

# From Jurassic shores to Cretaceous plutons: Geochemical evidence for paleoalteration environments of metavolcanic rocks, eastern California

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## ABSTRACT

Volcanic and plutonic rocks exposed in east-central California record a long history of metasomatism and/or metamorphism within the Mesozoic Cordilleran continental arc. We use whole-rock and mineral elemental compositions, along with standard and cathodoluminescence petrography to characterize alteration histories of Late Triassic to Middle Jurassic metavolcanic rocks in the Ritter Range, White-Inyo Mountains, and Alabama Hills. Although alkali-metasomatism is widespread and pervasive, ratios and abundances of Ce, Th, Tb, and Ta suggest that mafic protoliths from the White-Inyo Mountains were shoshonitic, whereas those from the Ritter Range were calc-alkaline. Alkali exchange apparently modified the compositions of many metavolcanic rocks. Much of this metasomatism may have occurred at low-temperature ( $T$ ) conditions, and attended or shortly postdated deposition of the volcanic protoliths. High  $\delta^{18}\text{O}$  values for K-rich metatuffs from the Ritter Range suggest that the K-metasomatizing fluid was low- $T$  seawater. In contrast, low  $\delta^{18}\text{O}$  values for K-rich metatuffs from the Alabama Hills and Inyo Mountains seem to reflect rock interaction with meteoric water prior to contact metamorphism. Jurassic metatuffs deposited in marine (Ritter Range)

and nonmarine (Alabama Hills, Inyo Mountains) settings display similar degrees of K for Na (or Ca) exchange that were affected by isotopically distinct fluids. Some alkali-metasomatism of Jurassic metavolcanic rocks is related to Cretaceous plutonism. In the Ritter Range and Alabama Hills, these effects are localized around pluton contacts, appear to be more vein related than pervasive, and overprint K-metasomatized assemblages.

## INTRODUCTION

Economic and petrologic concerns offer reasons to study the alteration of arc volcanic rocks. The emplacement of magmas into colder country rocks drives hydrothermal systems in volcanoplutonic arcs. Some of these systems create economic mineralization, such as porphyry base-metal and skarn deposits. Others may metasomatize and metamorphose significant volumes of rock, yet produce only minor amounts of economic mineralization (e.g., Barton et al., 1988, 1991a, 1991b). In long-lived arcs, volcanic rocks may undergo fluid-rock interactions when (or shortly after) they are deposited, or during later thermal and/or hydrothermal events (e.g., Seyfried et al., 1988; Criss and Taylor, 1986; Barton et al., 1991a, 1991b; Hanson et al., 1993; Battles and Barton, 1995).

Because metasomatism changes igneous rock compositions, identifying the alteration histories of metavolcanic rocks may be needed to assess the geochemical characteristics of their protoliths. For example, assessing the alkalinity of

metavolcanic rocks is important because in fresh volcanic rocks this property is used to: (1) classify magma series (e.g., Gill, 1981; Le Maitre et al., 1989; Müller and Groves, 1995), (2) interpret tectonic regimes of eruption or emplacement (e.g., Miller, 1978; Christe and Hannah, 1990), and/or (3) address properties of mantle sources (e.g., Luhr, 1992; Stolper and Newman, 1994). Because abundances of alkali and alkaline-earth elements in volcanic rocks are readily changed under a variety of post-eruptive pressure ( $P$ )- $T$  fluid conditions (e.g., Lipman, 1965; Noble, 1967; Scott, 1971; Hart et al., 1974), identifying alkali-metasomatic effects is a logical prerequisite to determining if metavolcanic rocks had alkaline protoliths.

Geochemically and mineralogically similar styles of alkali-metasomatism of volcanic rocks can occur in different environmental settings. For example, low- $T$  (<200 °C) K-metasomatism of felsic volcanic rocks has been attributed to: (1) density-driven downward flow of brines in playa-lake hydrologic systems (e.g., Chapin and Lindley, 1986; Dunbar et al., 1994; Leising et al., 1995), (2) distal parts of epithermal magmatic and meteoric fluid-flow systems (e.g., Barton et al., 1991a, 1991b), and (3) sea-floor weathering mechanisms (e.g., Munha et al., 1980; Staudigel et al., 1981, 1995; Alt et al., 1986). The variety of fluid sources and settings that produce low- $T$  K-metasomatism in relatively young and otherwise unmetamorphosed volcanic rocks underscores a need to document paleoalteration environments in terranes that

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have more complex thermal and fluid histories. Conversely, determining alteration histories may help to identify paleogeographic and paleotectonic settings of volcanism.

Evidence for low- $T$  alteration may be preserved even if volcanic rocks are affected by later contact metamorphism, a common phenomenon in long-lived arcs (Hanson et al., 1993; Dunn and Valley, 1992; Franklin et al., 1981). Hanson et al. (1993) delineated alteration styles of metavolcanic rocks from the Ritter Range, Sierra Nevada, California, on the basis of whole-rock and mineral major and minor chemical compositions, along with stable isotope data. Although these rocks were contact metamorphosed during Late Cretaceous time by the Sierra Nevada batholith, they preserve geochemical evidence of earlier, lithostratigraphically controlled, pervasive alteration. Some alteration effects were attributed to low- $T$  (<200 °C) reaction between Jurassic volcanic rocks and seawater shortly after deposition, 50 to 100 m.y. before contact metamorphism (Hanson et al., 1993).

This paper documents metasomatism and metamorphism of volcanic rocks from an approximately east to west transect across the central Sierra Nevada segment of the Cordilleran arc, in order to deduce settings of alteration and likely protoliths.

#### GEOLOGY OF THE CENTRAL SIERRA NEVADA SEGMENT OF THE CORDILLERAN ARC

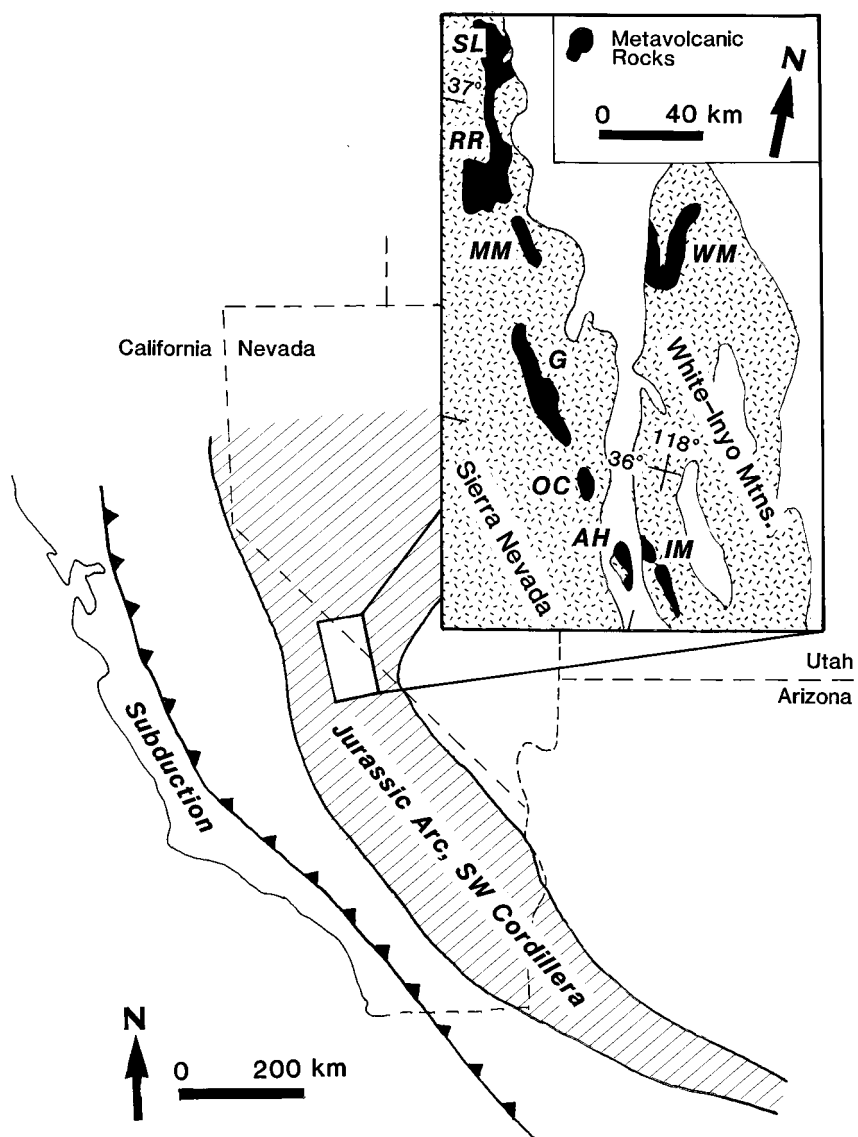
Eastern California is well suited for comparing Jurassic and Cretaceous alteration of metavolcanic rocks because (1) thick sections of approximately contemporaneous Jurassic metavolcanic rocks are preserved there, and each shows a range of protolith compositions; (2) exposures cross both the inferred Early to Middle Jurassic shoreline and the distal part of the Paleozoic continental margin; and (3) the intensity of contact metamorphism, which accompanied either Middle to Late Jurassic, or mid- to Late Cretaceous plutonism, or both, varies among the sections. The Cordilleran arc contains a long and areally extensive record of Mesozoic magmatism (Fig. 1, Saleeby et al., 1992; Saleeby and Busby, 1993; Schweickert and Lahren, 1993). In east-central California, Jurassic metavolcanic and plutonic rocks occur as pendants or screens within the northwest-trending, mostly Cretaceous Sierra Nevada batholith. Prominent localities of metavolcanic rocks are the Saddlebag Lake, Ritter Range, Mount Morrison, Goddard, and Oak Creek pendants (e.g., Saleeby, 1981; Schweickert and Lahren, 1993). East of the Sierra Nevada, Jurassic metavolcanic and plutonic rocks are exposed in the White-Inyo Mountains and the

Alabama Hills (Fig. 1; Dunne and Walker, 1993). Localities in the White Mountains, Ritter Range, Alabama Hills, and southern Inyo Mountains allow us to contrast metavolcanic rocks deposited in marine versus nonmarine settings, and to study protolith geochemical variations across the continental margin, as described in the following.

The depositional environments of volcanic rocks changed during the lifetime of the Cordilleran arc. In Early to Middle Jurassic time, a paleoshoreline separated marine from subaerial depositional settings of volcanic rocks (e.g., Busby-Spera, 1985; 1986; 1988; 1990; Saleeby

et al., 1992). In contrast, volcanism in the Cretaceous arc was entirely subaerial (Fiske and Tobisch, 1978, 1994). Roughly coeval Jurassic volcanic sequences were deposited in a marine setting in the Ritter Range, and subaerially in the Alabama Hills and southern Inyo Mountains. Although the depositional setting of much of the White Mountains sequence is unknown, it appears to be marine at its base (Early Jurassic time?) and is clearly subaerial at its top (Late Jurassic–Early Cretaceous time).

These localities allow us to study igneous geochemical variations across an autochthonous seg-



**Figure 1.** The Jurassic arc in eastern California. Localities of metavolcanic rocks are shown in black in the inset. Abbreviations: SL—Saddlebag Lake; RR—Ritter Range; MM—Mount Morrison; WM—White Mountains; G—Goddard; OC—Oak Creek; AH—Alabama Hills; IM—southern Inyo Mountains.

ment of the Jurassic arc in a transect from the edge of the Paleozoic continental margin to the shelf-slope boundary, and thus presumably from thinner to thicker continental crust. In the Ritter Range and Mount Morrison pendants, Late Triassic and Early Jurassic metavolcanic rocks unconformably overlie metamorphosed Paleozoic sedimentary rocks (Fiske and Tobisch, 1978; cf. Greene and Schweickert, 1995). The latter rocks correlate with strata in the White-Inyo Mountains, which pin the basement of this segment of the Jurassic arc to the North American continent (Stevens and Greene, 1995; cf. Kistler, 1990). A submarine channel sequence has been traced from the westernmost Inyo Mountains into the Mount Morrison pendant (Stevens and Greene, 1995). Right-lateral offset of this channel by cryptic Mesozoic faults is ~65 km (Kistler, 1990; Stevens and Greene, 1995).

### Local Geology of Jurassic Volcanic Sections

In the White Mountains, a lower, predominantly volcanic sequence is overlain by an upper, predominantly epiclastic sequence. (Fig. 2; Hanson et al., 1987). The oldest part of the section consists of interbedded marble and felsic metavolcanic rocks that compose a small pendant within the 165 Ma Barcroft Granodiorite (Gillespie, 1979; Stern et al., 1981). Marble layers as thick as 50 m were likely deposited in a marine environment (Hanson, 1986; cf. Fiske and Tobisch, 1978). An approximately 3-km-thick package of metamorphosed ash-flow tuffs, hypabyssal intrusions, and mafic volcanic flows is exposed along the range crest. Its base is locally intruded by the Barcroft Granodiorite, but at least part of this package is younger than 165 Ma: an ash-flow tuff within it yielded a zircon

U-Pb age of 154 Ma, and a hypabyssal intrusion at White Mountain Peak has an age of 137 Ma (Fig. 2; Hanson et al., 1987). The depositional setting of these rocks is unknown, owing to a lack of sedimentary intercalations. Most of the overlying sequence consists of metamorphosed alluvial fan and fluvial deposits exposed in down-faulted blocks along the crest and western side of the range (Fates, 1985; Hanson et al., 1987). Lithosomes within this interval include conglomerate, volcanic rocks, volcanogenic sandstone, siltstone, and a few tuffs. The White Mountains section was intruded by a Late Cretaceous batholith beginning ca. 100 Ma (Stern et al., 1981; Hanson et al., 1987; McKee and Conrad, 1996).

