TERRA RESEARCH

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 ($La/Nb = 0.57–0.73$; $K/Rb = 402–479$; $La_N/Yb_N = 8.4, 9.9$) and isotopic ratios ($^{87}Sr/^{86}Sr = 0.70323–0.70352$; $^{143}Nd/^{144}Nd = 0.512924–0.512996$; $^{206}Pb/^{204}Pb = 19.108, 19.250$; $^{207}Pb/^{204}Pb = 15.567, 15.589$; $^{208}Pb/^{204}Pb = 38.82, 38.85$) 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.

TERRA Nova (1989) 1, 195–202.

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; Ormerod *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 southeastwards, 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 Mammerickx, 1982; Mammerickx 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).

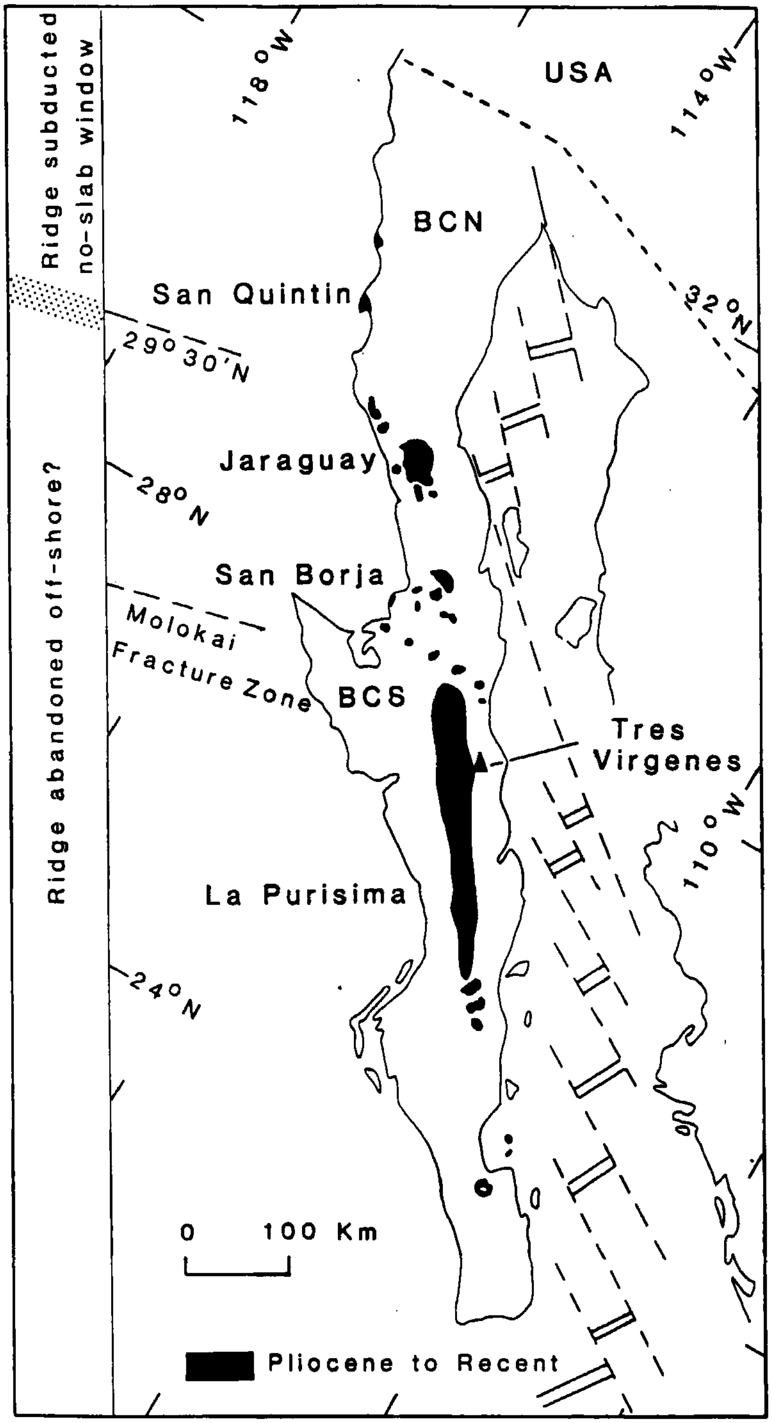

Fig. 1. *Map of Baja California, showing the locations of Pliocene to Recent volcanic fields (from Gastil* et al., *1975, 1979). Location of Pacific transform faults (29°30'N and Molokai fracture zone) from Klitgord and Mammerickx (1982). BCN – Baja California Norte; BCS – Baja California Sur.*

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 Quintín 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 (McFall, 1968; Gastil *et al.*, 1975, 1979; Hausback, 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 km^3 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 Purísima (including the Tres Vírgenes/ 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 Vírgenes (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 Purísima 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% SiO_2), 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

