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GENESIS OF THE SMARTVILLE ARC–OPHIOLITE, SIERRA NEVADA FOOTHILLS, CALIFORNIA

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To our friend, Dale.

ABSTRACT. Rare earth element analyses of metavolcanic rocks from the Smartville ophiolite, northern Sierra Nevada, Calif., permit sub-division of an otherwise uniform suite of pillowed and massive lavas. The *lower part* of the eruptive pile comprises pillowed, massive, and brecciated tholeiites, an intrusive dike-sill complex and part of a plutonic suite. The tholeiites are all light REE depleted (La/Sm = 1.01-1.54) with a range of $(Ce)_N$ = 6.5 to 26.0 and $(Yb)_N$ = 6.0 to 30.0. It is believed that the tholeiites were derived by partial melting of a LREE depleted source similar to the source for MORB. Subsequent precipitation of olivine, clinopyroxene, and plagioclase to form cumulates ($\approx$50 percent fractionation) produced the sub-parallel REE patterns at differing levels of enrichment. The *upper part* of the volcanic pile is characterized by basaltic–andesitic flows and abundant interbedded coarse to fine volcanic sediments. These "calc–alkaline" rocks are all light REE enriched (La/Sm = 2.14-2.5) with a range in $(Ce)_N$ = 17.0 to 28.0 and $(Yb)_N$ = 8.0 to 12.0. Comparison of the REE characteristics of this ophiolite with volcanic rocks from the ocean floor and ocean islands betrays the inadequacy of REE as a discriminant of tectonic setting. However, petrographic studies of volcanic sediments and sulfide ore deposits within the lava pile indicate that the ophiolite formed close to a group of active submarine and sub-areal volcanoes. The coeval nature of this tholeiitic and calc–alkaline explosive volcanism strongly suggests an island-arc setting.

INTRODUCTION

Recently proposed plate tectonic models for the evolution of the western Cordillera of the United States (Moores, 1970; Cady, 1975; Schweikert and Cowan, 1975; Burchfiel and Davis, 1975) involve collision of single or multiple island arcs with consuming plate margins on the edge of North America. Hence, most pre-batholithic Mesozoic[1] rocks can be interpreted as volcanic arc remnants, subduction complexes (Saleeby, 1975, 1978), or ancient oceanic lithosphere (Morgan, 1973; Moores and Menzies, 1975). Complex suturing at the collision boundary has produced extensive fault zones and melanges resulting in few complete ophiolite suites. The rocks at Smartville, Calif., constitute a suite similar to more complete ophiolites except for the apparent absence of a basal ultramafic cumulate sequence, metamorphic peridotites, and pelagic sediments interlayered with volcanic rocks.

Field and geochemical studies were undertaken in an attempt to define the tectonic setting of the ophiolite. Major and minor elements

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[1] Recent dating of plagiogranites from the Smartville ophiolite (McJunkin, Davis, and Criscione, 1979) reveal an initial $^{87}Sr/^{86}Sr$ ratio of 0.70321 ± 5 and a U/Pb age of 155 to 160 m.y. Saleeby and Moores (1979) also report a Pb–Pb age of 159 to 175 m.y., similar to the age of the Coast Range ophiolites.

appear to be highly labile during metamorphism, and, consequently, they are an inadequate method of defining tectonic environments. The apparent immobility of REE at greenschist facies and the abundance of comparative data from various tectonic settings (for example, Schilling, 1971, 1973; Gast, 1968; Kay, Hubbard, and Gast, 1970) encouraged the use of REE and specific trace elements in the analysis of the Smartville complex.

THE SMARTVILLE OPHIOLITE

The analyzed samples were collected from the Smartville ophiolite, Sierra Nevada foothills, Calif. This area (fig. 1) was originally studied by Lindgren and Turner (1894, 1895) and received much attention because of the abundant gold-bearing placers. Recent studies have been more concerned with the tectonic evolution of the western Cordillera (Moores, 1970; Burchfiel and Davis, 1975; Schweikert and Cowan, 1975) and de-

