Geochemical evidence for the tectonic setting of the Coast Range ophiolite: A composite island arc–oceanic crust terrane in western California

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ABSTRACT

The Middle to Late Jurassic age Coast Range ophiolite (CRO) of California contains two geochemically distinct volcanic rock associations that formed in different tectonic settings. Volcanic rocks from the southern CRO (Point Sal, Cuesta Ridge, Stanley Mountain, Llanada, Quinto Creek, and Del Puerto) and parts of the northern CRO (Healdsburg, Elder Creek) are similar to low-K tholeiites and calc-alkaline rocks of the island-arc suite. The thin volcanic sections of these ophiolite remnants suggest formation by intra-arc rifting. In contrast, volcanic rocks from Stonyford seamount and Paskenta in the northern CRO are transitional subalkaline metabasalts with geochemical characteristics similar to enriched mid-ocean ridge basalts or ocean-island tholeiites. These rocks are associated with Tithonian radiolarian cherts and may be part of the Franciscan Complex. Alternatively, they may represent a change in tectonic setting within the CRO during the Late Jurassic. Regardless, the CRO as currently conceived cannot be considered a single terrane with one mode of origin.

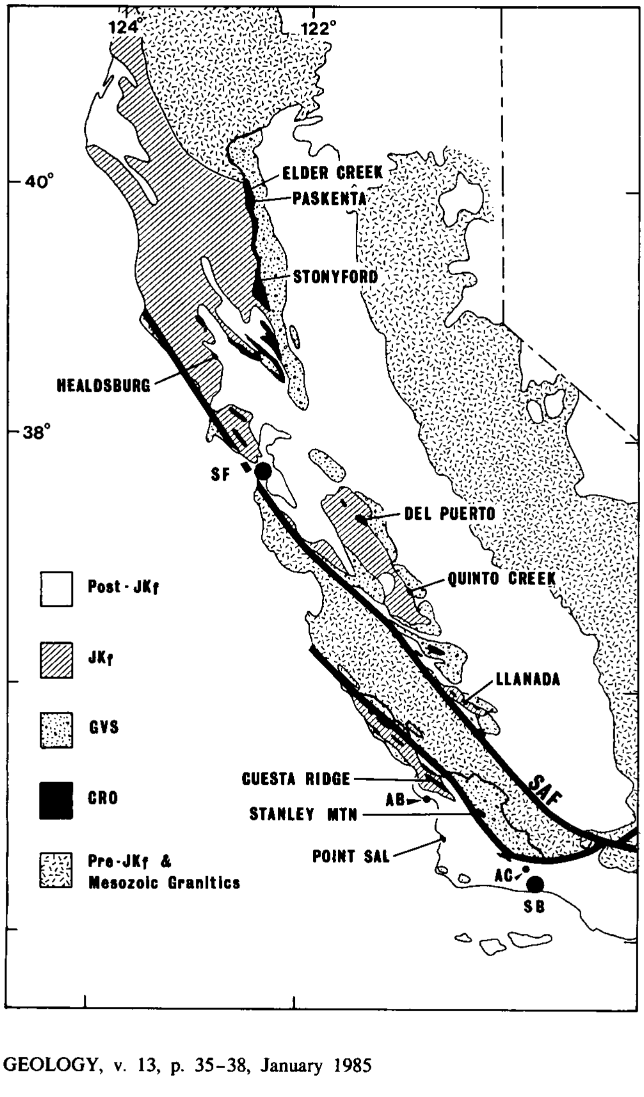

Figure 1. Simplified geologic map of California showing Coast Range ophiolite (CRO) localities discussed in text. Franciscan greenstone localities: AB = Avila Beach, AC = Aliso Canyon. Other abbreviations: JKF = Franciscan Complex, GVS = Great Valley Sequence, SAF = San Andreas fault, SB = Santa Barbara, SF = San Francisco.

