# Use of immobile trace elements to determine original tectonic setting of eruption of metabasalts, northern Sierra Nevada, California

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## ABSTRACT

New abundance data for Ti, Zr, Y, Sr, Cr, Hf, Ta, and Th in metamorphosed late Paleozoic basalts from the northern Sierra Nevada confirm that these rocks originated in an island arc. Furthermore, the data show that the original basalts belonged to the tholeiitic — rather than calc-alkalic — rock association of island arcs. Standard discrimination diagrams identify the island-arc tholeiite magma type; their utility was sternly tested by these thoroughly recrystallized (greenschist facies) rocks, whose island-arc origin had already been suggested by their petrography.

## INTRODUCTION

Metamorphosed Devonian to Permian volcanic rocks are extensively exposed in the northern Sierra Nevada, for about 125 km along the strike from Lake Almanor to south of Cisco Grove. The southern half of the belt of metavolcanic rocks is outlined in Figure 1. Little has been published regarding these rocks, which must play an important part in any paleogeographic reconstruction of the western edge of North America for late Paleozoic time. The stratigraphic framework has been sketched by D'Allura and others (1977); Durrell and D'Allura (1977) have described some of the petrographic details. We present here new trace-element data that confirm identification of the original tectonic environment of the rocks.

The metavolcanic rocks have been considered marine island-arc deposits, on the basis of primary phases and textures (see, for example, D'Allura and others, 1977). Garcia (1978) has prepared a summary of the characteristics of volcanic-arc deposits, and the reader is referred to his paper for a critical evaluation of criteria for recognition of such deposits in the rock record. One indicator of arc volcanism, for example, is the predominant fragmental texture of the resulting rocks. The northern Sierran metavolcanic rocks consist very largely of fragmental materials: tuff[1], lapilli tuff, lapillistone, tuff breccia, and volcanic breccia, as well as epiclastic rocks. Lava flows, nearly always pillowed, are also encountered, and dikes and sills are ubiquitous. The originally dacitic, andesitic, and basaltic rocks are generally prominently porphyritic. In the Long Lake–Gold Lake area (Fig. 1), phenocrysts originally consisted almost exclusively of quartz (dacites only), plagioclase (all rock types), clinopyroxene (andesites and basalts), and olivine (mostly confined to basalts in the Goodhue Formation). Many rocks in the Goodhue Formation, as well as pyroxene porphyry intrusive rocks and some rocks in the Taylor Formation, are so charged with large clinopyroxene phenocrysts as to appear ankaramitic.

The volumetrically overwhelming volcaniclastic rocks had a variety of modes of origin. Some that have been deciphered are: broken-pillow breccia; tuffaceous turbidites; epiclastic sandstone and siltstone; peperite; and probable grain- and debris-flow deposits, both pyroclastic and epiclastic.

D'Allura and others (1977) suggested the former presence of two island arcs: a Devonian arc that was separated from a Permian arc by a long interval of relative volcanic quiescence and pelagic sedimentation, represented by the chert-rich Peale Formation of Carboniferous age (Fig. 1). The Deonvian arc was composed of the dacitic Sierra Buttes, andesitic Elwell, and basaltic and andesitic Taylor Formations; the Permian arc was made up of the basaltic and andesitic Goodhue and andesitic Reeve Formations. The rock sequence, which contains no major unconformity, faces east and occupies the eastern, largely upright limb of the Almanor Anticline (D'Allura and others, 1977, Fig. 1).

The rocks were subjected to Mesozoic greenschist-facies metamorphism; they were thoroughly recrystallized and are locally conspicuously foliated. For example, original mafic pillow lava near the base of the Taylor Formation at Upper Salmon Lake (2 km south of Gold Lake) now consists largely of the assemblage albite-actinolite-chlorite-epidote-quartz-Ti, Fe minerals.

Sampling for chemical analysis was carried out north of the North Fork of the Yuba River, mostly in the Devonian island-arc assemblage. Figure 1, which discloses the sources of only 19 basalt samples among 58 analyzed specimens, shows that samples were collected in sections both along and across the strike of rock units. No fine-grained fragmental rocks were collected, because some of them demonstrably represent mixed provenances (for example, mixtures of Sierra Buttes and Taylor debris are common). Accordingly, collecting was necessarily biased toward the lava flows and intrusive rocks, although blocks in breccias were sampled at several places. Efforts were made to avoid pillow rims. The lava flows are commonly amygdaloidal, and the analyses of some specimens unavoidably reflect abundant amygdules. Most analyses are representative of hand specimens that considerably exceeded 1 kg in weight, so that small-scale metasomatic variations were minimized.

[1] For brevity, use of the prefix "meta-" will be discontinued at this point.

