Geochemical Aspects of Back-Arc Spreading in the Scotia Sea and Western Pacific [and Discussion]

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Geochemical aspects of back-arc spreading in the Scotia Sea and western Pacific

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The results of recent geochemical investigations of several island arc – marginal basin systems in the Scotia Sea area and in the western Pacific are outlined. Marginal basins in different stages of evolution are represented, from those in the initial stages of formation to those with an extensive and multiple history of back-arc spreading. Some are completely intraoceanic, others have developed at continental margins.

Basalts erupted at back-arc spreading centres seem to be as geochemically varied as those from normal mid-ocean ridges, and record evidence for similar processes of partial melting, fractional crystallization and magma mixing in their genesis. They appear to have been derived from mantle sources with incompatible trace element characteristics ranging from 'depleted' to 'enriched', but with the 'enriched' mantle sources being sampled during the earlier stages of back-arc spreading. Submarine back-arc basalts are more vesicular than their normal ocean ridge equivalents, and their corresponding glasses have higher water contents. This, together with other geochemical features such as the higher ratios of lithophile to high field strength elements in some back-arc basalts, suggests that a component from the subducted slab may be involved in their petrogenesis.

The chemistry of the corresponding arc volcanics is described in relation to the subduction and extensional history of marginal basin development. In intraoceanic arcs the early stages of arc magmatism are dominated by the eruption of large volumes of island arc tholeiites and subsidiary high-Mg andesites. In the Mariana region, after the initial volcanic arc is split and separated by back-arc spreading, the later frontal arc volcanics have calc-alkaline characteristics. Basalts erupted during the early stages of back-arc spreading more commonly have arc-like geochemical features when the marginal basin has developed through splitting of a calc-alkaline volcanic arc. The secular variation in the geochemistry of the arc volcanics may be related to the progressive development of a lithophile element enriched mantle source beneath the arc. This source contributes to the basalts produced during the early stages of arc rifting and back-arc spreading. Ophiolite complexes which represent marginal basin floor may well carry these arc-like geochemical features.

INTRODUCTION

Marginal basins are a common feature of the present plate tectonic régime. By definition, such features are linked with subduction of oceanic lithosphere, but the extent to which the subducting slab plays an active or a passive role in the back-arc extensional process is imperfectly understood. Geophysical aspects of modern marginal basins are summarized by Weissel (this symposium), the essential problems associated with them have been outlined by Uyeda (1977), and various proposed mechanisms to account for their development have been reviewed by Uyeda & Kanamori (1979) and Tarney & Windley (1981).

Geochemistry has a potential role to play in assessing the processes that occur during magma genesis in subduction zones, in the overlying mantle wedge and in the back-arc region. The compositions of the erupted marginal basin and island arc lavas can be used to assess the nature of their sources, in particular any contribution from the downgoing slab, provided the secondary effects due to partial melting and magma fractionation can be allowed for. Unfortunately there is probably less agreement among petrologists concerning the petrogenesis of magmas at convergent plate boundaries than in any other tectonic environment. Nevertheless, by comparing the geochemical features seen in marginal basin basalts with those generated at normal mid-ocean ridges and with lavas erupted at the associated island arcs, we hope to place constraints on the processes involved and to consider their implications for marginal basin development. Many ophiolite complexes have been regarded as fragments of marginal basin floor rather than normal ocean crust (Dewey 1976; Hawkins 1977; Saunders *et al.* 1979); thus it is useful to establish whether there are any significant differences between the source regions and magma-generating processes in back-arc environments compared with those at normal mid-ocean ridges.

In this contribution we review available geochemical data for marginal basin basalts and associated island arc lavas in three marginal basin-arc systems from the Scotia Sea area and in the Mariana arc system from the western Pacific, areas where there is a substantial quantity of tectonic and/or geophysical data concerning the evolution of the arc-basin systems. Only a limited quantity of geochemical data can be presented here; more extensive discussions of individual basins are published elsewhere.