In the Ritter Range, a faulted section consists of Late Triassic to Late Jurassic or Early Cretaceous metavolcanic rocks, interlayered with more than

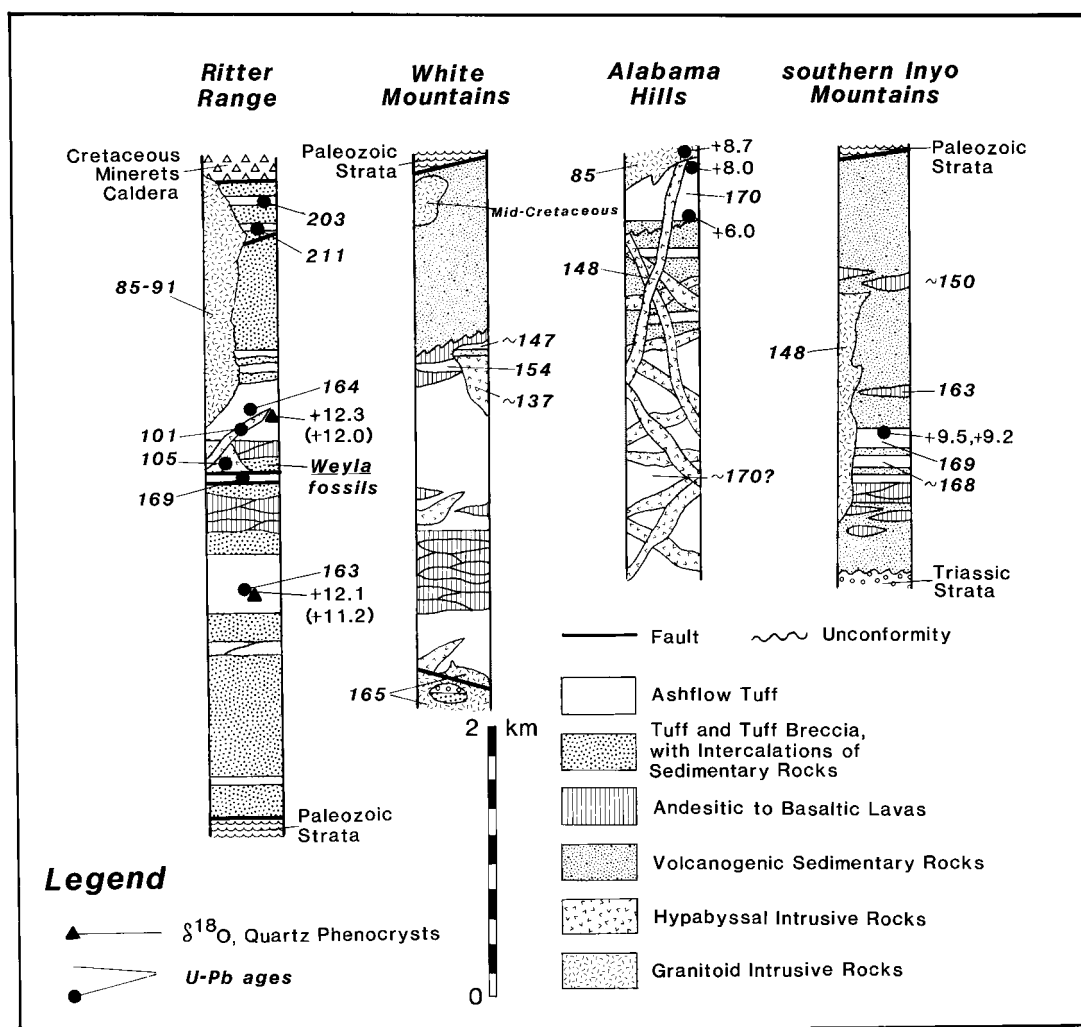


Figure 2. Pseudostratigraphic columns for the Ritter Range, White Mountains, southern Inyo Mountains, and Alabama Hills. New U-Pb radiometric ages of zircons for Ritter Range units (J. Saleeby, E. Warner Holt, O. Tobisch, R. Fiske, unpublished data) are indicated by dots. Both these and other zircon ages are noted in bold italics. New values of  $\delta^{18}\text{O}$  for samples from the Ritter Range, Alabama Hills, and southern Inyo Mountains are indicated by triangles; published data for Ritter Range units (Hanson et al., 1993) are shown in parentheses.

40 thin but laterally continuous beds of calc-silicate rocks and marble (Fig. 2; Fiske and Tobisch, 1978; Hanson et al., 1993). Marine fossils have been found in marble layers near the geographic center of and western edge of the pendant (Reinhardt et al., 1959; Fiske and Tobisch, 1978). The former locality contains the pelecypod *Weyla*. In western North America, *Weyla* is found in Sinemurian to possibly middle Toarcian strata (Damborenea and Manceñido, 1979); its presence indicates an Early Jurassic age (202 to 186 Ma, Gradstein et al., 1995). The metavolcanic rocks are of mafic to felsic compositions and consist of lava flows, ash-flow tuffs, tuff breccias, bedded tuffs, and lapilli tuffs. The section is cut by five granitic plutons and minor dikes, all of which range from 100 to 86 Ma in age (Bateman and Nokleberg, 1978; Bateman and Chappell, 1979; Stern et al., 1981; Bateman, 1983, 1988, 1992).

In the southern Inyo Mountains, three intervals of metavolcanic and metavolcaniclastic rocks make up a 3.1-km-thick section (Fig. 2; Dunne and Walker, 1993). The lowest interval consists of basal limestone-clast conglomerate, overlain by volcanogenic conglomerate, sandstone, and siltstone, mafic lava flows, and minor tuff. The middle interval is composed primarily of felsic ash-flow tuff and intermediate to felsic lava flows, and minor volcanic breccia, conglomerate, and sandstone. Most of the upper interval consists of sandstone and siltstone and less abundant conglomerate. All three intervals contain abundant sedimentary structures (e.g., raindrop impressions, mud-crack casts) that indicate deposition in flood plain, alluvial fan, and lacustrine environments (Garvey et al., 1993). The upper interval contains metavolcanic rocks that have a minimum age of about 150 Ma; it is intruded by dikes of inferred Late Jurassic and earliest Cretaceous ages. Minimum ages for the metavolcanic rocks of the middle interval are 168–169 Ma (Dunne and Walker, 1993).

In the Alabama Hills, metavolcanic strata are exposed in two intervals (Fig. 2; Dunne and Walker, 1993). The 2-km-thick lower interval consists of felsic ash-flow tuff overlying volcanogenic sedimentary rocks, both of which are cut by numerous (~60 vol %) hypabyssal pods, dikes, and sills. A 0 to 10-m-thick unit of shale, quartz arenite, and conglomerate separates this interval from an overlying, >450-m-thick interval of felsic ash-flow tuff. Both intervals are intruded by the 85 Ma Alabama Hills Granite, and by a 148 Ma dike of the Independence dike swarm (Chen and Moore, 1979). The tuff of the upper interval yielded a minimum age of 170 Ma, similar to a provisionally determined age for the lower interval (Fig. 2; Dunne and Walker, 1993; unpublished data).

## RESULTS

### Contact Metamorphism of Volcanic Rocks

Metavolcanic rocks of the Ritter Range and Alabama Hills were contact metamorphosed at hornblende-hornfels to transitional pyroxene-hornfels facies conditions, whereas those of the White and southern Inyo Mountains were metamorphosed at albite-epidote-hornfels facies conditions (Fig. 3). In all localities, felsic rocks contain less amphibole, epidote, biotite, and apatite, and more muscovite, quartz, K-feldspar, zircon, and tourmaline than mafic rocks (Fig. 3). These variations reflect protolith compositions.

Most of these metavolcanic rocks lack mineral assemblages that allow precise estimates of contact metamorphic *P-T* conditions. However,

in both the Ritter Range (Hanson et al., 1993); and the Alabama Hills, the presence of andalusite + K-feldspar in meta-ash-flow tuff units within 20 to 200 m of pluton contacts indicates a maximum metamorphic *T* = ~610 °C, at a maximum *P* = ~2 kbar (Chatterjee and Johannes, 1974). In the latter area, a few blocks of meta-ash-flow tuff in a complex mixed-rock zone are immersed in the Alabama Hills Granite. These blocks contain sillimanite + K-feldspar, an assemblage suggesting *T* > ~610 °C in the border zone. In both the Ritter Range and Alabama Hills, metamorphic plagioclase ranges from An<sub>20-40</sub>, and K-feldspar (Or<sub>>95</sub>) has pseudomorphed alkali-feldspar phenocrysts.

Most metavolcanic rocks in the White Mountains were probably metamorphosed in the biotite zone of the albite-epidote-hornfels facies, and

Mineral Assemblages of Metavolcanic Rocks												
Felsic Protoliths							Intermediate to Mafic Protoliths					
	RR n=18	WM n=5	IM n=11	AH n=8			RR n=7	WM n=7	IM n=4			
Qtz												
Ksp												
Plg												
Epi	.....											
Mus	-----											
Amp	-----											
Bio	-----											
Chl	.....											
Als												
Cc	.....											
Ht	-----											
Mt	-----											
Zr		.....										
Apt		.....										
Sph	.....											
Tou	-----											

**Key to lines:** Solid >80%, Dashed 80-50%, Dotted 49-20%, Blank <20% of samples

**Abbreviations:** RR, Ritter Range; WM, White Mtns.; IM, Inyo Mtns.; AH, Alabama Hills; Qtz, quartz; Ksp, K-feldspar; Plg, plagioclase; Epi, epidote; Mus, muscovite; Amp, amphibole; Bio, biotite; Chl, chlorite; Als, andalusite or sillimanite; Cc, calcite; Ht, hematite; Mt, magnetite; Zr, zircon; Apt, apatite; Sph, titanite; Tou, tourmaline.

**Note:** No mafic to intermediate protolith types from the Alabama Hills were analyzed; see text

**Figure 3.** The mineral assemblages of analyzed metavolcanic rocks, grouped by field and whole-rock chemical constraints on likely protoliths (Tables 1 and 2; retrograde minerals were ignored). Because only three samples from the Alabama Hills were analyzed, mineral assemblages were combined with data for five additional samples from this locality (for which chemical data are not reported).

hornblende-hornfels facies assemblages are restricted to ~50 m of contacts with the Barcroft Granodiorite. Albite-epidote-hornfels facies metamorphic conditions are evidenced by: (1) the presence of albite in most mineral assemblages rocks (although a few analyses of plagioclase from samples collected within ~50 m of the Barcroft Granodiorite contact display up to  $An_{15}$ ; Hanson, 1986); (2) a lack of metamorphic hornblende, again except within ~50 m of the Barcroft Granodiorite contact; and (3) the presence of biotite in most samples of appropriate bulk composition (Fig. 3).

Instead of biotite, metavolcanic rocks of the southern Inyo Mountains contain muscovite and chlorite, which coexist with albite ( $Ab_{95}$ ; Fig. 3). Some ash-flow tuff units preserve relict igneous alkali feldspar compositions of  $Or_{45-80}$  in grains that mostly yield  $Or_{95}$ . A meta-andesitic lava contains relict igneous alkali feldspar remnants in  $Or_{95}$  K-feldspar, as well as relict phenocrysts that locally preserve  $An_{45}$  plagioclase. The latter phenocrysts are partially replaced by albite ( $Ab_{95}$ ) and K-feldspar ( $Or_{95}$ ).

The age of contact metamorphism is well constrained in the Ritter Range, inferred in the Alabama Hills, and somewhat speculative in the White-Inyo Mountains. Sharp et al. (1993) reported an  $^{40}Ar/^{39}Ar$  age of 85 Ma for metamorphic hornblende from a mafic metavolcanic rock in the Ritter Range pendant. This age is only slightly less than the crystallization ages of the youngest granitoid rocks that cut the pendant (e.g., Bateman, 1992; also see below). We interpret the 85 Ma date to approximate the age of contact metamorphism of the pendant. Despite the high- $T$  metamorphic assemblages of most Ritter Range metavolcanic rocks, classic hornfels textures are mostly restricted to within 50 to 200 m of pluton contacts (Sorensen et al., 1993). Similar relationships of texture to pluton contacts are seen in the Alabama Hills. There, coarsening of the meta-ash-flow tuff of the upper interval (Dunne and Walker, 1993) appears within ~20 m of its contact with the 85 Ma Alabama Hills Granite. This texture and the absence of older granitoid plutons suggest Cretaceous contact metamorphism.

In the White Mountains, metamorphic hornblende is found in metavolcanic rocks only within ~50 m of the 165 Ma Barcroft Granodiorite. Its presence is the most reliable indicator of Jurassic contact metamorphism. However, much of the metavolcanic section is younger than 165 Ma (Hanson et al., 1987), and thus deposited after Barcroft Granodiorite emplacement. Such rocks were likely metamorphosed by the 90 to 100-Ma Pellisier Flats Granite. Albitization of some of the Jurassic section is related to contacts with this pluton (Anderson, 1937; Crowder and Ross, 1972).

The metavolcanic rocks of the southern Inyo Mountains also may have been metamorphosed during Jurassic and/or Cretaceous plutonism. However, Inyo Mountains metavolcanic rocks are so feebly recrystallized that even if they were heated by two episodes of plutonism, the combined thermal input of these events left little expression in their mineral assemblages and textures.

### Geochemistry of Metavolcanic Rocks

Some chemical features of the metavolcanic rocks are evidently of igneous origin, whereas others attest to metasomatic additions or losses (Tables 1 and 2; the Appendix describes sampling and analytical methods). Ranges and covariations of  $SiO_2$  with  $TiO_2$ ,  $Al_2O_3$ , and  $MgO$  resemble those for calc-alkaline, basaltic andesite to rhyolite suites from continental arcs (Fig. 4). However,  $CaO$ ,  $Na_2O$ , and  $K_2O$  contents of the metavolcanic suite are scattered compared to data for calc-alkaline, alkaline, and peralkaline arc rocks (Fig. 4).

The metavolcanic rocks resemble young, calc-alkaline volcanic rocks from continental arcs in their contents of many minor and trace elements (Figs. 5 and 6). Although some rocks have K, Rb, Ba and Th values similar to those of calc-alkaline volcanic rocks, others are much richer in these elements and poorer in Sr (or vice versa) than the latter suite (Fig. 5). Rocks from the Ritter Range generally show less enriched light rare earth elements (LREE) patterns than the other suites of metavolcanic rocks. Most rocks from the Ritter Range and White Mountains display slight negative Eu anomalies, whereas many rocks from the Inyo Mountains and Alabama Hills show slight positive Eu anomalies (Fig. 6).