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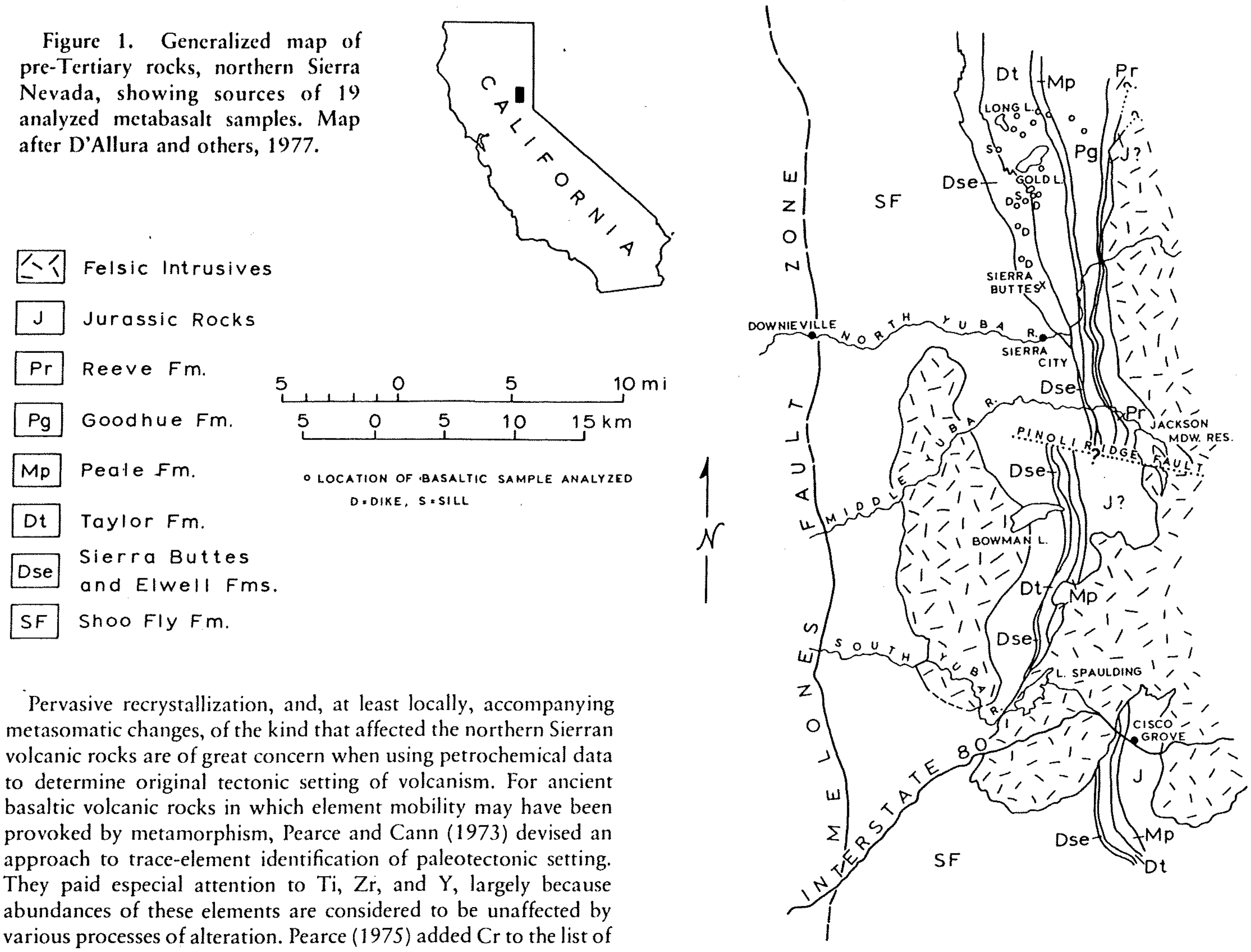
Figure 1. Generalized map of pre-Tertiary rocks, northern Sierra Nevada, showing sources of 19 analyzed metabasalt samples. Map after D'Allura and others, 1977.




Pervasive recrystallization, and, at least locally, accompanying metasomatic changes, of the kind that affected the northern Sierran volcanic rocks are of great concern when using petrochemical data to determine original tectonic setting of volcanism. For ancient basaltic volcanic rocks in which element mobility may have been provoked by metamorphism, Pearce and Cann (1973) devised an approach to trace-element identification of paleotectonic setting. They paid especial attention to Ti, Zr, and Y, largely because abundances of these elements are considered to be unaffected by various processes of alteration. Pearce (1975) added Cr to the list of immobile trace elements, and Wood and others (1979) have recently recommended the utility of Hf, Ta, and Th.

We have determined major- and trace-element concentrations in 58 northern Sierran rocks, which range continuously from basaltic to rhyolitic in terms of $SiO_2$ content. We report here Ti, Zr, Y, Sr, Cr, Hf, Ta, and Th abundances in 21 specimens that were originally basaltic (Table 1; two specimens, 18 and 22, were not analyzed by X-ray fluorescence, and so Zr and Y values are lacking for them).

## ANALYTICAL METHODS

Concentrations of Zr, Y, and Sr were measured by X-ray fluorescence analysis (XRF), and concentrations of Ti, Cr, Hf, Ta, and Th by instrumental neutron activation analysis (INAA). Both methods utilize thin disks formed by cold-pressing 200 mg of −170 mesh, whole-rock powder mixed with 200 mg of cellulose binder.