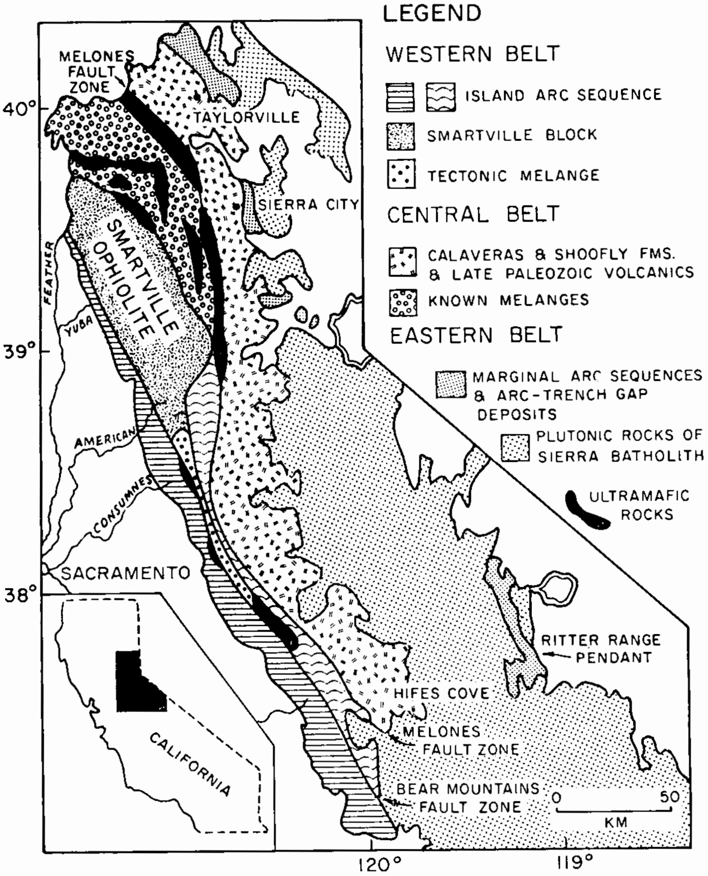

Fig. 1. Location map of the Smartville arc–ophiolite, northern Sierra Nevada, Calif. Tectonic data are taken from Schweickert and Cowan (1975).

tailed studies of the petrologic units (Cady, ms; Moores and Menzies, 1975; Menzies and others, 1975; Day, 1977; Buer, 1977; Kemp, 1977; Xenophontos and Bond, 1978).

The Smartville ophiolite, as originally defined by Menzies and others (1975) and Schweikert and Cowan (1975), is lenticular in shape (fig. 1) and is known to be an antiform with gently dipping limbs and a moderate plunge to the south. The ophiolite is bounded to the west by the "Bear Mountain Fault Zone" (fig. 1), until recently thought to be a major sutured boundary between ophiolitic rocks to the east and arc derived rocks to the west (Cady, 1975; Schweikert and Cowan, 1975; Moores and Menzies, 1975). Recent mapping, however, has shown that units to the west of the fault, or shear, zone have lithological equivalents to the east (Buer, 1977). Consequently it is now believed that only a moderate amount of movement occurred along this lineament, and that it is not a sutured boundary.

The lithological divisions of Menzies and Blanchard (1977) will be adopted throughout as representative of the major stratigraphic units of the area under discussion. These units are summarized in figure 2 and comprise: (A) an upper volcanic unit of volcanic-derived sedimentary rocks containing mafic and siliceous quartz-bearing clasts interbedded with differentiated flows (Xenophontos and Bond, 1978); (B) a lower

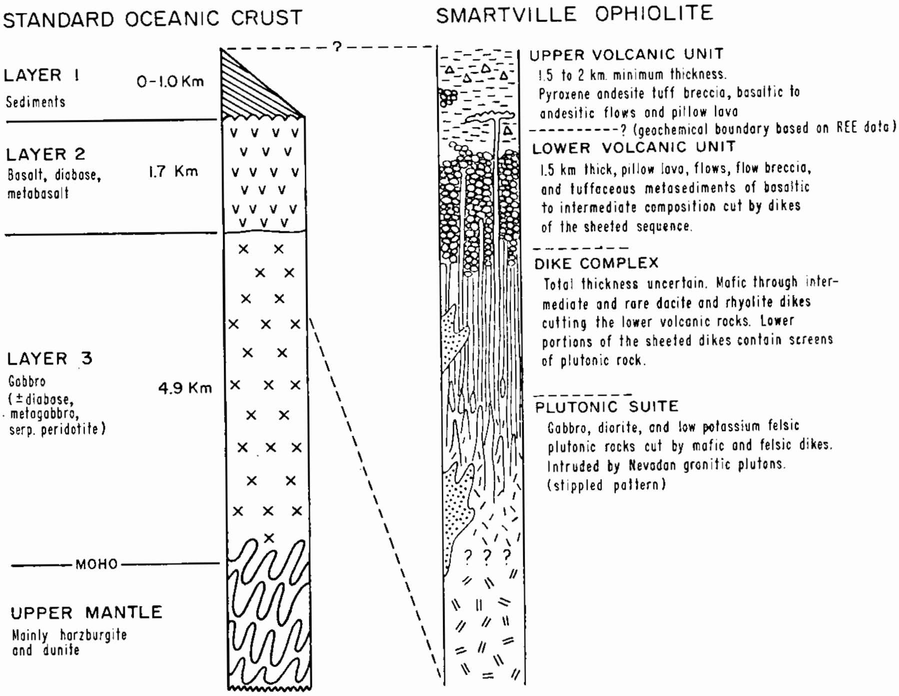

Fig. 2. Idealized columnar section of the Smartville arc–ophiolite. Geological data are from Menzies and others (1975) and Xenophontos (unpub.).

volcanic unit of pillowed and brecciated extrusives with minor sedimentary horizons; (C) a dike complex containing diabasic, andesitic, and dacitic intrusives in the northeastern portion (fig. 1) and quartz porphyries in the southeastern portion, and (D) a plutonic suite of trondjhemite, diorite, homogeneous gabbro, and layered anorthosite–gabbro–pyroxenite.