THE EAST SCOTIA SEA – SOUTH SANDWICH SPREADING CENTRE

The Scotia Sea, bounded by the extended loop of the Scotia Arc, represents a complex zone of microplates at the boundary of two major plates, the South American and the Antarctic (figure 1; see also fig. 1 in Barker & Hill, this symposium). Marine geophysical investigations (Barker 1972; Barker & Griffiths 1972; Barker & Hill, this symposium) have shown that active sea floor spreading is taking place behind the South Sandwich island arc some 440 km west of the South Sandwich trench. Spreading has been under way for about 8 Ma, the spreading rate has increased with time and is asymmetric in that accretion is favoured on the eastern (trench) side (Barker 1972, 1976; Barker & Hill 1980). The present volcanic arc may in fact have been built on marginal basin lithosphere generated at the South Sandwich Spreading Centre (Barker 1972; Saunders & Tarney 1979). However, an earlier volcanic arc, the Discovery arc (Barker *et al.* 1980) appears to have been in existence, about 16 Ma ago, to the southwest of the present volcanic arc. This arc may have developed in response to subduction northwestwards beneath the central Scotia Sea; the series of east–west magnetic lineations in the central Scotia Sea (Hill & Barker 1980) may reflect an earlier episode of back-arc spreading related to this subduction (Barker & Hill, this symposium).

The lavas making up the present South Sandwich arc and the earlier Discovery arc all belong to the island arc tholeiite series (Baker 1978; Barker *et al.* 1980). They are mainly tholeiitic basalts and basaltic andesites with generally low contents of incompatible elements. Rare earth element (r.e.e.) patterns vary from light r.e.e. depleted in samples with low total r.e.e. abundances to slightly light r.e.e. enriched in samples with higher total r.e.e. concentrations (Hawkesworth *et al.* 1977). Their Sr and Nd isotope compositions are displaced to the right of the mantle 'main trend' in the ΔSr–ΔNd correlation plot of O'Nions *et al.* (1977), indicating that a component of seawater Sr may be involved in their petrogenesis. However, more detailed petrochemical studies are required to establish the geochemical nature of the source regions of South Sandwich arc tholeiites and the relative importance of partial melting and fractional crystallization in their petrogenesis.