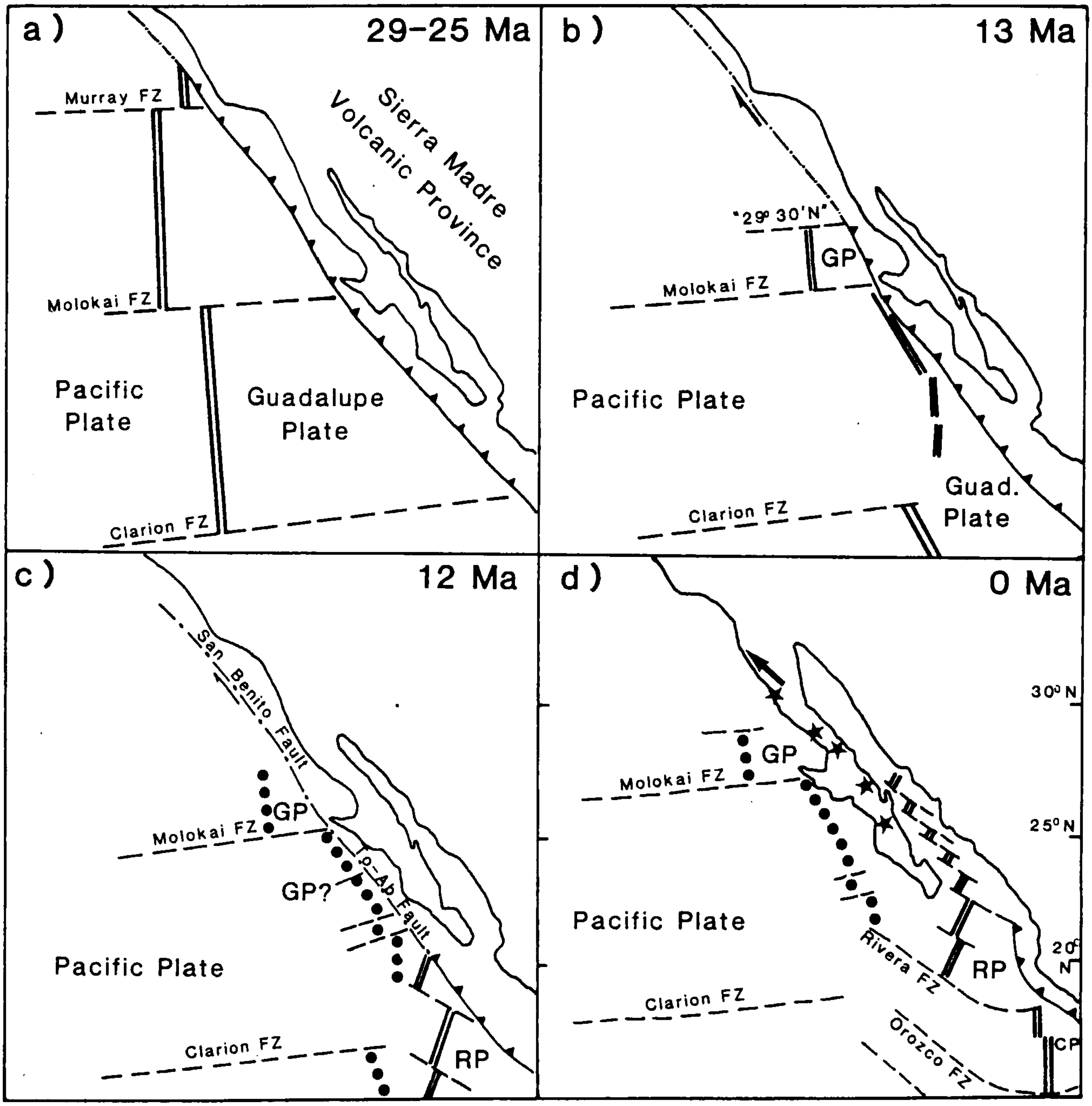

Fig. 2. *Generalized plate tectonic development of the eastern Pacific between 29 and 0 Myr. The present-day outlines of Baja California and the Gulf of California are shown for reference. GP = Guadalupe Plate; RP = Rivera Plate; CP = Cocos Plate; To–Ab Fault = Tosco–Abreojos Fault. Filled circles = abandoned spreading centre; stars = Late Cenozoic volcanic fields. Data sources: Klitgord and Mammerickx (1982); Mammerickx 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 Quintín 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 