Upper volcanic unit.—Pillowed and massive lavas are abundant within this unit, intercalated with variable amounts of coarse sediments. The sediments vary from boulder to pebble size in the west to pebble and sand size in the east. Turbidites (with abundant tabular lithic fragments) and vesicular dacitic? extrusives are reported locally within this unit. These siliceous extrusives are overlain by sandstones and conglomerates deposited by sediment gravity flow (Xenophontos and Bond, 1978). In the southeastern part of the Smartville Complex the upper volcanic unit is predominantly coarse grained turbidites, while other sections contain mainly pillowed and massive lava flows. Although relationships between the upper and lower units have not been mapped in detail, it appears that the upper unit grades into the lower unit by a gradual decrease in the amount of sediment. Consequently the upper and lower volcanic units represent the products of coeval volcanism within a single volcanic terrane (Xenophontos and Bond, 1978).

Lower volcanic unit.—The lower unit is characterized by a predominance of pillowed lavas, massive flows, flow breccias, and cross-cutting intrusives, with minor felsic volcanic rocks (altered to quartz–albite schists) in areas of sulfide mineralization (Kemp, 1977). Although the majority of the felsic rocks are pyroclastic, quartz–albite porphyries have also been reported by Xenophontos and Bond (1978) and Kemp (1977). Tuffites and associated precipitates of iron and silica overlie pyrite–chalcopyrite lenses. Throughout the lower volcanic unit intercalations of chert, coarse clastic horizons, fine sand, and silt occur between the pillowed and massive flows. These lithologies are, however, volumetrically insignificant. Xenophontos and Bond (1978) describe local occurrences of channels filled with coarse clastics within pillowed lava flows.

Dike complex.—This unit contains dikes and sills that vary significantly in type from diabases and quartz porphyries to pyroxenitic dikes (Day, 1977). Some of the dikes, in particular the porphyries, also occur within the upper volcanic unit and may be associated with highly differentiated extrusive rocks. Contacts between the dike complex and the overlying lower volcanic unit are gradational, being marked by a gradual increase in the amount of interdike pillow basalt. Similarly the gradation downward into the plutonic suite is evident as an increase in interdike screens of trondjhemite, diorite, and gabbro.

Plutonic suite.—This unit is not fully exposed, as it represents the core to the antiform at Smartville. The exposed part of the plutonic suite is composed of trondjhemite, diorite, hornblende-pyroxene gabbro, interlayered anorthosite, pyroxene gabbro, and pyroxenite. The trondjhemite occurs as segregations within vari-textured diorite, and the diorite can be traced into hornblende-pyroxene gabbro and homogeneous pyroxene gabbro. However, the exact relationship of the layered gabbro unit to the rest of the complex remains unclear.

Samples 576-54 thru ARC 1 are taken from the upper volcanic unit and include volcaniclastic and volcanic rocks and a late high level intrusion that cuts the lower volcanic unit (L.V.U.). Samples 576-97a through 576-120 are taken from the lower volcanic unit and were chosen in the hope of defining chemical variations vertically and horizontally through the ophiolite. A22a through A116 represent early intrusive suites in the dike complex below the L.V.U., and A111 and B8 represent late cross-cutting dikes. D11a through SMV 278 represent the upper fractionated members of the plutonic suite. D11a occurs as segregations in C-5 which itself grades into SMV 278.

ANALYTICAL PROCEDURE

Weighted aliquots of powdered samples were analyzed for rare earth elements (REE) by instrumental neutron activation analysis (INAA) in the laboratories of the Planetary and Earth Sciences Division of the Johnson Space Center. Samples were irradiated for 28 to 42 hrs in the Texas A&M nuclear reactor. Analytical procedures were identical to those described in Jacobs and others (1977). United States Geological Survey standard rocks BCR-1 and DTS-1 were used as irradiation monitors. Values for these secondary standards were previously determined by radiochemical neutron activation analysis in this laboratory (Jacobs and others, 1977).

RESULTS

Rare earth element data for rocks from the Smartville ophiolite are reported in table 1. Figure 3 (foldout) shows the chondrite-normalized rare-earth patterns for the Upper Volcanic Unit. All five samples are light REE enriched having higher light REE values than middle to heavy REE (La/Sm = 2.14-2.59). Normalized values of La and Lu range from 18.69 to 35.07 $(La)_N$ and 6.97 to 10.52 $(Lu)_N$, respectively. The volcanic flows (576-60, 67(i), 67(ii)) and the high level intrusive dike (576-54) have similar

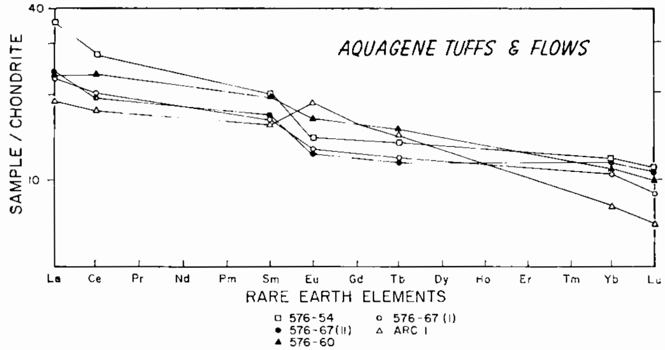

Fig. 3. Rare earth element distribution patterns for the upper volcanic unit (U.V.U.) of the Smartville arc–ophiolite.

