San Quintín volcanic field, Baja California, Mexico: 'within-plate' magmatism following ridge subduction

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ABSTRACT

The Holocene San Quintín volcanic province in northern Baja California comprises spinel-lherzolite-bearing alkali basalts. Trace element (La/Nb = 0.57–0.73; K/Rb = 402–479; La/Yb = 8.4, 9.9) and isotopic ratios (87Sr/86Sr = 0.70323–0.70352; 143Nd/144Nd = 0.512924–0.512996; 206Pb/204Pb = 19.108, 19.250; 207Pb/204Pb = 15.567, 15.589; 208Pb/204Pb = 38.82, 38.85) show that the lavas are compositionally indistinguishable from some ocean island, plume-associated basalts such as Hawaii and the Azores, and testify to an asthenospheric source for the magmas. The occurrence in Baja of such lavas may be related to the nature of the cessation of plate subduction beneath the peninsula; at present, San Quintín (and volcanic provinces to the north) are underlain by a 'no-slab window', whereas immediately to the south, remanent oceanic lithosphere may be preserved as a relict slab. This may act as a barrier to the upward passage of diapirs or magmas from the asthenosphere.


INTRODUCTION

The major and trace element characteristics of volcanism associated with subduction of oceanic lithosphere are well documented. Less well understood is the nature of magmatism following the interaction of an oceanic spreading centre with a volcanic arc. One area suitable for such a study is the peninsula of Baja California in north-west Mexico. Here subduction, which had been operating from Cretaceous times, ceased about 12 Myr ago in response to ridge/trench collision. Post-subduction volcanism in Baja California has since been confined to a series of discrete fields along the peninsula. These Miocene to Holocene volcanic rocks show compositional variations concomitant with the changing tectonic regime (Rogers et al., 1985; Saunders et al., 1987; Rogers and Saunders, 1989; Rogers et al., in prep.).

Here we focus upon the origin of the northernmost of these volcanic centres, the alkali basalts of the San Quintín field (Fig. 1). The lavas of this small volcanic province are apparently unique within the Baja region, being spinel-lherzolite-bearing alkali basalts with incompatible trace element abundances similar to ocean island basalts (OIB). They thus appear to represent melting of the asthenosphere, very similar to some Basin and Range lavas found in the USA (Menzies et al., 1983; Fitton et al., 1988; Orme ro et al., 1988). It is this association of OIB-type magmatism with a site of cessation of subduction, and in particular with a region of ridge subduction, that forms the main interest of this paper.

TECTONIC FRAMEWORK OF BAJA CALIFORNIA

The margin of northwestern Mexico and western USA underwent a major change of plate configuration during mid- to late-Tertiary times, when it transformed from a convergent to a strike-slip plate boundary. Collision of the ancestral East Pacific Rise (EPR) with the North American Plate at about 29 Myr resulted in two triple junctions which migrated northwestwards and southestwards, respectively, along the continental margin (Fig. 2a). The plate boundary between these two triple junctions developed a strong dextral strike-slip motion, and subduction of oceanic crust ceased.

Subduction along much of Baja California appears to have ceased simultaneously at about 12.5 Myr (Klitgord and Mamm erickx, 1982; Mamm erickx and Klitgord, 1982), before the Baja California peninsula separated from mainland Mexico (c. 5 Myr). There is some doubt as to whether the ancestral EPR was subducted at this time, or whether a small portion of the Guadalupe Plate, and the ridge, is abandoned offshore (Fig. 2). There does, however, appear to be an interesting dichotomy of the history of the subducting plate which is of relevance to the present study. North of a small, unnamed E–W transform fault at 29°30'N, it appears
that the spreading centre was actually subducted, potentially leading to the decoupling of the Pacific and Guadalupe Plates and the production of a 'no-slab window' as the leading plate continued to subduct, similar to the situation predicted beneath California, USA (Dickinson and Snyder, 1979).

South of this transform, if the ridge was abandoned, it is unlikely that such as 'no-slab window' could develop. The interest here is that the San Quintin field, which comprises basalts of a type not found elsewhere in Baja, lies to the north of the 29° 30' transform, and thus lies above the putative 'no-slab window'.