### Oxygen Isotope Systematics of Metatuffs

Quartz and K-feldspar phenocrysts from meta-ash-flow tuffs exposed in the Alabama Hills, southern Inyo Mountains, and Ritter Range were separated and analyzed for  $\delta^{18}O$  values (Table 3; Appendix). Two 164 Ma meta-ash-flow tuff units of the Ritter Range were each sampled >200 m from contacts with Cretaceous plutons. The average  $\delta^{18}O$  values for K-feldspar (+10.0‰ to +10.2‰) are fractionated by 2.1‰ with respect to quartz (+12.1‰ to +12.3‰).

The 170 Ma meta-ash-flow tuff of the Alabama Hills was sampled near its highest exposed stratigraphic level (sample AH95-06A) and near its base (sample AH95-02; Fig. 2; Table 3). Because the unit is cut out by the 85 Ma Alabama Hills Granite, sample AH95-06A was collected ~10 m and AH95-02 ~450 m from the pluton contact. Quartz and K-feldspar from AH95-06A yield  $\delta^{18}O$  values of 8.0‰ and

5.3‰, respectively; quartz and K-feldspar from AH95-02 display values of 6.0‰ and 3.4‰. Mineral fractionations are 2.7‰ and 2.6‰. Quartz (8.7‰), plagioclase (7.2‰), and alkali-feldspar (7.8‰) separates from the deuterically altered Alabama Hills Granite resemble  $\delta^{18}O$  values for the Sierra Nevada batholith (Table 3; cf. Taylor, 1986, p. 297).

The ca. 169 Ma meta-ash-flow tuff from the Inyo Mountains was sampled ~5 km away from pluton contacts. Both samples contain the low- $T$  metamorphic mineral assemblage chlorite + muscovite. Quartz and alkali-feldspar separates from sample IM95-09 yield typical igneous  $\delta^{18}O$  values (9.5‰ and 8.8‰, respectively; Table 3). Quartz from IM95-07A also shows a typical igneous value (9.2‰), but the  $\delta^{18}O$  for alkali feldspar (4.0‰) is lower than most igneous values (cf. Taylor and Sheppard, 1986). Inyo Mountains mineral pairs show fractionations of 0.7‰ for sample IM95-09, and 5.2‰ for IM95-07A. The fine-grained matrix of sample IM95-07A yields a  $\delta^{18}O$  value of 5.1‰, similar to its alkali-feldspar phenocrysts. The matrix of IM95-09, which has a  $\delta^{18}O$  value of 9.8‰, resembles the sample's quartz phenocrysts.

### Cathodoluminescence Petrography of Metavolcanic Rocks

Many minerals luminesce when bombarded by cathode rays, and quartz and feldspar minerals in hydrothermally altered and/or metamorphosed volcanic rocks commonly display cathodoluminescence (CL; e.g., Marshall, 1988). CL colors generally result from different trace element activators. For example, small amounts of  $Fe^{3+}$  produce red CL in albite,  $Fe^{2+}$  and  $Mn^{2+}$  yield yellow and green CL in more calcic plagioclase, and trace  $Ti^{4+}$  (or intrinsic CL intensified by this activator) causes blue CL in K-feldspar (Marshall, 1988, and references cited). The intensities and hues of CL in Figure 7 cannot be compared among samples, owing to the vicissitudes of photographic processing. Nevertheless, information about alteration and metamorphism can be gleaned from each image.

Except for the Inyo Mountains, most of the original igneous phenocrysts in the metavolcanic rocks have been replaced by other minerals. Together with scanning electron microscope (SEM) imagery and microprobe analyses, CL petrography sheds some light on the nature of these phenocryst replacements, along with the distribution and textural relations of albite, calcic plagioclase, and K-feldspar in rock matrices. In samples from the southern Inyo and White Mountains (Fig. 7, A and B) extremely fine grained, blue-luminescent K-feldspar has replaced delicate matrix textures that resemble those of igneous ash or glass. In

## PALEOALTERATION ENVIRONMENTS OF METAVOLCANIC ROCKS

TABLE 1. WHOLE-ROCK ANALYSES OF MAJOR AND MINOR ELEMENTS, IN WT% OXIDES

Ritter Range																	
	RR90-09A	RR90-09B	RR90-09C	HT	OH	F71-12	F71-13	F71-14	F71-15	F71-42	F71-43	F71-44	F71-46	F71-47	F71-48	F71-51	F71-68
SiO <sub>2</sub>	70.7	71.0	69.6	72.0	72.4	66.4	54.8	71.3	69.2	58.0	60.2	72.0	76.3	70.0	72.0	65.7	70.7
Al <sub>2</sub> O <sub>3</sub>	14.3	13.5	14.6	14.3	13.4	16.0	18.9	14.3	14.8	20.0	18.2	14.1	13.0	14.5	13.8	15.0	14.6
Fe <sub>2</sub> O <sub>3</sub>	1.8	1.2	0.8	2.6	1.3	3.6	7.1	2.2	2.3	5.7	5.7	2.3	1.1	2.3	1.9	4.8	3.2
FeO	0.4	0.8	0.5	1.0	1.6	0.3	1.4	1.0	0.7	0.8	0.6	0.2	0.2	0.3	0.2	0.2	0.3
MgO	0.3	0.6	0.1	1.6	0.4	1.7	3.3	0.3	0.5	1.8	1.7	0.9	0.2	0.3	0.1	1.8	0.2
CaO	1.2	1.0	0.7	1.2	1.1	1.8	6.0	0.5	1.2	0.8	2.7	2.3	0.0	0.9	1.0	3.9	2.4
Na <sub>2</sub> O	0.9	0.3	1.8	1.7	3.7	6.7	4.5	5.4	8.0	5.6	7.7	2.8	1.7	4.1	3.7	3.2	3.2
K <sub>2</sub> O	9.0	7.7	8.9	3.5	4.4	2.6	2.4	3.2	0.3	5.5	1.4	4.5	6.0	5.5	6.6	3.0	5.0
TiO <sub>2</sub>	0.3	0.3	0.2	0.3	0.1	0.4	0.7	0.4	0.6	0.7	0.6	0.2	0.2	0.3	0.2	0.7	0.4
P <sub>2</sub> O <sub>5</sub>	0.09	0.10	0.04	0.11	0.07	0.07	0.26	0.14	0.26	0.31	0.27	0.07	0.03	0.12	0.10	0.24	0.21
MnO	0.04	0.07	0.04	0.12	0.12	0.10	0.14	0.08	0.08	0.07	0.14	0.09	0.03	0.06	0.03	0.14	0.06
Total	99.03	96.57	97.28	98.43	98.59	99.67	99.50	98.82	97.94	99.28	99.21	99.46	98.76	98.38	99.63	98.68	100.27
Ritter Range (continued)																	
	F71-69	F71-70	F71-73	F71-75	F73-01	F73-04	F73-05	F73-07	Northern White Mountains								
SiO <sub>2</sub>	51.6	50.4	61.0	51.0	76.0	69.0	66.6	70.7	82784-27	72984-3	82484-18	WMP-2	82184-11B	71683-10	7484-17		
Al <sub>2</sub> O <sub>3</sub>	16.8	18.0	17.3	19.9	12.8	14.7	16.2	13.8	65.6	58.9	68.1	69.2	68.3	76.8	49.7		
Fe <sub>2</sub> O <sub>3</sub>	7.7	6.1	2.7	4.6	1.9	1.0	1.1	0.4	16.8	22.6	14.8	14.1	15.9	13.0	18.2		
FeO	2.2	4.2	4.2	6.4	0.6	2.6	3.0	3.5	3.2	3.7	2.7	3.6	2.6	0.9	9.3		
MgO	5.2	4.4	2.0	4.2	1.7	1.4	1.6	0.5	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.		
CaO	7.5	6.9	4.1	2.6	2.1	3.0	1.5	3.0	0.7	0.9	0.3	0.9	0.5	0.4	6.5		
Na <sub>2</sub> O	3.2	3.4	4.1	6.5	1.7	1.5	4.9	2.1	0.9	0.4	0.5	1.3	0.3	0.2	5.6		
K <sub>2</sub> O	3.5	3.4	3.4	1.4	2.4	5.1	3.5	3.2	2.2	3.4	2.3	5.5	3.9	4.7	5.2		
TiO <sub>2</sub>	0.9	1.0	0.8	1.0	0.2	0.3	0.4	0.3	9.8	9.2	8.9	4.2	6.4	2.2	2.7		
P <sub>2</sub> O <sub>5</sub>	0.37	0.36	0.30	0.36	0.21	0.14	0.13	0.12	0.6	0.5	0.5	0.6	0.5	0.2	1.0		
MnO	0.20	0.18	0.12	0.15	0.33	0.14	0.14	0.11	0.11	0.05	0.14	0.23	0.10	0.02	0.43		
Total	99.17	98.34	100.02	98.11	99.94	98.88	99.07	97.73	0.07	0.10	0.02	0.05	0.05	0.01	0.07		
Northern White Mountains (continued)																	
	81784-4	7484-21	81283-8	82583-11	71483-25	Alabama Hills			Southern Inyo Mountains								
SiO <sub>2</sub>	56.6	51.8	53.9	57.5	58.6	SI-87-22	SI-87-23b	SI-87-23a	SI-87-6X	SI-87-19b	SI-87-19c	SI-87-11					
Al <sub>2</sub> O <sub>3</sub>	18.0	17.5	18.3	16.5	17.7	68.5	73.5	74.0	52.4	55.7	57.5	57.6					
Fe <sub>2</sub> O <sub>3</sub>	7.5	8.3	10.4	7.9	6.8	14.8	13.6	13.3	16.9	20.0	19.0	16.4					
FeO	N.D.	N.D.	N.D.	N.D.	N.D.	3.1	1.7	1.8	7.7	6.4	6.3	6.6					
MgO	2.8	6.4	4.9	3.0	3.2	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.					
CaO	2.7	5.1	1.3	2.9	2.9	2.5	0.3	0.3	0.9	0.8	0.5	1.5					
Na <sub>2</sub> O	5.6	5.8	5.2	6.4	5.1	1.6	1.0	1.1	5.9	1.9	2.3	3.4					
K <sub>2</sub> O	3.2	2.7	4.0	2.6	3.6	1.8	3.0	3.0	5.0	4.8	3.1	6.3					
TiO <sub>2</sub>	1.0	0.8	1.2	0.9	0.9	4.3	5.4	5.6	3.4	6.1	7.8	3.1					
P <sub>2</sub> O <sub>5</sub>	0.37	0.38	0.46	0.40	0.30	0.4	0.2	0.2	1.0	0.5	0.7	0.8					
MnO	0.08	0.07	0.05	0.12	0.11	0.14	0.08	0.07	0.43	0.47	0.45	0.35					
Total	97.85	98.85	99.71	98.22	99.21	0.12	0.09	0.07	0.16	0.12	0.05	0.16					
Southern Inyo Mountains (continued)																	
	SI-85-6	SI-87-7	SI-87-3bx	SI-D20-9	SI-87-3x	SI-87-21a	SI-87-21b	SI-87-20a	SI-87-6	IM95-07A	IM95-09						
SiO <sub>2</sub>	66.5	68.5	68.8	69.0	69.6	71.4	71.6	71.9	73.6	73.1	73.5						
Al <sub>2</sub> O <sub>3</sub>	16.8	14.9	14.1	15.7	14.4	13.9	14.0	14.5	13.3	13.2	13.3						
Fe <sub>2</sub> O <sub>3</sub>	3.2	2.1	2.0	2.9	2.1	2.0	2.1	1.2	1.9	1.8	1.6						
FeO	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0.1	0.3						
MgO	0.2	0.1	0.1	0.3	0.1	0.2	0.3	0.1	0.1	0.2	0.2						
CaO	0.2	0.8	1.2	0.5	0.7	0.5	0.5	0.9	0.1	0.6	0.8						
Na <sub>2</sub> O	4.9	3.3	2.0	4.2	1.9	2.7	2.5	3.8	1.6	1.8	2.0						
K <sub>2</sub> O	6.3	7.8	7.9	5.6	8.3	6.4	6.4	6.1	7.8	6.5	5.4						
TiO <sub>2</sub>	0.6	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.3	0.3	0.2						
P <sub>2</sub> O <sub>5</sub>	0.12	0.06	0.06	0.09	0.06	0.09	0.09	0.04	0.07	0.09	0.08						
MnO	0.01	0.03	0.07	0.03	0.06	0.05	0.06	0.03	0.01	0.08	0.02						
Total	98.83	97.99	96.63	98.72	97.62	97.54	97.85	98.77	98.78	97.78	97.40						

Note: N.D. = not determined.

contrast, matrices of tuffs from the Ritter Range and Alabama Hills (Fig. 7, C and D) consist of coarser-grained mosaics of K-feldspar, nonluminescent (black) quartz, and yellow-green luminescent metamorphic plagioclase.