Martin) 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 Quintín lava flows contain spinel lherzolite nodules. These have been de-

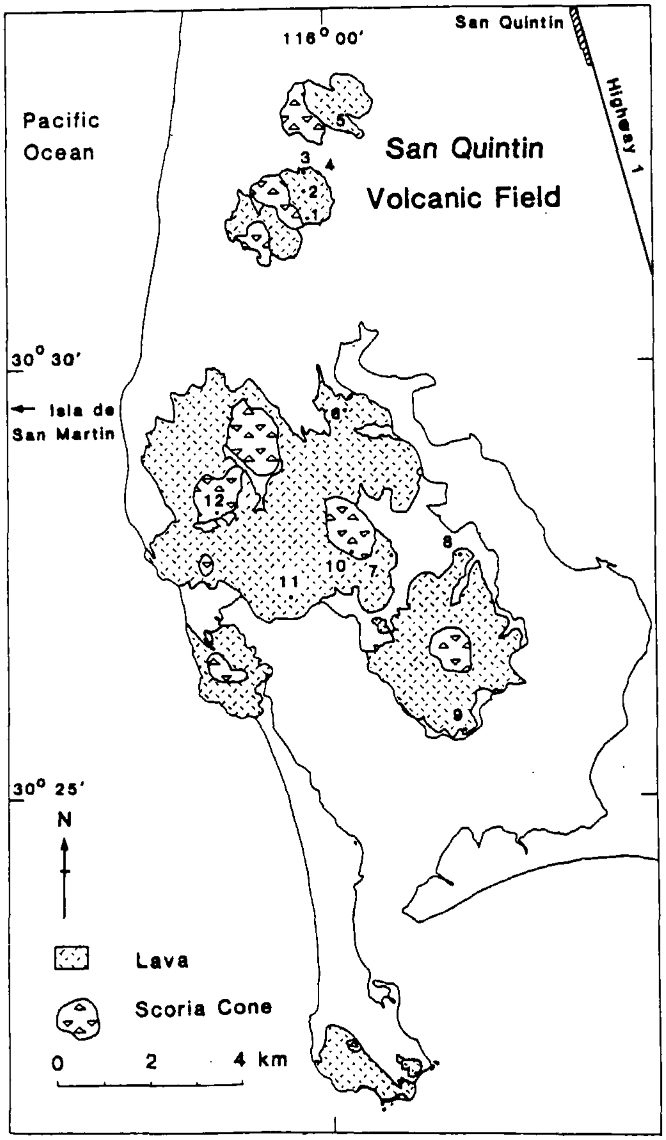

Fig. 3. *Map of the San Quintín volcanic field showing location of the samples analysed.*

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 ^{86}Sr/^{88}Sr = 0.1194 and to ^{87}Sr/^{86}Sr = 0.71022 for NBS987. Nd isotopes are similarly normalized to ^{146}Nd/^{144}Nd = 0.7219 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 Quintín volcanic rocks.