The computer-controlled, energy-dispersive XRF system employed a silver X-ray tube; a lithium-drifted, silicon detector; and an automatic, 20-position sample changer. The performance of a prototype of this system was described by Bonner and others (1975).

The method of absolute INAA used has been described by Heft (1977). Specimens were initially irradiated for 15 sec in the Livermore pool-type reactor at a thermal-neutron flux of $2 \times 10^{13}$ n/cm$^2$sec, allowed to decay 10 min, and the emitted gamma radiation measured by consecutive counts of 10, 20, and 40 min, using lithium-drifted, germanium detectors. A second irradiation of each specimen for 72 min was followed by a 133-min count after 3 days and a 333-min count after 15 days. Measurements were reduced to elemental abundances by computer codes.

U.S. Geological Survey rock standards BCR-1 and AGV-1 were run as unknowns together with the other specimens, and so accuracy can be estimated directly by reference to the most recent compilation of elemental abundances for BCR-1 and AGV-1 (Flanagan, 1976). Table 2 records precision and accuracy of replicate measurements. Apparent modest systematic errors in Y and Ta analyses led us to multiply by 1.18 the Y values utilized in Figures 2a and 4, and by 1.165 the Ta values used in Figure 5. Similarly, although there was no reason to expect a systematic error in determination of Cr, the Cr values plotted in Figure 3 were multiplied by 1.5.

## DISCRIMINATION DIAGRAMS

Certain ground rules must be observed when using the discrimination diagrams of Pearce and Cann (1973) to investigate paleotectonic environment of metavolcanic rocks (Fig. 2). A representative

TABLE 1. CONCENTRATIONS OF TRACE ELEMENTS IN 21 METABASALTS FROM THE NORTHERN SIERRA NEVADA, IN PPM

| Specimen number | $SiO_2$(wt %) | Ti | Zr | Y | Sr | Cr | Hf | Ta | Th |
|---|---|---|---|---|---|---|---|---|---|
| Goodhue Formation | | | | | | | | | |
| 48 | 49.6 | 3,750 | 50 | 13 | 510 | 254 | 1.23 | 0.09 | 1.88 |
| 49 | 55.1 | 3,490 | 46 | 12 | 191 | 176 | 1.37 | 0.12 | 2.06 |
| Peale Formation | | | | | | | | | |
| 50 | 48.6 | 4,775 | 57 | 12.5 | 204 | 134 | 1.31 | 0.25 | 1.93 |
| Taylor Formation | | | | | | | | | |
| 51 | 53.1 | 3,135 | 28 | 11 | 202 | 334 | 0.86 | .. | 1.31 |
| 26 | 52.0 | 2,100 | 22 | 9 | 155 | 224 | 0.72 | .. | 0.91 |
| 19 | 53.1 | 3,060 | 26 | 9.5 | 60 | 342 | 0.89 | 0.15 | 1.36 |
| 21 | 54.8 | 2,515 | 24 | 11 | 63 | 60 | 0.74 | .. | 0.89 |
| 25 | 56.9 | 3,770 | 24 | 14 | 84 | 669 | 0.73 | 0.06 | 2.18 |
| 24 | 60.5 | 2,795 | 31 | 13.5 | 144 | 272 | 0.89 | 0.08 | 3.09 |
| 18 | 54.2 | 3,015 | .. | .. | 188* | 51 | 0.71 | 0.10 | 1.29 |
| 22 | 54.4 | 3,800 | .. | .. | 102* | 51 | 0.72 | .. | 1.27 |
| 38 | 52.5 | 2,765 | 11 | 7 | 39 | 36 | 0.34 | .. | 0.41 |
| 44 | 53.1 | 2,590 | 19 | 10 | 68 | 48 | 0.69 | .. | 0.91 |
| 42 | 51.6 | 1,295 | 4 | 3 | 35 | 842 | .. | .. | .. |
| Elwell Formation (aphanitic sill) | | | | | | | | | |
| 35 | 56.4 | 2,635 | 20 | 11.5 | 54 | 16 | 0.66 | 0.07 | 0.40 |
| Small masses intruding the Sierra Buttes and Taylor Formations | | | | | | | | | |
| Pyroxene porphyry sill | | | | | | | | | |
| 13 | 48.7 | 2,660 | 16 | 7 | 326 | 156 | 0.30 | .. | 0.55 |
| Pyroxene-plagioclase porphyry dikes | | | | | | | | | |
| 37 | 49.5 | 3,360 | 39 | 11 | 375 | 33 | 1.02 | 0.21 | 1.16 |
| 11B | 52.8 | 2,260† | 25 | 10 | 193 | 165 | 0.63 | .. | 0.89 |
| Dikes having inconspicuous pyroxene phenocrysts | | | | | | | | | |
| 6 | 49.0 | 4,785 | 30 | 9.5 | 111 | 146 | 0.82 | .. | 6.30 |
| 11A | 52.3 | 2,785 | 24 | 9 | 185 | 217 | 0.75 | .. | 0.80 |
| Diabase dike | | | | | | | | | |
| 3 | 46.9 | 17,410 | 205 | 36.5 | 280 | 18 | 5.22 | 2.36 | 2.67 |

