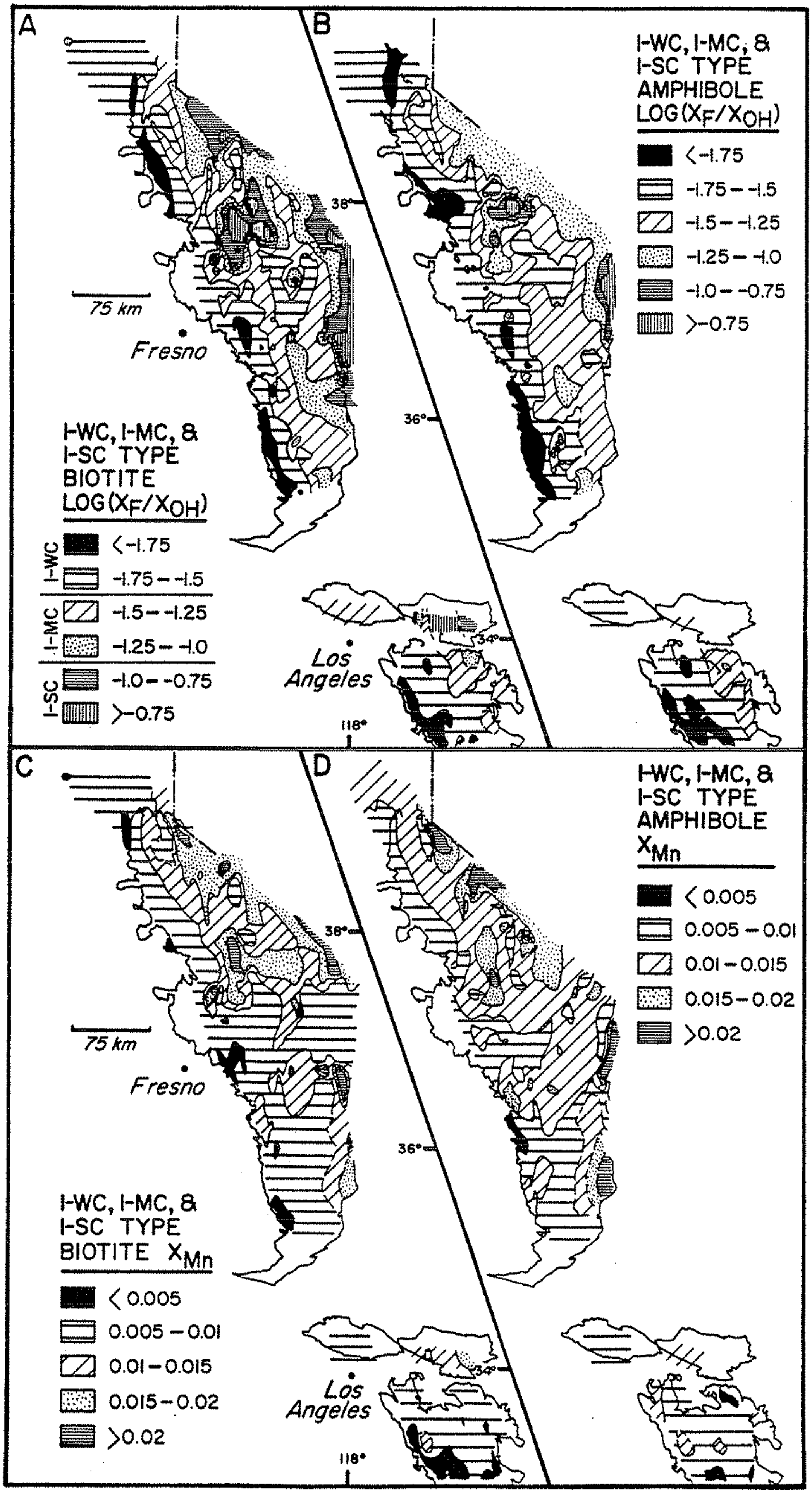


Figure 14. Regional distribution of mafic silicate assemblages lacking amphibole. Biotite granites are generally of I-SCR or I-SC type. Note that aluminous assemblages typically occur within I-SCR belts.

Figure 16. Regional trends in $\log(X_F/X_{OH})$ and X_{Mn} for I-WC–, I-MC–, and I-SC–type biotites and amphiboles (I-SCR types are excluded). A, B. Log (X_F/X_{OH}) contours for biotites and amphiboles. C, D. X_{Mn} contours for biotites and amphiboles. $\text{Log}(X_F/X_{OH})$ and X_{Mn} both increase systematically from west to east across the batholiths, although regions of $\log(X_F/X_{OH}) < -1.5$ may occur in the eastern SNB.