MAGMATIC ACTIVITY IN BAJA CALIFORNIA

Cenozoic volcanism commenced in Baja California at about 28 Myr and prior to 10 Myr was characterized by calc-alkaline basaltic andesite and andesite lavas with minor dacites and acid ignimbrites (McPhee, 1968; Gastil et al., 1975, 1979; Hansback, 1984; Sawlan and Smith, 1984; Saunders et al., 1987). Such lavas indicate that the magmatism was related to normal continental-margin subduction processes. Thereafter, (i.e. shortly following the cessation of subduction) the style of volcanism in Baja California changed. At 10 Myr an extensive 25-40 km² sequence of tholeiitic sheet flows (the Esperanza basalts) was erupted in central Baja from the developing proto Gulf of California rift (Sawlan and Smith, 1984). Later volcanism was largely confined to four widely separated centres, namely San Quintín, Jaraguay, San Borja and La Purisima (including the Tres Virgenes/San Ignacio area) (Fig. 1). The products of this volcanism show a remarkable diversity in composition, reflecting the complexity of the changing tectonic environment. Although in Baja California calc-alkaline type volcanism continues to the present day at the stratovolcano of Tres Virgenes (Ives, 1962; Sawlan, 1982) (Fig. 1), the predominant lava types are magnesian basaltic andesites and andesites, which have been erupted in the Jaraguay, San Borja and La Purisima volcanic fields. These have been termed bajaites by Rogers et al. (1985), and are characterized by high MgO contents (up to 8% MgO at 57% SiO₂), with correspondingly low Fe/Mg ratios. They also have high K/Rb, Na/K and La/Yb ratios and low Rb/Sr ratios (Rogers et al., 1985; Saunders et al., 1987; Rogers and Saunders, 1989).

North of the Jaraguay and San Borja volcanic fields, and overlying that part of the destructive margin where the
Fig. 2. Generalized plate tectonic development of the eastern Pacific between 29 and 0 Ma. The present-day outlines of Baja California and the Gulf of California are shown for reference. GP = Guadalupe Plate; RP = Rivera Plate; CP = Cocos Plate; To-Ab Fault = Tosco-Abreojos Fault. Filled circles = abandoned spreading centre; stars = Late Cenozoic volcanic fields. Data sources: Klitgord and Mannerickx (1982); Mannerickx and Klitgord (1982). 29°30'N = unnamed fracture zone at 29°30'. (From Saunders et al., 1987, reproduced courtesy Elsevier Science Publishers.)

Pacific-Guadalupe spreading centre is thought to have been actually subducted, are a number of young alkali basalt eruptives which comprise the San Quintin volcanic field (Woodford, 1928). The field lies about 260 km south of the Mexico–USA border and consists of 11 monogenetic basaltic scoria cones (including the offshore Isla San Martín) with fresh, blocky lava flows (Fig. 3). These have been erupted over about the last 75,000 years (Stroh, 1975) with some flows probably being less than 3000 years old (Gorsline and Stewart, 1962). Unlike any of the other volcanic fields in Baja California a number of the San Quintin lava flows contain spinel ilmenomagnesite nodules. These have been de-
San Quintín Volcanic Field

Fig. 3. Map of the San Quintín volcanic field showing location of the samples analysed.

scribed by Bacon and Carmichael (1978), Stroh (1975), Basu and Murthy (1977) and Cabanes and Mercier (1988).

ANALYTICAL TECHNIQUES

Twelve San Quintín basalts have been analysed for major and trace elements by XRF (Table 1) from which six samples were selected for Sr and Nd isotope ratio determinations: two of these (those at the extremes of the compositional range) have also been analysed for Pb isotopes. Hf, Ta, Th and the REE have been obtained on these latter two samples by INAA. Details of the XRF and INAA techniques employed are given by Saunders et al. (1987). Sr and Nd isotopes were measured at the Scottish Universities Research and Reactor Centre using a VG Micromass 54E thermal ionization mass spectrometer. Sr and Nd were separated using standard ion exchange techniques (MacIntyre and Hamilton, 1984). All Sr data are normalized to $^{87}Sr/^{86}Sr = 0.1194$ and to $^{143}Nd/^{144}Nd = 0.72122$ for NBS987. Nd isotopes are similarly normalized to $^{144}Nd/^{144}Nd = 0.70919$ and to $^{143}Nd/^{144}Nd = 0.51265$ for BCR-1. Pb isotopes were determined at the Open University at Milton Keynes using techniques described in Rogers et al. (in prep.).

GEOCHEMISTRY

All of the San Quintín basalts collected and analysed by us are ne-normative (2.3–8.1% ne); in a total alkalis versus silica plot (Fig. 4) they fall well into the Hawaiian alkali basalt field of MacDonald and Katsura (1964). They exhibit a restricted compositional range from relatively unevolved samples with high MgO, Ni and Cr contents through to slightly more fractionated basalts with correspondingly higher Fe/Mg ratios and lower Ni, Cr and V abundances (Table 1). These element enrichment and depletion trends are qualitatively consistent with crystal fractionation of olivine, clinopyroxene and spinel as suggested by Stroh (1975). The data for San Quintín basalts reported by Bacon and Carmichael (1978) are similar, with the exception of two analyses which have substantial normative hy.