*Note:* Specimens are listed in approximate stratigraphic order within each formation, youngest to oldest. The concentrations entered in the table for Y, Cr, and Ta are those measured, *uncorrected* for probable systematic errors (see text for explanation). Very high Cr concentrations in some of the specimens are thought to be due to correspondingly large volumes of clinopyroxene phenocrysts in those specimens (see text), but Cr contamination during sample crushing and grinding cannot be ruled out as a contributing factor.

* By instrumental neutron activation analysis.

† By X-ray fluorescence analysis.

TABLE 2. PRECISION AND ACCURACY OF ANALYSIS OF U.S. GEOLOGICAL SURVEY ROCK STANDARDS BCR-1 AND AGV-1

| Element | Number of determinations | Mean value (ppm) | Standard deviation, s (ppm) | Flanagan's 1976 value | Percent difference from Flanagan's value |
|---|---|---|---|---|---|
| BCR-1 | | | | | |
| X-ray fluorescence | | | | | |
| Y | 4 | 31.0 | 0.62 | 37.1(a)* | −16.4 |
| Sr | 4 | 315 | 6.3 | 330(r) | −4.5 |
| Zr | 4 | 179 | 3.9 | 190(m) | −5.8 |
| Instrumental neutron activation analysis | | | | | |
| Ti | 3 | 12,370 | 759 | 12,750(a) | −3.0 |
| Cr | 3 | 11.5 | 0.76 | 17.6(a) | −34.7 |
| Ta | 3 | 0.78 | 0.023 | 0.91(r) | −14.3 |
| Th | 3 | 5.99 | 0.092 | 6.0(r) | −0.2 |
| Hf | 3 | 4.88 | 0.059 | 4.7(a) | +3.8 |
| AGV-1 | | | | | |
| X-ray fluorescence | | | | | |
| Y | 4 | 18.1 | 0.17 | 21.3(a) | −15.0 |
| Sr | 4 | 642 | 6.4 | 657(r) | −2.3 |
| Zr | 4 | 231 | 5.0 | 225(r) | +2.7 |

* r = recommended, a = average, m = magnitude.

suite of at least ten samples should be randomly collected, the samples must be basaltic,[2] and it is helpful if cumulate crystals are present only in small amounts. Also, the diagram involving Sr (Fig. 2c) should not be used unless it can be shown that Sr was immobile during metamorphism. Problems of utilization of the diagrams even then remain; for example, there exists extensive overlap of the ocean-floor basalt and low-K tholeiite fields on the Ti-Zr diagram (Garcia, 1978), and transitional tectonic settings, such as a back-arc spreading center overlying a subduction zone, may lead to ambiguous results. Nevertheless, it appears to us that some of the misgivings recently expressed about the validity of the diagrams resulted because precautions stated by Pearce and Cann (1973) were ignored.

Selection of those specimens which are basaltic posed a problem. The chemical screen employed by Pearce and Cann (1973) for *fresh* basalts requires that the sum of CaO and MgO falls between 12 and 20 wt percent. Unfortunately, both Ca and Mg are quite capable of mobilization during greenschist-facies metamorphism, Ca more so than Mg. Indeed, the comparison in Table 3 of the means of major-element oxides for the Sierran basalts with those for fresh island-arc (low-K) tholeiites (which immobile trace elements will show the Sierran basalts originally to have been) suggests that some migration of major elements has occurred, the nature of which is approximately that expected by greenschist-facies metamorphism. The large standard deviations also doubtless partly reflect element mobility during metamorphism. In particular, CaO is 2% lower and MgO almost 1% higher in the Sierran basalts. Sr is correspondingly slightly lower (170 versus 207 ppm), and it appears that Ca and Sr were not always fixed during albitization of plagioclase.[3]

Use of the Pearce and Cann (1973) chemical screen admitted several samples that would be considered andesitic in terms of $SiO_2$ content alone, but the fact that the mean $SiO_2$ content is more than 2% higher in the Sierran basalts than in the island-arc tholeiites (Table 3), together with field and petrographic evidence for rock replacement by quartz, suggest that these samples represent basalts silicified during metamorphism. On the other hand, use of the Pearce and Cann screen resulted in exclusion of several samples that have $SiO_2$ contents less than 52%. Some of these are probably silicified ultramafic rocks, and some appear to be andesites slightly depleted in $SiO_2$; probably only one of them should *not* have been excluded. The 12% < (CaO+MgO) < 20% screen, therefore, seems to be more serviceable for the Sierran metavolcanic rocks than, say, $SiO_2$ content, and it has accordingly been retained in this work.