INTRODUCTION

The Cost Range ophiolite (CRO) of California is an assemblage of ultramafic, mafic, and minor felsic igneous rocks that are present in scattered localities over a 700-km-long segment of the California Coast Ranges. The tectonically disrupted and incomplete remnants of this ophiolite are depositionally overlain by Upper Jurassic terrigenous strata of the Great Valley Sequence and are in tectonic contact with Jurassic and younger rocks of the Franciscan Complex. A generalized stratigraphy for the ophiolite may be reconstructed from these dismembered remnants, consisting of serpentinized peridotite, pyroxenite, gabbro, minor diorite and plagiogranite, diabasic to microdioritic dike and sill complexes, and submarine volcanic rocks overlain by tuffaceous radiolarian chert (Bailey et al., 1970; Hopson et al., 1981). This lithologic succession is characteristic of ophiolite complexes and is similar to that inferred for oceanic crust. Zircon U-Pb isotopic ages from plagiogranites indicate that the CRO formed during a limited time period in the Middle to Late Jurassic, between 170 and 160 Ma (Hopson et al., 1981; J. M. Mattinson, 1984, personal commun.)

The CRO is an important tectonic element in California geology, and knowledge of its original tectonic setting is fundamental to understanding the Middle and Late Jurassic evolution of the Cordilleran margin. The CRO was originally recognized by Bailey et al. (1970), who suggested that it represents Mesozoic ocean crust upon which the Great Valley Sequence was deposited, and that juxtaposition with the Franciscan Complex occurred by eastward-directed underthrusting of the Franciscan rocks. This interpretation was largely supported by Hopson et al. (1981) in a detailed evaluation of 23 separate exposures that span the entire length of the CRO, ranging from Santa Barbara County in the south to Elder Creek in the north (Fig. 1).

This conclusion is controversial, however. Although origin of the CRO at a mid-ocean spreading center is inferred by many investigators (Bailey et al., 1970; Page, 1972; Bailey and Blake, 1974; Pike, 1974; Hopson and Frano, 1977; Hopson et al., 1981), others interpret the

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petrologic and stratigraphic relationships found at some locations to require an origin related to an island-arc setting (Evarts, 1977; Blake and Jones, 1981; Saleeby, 1981; Shervais and Kimbrough, 1983a). These contrasting interpretations have profoundly different implications for paleogeographic reconstructions of the western cordillera during the Mesozoic.

In order to test conflicting models for the origin of the Coast Range ophiolite, we have undertaken a geochemical reconnaissance of volcanic rocks from 10 CRO localities, shown in Figure 1. A detailed evaluation of these data will be presented elsewhere. In the following synopsis, we summarize the published field relationships of these rocks, some aspects of their major- and trace-element geochemistry, and the composition of unaltered clinopyroxene phenocrysts. We then discuss the implications these data have for possible origins of the CRO.

FIELD RELATIONS

Remnants of the Coast Range ophiolite may be divided into two geographic groups for purposes of discussion: (1) those north of San Francisco Bay constitute the northern CRO; (2) those south and east of the bay constitute the southern CRO. In this study the northern CRO is represented by the Healdsburg, Stonyford, Paskenta, and Elder Creek remnants; the southern CRO is represented by locations in the Diablo Range (Del Puerto, Quinto Creek, Llanada) and in the southern Coast Range (Cuesta Ridge, Stanley Mountain, Point Sal). The following summary of field relations is based mainly on detailed investigations by Bailey et al. (1970), Page (1972), Hopson and Frano (1977), Evarts (1977), Emerson (1979), Hopson et al. (1981), and MacPherson (1983).

The southern CRO includes six relatively large remnants of partially intact ophiolite, shown in Figure 1, and numerous smaller fragments that are largely incomplete. All have been disrupted by faulting to various degrees, and only two (Point Sal, Del Puerto) possess all of the lithologic components of an idealized ophiolite section. The volcanic sections of these remnants vary mainly in their thickness and composition (Hopson et al., 1981). The volcanic sections at Point Sal, Cuesta Ridge, Stanley Mountain, and Quinto Creek range in thickness from 0.3 to 1.35 km and consist mainly of pillowed and massive flows of spilite and keratophyre; quartz keratophyre is rare (Page, 1972; Hopson et al., 1981). The volcanic sections at Llanada (1.75 km thick) and Del Puerto (2.5 km thick) are thicker than those at other southern CRO localities and include abundant volcanic breccias that generally overlie mafic flows (Evarts, 1977; Emerson, 1979; Hopson et al., 1981). These sections contain abundant keratophyre, but spilite and quartz keratophyre are also common (Evarts, 1977; Emerson, 1979).