Sample	SQ1	SQ2	SQ3	SQ4	SQ5	SQ6	SQ7	SQ8	SQ9	SQ10	SQ11	SQ12
SiO_2	46.2	47.8	46.3	46.4	47.6	47.0	45.2	47.3	47.1	46.8	46.1	46.8
TiO_2	2.93	2.41	2.91	2.90	2.76	2.52	2.90	2.27	2.18	2.55	2.97	2.66
Al_2O_3	15.7	15.7	15.8	15.6	16.0	15.7	15.0	15.5	15.3	15.7	15.4	15.6
Fe_2O_3	13.5	11.3	13.7	13.7	12.6	11.1	12.5	11.4	11.3	11.1	12.6	11.4
MnO	0.20	0.17	0.19	0.19	0.18	0.17	0.18	0.17	0.17	0.17	0.19	0.18
MgO	6.8	8.3	6.8	6.8	6.7	8.6	8.7	8.8	9.0	8.6	8.6	8.8
CaO	8.3	8.5	8.1	8.2	7.9	8.9	9.3	9.3	9.2	8.8	9.4	9.0
Na_2O	3.7	3.7	4.0	3.9	4.0	3.7	3.4	3.1	3.2	3.9	3.4	3.6
K_2O	2.02	1.84	2.09	2.11	2.28	1.90	1.73	1.53	1.47	1.88	1.75	1.76
P_2O_5	0.80	0.62	0.88	0.74	0.76	0.62	0.54	0.54	0.51	0.61	0.58	0.58
Total	100.15	100.34	100.77	100.54	100.78	100.21	99.45	99.91	99.43	100.11	100.99	100.38
LOI	−0.05	−0.34	−0.02	−0.27	−0.18	−0.19	0.98	−0.24	−0.23	0.07	−0.10	−0.13
CIPW normative minerals*												
Or	11.94	10.87	12.35	12.47	13.47	11.23	10.24	9.04	8.69	11.10	10.34	10.40
Ab	20.87	22.98	19.83	19.73	22.38	18.53	15.12	21.79	21.28	18.07	16.39	18.75
An	20.36	21.06	18.93	19.04	18.97	20.66	20.60	23.96	23.09	19.69	21.81	21.42
Ne	5.65	4.28	7.55	7.10	6.30	6.97	7.24	2.31	3.05	8.07	6.52	6.25
Di	12.66	13.67	13.27	13.87	12.40	15.84	17.82	15.19	15.72	16.30	17.23	15.84
Ol	17.18	17.97	17.12	16.89	16.39	17.35	17.72	18.61	18.81	17.31	17.95	18.00
Mt	2.99	2.50	3.03	3.01	2.78	2.45	2.76	2.52	2.50	2.46	2.79	2.53
Ilm	5.56	4.58	5.53	5.51	5.24	4.79	5.51	4.31	4.14	4.84	5.64	5.05
Ap	1.85	1.44	1.85	1.71	1.76	1.44	1.26	1.25	1.18	1.41	1.34	1.34
Trace elements (ppm)												
Zr	301	268	306	302	328	261	243	217	203	255	253	246
Hf					7.69				4.48			
Nb	60	54	59	58	61	58	50	44	41	56	51	54
Ta					3.92				2.87			
Y	36	30	37	36	34	31	33	27	26	31	34	32
Sr	758	618	759	759	736	647	636	553	565	631	709	634
Rb	37	38	38	38	42	39	30	30	28	36	32	36
Th	5.9	6.9	5.6	6.7	5.4	5.4	6.2	5.0	3.9	4.9	7.2	4.9
Ga	21	19	20	21	20	19	19	19	20	19	20	19
Zn	103	84	101	99	92	82	86	81	80	80	90	83
Ni	86	151	83	80	89	156	136	168	162	160	144	174
Cr	87	223	86	82	104	237	193	258	277	251	187	225
V	181	204	177	178	174	214	251	227	215	220	239	227
Ba	470	440	468	495	507	472	428	370	377	449	436	450
La	43	39	43	41	41.0	39	37	31	27.9	37	36	36
Ce	85	71	87	88	78.7	69	74	58	54.9	73	67	69
Nd	41	32	44	41	41.9	34	35	28	28.8	32	34	35
Sm					8.3				6.0			
Eu					2.8				2.1			
Gd					8.6				6.4			
Tb					1.11				0.85			
Tm					0.19				0.23			
Yb					2.79				2.23			
Lu					0.44				0.36			
*Isotopes												
$^{87}Sr/^{86}Sr$		0.70331±4			0.70323±2		0.70328±2		0.70337±2		0.70352±3	0.70323±1
$^{143}Nd/^{144}Nd$		0.512924±19			0.512952±28		0.512934±22		0.512931±30		0.512978±24	0.512996±38
$^{206}Pb/^{204}Pb$					19.250±7				19.108±7			
$^{207}Pb/^{204}Pb$					15.567±7				15.589±6			
$^{208}Pb/^{204}Pb$					38.85±2				38.82±1			