All 11 (of 58) specimens having Cr contents greater than 250 ppm (corrected to 375 ppm in Fig. 3) display prominent clinopyroxene phenocrysts, and might be expected to represent lavas in which clinopyroxene accumulated. Six of the 11 specimens were identified as basalts by the chemical screen, and their analyses therefore appear in the discrimination diagrams in Figure 2. If all six indeed contain cumulate mafic crystals, one might think it fortuitous that all but one of them plot within the field of low-K tholeiites on the Ti-Zr diagram (Fig. 2b). The single offending specimen, 42 (representing a pillow lava at the base of the Taylor Formation), consistently falls outside all field boundaries in Figure 2. It is unusually low in both Zr and Ti (as well as other trace elements; see Table 1), and may have been depleted in these elements by accumulation of mafic phenocrysts. We conclude that crystal accumulation did not affect in an important way the abundances of Zr and Ti in these rocks.

TABLE 3. COMPARISON OF MEANS OF MAJOR-ELEMENT OXIDES (NORMALIZED TO 100 WT PERCENT) FOR 21 SIERRAN METABASALTS AND 46 FRESH ISLAND-ARC THOLEIITES

| | 21 Sierran metabasalts | | 46 fresh island-arc (low-K) tholeiites‡ |
|---|---|---|---|
| | Mean | Standard deviation | Mean |
| $SiO_2$ | 54.98 | 3.39 | 52.86 |
| $TiO_2$ | 0.66 | 0.56 | 0.83 |
| $Al_2O_3$ | 15.54 | 3.63 | 16.80 |
| FeO* | 10.14 | 1.55 | 10.41 |
| MgO | 6.91 | 1.85 | 6.06 |
| CaO | 8.54 | 1.89 | 10.52 |
| $Na_2O$ | 2.47 | 1.20 | 2.08 |
| $K_2O$ | 0.76† | 0.98 | 0.44 |

* Fe calculated as FeO.
† 19 determinations.
‡ From Pearce (1975).

In spite of the possibility that albitization of plagioclase resulted generally in modest loss of Sr in the Sierran basalts, most analyses plot within the field of low-K tholeiites in Figure 2c. One remarkable example of Sr (as well as Zr -) depletion is sample 38, collected from another pillow lava near the base of the Taylor Formation. Sample 38 is the other Taylor sample that consistently plots outside all field boundaries in Figure 2. It possesses abundant plagioclase phenocrysts (unaccompanied by clinopyroxene) and unusually high $Al_2O_3$ content (about 22%). $Na_2O$ also is very high (nearly 4%), but CaO is low (less than 6%) and Sr very low (39 ppm). Very little epidote occurs in albite pseudomorphs, but considerable epidote is present in adjacent amygdules, and the tuffaceous matrix between pillows is rich in epidote.

The procedure outlined by Pearce and Cann (1973) to identify the paleotectonic environment of eruption of a metabasaltic suite begins with use of the discrimination diagram involving Ti, Zr, and Y (Fig. 2a) to determine whether or not within-plate basalts are represented. Only sample 3 plots within field D. This rarely occurring diabasic dike rock has Zr, Ti, Y, Hf, and Ta abundances so much larger than those of all the other samples that it seems unrelated to them (Table 1). Indeed, it has many of the immobile trace-element characteristics of intraplate basalts, and we cannot at this time account for its presence among the island-arc tholeiites.

When intraplate basalts are not identified, one turns next to the Ti-Zr diagram (Fig. 2b), which better discriminates between the remaining magma types, provided that they are noncumulate. Except for the three specimens discussed above (3, 38, and 42), whose analyses plot outside all field boundaries, analyses cluster in fields A and B (mostly A), which are those characteristic of modern low-K

[2] Crystallization of Fe-Ti oxides from fractionated, more silicic liquids greatly modifies ratios involving Ti.

[3] Independent evidence of Sr mobility exists. R. W. Kistler (1980, written commun.) measured $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ in two samples of lavas collected from the Upper Devonian Elwell Formation. Sample 5, representing a sill, has $^{87}Rb/^{86}Sr = 0.061$, $^{87}Sr/^{86}Sr = 0.70616 \pm .00025$, Rb = 3.7 ppm, and Sr = 175 ppm. Sample 31, collected from a pillow lava, has $^{87}Rb/^{86}Sr = 0.515$, $^{87}Sr/^{86}Sr = 0.70759 \pm .00021$, Rb = 20.7 ppm, and Sr = 116 ppm. The isochron based on these two samples provides an apparent age of ~ 250 m.y., too young by about 100 m.y. Isotopic measurements of six rock samples collected from the still older Sierra Buttes Formation resulted in the same apparent age. Faunal evidence of the Upper Devonian age of the Elwell Formation has been reported by Anderson and others (1974) and Devay and Stanley (1979).