The northern CRO remnants vary widely in their field occurrence. Locations just north of San Francisco Bay (e.g., Healdsburg) have been affected by extensive Tertiary faulting, and only small remnants are preserved. Relatively intact slabs of ophiolite are found along the south fork of Elder Creek, near Paskenta. The lithologic succession in the Healdsburg and Elder Creek occurrences is similar to that found in the southern CRO, including the presence of keratophyre in the volcanic section (Bailey et al., 1970; Bailey and Blake, 1974; Hopson et al., 1981). Southward from Paskenta along the western side of the Sacramento Valley, the northern CRO is represented by a serpentinite-matrix melange containing scattered blocks and knockers of ophiolite-derived lithologies, mainly pillow lava. Chert blocks within this melange contain a Tithonian radiolarian fauna similar to that found in Franciscan cherts (Blake et al., 1984). At the southern end of the serpentinite melange belt, the Stonyford seamount (named by Hopson et al., 1981) forms a fault-bounded klippe comprising 2–3 km of pillow basalt (Hopson et al., 1981; MacPherson, 1983). On the basis of incipient development of high-pressure mineral assemblages and on the younger (Tithonian) age of associated cherts, MacPherson (1983) has correlated the Stonyford seamount (his "Snow Mtn. Complex") with the Franciscan Complex. We consider this possibility below.

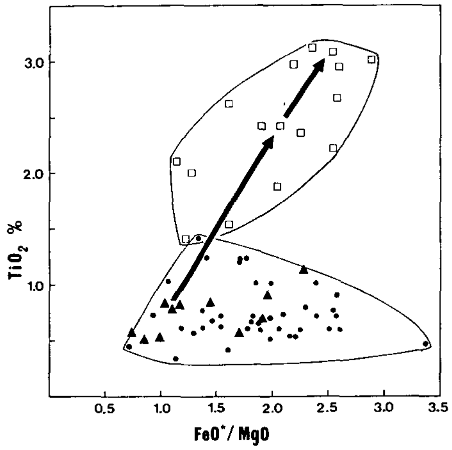

Figure 2. Plot of TiO_2 vs. FeO*/MgO for Stonyford and Paskenta in northern CRO (open squares), Healdsburg and Elder Creek in northern CRO (solid triangles), and southern CRO (solid dots). Heavy arrow shows trend for open-system fractionation of MORB. Data from Bailey and Blake (1974), Pike (1974), Evarts (1977), Hopson and Frano (1977), and this study.

PETROLOGY AND GEOCHEMISTRY OF THE VOLCANIC ROCKS

Twenty-three samples of metavolcanic rocks were selected from the collections of C. A. Hopson for analysis of 10 major elements and 20 trace elements by X-ray fluorescence. Ferrous iron and CO_2 were determined by wet chemistry, and H_2O by difference from the ignition loss. In addition, we collected nine Franciscan greenstones from the southern Coast Range and six Jurassic metavolcanic rocks from the western Sierra Nevada foothills to analyze for comparison. Additional data have been compiled from the literature (Bailey and Blake, 1974; Pike, 1974; Evarts, 1977; Hopson and Frano, 1977).

Volcanic rocks from the northern CRO and the southern CRO have fundamentally different major-element compositions that reflect differences in their liquid lines of descent. Volcanic rocks from the southern CRO are all subalkaline and include greenschist-facies spilites (basalts?), keratophyres (andesites?), and quartz keratophyres (dacites?). In contrast, volcanic rocks from the northern CRO form two distinct groups. Samples from the Healdsburg and Elder Creek ophiolite remnants include subalkaline spilites and keratophyres similar to those from the southern CRO. Greenschist-

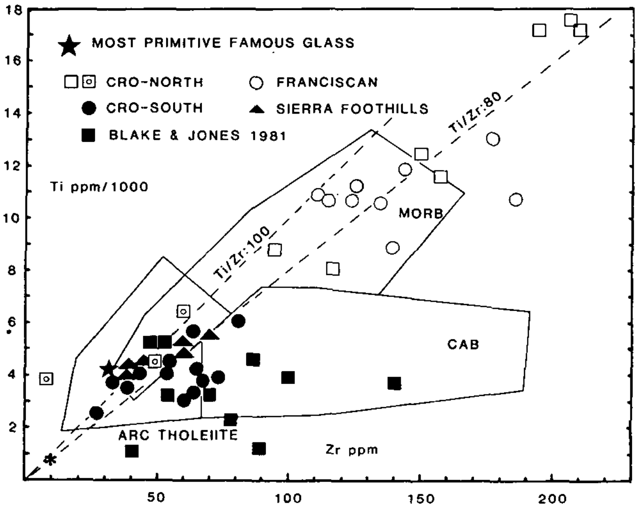

Figure 3. Ti-Zr plot after Pearce and Cann (1973). Data for CRO compared to Franciscan and Logtown Ridge (Sierra Nevada Foothills) greenstones. In northern CRO, open squares = Stonyford and Paskenta; circles in squares = Healdsburg and Elder Creek. Data from this study and Blake and Jones (1981).