*Calculated using $Fe_2O_3/FeO = 0.2$.

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 Quintín. For comparison, data for San Borja, Jaraguay, the Basin and Range Province, MORB and OIB are also depicted. San Quintín basalts exhibit a narrow range in $^{87}Sr/^{86}Sr$ (0.70323–0.70352) and $^{143}Nd/^{144}Nd$ (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 $^{87}Sr/^{86}Sr$ ratios (0.70352–0.70470) than the San Quintín basalts.

There is little difference in $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios between the two 'San Quintín' 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).

DISCUSSION

It is clear that alkali basalts from San Quintín share many of the trace element characteristics observed in

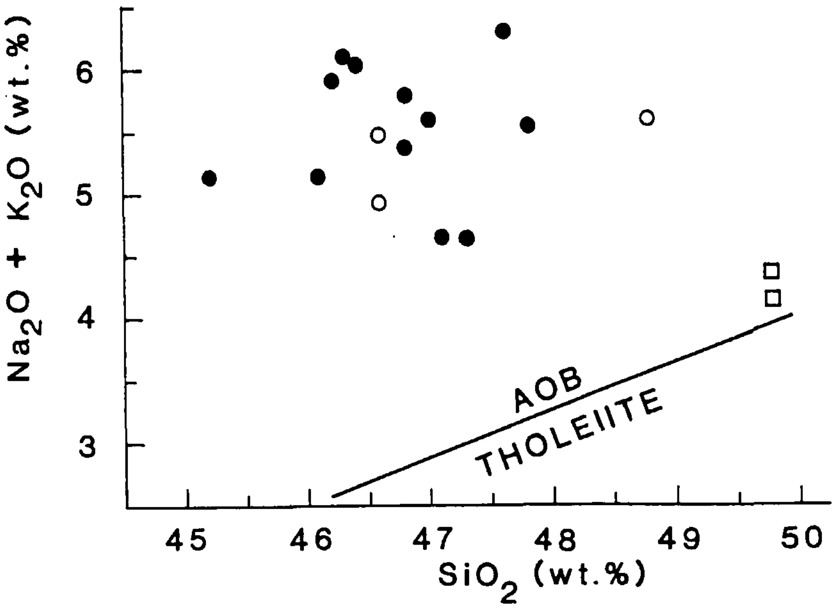

Fig. 4. *Plot of* Na_2O+K_2O *versus silica for San Quintín basalts. Additional data (open circles:* ne-*normative; squares:* hy-*normative) are from Bacon and Carmichael, 1978). Dividing line between alkaline and tholeiitic Hawaiian basalts is from MacDonald and Katsura (1964).*