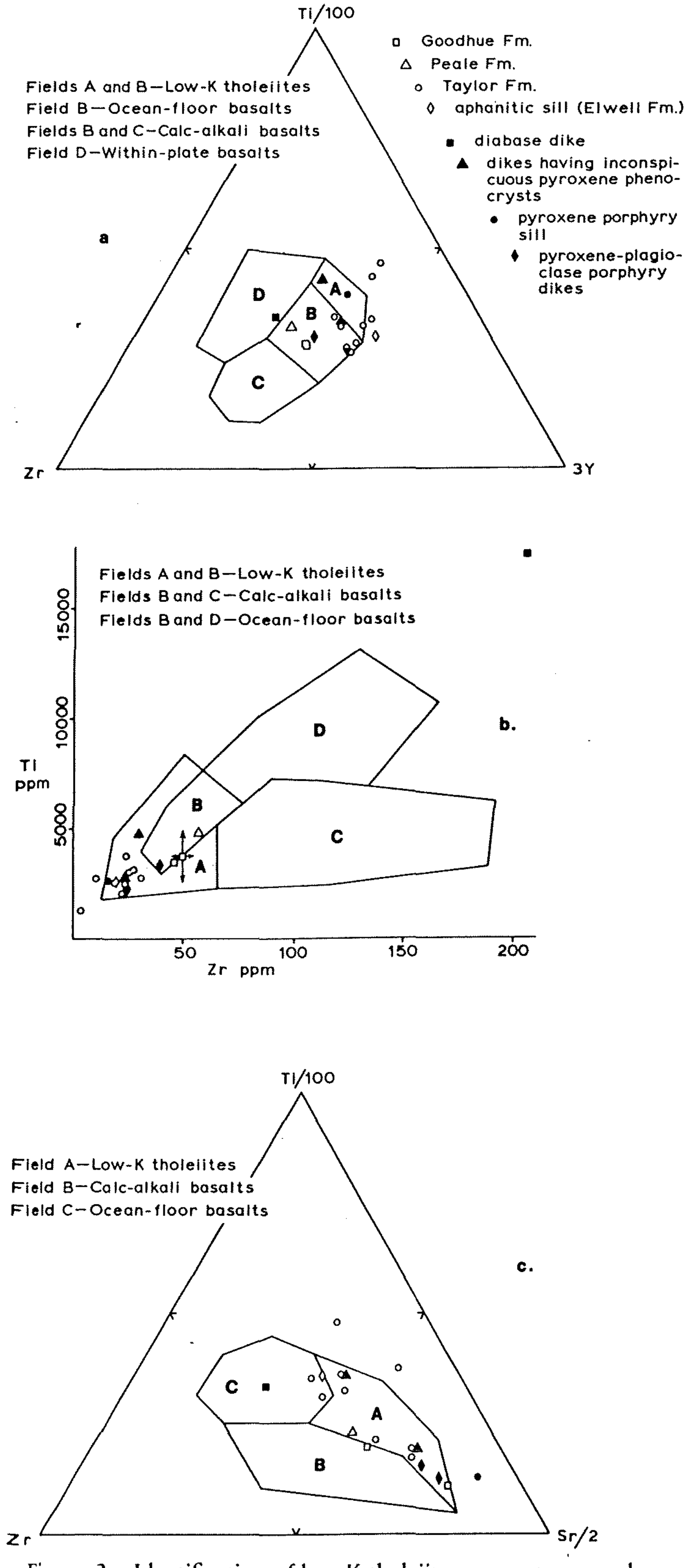



Figure 2. Identification of low-K tholeiite magma type employing Ti, Zr, Y, and Sr concentrations in 19 Sierran metabasalt samples. Discrimination diagrams from Pearce and Cann, 1973. Explanation of symbols in Figure 2a applies also to Figures 2b, 2c, 3, 4, and 5. Arrows in Figure 2b are confidence limits, at the 95% probability level, for three replicates of sample 48.

(island-arc) tholeiites. Garcia (1978, Fig. 4), however, plotted on the Ti-Zr diagram many analyses acquired since 1973, and, as a result, erected somewhat different field boundaries. These boundaries do not affect our conclusion that all but one of the 19 Sierran basalt samples represent island-arc tholeiites. Also, Garcia showed that overlap of the ocean-floor basalt and low-K tholeiite fields is complete; that is, some ocean-floor basalts have Ti contents as low as any of those found in low-K tholeiites. Indeed, he insisted that the Ti-Zr diagram cannot be used to distinguish ocean-floor basalts from low-K tholeiites, and that a plot of Ti against Cr (Fig. 3) has to be employed instead. We return to this point below.

Figure 2c incorporates Zr, Ti, and Sr data for the 19 Sierran basalt samples. This discrimination diagram should be applied to altered rocks, according to Pearce and Cann (1973), only when it can be shown that Sr was immobile. We obviously cannot prove that Sr was immobile during metamorphism, but the diagram discriminates the low-K tholeiite magma type, anyway. Of the four samples that plot relatively great distances from the low-K tholeiite field boundary, three are again the samples discussed above: 3, 38, and 42.