facies spilites from Stonyford seamount and from melange blocks near Paskenta are transitional subalkaline metabasalts similar to Franciscan greenstones from Avila Beach and Aliso Canyon in the southern Coast Range (Shervais and Kimbrough, 1984). The difference in fractionation trends between these two groups is illustrated by a plot of TiO_2 vs. FeO*/MgO, parameters that are less susceptible to alteration than other major elements (Fig. 2). The transitional subalkaline spilites from Stonyford and Paskenta in the northern CRO show a rapid increase in TiO_2 as FeO*/MgO increases, similar to that observed during the open-system fractionation of mid-ocean ridge basalt (MORB). In contrast, metavolcanic rocks from the southern CRO and from Healdsburg and Elder Creek in the northern CRO have low TiO_2 contents that do not increase with increasing FeO*/MgO (Fig. 2). As pointed out by Miyashiro (1973), this fractionation trend is characteristic of island-arc volcanic rocks.

However, volcanic and shallow intrusive rocks from throughout the CRO have been subject to hydrothermal alteration under low-greenschist-facies conditions (e.g., Evarts and Schiffman, 1983; Shervais and Kimbrough, 1983b). This alteration has resulted in extensive reconstitution of the primary igneous phases and mobilization of the more labile major and trace elements. Mineralogical changes observed in CRO volcanic rocks include the alteration of plagioclase to albite and the replacement of plagioclase, olivine, and glass by single-phase or multiphase assemblages of serpentine, calcite, quartz, chlorite, epidote, sphene, pumpellyite, and clay minerals. Clinopyroxene is the only major primary phase that is characteristically unaltered. The variable extent and intensity of this alteration limits the usefulness of major-element geochemistry in determining the original chemical affinities of these rocks. Nonetheless, trace-element and pyroxene compositional data discussed below support the subdivision of the volcanic rocks into two groups based on TiO_2 and FeO*/MgO variations.

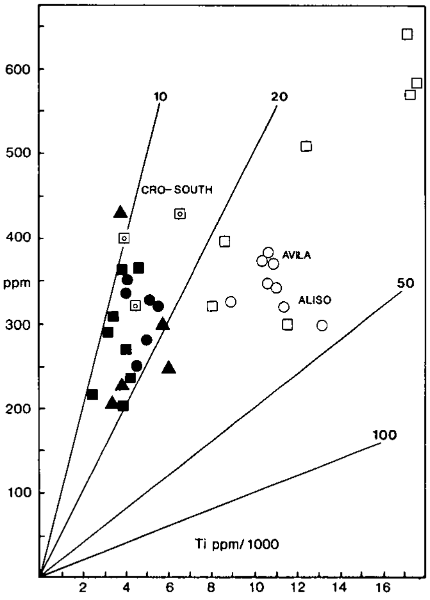

Figure 4. Plot of Ti vs. V, after Shervais (1982). Volcanic rocks from southern CRO (solid squares and triangles) and arc-related pillow basalts from Sierra Nevada Foothills (solid circles) have low Ti/V ratios, similar to island-arc tholeiites. Healdsburg and Elder Creek (circles in squares) in northern CRO also have low Ti/V ratios and are related to island-arc volcanism. In contrast, greenstones from Stonyford and Paskenta (open squares) have Ti/V ratios between 20 and 45, similar to Franciscan greenstones from Avila Beach and Aliso Canyon (open circles). These Ti/V ratios are characteristic of oceanic tholeiites and transitional basalts.

TRACE-ELEMENT GEOCHEMISTRY

Trace and minor elements that are immobile during low-temperature metamorphism have been used successfully as discriminants of ophiolite petrogenesis, a technique pioneered by Pearce and Cann (1973). Commonly used elements include Ti, Zr, Y, Cr, and the rare earth elements (REE). However, plots involving Y cannot be used in the southern CRO because this element has been leached by carbonate-rich alkaline solutions (Shervais and Kimbrough, 1983b).