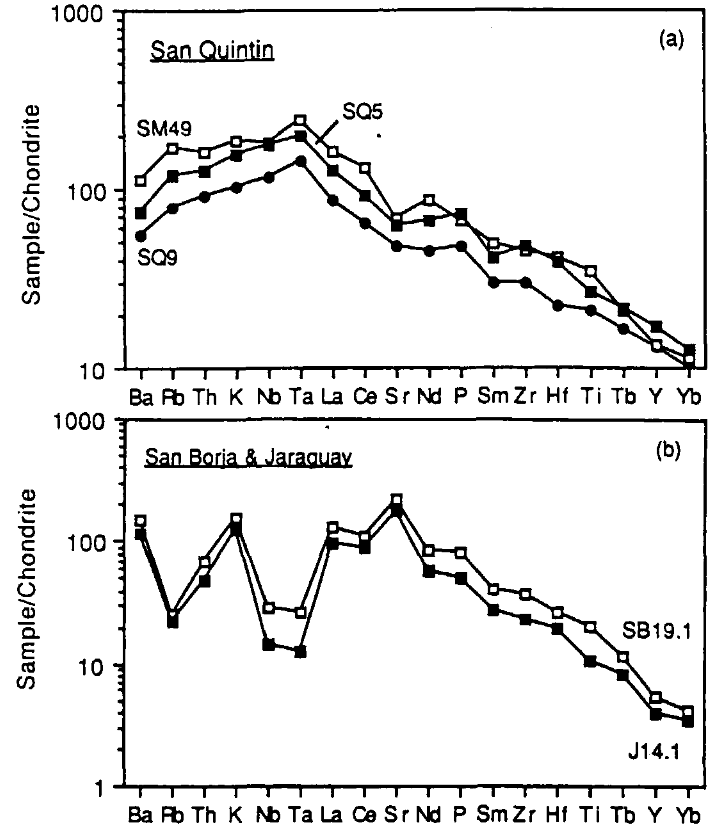

Fig. 5. *Chondrite-normalized (except* K, Rb *and* P*) spidergrams. Normalizing values from Thompson (1982). The order of the elements, from right to left, is one of increasing incompatibility as observed in mid-ocean ridge basalt (MORB) (Sun, 1980). (a) San Quintín basalts and an alkali basalt (SM49)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

OIBs, consistent with an asthenospheric source (Allègre *et al.*, 1981; Norry and Fitton, 1983; Fitton and Dunlop, 1985). Their low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$ ratios and the absence of Nb and Ta troughs in their spidergrams argue against any significant contamination by continental lithosphere. From this point of view they closely resemble some basalts from the western USA to which an asthenospheric source has also been attributed (Menzies *et al.*, 1983; Fitton *et al.*, 1988; Perry *et al.*, 1987; Ormerod *et al.*, 1988).

The point of interest here concerns the reason for the eruption, during the Holocene, of OIB or within-plate type volcanism at San Quintín as opposed to the contemporaneous bajaitic magmatism of the Jaraguay and San Borja volcanic fields. This occurrence of alkali basalts is even more remarkable when it is remembered that subduction has been operative beneath this region from at least Cretaceous to Upper Miocene times, and that they have been erupted immediately adjacent to the former trench unlike post-subduction alkali basalts from the Basin and Range (e.g. Menzies *et al.*, 1983; Fitton *et al.*, 1988).

The San Quintín field occurs north of the 29°30′N fracture zone where the magnetic anomaly evidence indicates that the Pacific–Guadalupe spreading centre was subducted (Mammerickx and Klitgord, 1982). If, as has been suggested earlier, the leading plate continued to subduct then it would seem possible that the San Quintín volcanic field overlies a 'no-slab window'. The Jaraguay and San Borja volcanic fields, on the other hand, occur where the spreading centre may not have been subducted, but simply abandoned: it may, therefore, be possible that a relict slab persists beneath these latter fields.