Pearce (1975, Fig. 5) introduced the Ti-Cr diagram to help distinguish ocean-floor basalts from island-arc (low-K) tholeiites. The Cr values plotted in Figure 3 have been multiplied by 1.5; nonetheless, all analyses but one are confined to the low-K tholeiite field. Sample 25, whose analysis falls in the ocean-floor basalt field, represents yet another lava in the Taylor Formation choked with large clinopyroxene phenocrysts; the voluminous clinopyroxene explains the very high Cr content. If crystal accumulation was active, the lava was not so depleted in Zr as to affect the location of its analysis within field A in Figure 2b.

The Ti-Cr plot lends weight to our identification of magma type in Figure 2b as low-K tholeiite. Garcia (1978) pointed out, however, that the distinction between the ocean-floor basalt and low-K tholeiite magma types is poor for basalts having Cr contents greater than 200 ppm and Ti contents less than 4,800 ppm. As 13 of the 21 analyses plotted in Figure 3 fall into this category, still another way of distinguishing between these two magma types would be helpful. Wood and others (1979, Fig. 3) have recently shown that the magma types are readily distinguished on a diagram utilizing Hf, Ta, and Th concentrations, and a plot of these data for the Sierran rocks (Fig. 5) is discussed below.

In connection with modeling studies to explain Ti, Zr, Y, and Nb variations in volcanic rocks, Pearce and Norry (1979, Fig. 3) prepared a plot of Zr/Y against Zr for several basaltic suites. The resulting diagram (Fig. 4) discriminates within-plate basalts from other basalts, especially island-arc basalts. All but 5 of 19 Sierran basalt samples plot along the low-Zr side of the island-arc basalt field. Analyses that fall outside this field are, again, for samples 3, 38, and 42; for the single Peale Formation sample (50); and for sample 13, representing a pyroxene porphyry sill. Sample 13, like 42, may have been somewhat depleted in Zr by crystal accumulation; Pearce and Norry (1979) omitted analyses of cumulate lavas when preparing the Zr/Y versus Zr diagram. Note that sample 3 again falls within the field characteristic of intraplate basalts.

Wood and others (1979, Fig. 3) devised a triangular diagram utilizing Hf, Ta, and Th data that distinguishes mid-ocean ridge and within-plate basalts (except for Hawaii) from each other and from Ta-depleted basalts erupted at converging plate margins. Analyses of more silicic, fractionated lavas may also be utilized in this diagram, as they plot close enough to the analyses of their basic parents to also be discriminated; similarly, analyses of silicic lavas

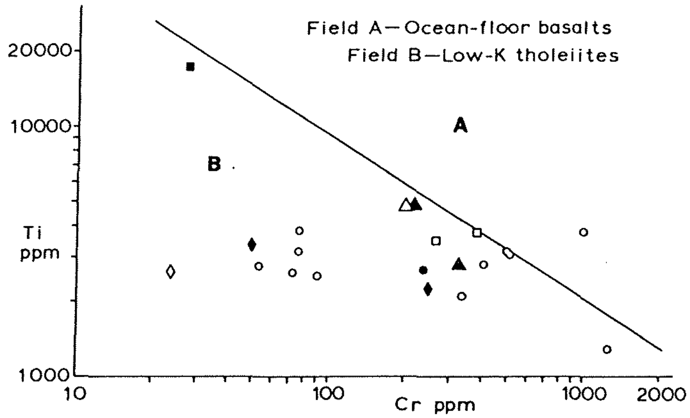



Figure 3. Identification of low-K tholeiite magma type using Cr and Ti concentrations in 21 Sierran metabasalt samples. Diagram from Pearce, 1975.

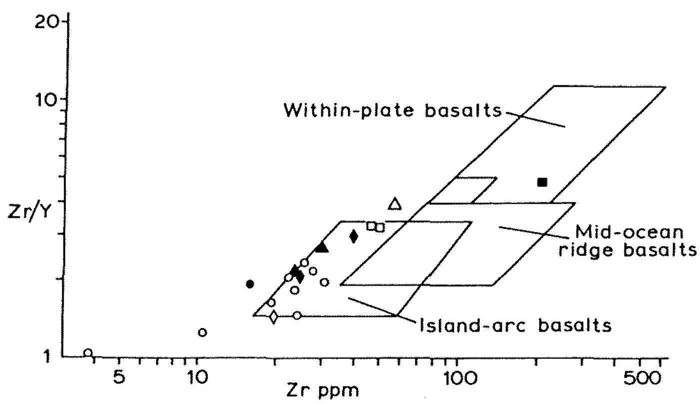



Figure 4. Identification of island-arc basalts utilizing Zr and Y concentrations in 19 Sierran metabasalt samples. Diagram from Pearce and Norry, 1979.

derived by partial melting of continental crust may be plotted. Accordingly, Figure 5 presents Hf, Ta, and Th data for all 58 Sierran samples except sample 42, in which none of these elements was detected. Also, Ta concentrations are so low in 40% of the samples that the concentrations could not be measured, and only the Th/Hf ratios of these samples are incorporated in the diagram. Only three analyses depart significantly from the field of magma types erupted at converging plate margins. One of these, for sample 3, is once again found in the field of intraplate basalts. Nineteen of the 20 analyses of Sierran basalt samples plotted in Figure 5 are thus clearly differentiated from those of mid-ocean ridge basalts. Indeed, they represent island-arc tholeiites.