TABLE 1
Rare earth element data (in ppm)

Upper Volcanic Unit

	576.67(1)	576-67(2)	576-60	576-54	ARC 1
La	7.9	7.5	7.6	11.6	6.2
Ce	17.2	17.5	20.6	24.1	15.3
Sm	3.1	2.9	3.6	3.5	2.8
Eu	0.83	0.99	1.1	0.95	1.2
Tb	0.55	0.55	0.66	0.63	0.66
Yb	2.2	2.0	2.2	2.3	1.5
Lu	0.36	0.29	0.33	0.36	0.24

Lower Volcanic Unit

	756-98b	576-101a	576-113	576-24b	376-120	576-20	576-97a	576-97b
La	4.6	2.1	5.6	3.9	3.5	3.4	4.2	7.3
Ce	13.1	5.8	15.8	12.6	9.1	10.1	13.5	23.1
Sm	3.5	1.3	3.7	3.8	2.8	3.1	4.2	7.2
Eu	1.3	0.48	1.2	1.5	0.97	0.98	1.5	2.8
Tb	0.85	0.38	0.84	1.0	0.68	0.70	0.95	1.5
Yb	2.6	1.19	2.86	3.2	2.4	2.6	3.2	5.9
Lu	0.43	0.19	0.45	0.49	0.38	0.41	0.52	0.90

Lower Volcanic Unit

	576-25a	576-28	12-19-20	25-32	576-92	576-126	576-122
La	3.5	3.1	4.4	24.1	2.7	3.2	3.4
Ce	8.9	8.5	8.9	5.9	11.5	9.6	9.7
Sm	2.3	2.6	2.2	2.4	3.1	2.6	2.5
Eu	0.86	0.89	0.77	0.83	1.1	0.92	0.85
Tb	—	0.62	0.59	0.66	0.66	0.61	0.56
Yb	2.2						
Lu	0.29	0.36	0.25	0.30	0.36	0.28	0.34

Dike Complex

	A22a	A116	B8	A111
La	16.2	4.7	5.6	20.6
Ce	44.1	15.8	17.8	57.2
Sm	9.4	4.8	5.1	9.4
Eu	2.5	1.6	1.5	1.4
Tb	2.2	1.2	—	2.02
Yb	8.3	3.9	4.1	9.4
Lu	1.2	0.54	0.59	1.4

Plutonic Members

	D-11a	C-5	SMV 278
La	11.5	2.0	1.3
Ce	40.3	1.9	3.5
Sm	10.8	2.7	1.2
Eu	2.1	0.97	0.68
Tb	2.6	0.63	0.34
Yb	10.7	2.2	1.1
Lu	1.6	0.32	0.16

profiles and may well be related. The andesitic breccia (ARC 1) is similar in REE characteristics except for a lower heavy REE content. Samples 576-67(i) and 576-67(ii) are glassy and porphyritic portions of the same rock, and they display almost identical REE abundances.

Figure 4 shows the rare-earth patterns for pillowed and massive lavas representing a vertical and lateral section through the lower volcanic unit (L.V.U.) of the ophiolite. All 15 samples are light REE depleted with lower light and heavy REE values relative to the middle REE (La/Sm = 1.01-1.54). $(La)_N$ ranges from 6.38 to 22.33, and $(Lu)_N$ ranges from 5.79 to 20.58. Negative europium anomalies are apparent in the majority of the samples. The most fractionated rock in the L.V.U. is the core of a plagioclase–phyric pillow (576-97b), and the least fractionated (576-101A) is a plagioclase–clinopyroxene phyric lava. Samples 576-97a and 576-97b represent rind and core samples of a single pillow. Each fragment has a similar La/Sm ratio and identical profile characteristics, but they differ greatly in their total REE contents (fig. 5).

The REE patterns for four samples from the Dike complex are shown in figure 6. The samples were chosen from late cross-cutting intrusives (A111 and B8) and early intrusions (A22a and A116). Both intrusive episodes contain light REE enriched and depleted dikes (table 1). The light REE enriched dikes have high ΣREE and negative europium anomalies with $(La)_N$ ranging from 49.09 to 62.43 and $(Yb)_N$ from 41.5 to 47.35. The light REE depleted dikes have lower ΣREE and negative europium anomalies. Both samples have light and heavy REE values lower than the middle REE values, somewhat similar to the lower volcanic unit. Data from other ophiolites are included on figure 5 for comparison.