The absence of OIB-type magmatism at Jaraguay, San Borja and La Purísima suggests that relict slab material beneath these regions may act as a barrier to the upward passage of asthenospheric diapirs or magmas. At San Quintín where there is a 'no-slab window' and no such barrier exists, it is envisaged that OIB-type magmas are able to reach the surface as a result of upwelling and subsequent melting of the asthenosphere as it occupies the space left by the descent of the leading plate. The latter is similar to a model

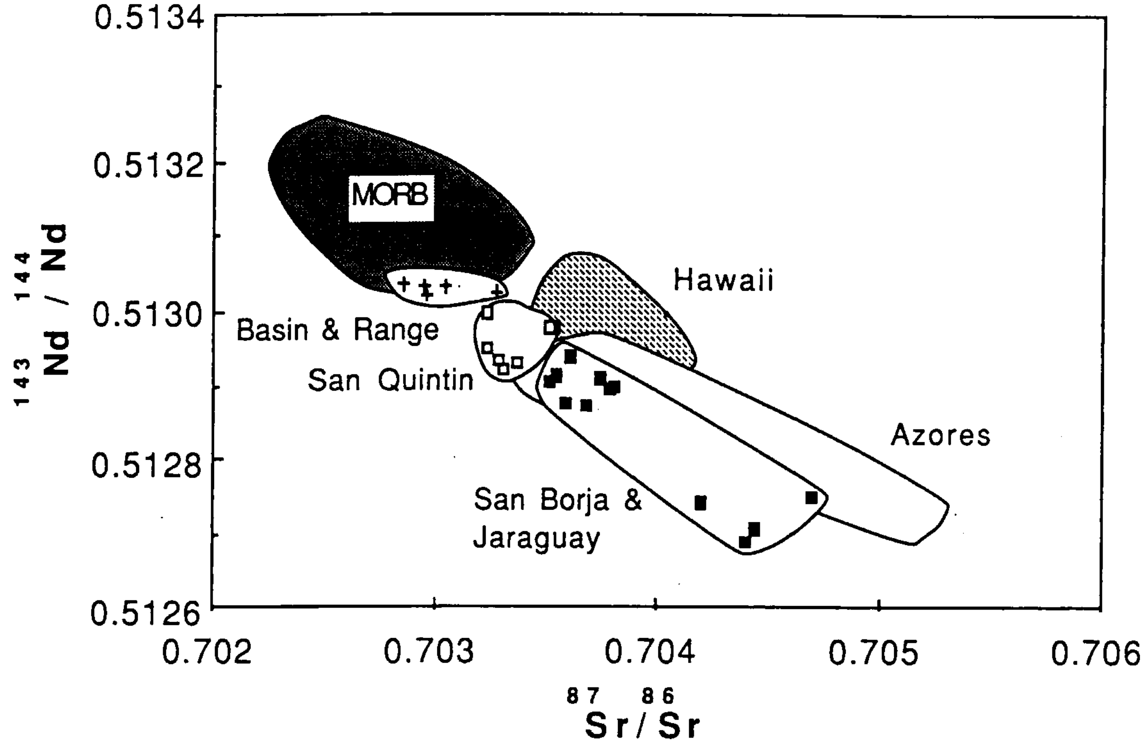

Fig. 6. ^{143}Nd/^{144}Nd *versus* ^{87}Sr/^{86}Sr *isotopic ratios showing San Quintín basalts compared to MORB (Allègre* et al., *1980; White and Hofmann, 1982), southern Basin and Range (Menzies* et al., *1983), Hawaii (Stille* et al., *1983), Azores (White and Hofmann, 1982) and bajaites from San Borja and Jaraguay (Rogers* et al.*; in prep.).*

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.

ACKNOWLEDGEMENTS

Fieldwork in Mexico is funded by NERC grant GR3/4957. We are grateful to Chris Hawkesworth for use of the isotope facilities at the Open University. Isotope studies at SURRC are supported by NERC and the Scottish Universities. Drs J.G. Fitton, S.A. Nelson and J.A. Wolff are thanked for their reviews.

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Received 7th December 1988,
Revised 8th March 1989