Pseudomorphs of alkali-feldspar phenocrysts show two main types of luminescence. Blue-

luminescent K-feldspar (Or<sub>95</sub>) has replaced alkali-feldspar phenocrysts in samples from the White Mountains, Ritter Range, and Alabama Hills (Fig. 7, B–D). Brownish-purple-luminescent K-feldspar has replaced phenocrysts and crystal fragments of alkali feldspar in the Inyo Mountains sample (Fig. 7A), and also appears as patches

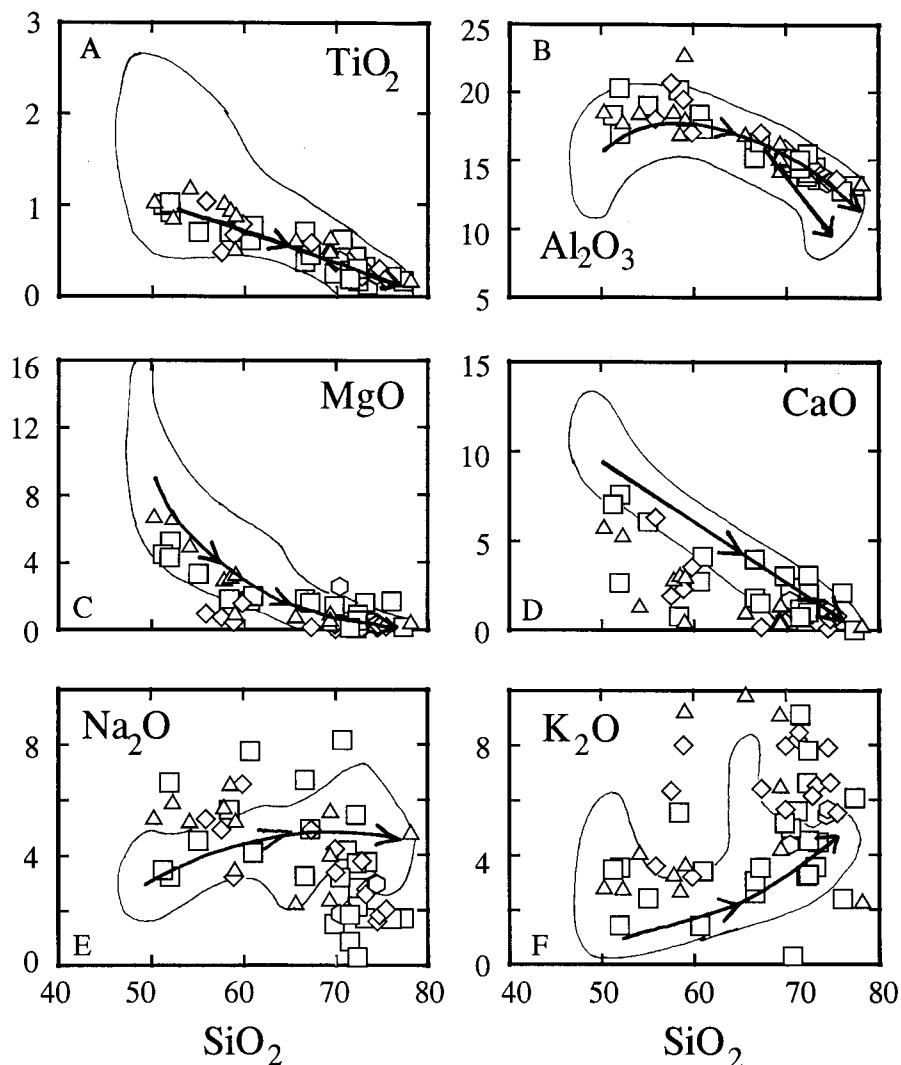
within the blue-luminescent K-feldspar replacements of phenocrysts in the Ritter Range sample (Fig. 7C).

The luminescence of former plagioclase phenocrysts varies among samples. In the Inyo Mountains sample (Fig. 7A) plagioclase phenocrysts consist of relict igneous plagioclase (green specks),

TABLE 2. WHOLE-ROCK ANALYSES OF TRACE ELEMENTS

	Ba	Co	Cr	Cs	Hf	Rb	Sr	Sb	Ta	Th	U	Zn	Zr	Sc	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Y	Nb	
Ritter Range																									
RR90-09A	2534	1.9	<1.7	7.3	4.2	283	90	4.9	1.05	16.3	2.9	10	84	3.9	39.4	67.8	22.4	4.2	0.85	0.45	1.71	0.24	19	N.D.	N.D.
RR90-09B	929	1.4	<1.9	11.5	4.0	353	40	1.0	1.1	17.6	2.8	14	105	4.1	33.4	63.3	18.7	3.3	0.62	0.38	1.50	0.22	N.D.	N.D.	N.D.
RR90-09C	2934	0.9	<1.3	5.9	4.3	261	156	6.3	1.2	15.7	3.2	8	55	3.2	45.8	81.5	27.0	4.8	0.82	0.44	2.20	0.32	N.D.	N.D.	N.D.
HT	1380	7.2	47.3	26.6	3.7	171	206	1.5	0.98	14.0	1.5	37	140	5.0	36	61	23	3.9	0.82	0.33	2.10	0.31	N.D.	N.D.	N.D.
OH	1060	3.7	84.4	3.5	3.2	129	94	1.1	0.97	11.7	2.9	47	97	4.5	32	57	22	4.4	0.43	0.54	2.10	0.31	N.D.	N.D.	N.D.
F71-12	674	8.5	12.5	4.5	6.1	99	239	5.5	0.84	15.3	2.3	84	127	9.1	24	43	17	3.2	0.63	0.30	1.60	0.27	N.D.	N.D.	N.D.
F71-13	1080	27.4	11.0	9.4	2.1	66	601	1.4	0.39	2.9	1.4	105	81	17.2	16	29	15	3.3	1.02	0.43	1.70	0.25	N.D.	N.D.	N.D.
F71-14	859	1.9	8.1	2.7	6.0	80	99	2.9	1.39	10.8	4.0	127	255	8.9	34	62	31	6.2	1.36	1.01	3.90	0.57	N.D.	N.D.	N.D.
F71-15	147	3.2	4.9	0.9	5.5	7	170	2.1	1.18	9.7	5.0	33	230	10.5	36	72	34	7.2	1.50	1.04	3.60	0.52	N.D.	N.D.	N.D.
F71-42	1060	13.5	3.4	8.2	3.5	204	231	4.3	0.52	4.1	2.8	135	136	13.6	33	61	31	6.6	1.56	0.96	2.60	0.37	N.D.	N.D.	N.D.
F71-43	497	13.1	5.9	4.5	3.1	63	451	0.8	0.46	3.7	1.3	101	121	13.9	21	38	20	4.1	1.17	0.56	2.10	0.32	N.D.	N.D.	N.D.
F71-44	1350	2.9	14.5	7.6	2.8	162	161	0.9	0.69	8.9	2.4	51	108	3.4	31	52	18	3.1	0.61	0.32	1.50	0.23	N.D.	N.D.	N.D.
F71-46	924	0.9	6.0	5.3	3.5	210	60	0.7	1.40	22.7	2.3	32	93	2.4	32	51	21	3.6	0.44	0.37	2.00	0.33	N.D.	N.D.	N.D.
F71-47	1770	2.9	5.0	3.3	5.2	171	117	2.1	1.10	15.8	2.5	23	175	3.8	44	74	25	4.1	0.87	0.54	2.10	0.30	N.D.	N.D.	N.D.
F71-48	1800	1.7	5.4	2.2	4.4	182	108	1.7	1.21	17.0	2.2	10	158	3.4	38	64	23	3.9	0.69	0.45	1.80	0.28	N.D.	N.D.	N.D.
F71-51	1270	5.8	9.5	24.7	4.5	136	596	3.9	0.81	7.4	4.0	92	177	18.3	34	65	32	7.8	1.66	1.06	3.80	0.57	N.D.	N.D.	N.D.
F71-68	1240	2.5	11.5	2.8	2.9	136	333	6.2	0.63	8.0	2.7	12	131	7.2	27	46	19	3.7	0.94	0.43	1.40	0.20	N.D.	N.D.	N.D.
F71-69	812	29.8	38.9	8.2	2.3	90	685	1.7	0.33	3.9	1.6	105	75	26.1	23	40	22	5.0	1.38	0.63	1.90	0.36	N.D.	N.D.	N.D.
F71-70	738	27.1	10.7	15.7	2.2	121	596	1.5	0.20	3.2	1.6	74	79	27.7	19	35	23	5.2	1.53	0.78	2.30	0.32	N.D.	N.D.	N.D.
F71-73	1620	11.4	10.6	20.8	3.4	149	364	1.3	0.84	9.3	2.4	56	140	16.0	31	51	24	5.0	1.18	0.65	2.60	0.49	N.D.	N.D.	N.D.
F71-75	1210	30.7	20.7	5.3	3.2	34	268	1.0	0.70	7.1	1.9	113	115	29.8	26	52	28	6.0	1.34	0.87	2.70	0.53	N.D.	N.D.	N.D.
F73-01	1660	4.2	40.7	23.5	2.2	128	268	4.9	0.98	11.3	2.0	44	81	4.7	27	49	17	3.4	0.63	0.41	2.20	0.33	N.D.	N.D.	N.D.
F73-04	1590	5.7	64.0	21.2	2.7	221	155	0.5	0.62	8.7	2.4	27	108	4.8	29	49	19	3.4	0.72	0.34	1.50	0.24	N.D.	N.D.	N.D.
F73-05	2180	5.3	34.8	14.9	5.1	123	267	0.7	0.98	12.1	3.2	59	109	7.8	30	50	19	3.6	0.80	0.20	1.90	0.31	N.D.	N.D.	N.D.
F73-07	1210	4.3	122.0	11.2	2.9	125	155	1.5	0.95	12.8	3.9	44	96	3.8	33	52	20.0	3.6	0.77	0.39	1.70	0.27	N.D.	N.D.	N.D.
White Mountains																									
82784-27	3130	3.9	1.0	N.D.	7.4	216	174	N.D.	1.57	16.4	4.2	38	299	N.D.	41.5	78	32.0	6.2	1.41	0.70	2.67	0.41	N.D.	N.D.	N.D.
72984-3	1460	1.9	4.3	N.D.	13.3	293	126	N.D.	3.30	31.6	6.6	27	542	N.D.	78.4	144	48.9	9.9	1.32	1.08	5.80	0.82	N.D.	N.D.	N.D.
82484-18	2110	2.6	2.2	N.D.	6.6	164	196	N.D.	1.46	15.6	3.5	14	309	N.D.	43.5	82	31.0	6.2	1.23	0.69	2.85	0.41	N.D.	N.D.	N.D.
WMP-2	1011	7.6	9.1	N.D.	7.4	113	217	N.D.	1.61	14.8	2.7	36	306	N.D.	45.4	86	30.8	6.4	1.17	0.69	2.80	0.43	N.D.	N.D.	N.D.
82184-11B	1070	1.7	0.5	N.D.	8.1	170	126	N.D.	1.90	17.4	4.2	36	287	N.D.	57.5	104	41.0	7.4	1.13	0.78	3.39	0.50	N.D.	N.D.	N.D.
71683-10	497	0.4	0.8	N.D.	6.6	82	433	N.D.	2.03	20.0	3.1	14	229	N.D.	48.5	93	28.3	5.5	0.57	0.61	3.29	0.46	N.D.	N.D.	N.D.
7484-17	437	19.9	33.8	N.D.	3.3	154	523	N.D.	0.51	3.8	1.2	37	150	N.D.	26.3	52	25.7	5.9	1.36	0.71	1.95	0.32	N.D.	N.D.	N.D.
81784-4	1430	19.2	58.6	N.D.	4.8	90	420	N.D.	0.85	7.4	1.6	47	237	N.D.	35.8	71	28.0	5.7	1.36	0.64	2.31	0.36	N.D.	N.D.	N.D.
7484-21	393	15.1	50.6	N.D.	3.2	220	590	N.D.	0.52	5.0	2.1	31	119	N.D.	32.7	55	21.0	4.4	1.03	0.50	1.60	0.26	N.D.	N.D.	N.D.
81283-8	1870	25.9	53.6	N.D.	5.6	103	254	N.D.	1.01	6.6	1.6	69	260	N.D.	53.9	103	42.0	8.6	2.05	0.92	2.74	0.43	N.D.	N.D.	N.D.
82583-11	1780	9.4	52.2	N.D.	4.5	76	235	N.D.	0.84	7.1	1.8	79	222	N.D.	29.8	66	27.6	4.5	1.10	0.47	1.90	0.29	N.D.	N.D.	N.D.
71483-25	1520	18.9	67.5	N.D.	4.7	98	500	N.D.	0.81	9.2	1.9	56	150	N.D.	36.7	67	27.4	5.5	1.26	0.61	2.05	0.31	N.D.	N.D.	N.D.
Inyo Mountains																									
SI-87-6X	64	N.D.	N.D.	N.D.	2.0	120	420	N.D.	2.00	6.2	2.8	N.D.	130	N.D.	35.6	71	32.3	5.3	2.50	0.90	1.90	0.41	20	16	
SI-87-19b	840	N.D.	N.D.	N.D.	4.0	180	690	N.D.	2.00	17.4	2.0	N.D.	240	N.D.	59.5	109	46.6	8.5	2.70	1.20	2.80	0.51	28	23	
SI-87-19c	650	N.D.	N.D.	N.D.	4.0	160	640	N.D.	2.00	15.3	2.1	N.D.	260	N.D.	50.1	97	40.5	6.8	2.40	1.00	1.90	0.42	22	22	
SI-87-11	1000	N.D.	N.D.	N.D.	4.0	60	680	N.D.	1.00	11.1	3.2	N.D.	200	N.D.	78.2	90	37.3	6.3	2.60	0.90	1.70	0.44	19	13	
SI-85-6	1850	N.D.	N.D.	N.D.	10.0	190	170	N.D.	3.00	33.5	6.6	N.D.	480	N.D.	78.8	145	56.9	9.0	3.10	1.20	2.80	0.63	25	30	
SI-87-7	460	N.D.	N.D.	N.D.	7.0	190	36	N.D.	2.00	23.9	4.8	N.D.	440	N.D.	73.7	133	47.2	6.5	1.60	1.00	2.90	0.55	21	25	
SI-87-3bx	860	N.D.	N.D.	N.D.	7.0	220	140	N.D.	2.00	24.7	4.6	N.D.	390	N.D.	65.3	119	43.9	6.4	1.90	0.80	2.10	0.48	13	26	
SI-D20-9	1680	N.D.	N.D.	N.D.	8.3	157	222	N.D.	1.00	9.3	2.9	N.D.	364	N.D.	46.8	88	43.2	7.1	1.42	1.00	2.40	0.39	26	17	
SI-87-3ax	450	N.D.	N.D.	N.D.	6.0	200	170	N.D.	2.00	28.0	4.4	N.D.	410	N.D.	83.1	146	55.6	8.6	1.60	0.90	1.70	0.41	11	24	
SI-87-21a	950	N.D.	N.D.	N.D.	2.0	210	100	N.D.	2.00	23.6	3.8	N.D.	110	N.D.	37.6	68	22.7	3.7	1.60	0.60	1.80	0.42	13	13	
SI-87-21b	970	N.D.	N.D.	N.D.	2.0	200	100	N.D.	2.00	22.8	3.6	N.D.	110	N.D.	36.4	67	22.2	3.6	1.60	0.50	1.50	0.33	12	12	
SI-87-20a	1470	N.D.	N.D.	N.D.	4.0	170	460	N.D.	2.00	14.6	3.4	N.D.	170	N.D.	51.0	91	32.9	5.2	2.40	0.80	2.00	0.52	19	17	
SI-87-6	500	N.D.	N.D.	N.D.	2.0	190	28	N.D.	2.00	27.5	2.6	N.D.	100	N.D.	34.4	61	21.8	2.8	0.90	0.40	1.30	0.27	8	12	
IM95-07A	662	2.5	1.6	3.5	3.5	194	80	1.3	1.42	23.2	3.0	15	107	3.6	31.7	5									





**Figure 4.** Variation diagrams of major and minor elements for metavolcanic rocks from eastern California. Symbols indicate localities, as noted: squares—Ritter Range, triangles—White Mountains, diamonds—Inyo Mountains, hexagons—Alabama Hills. All analyses are recalculated on an anhydrous basis. A solid line bounds the field for 133 analyses of young volcanic rocks from the Mexican volcanic belt, compiled from Luhr and Carmichael (1980), Mahood (1981), Nelson and Livieres (1986), Luhr et al. (1989), Nelson and Hegre (1990), and some unpublished analyses by J. F. Luhr (1996, personal commun.), along with data for other calc-alkaline suites from continental arcs (Jakes and Smith, 1970; Mackenzie and Chappell, 1972; Keller, 1974; Smith et al., 1977, 1979; Smith and Johnson, 1981). The solid lines with arrowheads indicate trends defined by calc-alkaline volcanic rocks from the Mexican Volcanic Belt.

partially replaced by albite (reddish blotches), K-feldspar (blue specks), and calcite (bright orange specks). In the White Mountains sample, plagioclase phenocrysts are replaced by strongly CL-zoned albite that luminesces brownish- to dull-reddish-purple (Fig. 7B). Dull-red-luminescent albite has replaced plagioclase phenocrysts in the Ritter Range sample (Fig. 7C). In both samples, a

few albite grains display thin selvages or patches of blue-luminescent K-feldspar (Fig. 7, B and C). In the Alabama Hills sample, former plagioclase phenocrysts are now aggregates of dull yellow-green-luminescent  $An_{20-40}$  plagioclase, bright-orange-luminescent calcite specks, and blue-luminescent K-feldspar (Fig. 7D). The plagioclase is likely of metamorphic origin.