Trace-element data for CRO volcanic rocks is sparse. In addition to our data (23 analyses), Menzies et al. (1977) have reported REE data for 13 spilites from Point Sal, Blake and Jones (1981) have published REE and other trace-element data for 10 CRO lavas, mostly keratophyres, and Williams (1983) reported unpublished trace-element data for one basalt and nine dike rocks from a newly described ophiolite remnant near Mount Diablo.

All volcanic rocks from the CRO with the exception of some keratophyres and quartz keratophyres have Ti/Zr ratios in the same range of MORB (Pearce and Cann, 1973; Fig. 3). Northern CRO volcanic rocks from Stonyford and the Paskenta melange blocks are high in both Ti and Zr and are enriched in light REE, with chondrite-normalized La/Zr = 2.5–4.5, similar to either enriched MORB or ocean-island tholeiites (Pearce and Cann, 1973). Southern CRO volcanic rocks and those from Healdsburg and Elder Creek in the northern CRO are low in Ti and Zr and tend to have flat REE patterns (chondrite-normalized La/Zr = 0.9–1.5), similar to normal MORB or island-arc tholeiites.

A plot of Ti vs. V (Fig. 4) is useful in distinguishing MORB from island-arc volcanic rocks. Shervais (1982) has shown that the fractionation of V from Ti during partial melting and fractional crystallization is a function of oxygen fugacity, and that Ti/V ratios of volcanic rocks increase in the order island-arc volcanic < MORB < alkali basalts. All volcanic rocks from the southern CRO and those from Healdsburg and Elder Creek in the northern CRO have Ti/V < 25, characteristic of island-arc tholeiites and some back-arc basin basalts. Northern CRO volcanic rocks from Stonyford and Paskenta have Ti/V = 20–40, similar to both normal and enriched MORB, ocean-island tholeiites, and most back-arc basin basalts (Shervais, 1982). They are also similar to mildly alkaline and transitional subalkaline Franciscan greenstones from Avila Beach and Aliso Canyon in the southern Coast Range (Shervais and Kimbrough, 1984). The compositional similarity of the Stonyford and Paskenta spilites to Franciscan volcanic rocks suggests that these rocks may be part of the Franciscan Complex and not true CRO. MacPherson (1983) has made this correlation

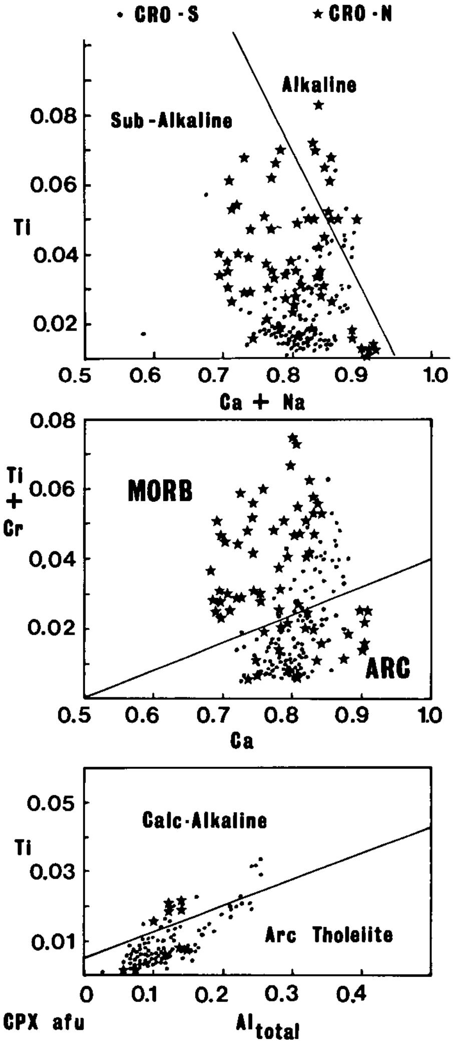

Figure 5. Clinopyroxene phenocryst compositions (in atomic formula units/6 oxygens) plotted on discriminant diagrams of Letterier et al. (1982). Stars = northern CRO; dots = southern CRO. Middle diagram contains only "subalkaline" compositions from top diagram; bottom diagram contains only "arc" compositions from middle diagram.

for the Stonyford seamount; our data extend it to the Paskenta melange blocks.