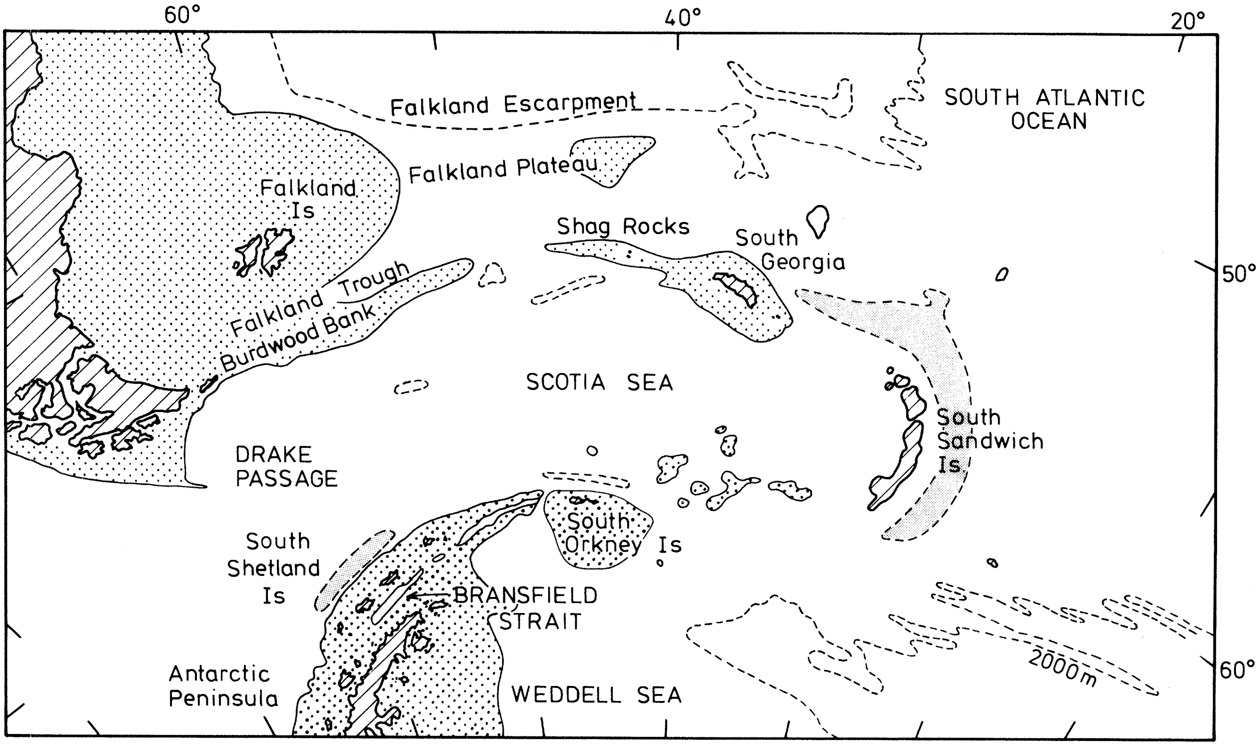

FIGURE 1. Sketch map of the Scotia Sea area (adapted from Hill 1979). For the plate tectonic framework of the region see Barker & Hill (this symposium, fig. 1) and for details of the S Chile marginal basin see Dalziel (this symposium, figs 1–5). Ornament as in figure 3.

The geochemistry of dredged basalts from the South Sandwich Spreading Centre (S.S.S.C.) has been studied by Tarney *et al.* (1977), Saunders & Tarney (1979) and Saunders *et al.* (1980*b*). In terms of petrography and major elements the basalts are similar to those from normal mid-ocean ridges. However, basalts from two of the dredge sites (22 and 24) are unusually vesicular considering their depth of extrusion (*ca.* 2000 m) and are also rather aluminous (*ca.* 16–18% Al_2O_3). Muenow *et al.* (1980) have shown that the basalt glasses from these dredge sites have higher primary H_2O contents and H_2O/CO_2 ratios than basalt glasses from normal mid-ocean ridges, a characteristic that has been found in some other back-arc basalts (Garcia *et al.* 1979). The water, probably derived from dehydration of altered basalts in the downgoing slab, may have entered the source regions in the back-arc region. This would accord with the moderately high alumina contents and the fact that many of the dredge 24 basalts in particular are quartz-normative (cf. Green 1973).

Rare earth element patterns for the S.S.S.C. basalts (figure 2) vary from flat to moderately light r.e.e. enriched ($Ce_N/Yb_N = 0.92–1.43$). There is a positive correlation between Ce_N/Yb_N ratio and abundances of incompatible minor and trace elements (e.g. Ti and Zr). Saunders &

Tarney (1979) argued that most of the trace element abundances and ratios could be reconciled with different degrees of partial melting of a similar mantle source (with superimposed fractional crystallization). However, there were some anomalies. Vesicular basalts from dredges 22 and 24 had higher Ba/Zr, K/Zr and Rb/Zr ratios. Also basalts from these two dredges had higher ^{87}Sr/^{86}Sr ratios, and there was an overall positive correlation between ^{87}Sr/^{86}Sr ratio and Sr/Zr ratio. This, plus the fact that the basalts are fresh and that the leaching technique did not significantly reduce the Sr isotope ratios, indicates that higher Ba, K and Rb contents and higher ^{87}Sr/^{86}Sr ratios in the more vesicular basalts are primary. The most logical explanation is that water derived from the subducted slab is also carrying small amounts of the more mobile lithophile elements, along with seawater Sr, into the source regions of the back-arc basalts. Hydrous melting conditions may also account for the fact that dredge 24 basalts have the lowest concentrations of r.e.e. and other immobile trace elements (as would be expected with higher degrees of melting) but more evolved major element compositions (greater range of Fe/Mg, quartz normative and lower Cr and Ni contents), as would be expected if they had subsequently undergone more olivine fractionation. Dredge 24 basalts thus have some arc-like characteristics. Note also that in spite of having higher large ion lithophile (l.i.l.) elements (light r.e.e., K, Rb, Ba, Sr) and ^{87}Sr/^{86}Sr ratios than normal mid-ocean ridge basalts (m.o.r.b.), the S.S.S.C. basalts still have low Nb contents and high Zr/Nb ratios, whereas comparable l.i.l. element enriched 'transitional' basalts in the North Atlantic have higher Nb contents and lower Zr/Nb ratios (Tarney *et al.* 1979, 1980). This enrichment in the l.i.l. elements relative to Nb, Ta, Zr, Hf, Ti and the heavy r.e.e. (the high field strength or h.f.s. elements) is a characteristic feature of island arc magmas (Saunders *et al.* 1980*a*, *c*).