Quartz phenocrysts and crystal fragments luminesce reddish-purple in the Inyo Mountains sample (Fig. 7A), but are nonluminescent (black) in the other samples (Fig. 7, B–D). Because quartz phenocrysts in Inyo Mountains samples display igneous  $\delta^{18}O$  values, their luminescence may also be a relict igneous feature that survived both K-metasomatism and metamorphism.

## DISCUSSION

### Alkali Abundances in Metavolcanic Rocks: Protolith or Alteration Features?

Many of the metavolcanic rocks from eastern California show much higher or lower K/Na than young, fresh, calc-alkaline arc volcanic rocks (Table 1, Fig. 4). To what extent are such alkali-element ratios of primary igneous origin? Following work by Miller (1978), Christe and Hannah (1990) grouped metavolcanic rocks of the White-Inyo Mountains in a “high-K lower Mesozoic magmatic province.” Christe and Hannah (1990) concluded that the alkali abundances and elevated K/Na of Jurassic metavolcanic rocks from both this region and ones from the Kettle Rock sequence of the northern Sierra Nevada reflect protolith characteristics. Fresh alkaline volcanic rocks from arcs are much richer in K, Rb, Ba, Na, and Sr than calc-alkaline ones (e.g., Gill, 1981), and are typically identified by plots of  $SiO_2$  versus  $K_2O$  or versus  $(K_2O + Na_2O)$ . Because such correlations can be disturbed by alkali alteration, less mobile elements should be used to detect alkaline protoliths of metavolcanic rocks (e.g., Pearce, 1982). High-K (shoshonitic) basalts are enriched in other large ion lithophile elements (e.g., Th) and light REE (e.g., Ce) with respect to heavy REE (e.g., Yb) and high field strength elements (e.g., Ta) compared with calc-alkaline basalts. Ratios of these elements may discriminate between the two magma series (Pearce, 1982). However, even moderate igneous fractionation can change Ce/Yb, Th/Yb, and Ta/Yb enough to “confuse” the plotted field boundaries, which are based on basalt compositions. In the eastern California localities basalts are rare, but basaltic andesites are not, so we have stretched the applicability of the discriminant diagrams a bit by using analyses of the latter rocks (Fig. 8). With this caveat in mind, values for the Ritter Range rocks are within calc-alkaline fields, whereas the White and Inyo Mountains rocks show alkaline (shoshonitic) affinities (Fig. 8, A and B). Christe and Hannah (1990) did not report data for Ta, so comparison samples from the Kettle Rock sequence are not plotted.

Can the degree of alkali and alkaline earth element enrichment observed in the metavolcanic rocks of eastern California be due solely to a



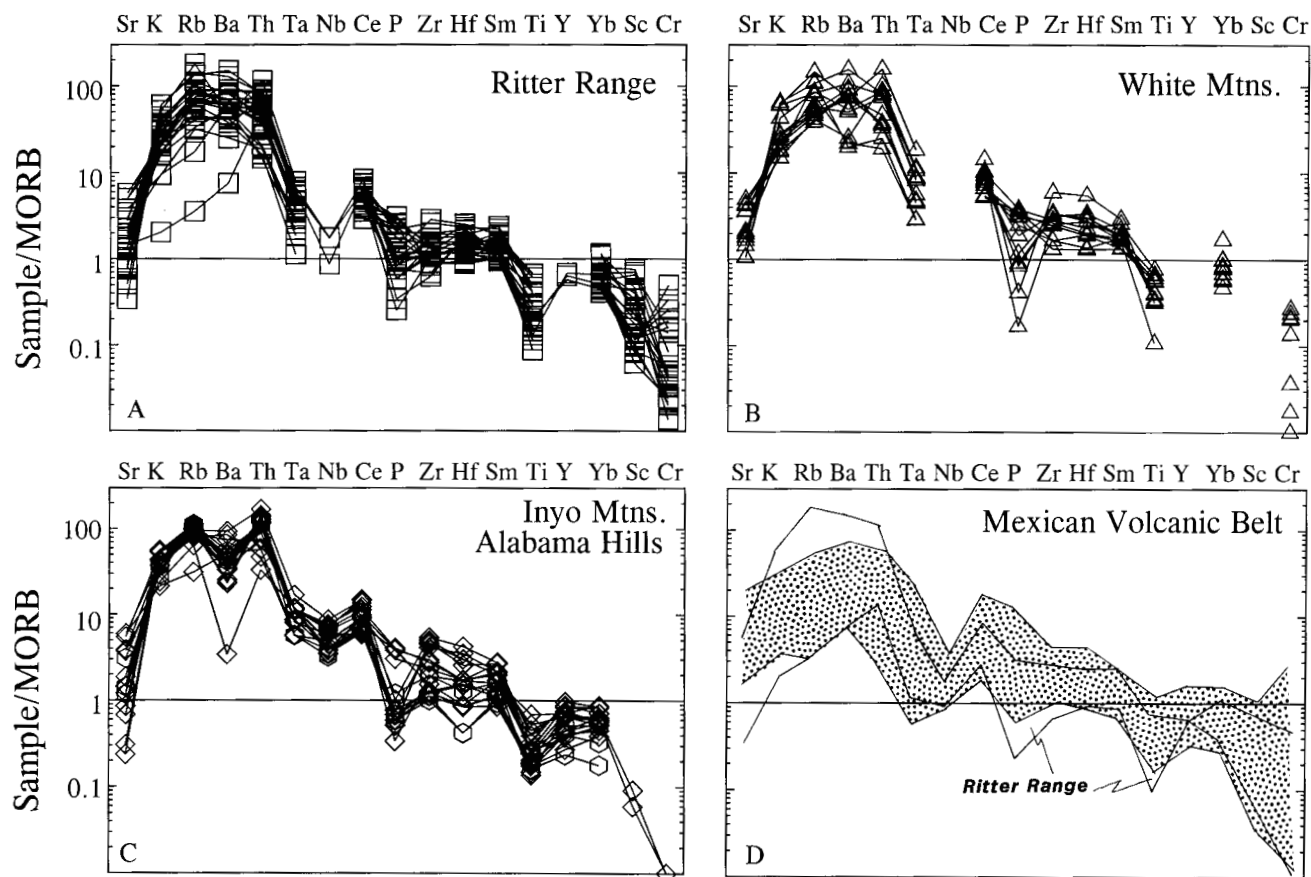


Figure 5. "Spider diagrams" of minor and trace elements for metavolcanic rocks from eastern California. Symbols are as in Figure 4. All analyses are recalculated on an anhydrous basis and normalized to values for average mid-oceanic-ridge basalt (MORB) of Pearce (1982). The stippled pattern in D defines a field of 86 analyses of young calc-alkaline volcanic rocks of the Mexican Volcanic Belt (for references, see the caption for Fig. 4). The outlined, unshaded region in D represents values for the Ritter Range (shown in A).

high-K igneous protolith assemblage? We think not. Na and Sr contents of the metavolcanic rocks anticorrelate with those of K and Rb, which points to alkali exchange as a means to produce the values seen in the suite (Figs. 9 and 10). Comparison with suites of modern fresh igneous rocks with the metavolcanic rocks and K-metasomatized Tertiary igneous rocks show that alkali exchange is not an important igneous fractionation process (Figs. 9 and 10). Instead, the alteration trends defined by pairs of fresh (or less altered) and K-altered Tertiary igneous rocks are mimicked by the data for the metavolcanic rocks (Figs. 9 and 10).

There is little evidence that the felsic metavolcanic rocks of eastern California had alkaline or peralkaline protoliths (Figs. 9 and 10). Alkaline and peralkaline rhyolites from the Aeolian arc, Papua New Guinea, and the Mexican Volcanic Belt show variable but dramatic enrichments in Zr/Ti and depletions in Ba/Ti with respect to as-

sociated calc-alkaline rocks. However, data for alkaline and peralkaline rhyolites show little overlap with values for the felsic metavolcanic rocks. At a given K/Al and Ti content, the metavolcanic rocks are much richer in Ba than are alkaline or peralkaline rhyolites. A comparison with data for K-metasomatized Tertiary volcanic rocks of the southwestern United States (Fig. 10A) suggests that the extreme Ba-enrichment seen in the felsic metavolcanic rocks more likely reflects metasomatism than igneous fractionation. REE patterns of alkaline and peralkaline rhyolites tend to display very large negative Eu anomalies (e.g., Jakes and Smith, 1970; Mackenzie and Chappell, 1972; Keller, 1974; Smith et al., 1977; 1979; Smith and Johnson, 1981), a feature not seen in the REE patterns of the felsic metavolcanic rocks.

We conclude that the alkali systematics and much of the alkali abundances in the metavolcanic rock suites reflect metasomatism. Trace el-

ement data show evidence for mildly alkaline protoliths of mafic rocks from the White-Inyo Mountains, but the associated felsic rocks lack strong evidence of alkaline or peralkaline protoliths. This result is not paradoxical; Pleistocene to Recent volcanoes in New Guinea and active volcanoes in the Mexican Volcanic Belt (Smith and Johnson, 1981; Mackenzie and Chappell, 1972; Nelson and Liveres, 1986; Luhr et al., 1989) have erupted calc-alkaline and alkaline series lavas in close spatial proximity more or less contemporaneously.

#### Replacement Mineralogy of Metavolcanic Rocks

CL petrography provides evidence for: (1) widespread and abundant development of K-feldspar in rocks that show varying intensities of contact metamorphic recrystallization; (2) remnants of igneous plagioclase in relict phenocrysts

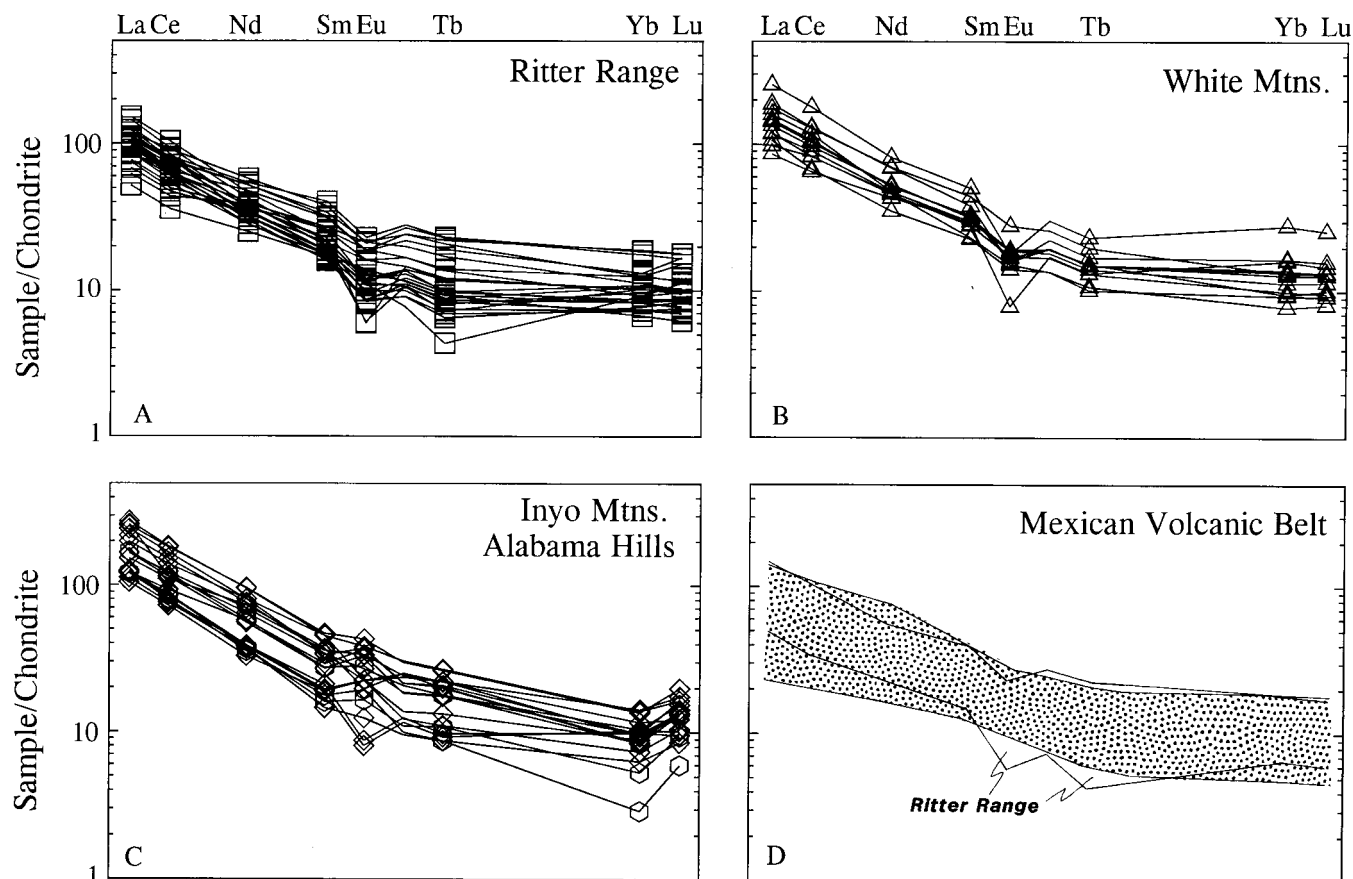


Figure 6. Rare earth element patterns for metavolcanic rocks from eastern California. Symbols are as in Figure 4. All analyses are recalculated on an anhydrous basis and normalized to average values for C1 chondrite values (Anders and Ebihara, 1982), multiplied by a factor of 1.31. The stippled pattern in D defines a field for 86 analyses of young calc-alkaline volcanic rocks of the Mexican Volcanic Belt (for references, see the caption for Fig. 4). The outlined, unshaded region in D represents the values for the Ritter Range shown in A.