PYROXENE CHEMISTRY

The minor-element content of clinopyroxene is sensitive to that of the parent magma and may be used to distinguish pyroxenes from different tectonic settings (Nisbet and Pearce, 1977; Leterrier et al., 1982). This technique is especially useful in the evaluation of altered rocks in which whole-rock data are suspect. We have analyzed 191 clinopyroxene phenocrysts from 28 CRO volcanic rocks. Clinopyroxenes from Stonyford and Paskenta in the northern CRO have compositions transitional between subalkaline and alkaline pyroxenes, with affinities to subalkaline oceanic basalts (Fig. 5). Clinopyroxenes from the southern CRO and from Healdsburg and Elder Creek in the northern CRO are consistently subalkaline and are similar to those of island-arc tholeiites. They are distinct from both oceanic and alkalic clinopyroxenes (Fig. 5). These results correlate with whole-rock major- and trace-element compositions. Thus, at 8 of the 10 localities studied here, the clinopyroxenes are similar to those found in island-arc volcanic rocks, whereas the others resemble oceanic basalts.

DISCUSSION

Volcanic rocks from ophiolite remnants in the southern CRO and from the Healdsburg and Elder Creek remnants in the northern CRO are geochemically similar to one another and to rock associations found in immature island arcs. The idea that parts of the CRO formed in an island arc was first proposed by Evarts (1977) for the Del Puerto locality. Our data show that 8 of the 10 localities studied here are geochemically similar and evidently formed in an island-arc setting. However, they are stratigraphically thinner than the crust usually found in island arcs and are even thin compared to standard ocean crust (Hopson et al., 1981). The volcanic sections at Point Sal and Cuesta Ridge include Cr-rich, olivine-clinopyroxene phyric basalts that are compositionally similar to boninites and arc-related ankaramites. These features suggest that parts of the CRO formed by intra-arc or fore-arc rifting. Major volcanic centers in the Diablo Range (Del Puerto and Llanada) are separated by ophiolite with a thin volcanic section and little pyroclastic sedimentation (Quinto Creek). These differences may represent a primary feature of ophiolite formation in an incipient or rifted island-arc setting where arc volcanic centers are separated by thinner, marginal basin-type crust. In contrast, volcanic rocks from the Stonyford seamount and the Paskenta melange blocks are transitional subalkaline basalts that are compositionally similar to enriched MORB or ocean-island tholeiites. These rocks are also similar both geochemically and petrographically to mildly alkaline and transitional subalkaline volcanic rocks found within the Franciscan Complex at Avila Beach and Aliso Canyon in the southern Coast Range (Shervais and Kimbrough, 1984). MacPherson (1983) has argued convincingly for correlation of the Stonyford seamount (Snow Mountain Complex) with the Franciscan Complex. This interpretation is supported by our data and by the association of the Stonyford and Paskenta volcanic rocks with radiolarian cherts of Tithonian age (Blake et al., 1984). However, at the recently described Mount Diablo ophiolite remnant, pillow basalts and diabase dikes that are geochemically similar to normal MORB crosscut older dike rocks with island arc–type geochemistry (Williams, 1983). These relationships suggest a change in tectonic setting from island-arc to back-arc basin. The Stonyford and Paskenta volcanic rocks may represent a similar change in tectonic setting, the younger seamount volcanism being superimposed on the older arc-related volcanic sequence.

Formation of the entire CRO inboard and above an eastward-dipping subduction zone is supported by the occurrence of blueschist and eclogite facies clasts in the eastern part of the Franciscan Complex that range in age from 150 to 160 Ma (Coleman and Lanphere, 1971; Suppe and Armstrong, 1972; Mattinson, 1981). These overlap the age of the CRO and imply that a mid-Jurassic subduction zone lay in a position analogous to that of the Franciscan rocks now, *west* of the CRO as currently exposed.

SUMMARY

The geochemical data presented above indicate that at least two separate volcanic associations are present in what heretofore has been considered the CRO: (1) an older, Middle Jurassic association related to island-arc volcanism and (2) a younger, Late Jurassic association with oceanic affinities. Geochemical and stratigraphic relationships of the island-arc association suggest formation of these rocks by arc volcanism and intra-arc rifting. In contrast, geochemical and field evidence suggest that the oceanic assemblages found at Stonyford and Paskenta may be part of the Franciscan Complex and represent seamount and possibly spreading-center volcanism.

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