## CONCLUSIONS AND DISCUSSION

Except for a few specimens whose trace-element abundances were affected by accumulation of mafic crystals or albitization of plagioclase, and a single diabasic specimen that is unrelated to all the others, analyses of Sierran metabasalts plot within the low-K tholeiite fields on all four discrimination diagrams currently in common use (Figs. 2, 3). Also, most analyses plot within the island-arc basalt field on the Zr/Y versus Zr diagram (Fig. 4) and within the field of magma types erupted at converging plate margins on the diagram involving Hf, Ta, and Th (Fig. 5). Clearly, the immobile trace-element chemistry of these rocks confirms the island-arc origin predicted by their petrographic characteristics. Furthermore, it shows that the basalts belonged to the tholeiitic, rather than the calc-alkalic, rock association in island arcs (Jakeš and White, 1972), a finding not anticipated at the outset of this study.

None of the Sierra Buttes rocks, because they were originally uniformly dacitic (present $SiO_2$ contents range from 66% to 78.5%), has been included in this study, and it is important to know whether or not they, too, belonged to the tholeiitic rock association.[4] They are tentatively identified as calc-alkalic, based on a plot of $SiO_2$ against FeO*/MgO (Miyashiro, 1974, Fig. 1A); the correlation of $SiO_2$ with FeO*/MgO is very poor. Rare-earth–abundance patterns have been used to distinguish rocks of the tholeiitic and calc-alkalic rock associations, even at high $SiO_2$ contents (Jakeš and Gill, 1970), and we are preparing REE patterns for all of the Sierran specimens (all were subjected to INAA), with a special effort to discover whether the Sierra Buttes dacites were tholeiitic or calc-alkalic. Should the Sierra Buttes Formation prove to be calc-alkalic, the Sierran island arc would contrast strikingly with the classic Japanese arc, where volcanism began with eruption of tholeiitic rather than calc-alkalic lavas.

Finally, Table 3 indicates that major-element-oxide means for the 21 Sierran basalt samples generally do not differ much from those for the 46 fresh, southwestern Pacific, island-arc tholeiites reported by Pearce (1975, Table 6). Such significant differences as do exist mostly may be attributed to greenschist-facies metamorphism

[4] Analyses of ten Sierra Buttes dacites do, in fact, appear in Figure 5, all within the field of magma types erupted at converging plate margins, but this diagram does not permit distinction between the tholeiitic and calc-alkalic rock associations.

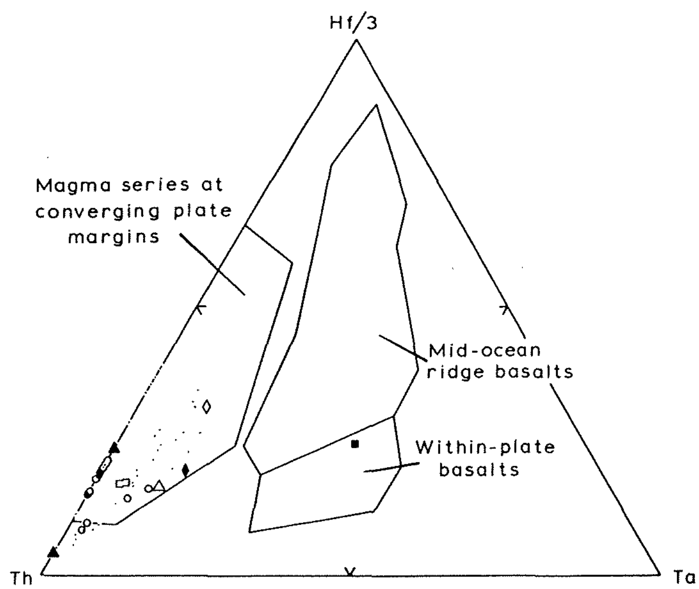



Figure 5. Identification of magma series erupted at converging plate margin, employing Hf, Ta, and Th concentrations in 20 Sierran metabasalt samples (symbols as in Fig. 2a) and 37 additional Sierran samples ranging in $SiO_2$ content from 48.1% to 78.5% (analyses represented by dots). Ta concentrations were below the detection limit in samples whose analyses are plotted along the Th-Hf/3 side of the triangle. Diagram from Wood and others, 1979.

of the Sierran rocks. Most of the 58 Sierran samples contribute to a single, clearly tholeiitic trend on Miyashiro's (1974) graph of $SiO_2$ against FeO*/MgO. Analyses of the Sierra Buttes rocks plot well off this trend, as does the analysis of the single diabasic dike sample. All but five of the remaining 46 specimens compose a trend line whose correlation coefficient is +0.84; all formations sampled but the Sierra Buttes are involved in the tholeiitic trend.

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