TABLE 3. OXYGEN ISOTOPE DATA FOR  
ASH-FLOW TUFF UNITS

	Quartz	K-Feldspar	Others*
<u>Alabama Hills</u>			
85 Ma Granite	8.7	7.8	plg 7.2
170 Ma Ash-flow Tuff			
AH95-02	6.0	3.4	
AH95-06A	8.0	5.3	
<u>Southern Inyo Mountains</u>			
169 Ma Ash-flow Tuff			
IM95-07A	9.2	4.0	mat 5.1
IM95-09	9.5	8.8	mat 9.8
<u>Ritter Range</u>			
164 Ma, Structurally Lower Ash-flow Tuff			
Average <sup>†</sup>	12.1	10.2	
164 Ma, Structurally Higher Ash-flow Tuff			
Average <sup>§</sup>	12.3	10.0	

Note: Values are of  $\delta^{18}\text{O}$ , relative to standard mean ocean water (SMOW).

\*plg = plagioclase, mat = matrix.

<sup>†</sup>Quartz from 8 samples; alkali feldspar from 9 samples.

<sup>§</sup>Quartz from 8 samples; alkali feldspar from 7 samples.

from the Inyo Mountains; (3) the presence of red-luminescent, probably igneous quartz only in the low-*T* metamorphosed rocks of the Inyo Mountains; and (4) growth of metamorphic  $\text{An}_{20-40}$  plagioclase in samples from the Ritter Range and Alabama Hills. These results parallel the variations of metamorphic grade expressed by the overall mineral assemblages of the localities. The CL images also reveal possible mechanisms for alkali-metasomatism and phenocryst replacement in the Inyo and White Mountains. In those samples, the preservation of delicate igneous textures by K-feldspar suggests that volume changes during K-metasomatism were probably minor. This is consistent with alkali exchange mechanisms that essentially balance K gain with Ca and Na loss, and/or Na gain with Ca or K loss. Only the Alabama Hills sample, which was obtained within 20 m of a pluton contact, shows evidence for much matrix grain growth (Fig. 7D, cf. Fig. 11, A and B). This suggests that some meta-



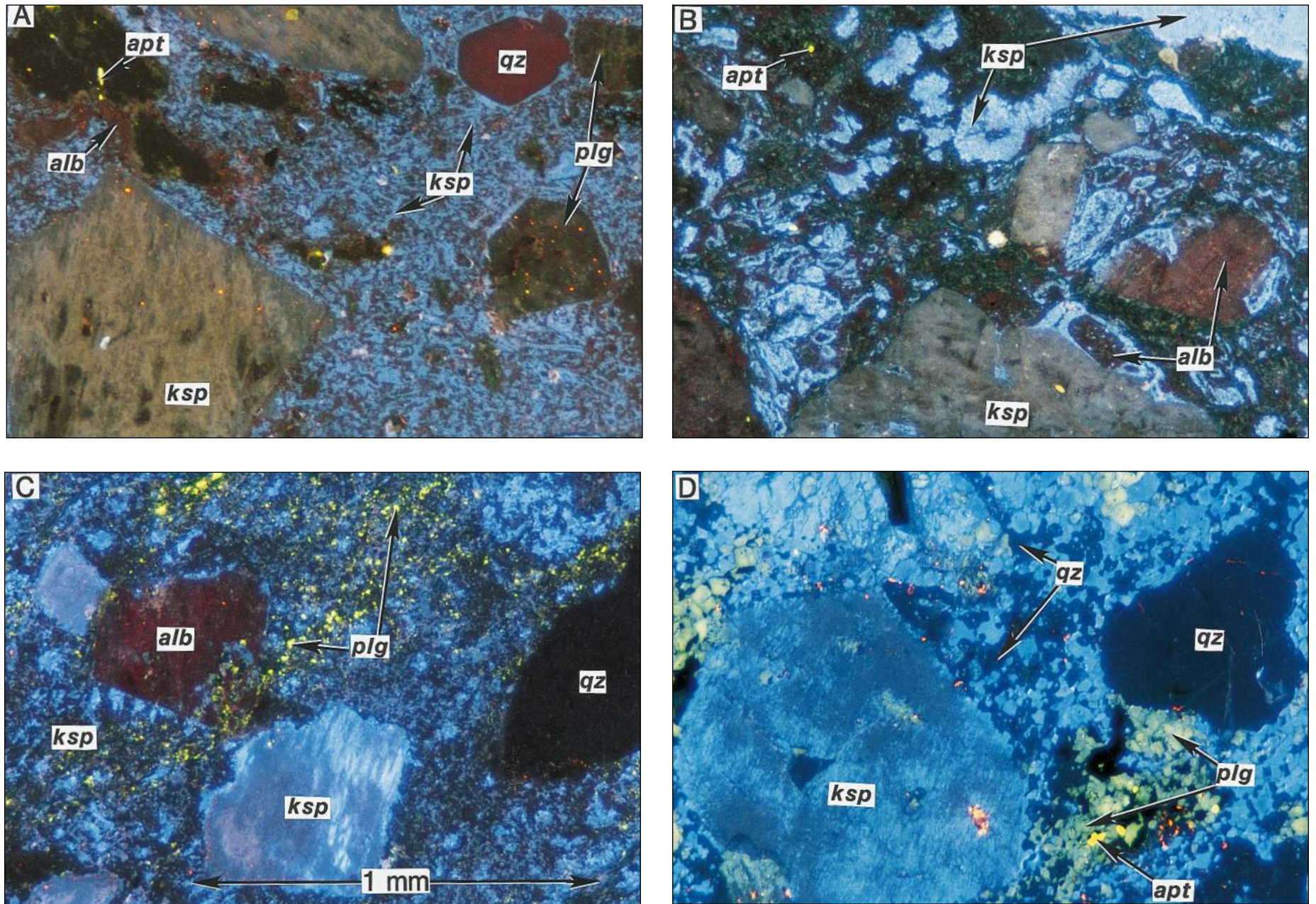
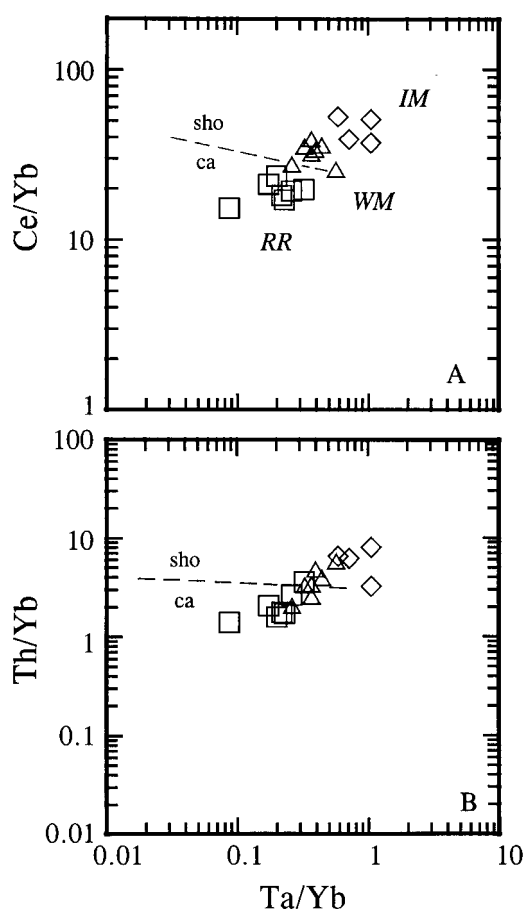


Figure 7. Cathodoluminescence of samples from the Inyo Mountains (A; sample SI-87-21A), White Mountains (B; sample 72984-3), Ritter Range (C; sample F71-46), and Alabama Hills (D; sample SI-87-23A). The long dimension in all four images is 1.6 mm.

Abbreviations: plg—plagioclase, qz—quartz, ksp—K-feldspar, alb—albite, apt—apatite. See text for additional explanation.





**Figure 8.** Variations of Ce/Yb versus Ta/Yb and of Th/Yb versus Ta/Yb in mafic metavolcanic rocks. No data are shown for the Alabama Hills, because only analyses with  $\text{SiO}_2 < 62 \text{ wt}\%$  are plotted. Pearce (1982) proposed the discriminant between shoshonitic (sho) and calc-alkaline (ca) basalts, shown as fields separated by the dashed line. RR—Ritter Range; WM—White Mountains; IM—Inyo Mountains. Symbols are as in Figure 4.

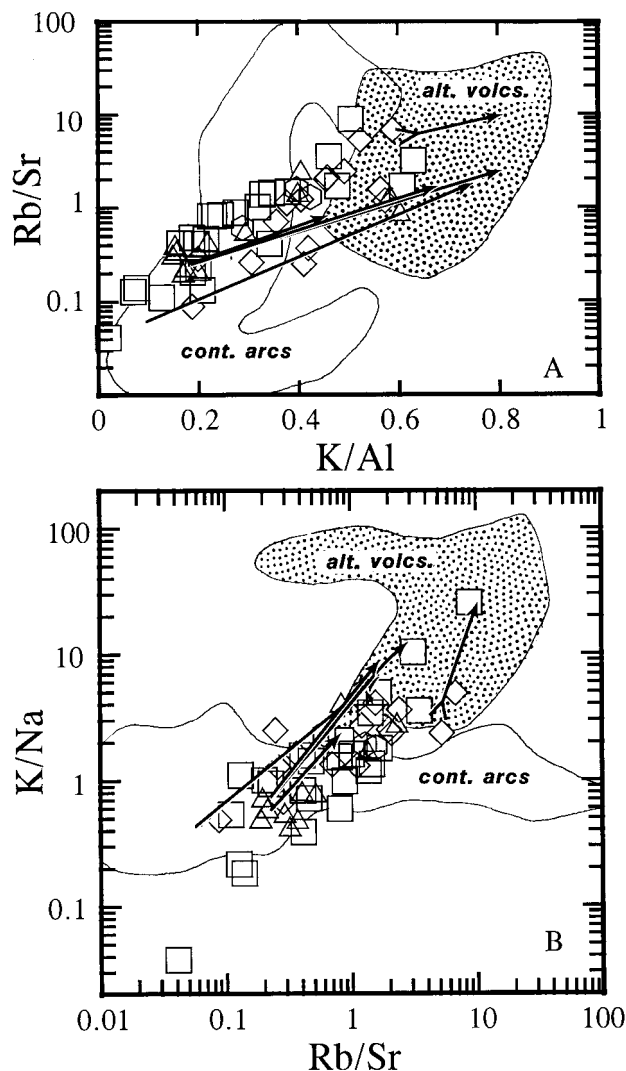
volcanic rocks may preserve textures that reflect lower  $T$  and/or earlier alkali-metasomatic effects rather than contact metamorphism. Albite and K-feldspar should be stable phases in K- and/or Na-rich bulk compositions even over the wide range of contact metamorphic temperatures recorded by the mineral assemblages of these rocks. Grains of these minerals that formed by relatively low- $T$  alkali-metasomatism might persist during later, higher  $T$  contact metamorphism, barring penetrative deformation or significant fluid infiltration.

**Oxygen Isotope Evidence for Fluid Sources.** *Ritter Range.* The abundant alkali-metasomatism of the metavolcanic sections testifies to interactions between these rocks and fluids. Oxygen isotope data can help constrain temperatures and environments of fluid-rock interactions (e.g., Criss and Taylor, 1986; Valley, 1986). However,  $\delta^{18}\text{O}$

values of metasomatized and/or contact-metamorphosed volcanic rocks may reflect both magmatic and fluid-rock effects (e.g., Taylor and Sheppard, 1986; Criss and Taylor, 1986). Our interpretation of the somewhat small set of  $\delta^{18}\text{O}$  data presented here is supported by a larger data set and additional geological constraints for the Ritter Range (Hanson et al., 1993). There, metavolcanic rocks are found in three structural settings: (1) nearly vertical layers of a Triassic to Early Cretaceous “lower section”; (2) fault-bounded slivers of vertical layers of Triassic to Jurassic rocks (the “lower-section rocks near Nydiver Lakes” of Hanson et al., 1993); and (3) a gently dipping mid-Cretaceous “upper section.” Rocks in all three settings are alkali altered and intruded by the Late Cretaceous Kuna Crest granodiorite. The upper section is also intruded by the mid-Cretaceous Shellenbarger granite.