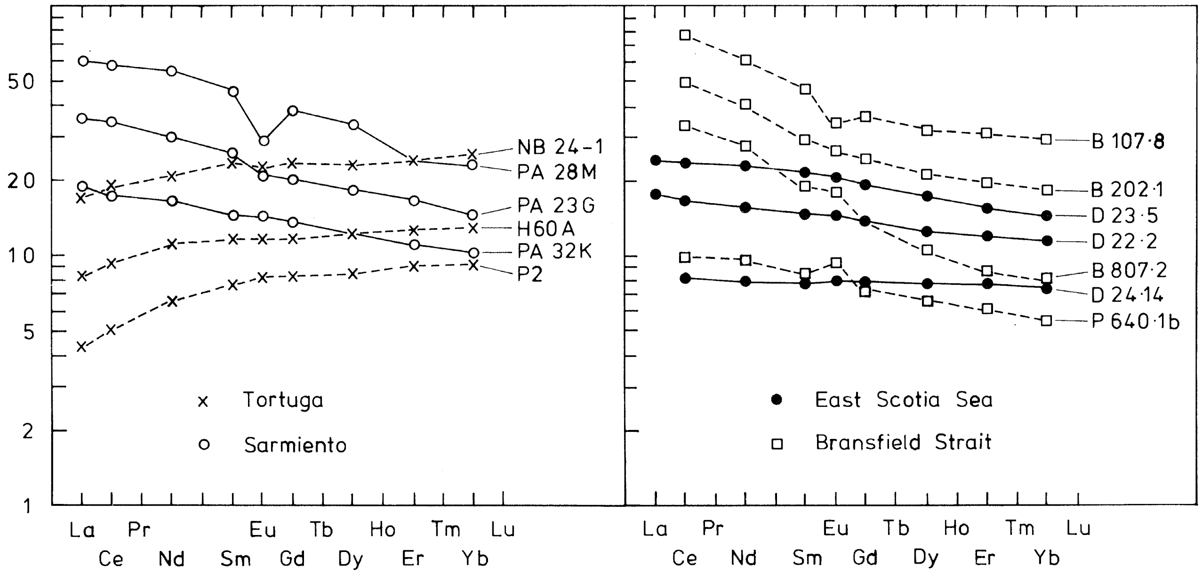

FIGURE 2. Representative chondrite-normalized r.e.e. patterns for marginal basin basalts from the South Sandwich Spreading Centre, East Scotia Sea (D23.5, D22.2, D24.14; Saunders & Tarney 1979), from Deception (B107.8, B202.1) Bridgeman (P640.1b) and Penguin (B807.2) volcanoes in Bransfield Strait (Weaver *et al.* 1979) and from the Sarmiento (PA28M, PA23G, PA32K; Saunders *et al.* 1979) and Tortuga (NB24-1, H60A, P2; Stern 1979) ophiolite complexes in southern Chile.

BRANSFIELD STRAIT MARGINAL BASIN

The magmatic history of the northern Antarctic Peninsula in terms of the plate tectonic evolution of the area has been summarized by Tarney *et al.* (1981). Cessation of igneous activity in the Peninsula is related to the progressive northwest consumption of the Aluk Ridge beneath the Peninsula during the Tertiary; the active and recently active volcanoes in Bransfield Strait represent the last vestiges of this activity. Bransfield Strait (figure 1) is regarded as a small marginal basin (Barker & Griffiths 1972; Davey 1972; Barker 1976) which has opened during the last 1–2 Ma in response to continued subduction beneath the Peninsula (South Shetland Islands) when spreading in the Drake Passage slowed down or stopped about 4 Ma ago (Barker 1976).