Three samples from the plutonic suite (fig. 6) that underlies the dike complex were chosen since they display gradational contacts. The plagiogranite (D-11a) occurs as discrete segregations in the diorite (C-5) that

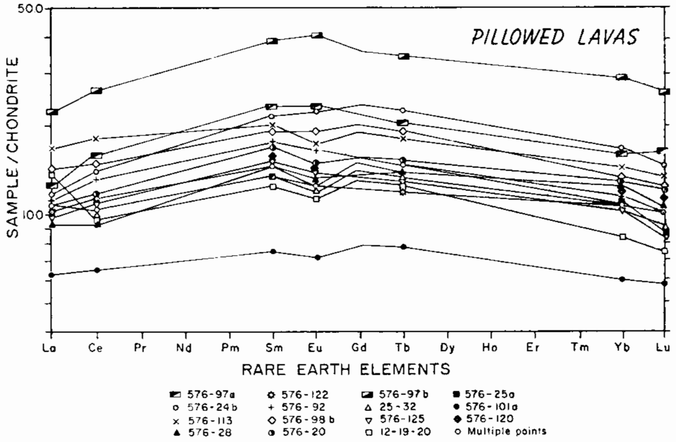

Fig. 4. Rare earth element distribution patterns for the lower volcanic unit (L.V.U.) of the Smartville arc–ophiolite.

grades into the gabbro (SMV 278). All three samples are light REE depleted with light and heavy REE values lower than middle REE values. $(La)_N$ ranges from 4.02 to 34.9 and $(Yb)_N$ from 5.62 to 53.9. A change from a positive to a negative europium anomaly is observed from the gabbro to the plagiogranite. Fractionated plutonic rocks from Troodos and Point Sal (Kay and Senechal, 1976; Menzies, Blanchard, and Jacobs, 1977) are included in figure 6 for comparison. The plagiogranite from Smartville has REE concentrations somewhat similar to those of an oceanic plagiogranite reported by Shih (ms).

REE MOBILITY

The analyzed lavas from Smartville have all been metamorphosed to greenschist facies, and consequently the concentrations of some elements may have changed from their original values. Studies of major and minor elements, summarized in table 2, indicate that because of their mobility during alteration their use in defining geochemical trends is somewhat limited.

Consideration of published REE analyses of metabasalts reveals that the following parameters are known to affect the mobility of trace and rare earth elements: (A) temperature: — zeolite versus greenschist facies (for example, Hermann, Potts, and Knake, 1974); (B) rock crystallization history (Frey, Bryan, and Thompson, 1974; Humphris, Morrison, and Thompson, 1978); and (C) length of time of exposure to seawater (Menzies and others, 1977).

In an attempt to assess the mobility of the REE a core and rind of a pillow were analyzed and a glassy and holocrystalline portion of another

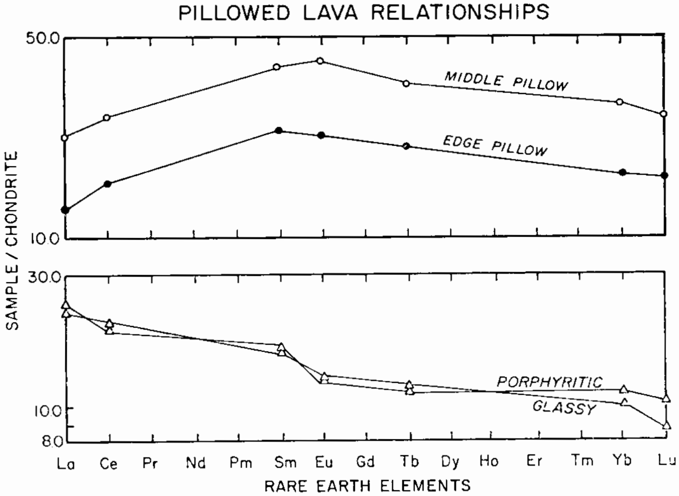

Fig. 5. Effect of alteration on the mobility of the REE. The *upper* figure represents a core and pillow rind, and the *lower* figure is a glassy and holocrystalline portion of the same pillow.