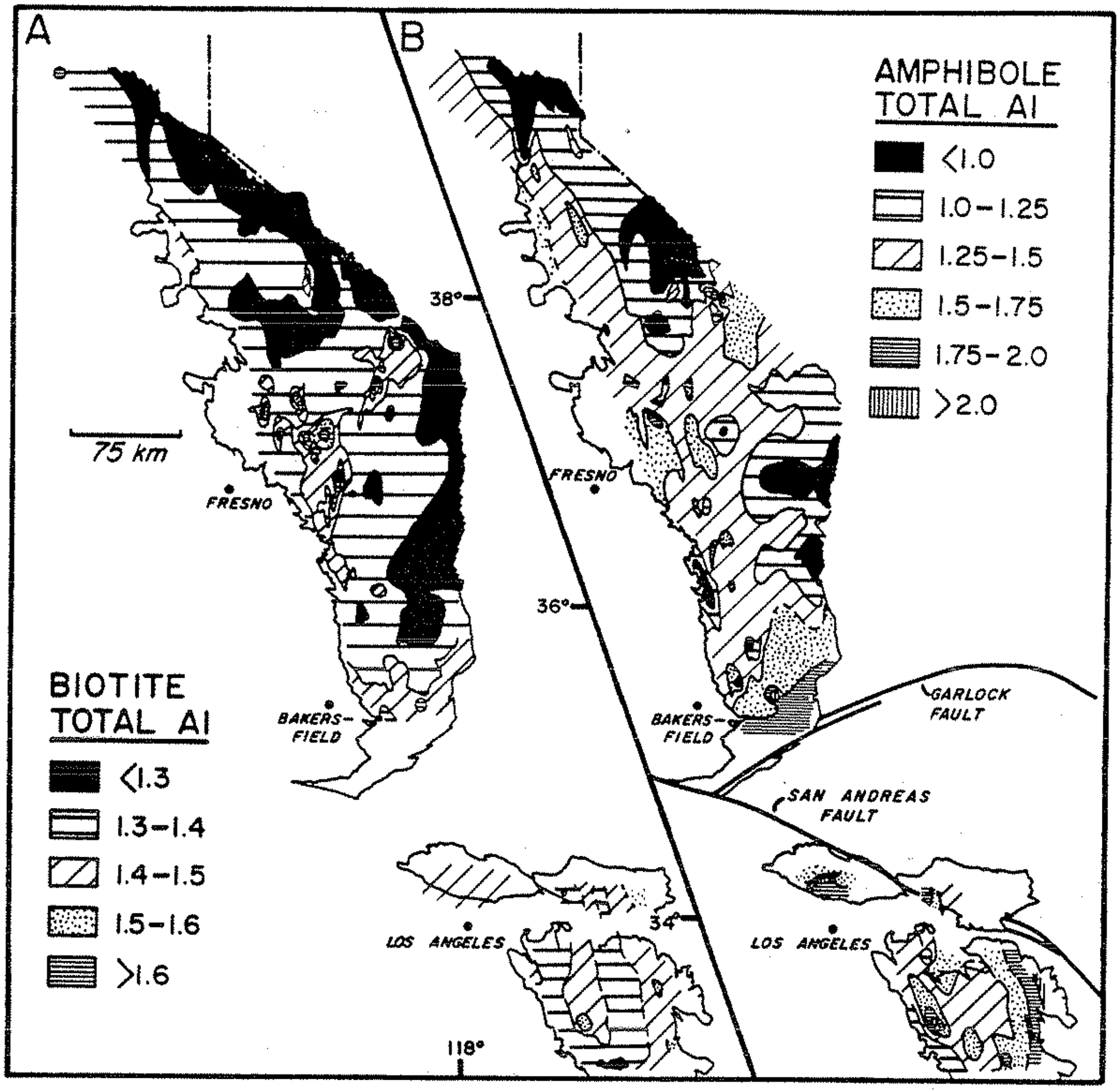


Figure 18. Regional contours of total aluminum (formula units) in biotites and amphiboles of I-WC, I-MC, I-SC, and I-SCR types. A. Regions of high total Al (>1.5) generally occur where biotite coexists with aluminous phases such as muscovite, garnet, and tourmaline (compare with Fig. 14). B. Al in amphibole. Note broad west-to-east decreases in Al in SNB and west-to-east increases in the Al in PRB. The SGB shows highest overall amphibole Al content.

the highest F content attained is that of the I-MC types of the San Jacintos. The rocks of the SGB are generally of I-MC type, but we note that the occurrence of I-SC types is restricted to the western part of the range. Differences in the biotite and amphibole regional systematics are largely due to the fact that many I-SC and I-SCR samples contain biotite but no amphibole. The contours of amphibole compositional parameters thus are derived from fewer data than are the ones for biotite.