The South Shetland Islands represent an ensialic island arc which is separated from the Antarctic Peninsula mainland by the 65 km wide Strait. The crustal structure of Bransfield Strait is essentially oceanic (Ashcroft 1972) but with a thicker main crustal layer. There is a narrow trough, 2 km deep, along which runs a line of seamounts from Deception Island to Bridgeman Island and beyond, but there has also been recent off-axis volcanic activity near Penguin Island on the northwest fault bounded edge of the trough. The petrology and geochemistry of the volcanic lavas in Bransfield Strait, on the South Shetland Islands and on the mainland Peninsula have been described by Tarney *et al.* (1977), Weaver *et al.* (1979), Saunders *et al.* (1980*c*), Weaver *et al.* (1980) and Tarney *et al.* (1981).

There has been continual volcanic activity on the South Shetland Islands since the early Mesozoic. Most of the lavas are low-K basalts and basaltic andesites with moderately high Al_2O_3, little significant iron enrichment and fairly high concentrations of Sr and Ba, but low content of K and Rb. Their r.e.e. patterns (figure 2) are moderately fractionated ($Ce_N/Yb_N = 2–8$). These overall characteristics are unlike those of the South Sandwich Islands arc tholeiites, and they are best described as low-K calc-alkaline lavas.

The volcanic islands of Deception, Bridgeman and Penguin are clearly linked to the recent back-arc spreading activity in Bransfield Strait. They provide information on magma compositions generated during the earliest stages of back-arc spreading, during the transition from continental margin magmatism to essentially ocean floor magmatism. Weaver *et al.* (1979) have described the petrology and geochemistry of these lavas in detail. Deception lavas range from olivine basalts to rhyodacites and can be reasonably related with the use of fractional crystallization models. Bridgeman lavas, on the other hand, are basaltic andesites with limited compositional variation. Penguin lavas are mildly alkaline olivine basalts that display a moderate compositional range interpreted as being due to fractionation of olivine with minor clinopyroxene.

In some respects the geochemical characteristics of these lavas resemble ocean floor basalts. Deception and Penguin lavas have high Na/K ratios, low K and Rb contents and high K/Rb ratios. Deception dacites have over 7% Na_2O, and in this and other respects appear to be subaerial equivalents of oceanic plagiogranite (Weaver *et al.* 1979). Zr/Nb ratios are high, similar to the ratios in depleted m.o.r.b.; even the Penguin alkalic basalts have high Zr/Nb ratios. In other respects, however, they differ from ocean ridge basalts. The levels of Ba and Sr are far too high; rare earth patterns for Deception and Bridgeman are light r.e.e. enriched with $Ce_N/Yb_N \approx 2$; Penguin lavas are even more so with $Ce_N/Yb_N \approx 4$. Their $^{87}Sr/^{86}Sr$ ratios (0.7034–0.7039) are also elevated. Compared with trace element relations in North Atlantic ridge basalts, where trace elements behave coherently (see, for example, Tarney *et al.* 1979), many groups of trace elements are decoupled in their behaviour in the Bransfield Strait lavas. Hence although, in their modelling of the likely source compositions of the Bransfield Strait magmas, Weaver *et al.* (1979) found that the magmas had certain geochemical features in common, there were also some significant differences. In general the geochemical characteristics are transitional between those of ocean floor basalts and those of the more distinctly calc-alkaline lavas of the adjacent South Shetland arc.

Some indication of the processes taking place is suggested by comparison of the Bridgeman basaltic andesites with the Deception lavas. They have similar $^{87}Sr/^{86}Sr$ ratios (0.7035) and their r.e.e. patterns are parallel. However, Bridgeman lavas have much lower absolute abundances of r.e.e. and other immobile trace elements than Deception basalts, which would accord with a higher degree of melting. On the other hand, they have distinctly higher K/Zr, Rb/Zr and Ba/Zr ratios and of course are more siliceous and aluminous than Deception lavas. These relations are very similar to those observed in the dredged basalts from the South Sandwich Spreading Centre, and suggest that the Bridgeman lavas may have been generated under more hydrous conditions, probably with some K, Rb and Ba being added from the downgoing slab. No doubt such hydrous conditions would tend to favour the development of more siliceous magmas during subsequent fractionation.