Figure 5(a) shows a chondrite-normalized spidergram for two basalts from San Quintín representing the extremes of the narrow compositional range shown by our samples. Despite their eruption within a region which had experienced prolonged earlier subduction they have spidergrams which are indistinguishable from those of typical ocean island basalts such as the Azores (Fig. 5a). The San Quintín lavas do not show the characteristic high La/Nb(Ta) ratios of subduction-related magmas (e.g. Saunders et al., 1980; Gill, 1981). This is in contrast to the spidergrams of basalts and andesites (bajaites) from the San Borja and Jaraguay volcanic fields which show large troughs in Nb and Ta (Fig. 5b). Most San Borja and Jaraguay volcanic rocks are qtz-normative, although there was a pulse of ne-normative lavas at about 4 Myr. The latter, however, do not resemble the ne-normative alkali basalts at San Quintín as they also possess the unusual subduction-related bajaitic chemical signature, representing one end of the bajaite
Table 1. Major element, trace element and isotope data for San Quintin volcanic rocks.

<table>
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<tr>
<th>Sample</th>
<th>SQ1</th>
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<th>SQ3</th>
<th>SQ4</th>
<th>SQ5</th>
<th>SQ6</th>
<th>SQ7</th>
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<td>0.07</td>
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| Compositional series (Rogers et al., 1985; Saunders et al., 1987; Rogers and Saunders, 1989; Rogers et al., in prep.). | Sr and Nd isotope data are shown in Fig. 6, again covering the entire spectrum of compositions found at San Quintin. For comparison, data for San Borja, Jaraguay, the Basin and Range Province, MORB and OIB are also depicted. San Quintin basalts exhibit a narrow range in ⁸⁷Sr/⁸⁶Sr (0.70323–0.70352) and ¹⁴⁳Nd/¹⁴⁴Nd (0.512924–0.512996) ratios, plotting close to MORB and the Basin and Range and partly overlapping with the compositional fields occupied by OIB from Hawaii and the Azores (Fig. 6). The bajaites from San Borja and Jaraguay have significantly higher ⁸⁷Sr/⁸⁶Sr ratios (0.70352–0.70470) than the San Quintin basalts. There is little difference in ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb ratios between the two `San Quintin' samples analysed despite their being at the extremes of chemical variation; the data overlap with the most radiogenic Pb compositions reported for normal MORB (Sun, 1980) and fall on the 1.7 Ga secondary Pb–Pb isochron or mixing line (Chase, 1981). |
Fig. 4. Plot of Na$_2$O + K$_2$O versus silica for San Quintin basalts. Additional data (open circles: non-normative; squares: hy-normative) are from Bacon and Carmichael, 1978. Dividing line between alkaline and tholeiitic Hawaiian basalts is from MacDonald and Katsur (1964).

Fig. 5. Chondrite-normalized (except K, Rb and P) spidergrams. Normalizing values from Thompson (1982). The order of the elements, from right to left, is one of increasing incompatibility as observed in mid-ocean ridge basalt (MORB) (Sun, 1980). (a) San Quintin basalts and an alkali basalt (SM49) from Sao Miguel island in the Azores (Sao Miguel data from Storey et al., 1989). (b) San Borja and Jaraguay Holocene basaltic; data from Saunders et al. (1987).
proposed for the occurrence of OIB-type basalts in the Basin and Range (Omerod et al., 1988).

There is, however, no conclusive geochemical or geophysical evidence to suggest the continued presence of a slab beneath the southerly volcanic fields. It could, therefore, be also argued that San Quintin may simply represent the first manifestation of a new mantle plume which may in future cause OIB-type magmatism further south in Baja California as the peninsula continues to drift northwards on the Pacific Plate. None the less, it is a remarkable coincidence that the only place in Baja California where OIB-type alkali basalts are erupted is located in the area beneath where the ridge was subducted, whereas elsewhere on the peninsula where the ridge may have been abandoned offshore, these rocks are absent.

SUMMARY
In Baja California, bajaites and OIB-type volcanism post-date the cessation of subduction, their occurrence being related to two possible scenarios. Where the spreading centre is not subducted, it is probable that for some time after actual subduction has ceased relict slab material provides a physical barrier to the rise of diapirs and/or magmas from the underlying asthenosphere. Indeed, the distinctive bajaite magma series is attributed to the unusual melting regimes that are likely to arise during the thermal re-equilibration of the remanent slab with surrounding mantle (Saunders et al., 1987; Rogers and Saunders, 1989). Alternatively, during oblique collision, and where the ridge is consumed at the trench and the leading plate continues to subduct, 'a no-slab window' may develop allowing upwelling of the underlying asthenosphere with resultant OIB-type magmatism.

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