As is the case with F/OH, Mn increases from west to east across the batholiths, owing to the incompatible behavior of Mn in silicate magmas. The highest Mn values are found in the eastern SNB and SBB, associated with I-SC granites (Figs. 16C, 16D). We have omitted the I-SCR types from the contoured data set for clarity.

The regional variations in $\log(X_{Mg}/X_{Fe})$ highlight the presence of I-SCR types (Figs. 17A, 17B). Here, all granitic rock types (I-WC, I-MC, I-SC, and I-SCR) have been contoured as one data set. Except for isolated plutons in the eastern SNB and PRB, the Fe-rich silicates [$\log(X_{Mg}/X_{Fe}) < -0.2$ for biotite; $\log(X_{Mg}/X_{Fe^{2+}}) < -0.1$ for amphiboles] are restricted to narrow northwest-trending belts in the western SNB and PRB corresponding to the occurrence of I-SCR granites. In contrast, the highest values of $\log(X_{Mg}/X_{Fe})$ are generally found in the northern and eastern SNB samples.

Figures 17C and 17D show regional variations in X_{Cl}. All I-WC, I-MC, I-SC, and I-SCR types have been contoured as a group in this plot. Although the patterns are not exceedingly well defined, the highest values are associated with the Fe-rich silicates of I-SCR affinity and, somewhat surprisingly, some of the Mg-rich silicates of the eastern SNB and PRB. "Mg-Cl avoidance" (Munoz, 1984) is not the sole controlling factor in regional variation of Cl content. Inspection of Figures 17C and 17D demonstrates that amphiboles typically have higher X_{Cl} than do coexisting biotites (see Fig. 12D).

The regional distributions of total Al in biotite and amphibole are crudely similar but are significantly different in detail. The regions of highest total aluminum in biotite are generally found in association with I-SCR types where biotite coexists with the aluminous phases muscovite, garnet, or tourmaline (Fig. 18A). The lowest Al contents are found in the I-WC–, I-MC–, and I-SC–type biotites of the northern and eastern SNB. In contrast, regional patterns in total Al in amphibole (Fig. 18B) reflect depth of emplacement of the magmas, as deduced elsewhere (Hammarstrom and Zen, 1986). Given the appropriate mineral buffer assemblages, increases in total Al are positively correlated with increases in crystallization pressure (Hammarstrom and Zen, 1986). We note, however, that in Figure 18B, we have included data from all of

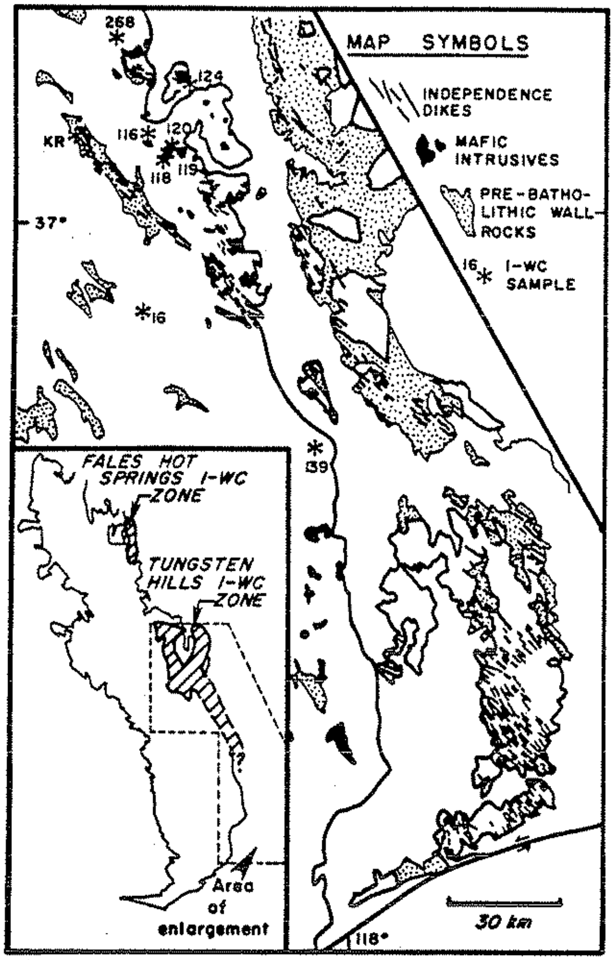


Figure 20. Distribution of I-WC types in eastern Sierra Nevada batholith. Insert shows Fales Hot Springs and Tungsten Hills I-WC zones. Enlargement illustrates spatial association of I-WC types of Tungsten Hills I-WC zone with mafic intrusives and Independence dike swarm of eastern SNB. Base geology from Jennings and others (1977) and Chen and Moore (1979).