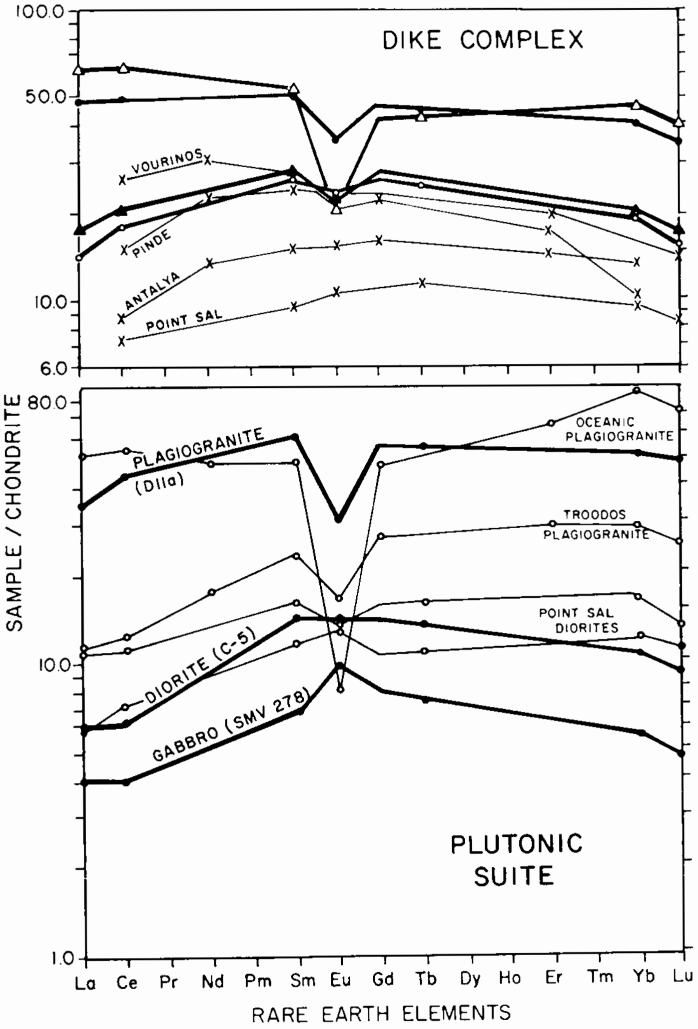

Fig. 6. Rare earth element distribution patterns for the Dike Complex (D.C.) and the plutonic suite of the Smartville arc–ophiolite. Comparative data in the upper figure are from Montigny (ms) and Menzies, Blanchard, and Jacobs (1977) and in the lower figure from Shih (ms), Kay and Senechal (1976), and Menzies, Blanchard, and Jacobs (1977).

pillow (fig. 5). There seems to be no preferential mobility of the light REE in the glassy portion of the pillow relative to the crystalline portion (fig. 5). This is also the case in the rind and core samples, although there is a vast difference in the level of enrichment (that is, ΣREE). The core and the rind have retained identical La/Sm ratios, and overall the REE profiles are parallel but at different levels of enrichment. Although such a feature is characteristic of the REE differences generated by fractional crystallization, extreme internal fractionation of olivine + clinopyroxene + plagioclase, as described by Yagi (1964) for Reykjanes tholeiites, has not been observed in these pillows. Consequently the observed patterns in the Smartville pillows may be the result of alteration. Hellmann and Henderson (1977) described REE variations in metabasalts, and they argue that alteration can elevate the ΣREE content producing REE trends that mimic differentiation systematics. Other studies, however, (Frey, Bryan, and Thompson, 1974; Wood, Gibson, and Thompson, 1976; Menzies, Blanchard, and Jacobs, 1977; Humphris, Morrison, and Thompson, 1978) indicate that the light REE are labile, and alteration produces very *irregular* REE patterns. Experimentally altered basalts are presently being analyzed for rare earth and trace elements in an attempt to evaluate REE mobility during alteration.

FRACTIONAL CRYSTALLIZATION

Petrographic studies of lavas from the lower volcanic unit of the Smartville ophiolite indicate that fractional crystallization of plagioclase–clinopyroxene–(olivine) has played an important role in generating the spectrum of tholeiitic lava compositions. For the majority of these plagioclase–(clinopyroxene) phyric lavas with high ΣREE, TiO_2, and low Cr_2O_3, plagioclase and clinopyroxene are the most important fractionating phases. Positive correlations exist between the level of REE enrichment and the content of FeO, TiO_2, and other elements; for example, the most fractionated lava contains 19.55 FeO and 8.7 Na_2O compared to the least fractionated lava that contains 7.35 FeO and 3.9 Na_2O. REE variations

TABLE 2
Major element data

	Upper Volcanic Unit[1]	Lower Volcanic Unit[2]
SiO_2	52.19-56.12	41.21-58.00
TiO_2	0.59- 0.75	0.41- 1.76
Al_2O_3	17.06-19.23	11.66-17.47
Fe_2O_3	6.53- 7.89	6.80-12.80
MgO	3.92- 4.84	2.88- 6.73
MnO	0.13- 0.17	0.14- 0.23
CaO	7.34- 9.01	3.88-18.07
K_2O	0.78- 1.32	0.01- 2.57
Na_2O	2.72- 3.71	2.14- 6.03
P_2O_5	0.17- 0.20	0.07- 0.18
Loss on ignition	2.74- 3.40	2.28-11.73

[1] Upper Volcanic Unit = calc-alkaline suite
[2] Lower Volcanic Unit = tholeiitic suite

in the lower volcanic unit are compatible with low presure crystallization models, similar to those proposed for European (Allegre, Montigny, and Bottinga, 1973) and California ophiolites (Menzies, Blanchard, and Jacobs, 1977). From previous studies (Schilling, 1971; Menzies and others, 1977) it is clear that the source for light REE depleted tholeiitic liquids is a light REE depleted peridotite with a REE abundance of 2 to 3× chondrite. Upon partial melting (20-30 percent), primary liquids at approx 10× chondrite (Allegre, Montigny, and Bottinga, 1973) will be generated. Removal of olivine–clinopyroxene–plagioclase cumulates from these primary liquids ($\geqslant$50 percent crystallization) is a process capable of producing the bulk of the Smartville metatholeiites.