Quartz and whole-rock  $\delta^{18}\text{O}$  values for 12 of 13 lower-section rocks range from  $+11.1\text{‰}$  to  $+16.0\text{‰}$  (sample B87–37a has a  $\delta^{18}\text{O}$  of  $+7.4\text{‰}$ ; Table 3 of Hanson et al., 1993). These  $\delta^{18}\text{O}$  values could reflect protoliths like the high- $\delta^{18}\text{O}$  tuffs from the Tuscan magmatic province (Taylor and Turi, 1976). However, the wide areal extent of high- $\delta^{18}\text{O}$  rocks in the pendant and occurrence of the highest  $\delta^{18}\text{O}$  values in oxidized and locally Mn- and Sr-rich units of piemontite- and braunite-bearing ash-flow tuff argue against these being igneous values (Hanson et al., 1993). Units with similar field aspects and silica contents (and thus of likely protoliths) to these high  $\delta^{18}\text{O}$  rocks are also present in the other two structural settings of the Ritter Range. Four of five whole-rock and quartz  $\delta^{18}\text{O}$  values for the “lower-section rocks near Nydiver Lakes” range from  $+4.1\text{‰}$  to  $+4.8\text{‰}$ ; the fifth (sample F85–7) has a  $\delta^{18}\text{O}$  of  $+7.5\text{‰}$  (Table 3 of Hanson et al., 1993). Whole-rock  $\delta^{18}\text{O}$  values for four of five samples of meta-ash-flow tuff from the upper section range from  $+2.1\text{‰}$  to  $+6.2\text{‰}$ ; the fifth (sample F77–17) has a  $\delta^{18}\text{O}$  of  $+7.5\text{‰}$ . Whole-rock and quartz  $\delta^{18}\text{O}$  values for the Kuna Crest granodiorite are  $+9.0\text{‰}$  and  $+7.9\text{‰}$ , respectively, and whole-rock  $\delta^{18}\text{O}$  for the Shellenbarger granite is  $+7.5\text{‰}$  (Table 3 of Hanson et al., 1993). The data for these plutonic rocks agree fairly well with the  $\delta^{18}\text{O}$  values ( $+5.5\text{‰}$  to  $+8.5\text{‰}$ ) that Taylor (1986) reported for the Sierra Nevada batholith.

Very high ( $>+10\text{‰}$ )  $\delta^{18}\text{O}$  values in ash-flow tuffs are attributed to assimilation of large amounts of metasedimentary rock, whereas assimilation of meteoric-water-altered roof rocks of calderas is thought to produce very low ( $<+5\text{‰}$ )  $\delta^{18}\text{O}$  values in both ash-flow tuffs and associated plutonic rocks (e.g., Taylor and Sheppard, 1986; Larson and Geist, 1995). It seems geologically implausible that both of these mechanisms operated in close proximity to produce numerous units of felsic rocks with observed  $\delta^{18}\text{O}$  values  $>+10\text{‰}$  throughout a  $20 \text{ km}^2$  area in structural setting 1 (including the 164 Ma meta-ash-flow tuff units of Table 3) along with felsic rock units that show  $\delta^{18}\text{O} < +5\text{‰}$  in setting 2. The contrast between the  $\delta^{18}\text{O}$  value of  $+7.5\text{‰}$  for the Shellenbarger granite porphyry, which is interpreted to be a hypabyssal subcaldera intrusion, and values of  $+2.1\text{‰}$  to  $+6.2\text{‰}$  for coeval upper section rocks that represent caldera fill and collapse deposits (Fiske and Tobisch, 1994), argues against a magmatic origin for the low  $\delta^{18}\text{O}$  values in structural setting 3 (cf. Larsen and Geist, 1995). Furthermore, Late Cretaceous plutonic rocks and at least one sample from each structural setting all show  $\delta^{18}\text{O}$  values typical of the Sierra Nevada batholith. It seems unlikely that most of the magmas that produced the Jurassic to Early Cretaceous Ritter Range vol-



**Figure 9.** Alkali and alkaline-earth element systematics for metavolcanic rocks from eastern California. All analyses are recalculated on an anhydrous basis. Symbols are as in Figure 4. Fields for analyses of calc-alkaline, alkaline, and peralkaline volcanic rocks from continental arcs (Mexican Volcanic Belt, Aeolian arc, Papua New Guinea) are outlined in solid lines. The stippled pattern denotes a field for K-metasomatized Tertiary volcanic rocks from California and Arizona (Glazner, 1988; Roddy et al., 1988; Hollocher et al., 1994). Barbless arrows connect analyses of probable protolith and alteration product reported by Glazner (1988); barbed arrow connects less- with more-K-metasomatized volcanic rocks as per Hollocher et al. (1994). A shows Rb/Sr versus K/Al; B shows K/Na versus Rb/Sr. References for the comparison data for unaltered igneous rocks are in the caption for Figure 4.

canic section were highly contaminated by crust that had locally heterogeneous  $\delta^{18}\text{O}$  values, yet the Late Cretaceous, pluton-producing magmas emplaced into the volcanic section were not. For all of these reasons, Hanson et al. (1993) interpreted most of the  $\delta^{18}\text{O}$  values of metavolcanic rocks from the Ritter Range to reflect pre-Late Cretaceous alteration regimes rather than primary

igneous values. Hanson et al. (1993) attributed the high  $\delta^{18}\text{O}$  values of lower section rocks to low- $T$  ( $<200^\circ\text{C}$ ) interaction with seawater, and concluded that meteoric water infiltration produced low  $\delta^{18}\text{O}$  values along the bounding fault zone of an Early Cretaceous caldera complex (the Nydiver section), and within coeval caldera deposits (the upper section).

The 2.1‰ fractionation between average  $\delta^{18}\text{O}$  values for Ritter Range quartz and K-feldspar pairs (Table 3) suggests high- $T$  (i.e., igneous or contact metamorphic) rather than low- $T$  ( $<200^\circ\text{C}$ ) equilibration. However, K-feldspar “phenocrysts” of  $\text{Or}_{95}$  are clearly not of igneous origin. Many single-crystal quartz phenocrysts: (1) are typically riddled with  $\text{H}_2\text{O} \pm \text{CO}_2$ , (l + v)-bearing fluid inclusions; (2) show no cathodoluminescence; and (3) contain pseudomorphs of melt inclusions that consist of metamorphic minerals. Furthermore, many “quartz phenocrysts” in hand sample consist of polycrystalline aggregates of quartz grains that display polygonal or ragged boundaries in thin section. Because we interpret both quartz and K-feldspar to pseudomorph or replace original igneous phenocrysts, we conclude that the fractionation of  $\delta^{18}\text{O}$  values between quartz and K-feldspar reflects high- $T$  reequilibration of high  $\delta^{18}\text{O}$  whole-rock values imposed at lower- $T$  conditions.

**Alabama Hills and Inyo Mountains.** Although we have analyzed relatively few samples from the Alabama Hills and Inyo Mountains, their  $\delta^{18}\text{O}$  values contrast with those for the lower section rocks of the Ritter Range (Table 3). The 170 Ma meta-ash-flow tuff of the Alabama Hills shows fractionations of  $\delta^{18}\text{O}$  that suggest that quartz and K-feldspar equilibrated under high- $T$  ( $>\sim 600^\circ\text{C}$ ) conditions. However, one of the quartz and both of the K-feldspar samples show lower  $\delta^{18}\text{O}$  values than are typical of felsic volcanic rocks (Table 3, cf. Taylor and Sheppard, 1986). Because the two samples are from different parts of the same ash-flow tuff unit and the K-feldspar phenocryst compositions are  $\text{Or}_{95}$ , it seems unlikely that these low values are of igneous origin. Meteoric-hydrothermal water circulation systems centered upon granitoid plutons can produce nonigneous  $\delta^{18}\text{O}$  values in altered volcanic rocks, but such rocks generally display disequilibrium mineral-pair fractionations (e.g., Criss and Taylor, 1986). Sample AH95-02, which shows the lower of the  $\delta^{18}\text{O}$  values for quartz and K-feldspar, was collected farthest from the pluton contact. The pluton, which displays mineralogical effects of hydrothermal alteration, exhibits magmatic values for quartz, plagioclase, and alkali feldspar. These features are atypical of meteoric-hydrothermal systems, in which the lowest  $\delta^{18}\text{O}$  values are centered on the pluton and increase in country rocks with distance from pluton contacts. Accordingly, we suggest that the  $\delta^{18}\text{O}$  values for sample AH95-06A record the release of magmatic fluids from the Alabama Hills Granite into the meta-ash-flow tuff unit, which had earlier been K-metasomatized by water with a meteoric signature. Because models of fluid flow around cooling plutons (e.g., Hanson et al., 1993; Hanson, 1995) show that this

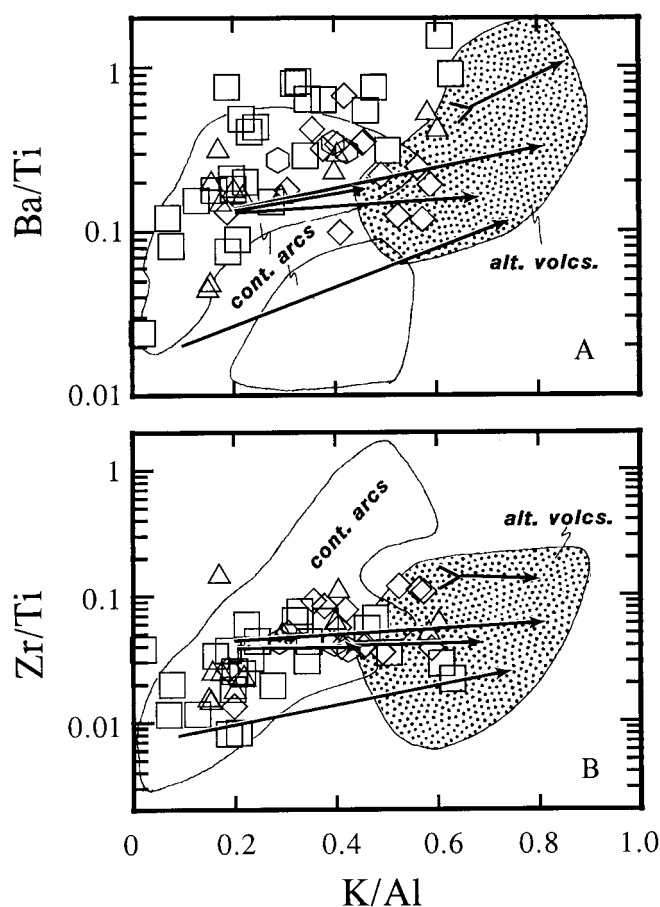


Figure 10. Ba/Ti (A) and Zr/Ti (B) versus K/Al in metavolcanic rocks. All analyses are recalculated on an anhydrous basis. Symbols are as in Figure 4. Patterning, fields, and arrows are defined in the caption for Figure 9. References for comparison data are in the captions of Figures 4 and 9.

sequence of events is unlikely in a single plutonic episode, we interpret the low  $\delta^{18}\text{O}$  values of sample AH95-02 to reflect a pre-Cretaceous alteration event. The very low- $T$  contact-metamorphosed metatuffs of the Inyo Mountains may record an arrested alteration process. Sample IM95-09 seems to have largely retained what are presumably its original igneous  $\delta^{18}\text{O}$  values (Table 3). This is consistent with the local preservation of igneous K-feldspar and plagioclase compositions and the apparent magmatic growth zoning of CL seen in quartz phenocrysts and crystal fragments in many of the Inyo Mountains rocks. In contrast, the matrix and K-feldspar phenocrysts of sample IM95-07A show  $\delta^{18}\text{O}$  values that suggest alteration by meteoric water. It is interesting to note that low- $T$  K-alteration of unmetamorphosed Tertiary ash-flow tuffs is typically manifested first in the matrix, then in plagioclase phenocrysts, and finally in sanidine

phenocrysts (e.g., Lindley, 1985). Despite a very low- $T$  contact-metamorphic overprint, the  $\delta^{18}\text{O}$  and compositional effects of arrested or incomplete Jurassic K-metasomatism may be preserved in some metatuffs of the Inyo Mountains.

#### From Jurassic Shores . . .

The infiltration of alkali-rich fluids from various sources at low- $T$  conditions has been called upon to explain widespread, pervasive Na and K alteration of volcanic rocks (e.g., Chapin and Glazner, 1983; Liesing et al., 1995; Battles and Barton, 1995; Barton and Johnson, 1996). Battles and Barton (1995) attributed sodic alteration of Permian to Jurassic rocks of the Cordilleran arc to isotopically heavy, moderately to highly saline fluids of marine, formational, and/or meteoric origin. Dunbar et al. (1994) interpreted pervasive, regional, low- $T$ , K-metasomatism of

Tertiary ash-flow tuffs near Socorro, New Mexico, to reflect infiltration of brines from overlying playa lake systems, and Leising et al. (1995) extended this interpretation to K-metasomatized Tertiary volcanic rocks from the Harcuvar Mountains of southwestern Arizona. Potassically altered Tertiary ash-flow tuffs typically display whole-rock  $\delta^{18}\text{O}$  values  $>+1\text{‰}$  (Chapin and Lindley, 1986; Roddy et al., 1988; Glazner, 1988; Dunbar et al., 1994).

The low  $\delta^{18}\text{O}$  values for quartz and K-feldspar in K-metasomatized ash-flow tuffs of the Inyo Mountains and Alabama Hills contrast with the high  $\delta^{18}\text{O}$  values reported for terranes that are interpreted to have been infiltrated by nonmagmatic, low- $T$  brines in terrigenous fluid-rock systems (Chapin and Lindley, 1986; Glazner, 1988; Roddy et al., 1988; Dunbar et al., 1994). What if somewhat higher  $T$  hydrothermal systems produced the K-alteration seen in the Inyo Mountains and the Alabama Hills? Fox and Miller (1990) documented abundant sodic alteration of Jurassic plutons in southeastern California. If coeval plutons were being albitized at depth beneath the volcanic sections of the Inyo Mountains and Alabama Hills, meteoric-hydrothermal fluids enriched by Na-for-K exchange at depth could potentially rise and potassically alter an overlying volcanic section, a mechanism similar to that proposed for the Ann-Mason porphyry copper deposit (Dilles and Einaudi, 1992). However, the presence of unit-scale, alternating Na- and K-metasomatism in intercalated units argues against fluid-rock interactions in a simple meteoric-hydrothermal system. A spatial association between zones of K- and Na-metasomatism and Jurassic pluton contacts has been noted at Yerington, Nevada, and elsewhere in the Jurassic Cordilleran arc, in which heat from plutons has driven reactions between rocks and metasomatic fluids from various sources (Carten, 1986; Dilles and Einaudi, 1992; Battles and Barton, 1995). However, unit-scale K- and Na-metasomatism in the Inyo Mountains is not obviously spatially organized with respect to (the admittedly distant) contacts of either Jurassic or Cretaceous plutons. Although K-metasomatism of metatuffs from the Inyo Mountains and Alabama Hills may have been driven by plutonic or volcanic heat, it need not represent the lower  $T$  parts of focused hydrothermal systems related to Jurassic plutonism.