Figure 19 illustrates the occurrence of I-SCR plutons in relation to the pendant terranes containing reduced pelitic rocks. It is immediately obvious that a remarkable correlation exists between the locations of the pelitic sedimentary wall-rock terranes and the I-SCR plutons. Equally impressive is the lack of I-SCR plutons and graphite-bearing roof pendants north of approximately latitude 37°30′N. in the SNB and within the regions we have sampled in the SBB and SGB. The close spatial association of I-SCR intrusives with terranes containing reduced pelitic wall rocks strongly suggests that they are genetically related.

I-WC Types of the Eastern Sierra Nevada Batholith

As discussed above, I-WC intrusives may occur in both the western and eastern Sierra Nevada batholith. The presence of I-WC quartz diorites and granodiorites in the eastern Sierra, however, is at variance with the general west-to-east petrologic trend toward more silicic plutons in the eastern portions of the batholith. There is a small region of I-WC magmatism in the northeastern Sierra Nevada batholith and a more extensive I-WC zone in the central-eastern part of the range. These eastern regions where I-WC types may occur are herein referred to as the "Fales Hot Springs" and "Tungsten Hills" I-WC zones (Fig. 20).

Several important geologic and petrologic features correlate with the zones of anomalous I-WC magmatism. First, mafic intrusive rocks occur as isolated bodies along the eastern margin of the batholith in the vicinity of both the Fales Hot Springs and Tungsten Hills I-WC zones (compare with Bateman, 1965; Kistler and Peterman, 1973). In the Tungsten Hills region, the mafic intrusives range in age from Triassic to Late Cretaceous (Fig. 20) (Bateman, 1965; Stern and others, 1981; Frost, 1986). Second, the position of the Tungsten Hills I-WC zone correlates with the northern portion of the Upper Jurassic Independence dike swarm (Moore and Hopson, 1961), a geologic feature which is most probably a manifestation of crustal thinning (Fig. 20) (Chen and Moore, 1979). As discussed in detail in Ague and Brimhall (1988), the spatial association of eastern I-WC types with mafic intrusives and the Independence dike swarm suggests that I-WC magmas intruded a region of anomalously thin or perhaps absent continental crust in the eastern Sierra which may have persisted throughout the Mesozoic.

DISCUSSION AND CONCLUSIONS

We have demonstrated that spatial variations in whole-rock geochemistry and mafic and accessory mineral compositions define both smooth regional-scale gradients and abrupt local-scale discontinuities in the batholiths of California. In the presence of appropriate mineral buffer assemblages, the variations in mineral chemistry indicate differences in critical magmatic intensive variables which in turn provide important constraints upon the geochemical character of the magmatic source components involved in pluton formation and the petrologic evolution of the batholiths. The reasons for these variations and their importance in elucidating processes of batholith development are detailed in Ague and Brimhall (1988), but we summarize the general implications of the regional variations in geochemistry here.

Both $\log(X_F/X_{OH})$ and X_{Mn} in mafic silicates display regional-scale west-to-east increases from I-WC to I-MC and I-SC types, broadly reflecting the incompatible nature of F and Mn. At a more fundamental level, the variation in $\log(X_F/X_{OH})$ illustrates eastward increases in f_{HF}/f_{H_2O} attending magma crystallization and indicates that at least one of the source components of the eastern magmas was more enriched in F relative to H_2O than the source(s) of the western plutons. The regional gradients in whole-rock geochemistry and mineral chemistry imply the involvement of highly differentiated materials with elevated F/H_2O, most probably derived from the continental craton of western North America, in the formation of the eastern I-MC and I-SC intrusives. I-WC quartz diorites and granodiorites also occur in the eastern Sierra Nevada batholith, associated primarily with regions of crustal thinning active at least as far back as Jurassic time. In addition, although high values of X_{Cl} are generally found in the Fe-rich I-SCR silicates owing to the low energy of the Fe-Cl bond in the structure of mafic phases (Mg-Cl avoidance; Munoz, 1984), significant regions of Mg- and Cl-rich ferromagnesian phases occur in the eastern SNB and PRB, which implies the involvement of a Cl-rich source in the generation of these magmas.

In contrast to the regional-scale compositional variations defined by the I-WC, I-MC, and I-SC intrusives, the I-SCR granites generally

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