If we assume a similar parental liquid for the plutonic suite (fig. 6), some constraints can be placed on the origin of the plagiogranite. Within the Smartville area plagiogranites occur either as segregations within the plutonic suite or as screens within the dike complex. Chemically, the Smartville plagiogranite is more fractionated than equivalents from Troodos (Kay and Senechal, 1976) or Point Sal, Calif. (Menzies, Blanchard, and Jacobs, 1977), but it is similar to an oceanic aplite (Shih, ms). Although, the marked negative europium anomaly in oceanic aplites cannot be reproduced by simple fractionation models (Shih, ms), similar models (for example, Allegre, Montigny, and Bottinga, 1973) adequately reproduce the REE abundance profiles of ophiolitic plagiogranites after $\geqslant$90 percent solidification. This is compatible with field observations, since the plagiogranite occurs as small irregular bodies within vari-textured diorites. The vari-texture is probably produced by a sporadic distribution of fluids and volatiles, particularly common in rocks formed during a late stage of fractionation. Similarly, Allen (ms) invoked fractional crystallization for the origin of the Troodos plagiogranites, but he did admit that other mechanisms, for example, liquid immiscibility, could account for the divergent iron and alkali trends on AFM diagrams, segregation textures, and iron-rich cumulates (Allen, ms). Liquid immiscibility was recently invoked (McBirney and Nakamura, 1974) to explain the origin of similar felsic rocks in the Skaergaard stratiform intrusion, Greenland. In the case of Smartville, however, fractional crystallization and subsequent entrapment of late stage liquids as segregations in chemically evolved rocks (diorites) adequately explain the origin of plagiogranite.

Since the upper volcanic unit comprises abundant sedimentary volcanic rocks and very few extrusive or intrusive rocks, it is difficult to evaluate the genesis of these light REE enriched lavas on the basis of a few samples. We can surmise from the limited data that the source for the upper volcanic rocks is somewhat different from that of the tholeiites. The calc–alkaline volcanics have a La/Sm ratio of 2.14 to 2.59 compared with a La/Sm ratio of 1.01 to 1.54 for the tholeiites. Such a marked difference in REE characteristics cannot be produced by fractionation models.

PALEOGEOGRAPHY AND TECTONIC SETTING

Sediments

Detailed studies of the petrology, sedimentation, and paleogeography of the Smartville ophiolite and the surrounding area indicate that the ophiolite did not form in a conventional ocean ridge or a mature back arc basin (Xenophontos and Bond, 1978). The sedimentary rocks of the Smartville ophiolite can be categorized as non-pumiceous and pumice-bearing types. All sediments are texturally immature, since pebble and sand grains are angular, and many mineral grains are almost perfect euhedra. The occurrence of needle-sharp edges typical of shattered crystals shows that these sediments have been transported only a short distance. Most of the sedimentary rocks are poorly sorted containing very coarse and very fine material. The angularity of the clasts and existence of volcanic lithic fragments and pumice suggests that the Smartville sediments were produced by volcanic processes such as submarine explosions and autobrecciation of intrusives and extrusives (Xenophontos and Bond, 1978). It is postulated that the ophiolite formed close to, or possibly within, a group of active volcanoes (fig. 7). This is compatible with the abundance of coarse volcanic derived pumiceous sediments and coarse volcanic clasts, the deposition of the sediments in channels cut into steep slopes (flanks to volcanoes?), and the basaltic, andesitic, and dacitic composition of the clasts. The abundance of pumice in the sediments led Xenophontos and Bond (1978) to postulate further that some of the active vents must have been above sealevel or in shallow-water. Such an environment provides the large expansion of gas needed to produce pumice. If any of the vents were sub-areal, marginal beaches must have been rare or absent, since the lack of textural maturity in the sediments precludes river or marine transportation.

Sulfide mineralization.—The preceding paleogeographic assessment of the Smartville terrain is compatible with that invoked by Kemp and

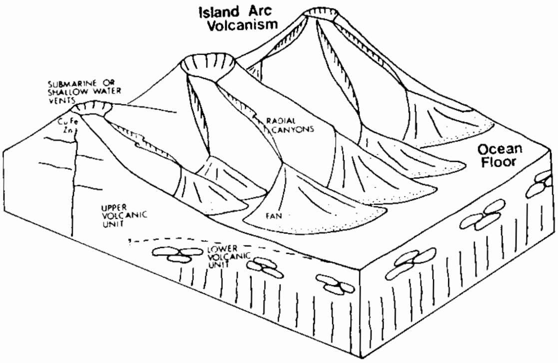

Fig. 7. Tectonic setting of the Smartville ophiolite on the flanks of an island arc (modified after Xenophontos and Bond, 1978). Note that the calk-alkaline submarine vents are the source of the copper mineralization and much of the volcanic clasts and pumice found in sediments overlying the tholeiitic lower volcanic unit.