Mesozoic marginal basin complex, southern Chile

The 'rocas verdes' mafic igneous rocks of southern Chile were interpreted by Dalziel *et al.* (1974) as representing the mafic floor of an autochthonous marginal basin which developed at the Pacific margin of southernmost South America in the late Jurassic but which was closed and uplifted during the middle Cretaceous. Various aspects of the sedimentary, stratigraphic, structural and igneous history of the basin together with petrographical, mineralogical and geochemical aspects of the mafic igneous rocks and their metamorphism have been studied by Stern *et al.* (1976), Tarney *et al.* (1976, 1979), Bruhn & Dalziel (1977), de Wit (1977), de Wit & Stern (1978), Bruhn *et al.* (1978), Elthon & Stern (1978), Saunders *et al.* (1979), Stern & Elthon (1979), Elthon (1979), Suarez (1979) and C. R. Stern (1979, 1980); Dalziel (this symposium) summarizes the tectonic history of the basin.

The volcano-sedimentary basin is narrow in the north (at Sarmiento) and wider 600 km to the south (at Tortuga) near Cape Horn (see Dalziel, this symposium). de Wit (1977) estimates the original width of the basin in the north and south as less than 50 km and more than 100 km respectively; however, if the *en echelon* nature of the preserved mafic slices of the basin floor is original, the basin may have been narrower than this. Extensive outpourings of silicic volcanics (Série Tobifera) preceded the opening of the basin, and a penecontemporaneous island arc assemblage (Hardy Formation) occurs on the Pacific side of the basin in the south (Suarez 1979). Volcanic turbidites of Cretaceous age (the Yahgan Formation) infill the basin. The south Chile basin is ensialic: its original form may have resembled that of Bransfield Strait or the Gulf of California. The sedimentary infill was considerably deformed during basin closure in the mid-Cretaceous (Bruhn & Dalziel 1977). The mafic igneous rocks were, however, only locally deformed and their present metamorphic state reflects that developed during sea floor hydrothermal activity (Saunders *et al.* 1979; Stern & Elthon 1979).

The mafic basin floor resembles that of a typical ophiolite section except that (being autochthonous) there is no ultramafic unit exposed. Gabbros are overlain by a well developed sheeted dyke unit and by a thick series of pillow lavas. Silicic plagiogranites occur beneath the sheeted dyke unit at Sarmiento (Saunders *et al.* 1979) and there are equivalent silicic dykes and pillows too; however, there are no plagiogranites in the south at Tortuga (C. R. Stern 1979). The original hydrothermal activity caused considerable redistribution of K and Rb in the dykes and pillow lavas at Sarmiento (Saunders *et al.* 1979), although both Saunders *et al.* and Stern & Elthon (1979) considered that original abundances were preserved in the fresher (and higher metamorphic grade) dykes and gabbros.

Detailed geochemical studies have been undertaken of the Sarmiento (Saunders *et al.* 1979) and Tortuga (C. R. Stern 1979) portions of the marginal basin. Mafic rocks from the Sarmiento complex exhibit a strong tholeiitic trend of iron enrichment, and there are systematic increases in Ti and other incompatible trace elements. R.e.e. patterns (figure 2) are light r.e.e. enriched ($Ce_N/Yb_N \approx 2$; similar to Deception basalts), and increase in abundance in the more iron-rich basalts, with the development of negative Eu anomalies. The plagiogranites have r.e.e. patterns which are essentially parallel with those of the basalts, but of higher abundance and with more marked Eu anomalies. Saunders *et al.* (1979) considered that these geochemical features could be attributed to closed-system crystal fractionation in small magma chambers, with extensive separation of titanomagnetite in the later stages permitting the rapid fractionation towards plagiogranite. These geochemical features are closely similar to those of Deception volcano (Weaver *et al.* 1979). The fresher rocks at Sarmiento have relatively high K_2O and Rb contents and low K/Rb ratios. Saunders *et al.* (1979) suggested that the Sarmiento magmas may have been derived from a mantle source that had been enriched in l.i.l. elements.