For all of these reasons, we interpret the high  $\delta^{18}\text{O}$  values observed for K-metasomatized meta-ash-flow tuffs of the Ritter Range and the low  $\delta^{18}\text{O}$  values measured in similar rocks from the Inyo Mountains to reflect different fluid sources: namely, seawater and meteoric water. We conclude that the K-metasomatic effects in Jurassic metavolcanic rocks of eastern California

to in effect “track” the Jurassic shoreline in this region by preserving the  $\delta^{18}\text{O}$  values of waters that altered the rocks.

### ... to Cretaceous Plutons

Modest amounts of alkali metasomatism of the metavolcanic rocks are linked to mid- and Late Cretaceous plutonism. Such alteration is predominantly sodic (Na) or sodic-calcic (NaCa). In the White Mountains, it is expressed by albitization centered on the Cretaceous Pellisier Flat Granite (Anderson, 1937; Crowder and Ross, 1972). In the Ritter Range and Alabama Hills, Na and NaCa alteration of Cretaceous plutons and country rocks is generally manifested by sparse, centimeter-scale alteration haloes around veins. Such veins are widespread in the Ritter Range, but less common in the Alabama Hills. Although pervasive K-for-Na exchange is seen in some meta-ash-flow tuffs of the Ritter Range, it only affects rocks within ~50 to 200 m of contacts with the Kuna Crest granodiorite (Sorensen et al., 1993). This Cretaceous metasomatism produced  $\text{An}_{97}$  plagioclase, andalusite, and  $\text{Or}_{95}$  microcline in rocks that evidently underwent significant growth of matrix grains and concomitant grain-size reduction of relict phenocrysts (Sorensen et al., 1993).

Cathodoluminescence illuminates the replacement style of NaCa alteration of the 170 Ma meta-ash-flow tuff of the Alabama Hills (Figs. 2 and 11). Veining and attendant alteration of this unit are common only within ~20 m of the contact with the Alabama Hills Granite. There, as shown by sample AH95-06A, veins of dark green hornblende and brown biotite are surrounded by alteration haloes about two to three vein widths wide (Figs. 11, A and C). Within these haloes,  $\text{An}_{20-40}$  plagioclase has replaced K-feldspar of both phenocrysts and matrix. Two blue-luminescent K-feldspar phenocryst pseudomorphs farther from the vein show incipient replacement along cracks by yellow-green-luminescent  $\text{An}_{20-40}$  plagioclase grains that have magenta-luminescent albite rims. In the black and white SEM backscattered electron image, the phases are shown as white to light gray hornblende and biotite, medium gray K-feldspar, and darker gray  $\text{An}_{20-40}$  plagioclase. Such plagioclase is rare and sporadic in samples distant from the contact. For example, sample AH95-02, sampled ~450 m from the contact (Fig. 11B), lacks biotite + hornblende veins and attendant NaCa alteration, and also shows lesser amounts of matrix grain growth than does sample AH95-06A (Fig. 11 A and C). This comparison shows that Na and NaCa alteration related to Cretaceous pluton contacts in the Alabama Hills is fairly easily distinguished from the pervasive K-alteration that it

overprints. In summary, the alkali-metasomatism that accompanied Cretaceous plutonism appears to be either restricted to rocks within at most a few hundred meters of pluton contacts, or vein related. It is distinguishable from the effects of earlier alkali-metasomatism by its relatively restricted scale and vein-related style.

### CONCLUSIONS

1. Trace element data suggest that mafic metavolcanic rocks of the White-Inyo Mountains, which were erupted continentward of their calc-alkaline counterparts in the Ritter Range, had shoshonitic protoliths.

2. Much of the Jurassic metavolcanic sections in the Ritter Range, White-Inyo Mountains, and Alabama Hills are pervasively alkali metasomatized. Rhyolitic ash-flow tuffs from these localities tend to be K-metasomatized.

3. Much of the alkali-metasomatism seen in Jurassic metavolcanic rocks of eastern California is likely related to syndepositional or slightly postdepositional fluid-rock interaction, rather than to Cretaceous plutonism. The  $\delta^{18}\text{O}$  values of K-metasomatized ash-flow tuffs may reflect marine (Ritter Range) versus nonmarine (Alabama Hills, Inyo Mountains) depositional and alteration environments, and thus “track” the Jurassic shoreline.

4. Alkali metasomatism associated with Cretaceous plutonism ranges from local Na for K exchange in the Alabama Hills, to albitization in the White Mountains, to local K for Na exchange in the Ritter Range. All appear to be restricted in scale compared with earlier alkali-metasomatic effects and/or related to veining and contact-metamorphic recrystallization.

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### APPENDIX. SAMPLING AND ANALYTICAL METHODS USED IN THIS STUDY

#### Sampling

Somewhat ironically, the samples discussed in this paper were collected specifically to *avoid* alteration. Most of the Ritter Range samples were collected by R. S. Fiske and O. T. Tobisch in 1970–1971, as part of a U.S. Geological Survey regional mapping study aimed at characterizing the protoliths of the lower section. For this reason, they avoided samples with obvious evidence of alteration, as manifested by veining and patchy mineralization. Samples from the White Mountains were collected by R. B. Hanson in 1983–1985. His goals were to represent the range of mafic-to-felsic lithologies and the stratigraphy, and to achieve geographic coverage from south to north on the range crest. He also avoided collecting rocks with obvious veining or replacement features. Samples from the southern Inyo Mountains and Alabama Hills were collected in 1985–1987 by G. C. Dunne and J. D. Walker as part of a structural study of the section in conjunction with a program of U/Pb radiometric dating of zircons. They collected samples that appeared to be the least altered and representative of major units in these two areas, from outcrops that were not immediately adjacent to intrusive contacts.

#### Analytical Methods

Because this report uses data obtained in several labs over a 20+ year period, we include an explanation of the analytical methods.

**Mineral Analyses.** Electron probe microanalyses of feldspar from the Ritter Range and White Mountains were carried out by R. B. Hanson, and those of feldspar from the Inyo Mountains and Alabama Hills were carried out by S. S. Sorensen. These results are quoted in the section on contact metamorphism and the discussion, but are not presented in tables or figures. Hanson used the ARL-EMX and Cameca Camebax microprobes at the University of California, Los Angeles, for his analyses of minerals from the White Mountains. He recalculated analyses from the ARL-EMX using Bence and Albee (1968) corrections, whereas data from the Cameca Camebax were reduced with ZAF corrections. Hanson and Sorensen obtained mineral data for the Ritter Range, Inyo Mountains, and Alabama Hills with the ARL-SEMQ microprobe in the Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution. The accelerating voltage was 15 kV, and the sample current 0.025 mA; data were reduced using the corrections method of Albee and Ray (1970).

**Whole-Rock, Major Element Analyses.** X-ray fluorescence (XRF) analyses of major elements for samples from the Ritter Range were carried out in the now-defunct XRF and rapid rock analysis facilities of the former analytical laboratories of the U.S. Geological Survey in the mid- to late 1970s. Reports made to the submitters and a database search conducted in 1996 indicate that that method was essentially that described in U.S. Geological Survey Bulletin 1144-A, supplemented by atomic absorption analyses. XRF analyses of samples from the White Mountains were carried out at the University of California, Los Angeles, using “museum piece” Phillips XRF equipment in a now-defunct analytical facility. Analytical methods were cited in Hanson (1986). XRF analyses of samples from the southern Inyo Mountains and the Alabama Hills were carried out by X-Ray Assay Laboratories, 1885 Leslie Street, Don Mills, Ontario, Canada.



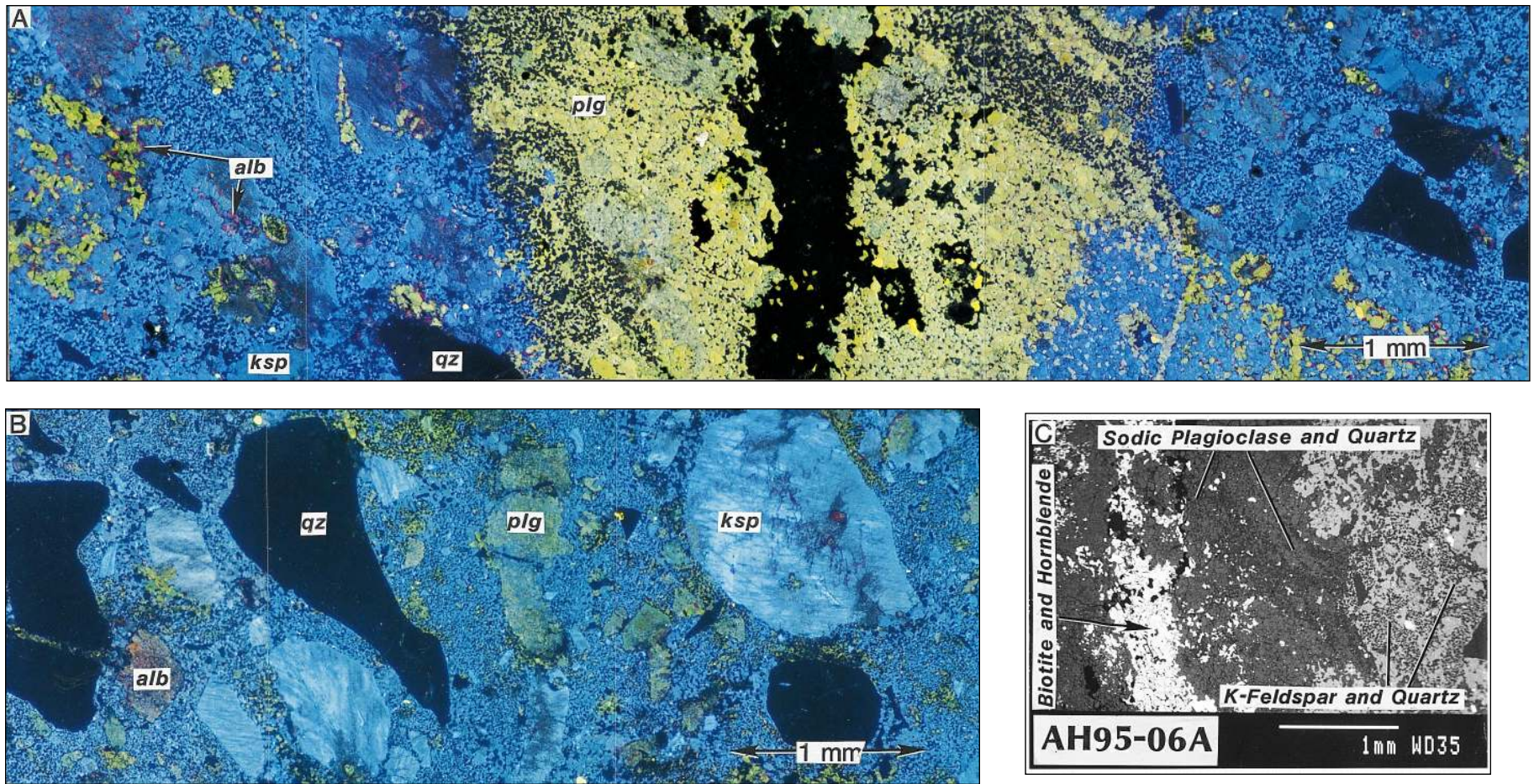


Figure 11. Sodic-calcic alteration of meta-ash-flow tuff related to Cretaceous plutonism, Alabama Hills. The color images (A and B) show cathodoluminescence. In A, an envelope of yellow-luminescent  $An_{20-40}$  plagioclase extends ~2 mm outward from a 0.5 mm biotite-hornblende vein in sample AH95-06A, collected ~20 m from a pluton contact. B illustrates

cathodoluminescence in sample AH95-02, collected ~450 m from the same pluton contact. The black and white photo (C) is a scanning electron microscope backscattered electron image of the central right area of A. See text for further explanation.



**Whole-Rock, Trace Element Analyses.** Instrumental neutron activation analyses (INAA) of samples from the Ritter Range and White Mountains were performed at the now-defunct U.S. Geological Survey radiochemistry laboratory at Reston, Virginia. Aliquants (200–500 mg) of powdered rock samples were irradiated in the TRIGA reactor at the U.S. Geological Survey, Denver, Colorado, at a flux of  $\sim 2 \times 10^{12}$  n/cm<sup>2</sup>/s for 8 hr. For both sets of samples, the standard was a powdered obsidian spiked with a variety of elements. Samples were counted on Ge(Li) intrinsic Ge, and low-energy photon detectors between 1 and 8 weeks after irradiation. The data were reduced using the SPECTRA program modified for interactive plotting of photopeaks (Grossman and Baedeker, 1987), and were also corrected for spectral and fission-product interferences (Baedeker and McKown, 1987). Estimated precision of most of the INAA data is better than  $\pm 10\%$  based on counting statistics, and control samples run as unknowns agreed within the analytical uncertainties. INAA analyses of trace elements for samples from the southern Inyo Mountains and Alabama Hills were carried out at X-Ray Assay Laboratories.

**Oxygen Isotope Analyses.** Quartz and alkali feldspar phenocrysts were removed from ash-flow tuff units of the Ritter Range, Inyo Mountains, and Alabama Hills by handpicking coarse fractions of the crushed rock sample. Oxygen was extracted from the samples with the laser fluorination apparatus (modified after Sharp, 1990) in the Department of Geosciences, University of Arizona, and analyzed by a Delta-S mass spectrometer in that department. The data for quartz were corrected by adding 0.75‰ to the analytical results, based on data for a variety of in-house and published standards that were run along with the unknowns. The analyses are reproducible within  $\pm 0.5\%$  of  $\delta^{18}\text{O}$ .

**Cathodoluminescence Petrography.** Cathodoluminescence (CL) images were obtained by standard photographic techniques with a conventional microscope-adapted camera. To create CL, uncovered, uncoated thin sections were subjected to electron bombardment from a cold cathode ray tube instrument at the Department of Mineral Sciences, National Museum of Natural History. Viewing conditions for all samples were preset to 20 kV, 0.5 mA on this current-regulating apparatus.

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