Payne (1975) for the sulfide mineralization at Smartville. Stratabound bodies of pyrite, chalcopyrite, and pyrrhotite and accompanying alteration are interpreted by Kemp (1977) as products of subaqueous fumarolic activity (fig. 8) intimately associated with calc–alkaline (dacitic to rhyolitic) explosive volcanism. Many of the sulfide lenses occur within permeable felsic pyroclastics and are overlain by a mixture of volcanic ash, devitrified glass, and precipitates of iron and silica. The sulfide lenses occur within both the upper and lower volcanic unit in zones (sometimes pipe-like) of pervasively altered rock. Such an occurrence is similar, if not identical, to other massive sulfide deposits related to calc–alkaline volcanism, for example, Kuroko, Japan or Noranda, Canada (Kemp, 1977).

Volcanic rocks.—It seems clear from the detailed studies of the sediments and ore deposits intimately associated with the Smartville ophiolite that the complex formed close to a line of active volcanoes. This helps constrain the tectonic setting to that of a young inter-arc basin, the edge of a marginal basin close to an arc or the flanks of an island-arc (Menzies and Blanchard, 1977; Xenophontos, Moores, and Menzies, 1978). We can now evaluate the extent to which the chemistry of the volcanic rocks is compatible with such a model.

Studies of island arc volcanic rocks (Jakeš and White, 1969; Jakeš and Gill, 1970; Gill, 1970) have produced single and multiple stage models (Ringwood, 1974; Kay, 1977; DePaolo and Wasserburg, 1977). On the basis of rare earth and trace element concentrations, Jakeš and Gill (1970) defined an early cycle of volcanic activity characterized by light REE depleted tholeiites (island-arc tholeiites) and a later cycle of light REE enriched calc–alkaline volcanism. This is compatible with the coeval calc–alkaline and tholeiitic volcanism at Smartville. In general, tholeiitic arc rocks have low abundances of incompatible elements (10-30× chondrite), low K/Na ratios, and SiO_2 content of approx 55 percent (Ringwood, 1974). Island-arc tholeiites are in most instances indistinguishable from ridge tholeiites. The calc–alkaline rocks, however, have a higher relative abundance of the incompatible elements (30-100× chondrite), high K/Na ratios, and an SiO_2 content of approx 60 percent. The chemistry of all island-arcs do not, however, fit into this rather generalized model (Arculus and Johnson, 1978).

Comparison of the REE distribution patterns of the Smartville tholeiitic and calc–alkaline rocks with volcanic rocks from known tectonic settings betrays the inadequacy of REE as a discriminant of tectonic environment. The Smartville tholeiitic pillow lavas have higher La/Sm ratios (La/Sm = 1.01-1.54) than the majority of mid-ocean ridge tholeiites (La/Sm = 0.38-1.06) reported by Bryan and others (1976) from the Atlantic, Pacific, and Indian Oceans. However, Blanchard and others (1976) reported highly fractionated plagioclase-accumulative basalts from near the FAMOUS area that display higher La/Sm ratios (La/Sm = 1.5-1.65) A similar comparison with other ophiolitic lavas (Menzies, 1976; Smewing and Potts, 1976; Kay and Senechal, 1976; Montigny, ms; Menzies, Blanchard, and Jacobs, 1977) reveals that the Smartville tholeiites are somewhat more fractionated and have a higher La/Sm ratio than the majority of ophiolite metatholeiites. Similarly the association of light REE enriched (La/Sm = 1.01-1.54) and light REE depleted (La/Sm = 2.14-2.59) volcanic rocks can evolve in a variety of tectonic settings. For example, Fleet, Henderson, and Kempe (1976) reported pyroclastics, associated with oceanic tholeiites, from the Indian Ocean that have a REE content similar to the Smartville pyroclastic rocks. However, volcanic rocks from the Mid-Atlantic ridge and Azores (Bryan and others, 1976), Discovery Seamount (Kempe and Schilling, 1974), and oceanic island arcs (Jakeš and Gill, 1970) all have REE chemistries comparable to the Smartville rocks.

CONCLUSIONS

No aspect of the trace and rare earth element chemistry of volcanic rocks from the Smartville ophiolite, Calif. will uniquely define a tectonic setting. The coeval nature of the calc–alkaline and tholeiitic volcanism is compatible with various oceanic environments. However, geochemical evidence combined with detailed investigations of the environment of formation of the volcanic sediments and the sulfide ore deposits can constrain the tectonic setting to that of an island arc.

The Smartville ophiolite is postulated to have formed close to a line of active calc–alkaline volcanoes, some of which were at or near sealevel. Resultant explosive sub-aqueous calc–alkaline volcanism deposited sulfide ores in and around active fumaroles and produced the abundance of pumice now present in the sediments. Vast quantities of volcanic debris were swept down the flanks of these calc–alkaline volcanoes forming sediment fans over nearby tholeiitic basement rocks. The coeval nature of the tholeiitic and calc–alkaline volcanism implies that both episodes of volcanism occurred within the arc environment.

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