Tortuga basalts exhibit a similar increase in incompatible element levels to that of levels in Sarmiento basalts, but show a much more limited range in Fe/Mg ratio. C. R. Stern (1979) attributed this to open-system fractionation (O'Hara 1977), the more rapid spreading rate in this part of the basin permitting the development of continuous magma chambers. However, Tortuga basalts show light r.e.e. depletion (figure 2), and have low K_2O and Rb contents and high K/Rb ratios, features very different from those at Sarmiento, and suggest derivation from a more depleted mantle source similar to that of normal m.o.r.b.

Dykes and sills flanking the Tortuga complex, however, have r.e.e. patterns similar to those of Sarmiento basalts (Stern 1980). Assuming that these were emplaced during the initial stages of back-arc basin opening, then this indicates a secular change of basalt composition with time. A comparable relation is seen in Bransfield Strait between the axis volcanics (Deception, Bridgeman) and the flank volcanics (Penguin).

It is worth noting too that basalts from the Gulf of California (Saunders *et al.* 1981) exhibit trace element distributions similar to those in the Chilean marginal basin. Thus basalts from the mouth of the Gulf and along the East Pacific Rise are essentially N-type m.o.r.b. with low Sr/Zr ratios, Ce_N/Yb_N ratios less than 1 and high Zr/Nb ratios, and resemble Tortuga basalts. However, basalts from the narrower central part of the Gulf have higher Sr/Zr ratios and show light r.e. enrichment (Ce_N/Yb_N = 1–2), but still retain high Zr/Nb ratios; thus they are chemically similar to mafic rocks from the Sarmiento complex.

There appear to be two possible explanations for this secular variation. The first is that the subcontinental mantle beneath the Andean margin may have been chemically layered, to the extent that the upper part had suffered metasomatism by lithophile element enriched fluids, perhaps derived from the downgoing slab or as a result of normal incipient melting processes in the low-velocity zone. Thus, during the limited extension seen at Sarmiento and during the early stages of extension at Tortuga, this metasomatized mantle may have supplied the basaltic liquids; however, with the continued diapirism and extension seen at Tortuga, where the basin is wider, deeper level normal 'depleted' mantle may have provided the source for the m.o.r.b.-like Tortuga basalts as the enriched source was dissipated. The second explanation relies on the dynamic melting model of Langmuir *et al.* (1977), as amplified by Wood (1979) and Duncan & Green (1980). The essentials of this model provide for the generation of basaltic liquids at low degrees of partial melting at greater depth during the initial stages of diapiric uprise. These liquids would have 'enriched' characteristics as exhibited by the Sarmiento basalts and those flanking the Tortuga complex. Further uprise of this (now more refractory) diapir could lead to the generation of basaltic liquids that are light r.e.e. depleted and similar to normal m.o.r.b. With this model it is normally necessary to specify that the first melts are incompletely removed to maintain reasonable trace element abundances in the second stage melts (Langmuir *et al.* 1977). However, Elthon (1979) has described high magnesian (*ca.* 18% MgO) dykes from the Tortuga complex which could potentially represent second stage melts of more refractory material.

Distinguishing between these two models is difficult. The mantle heterogeneity model would imply some difference in $^{87}Sr/^{86}Sr$ ratios between the two sources. The altered nature of the basalts precludes the use of such a tool (although in Bransfield Strait volcanics the 'flank' lavas of Penguin Island do have higher Sr isotope ratios than those of Deception and Bridgeman Islands). Nevertheless we lean towards the mantle heterogeneity model for the following reason. First stage melts, generated by low degrees of melting, should produce melts enriched in the more incompatible elements: light r.e.e., K, Rb, Ba, etc., *and* Nb. Such basaltic liquids in the North Atlantic (FAMOUS area), regarded by Langmuir *et al.* (1977) as first stage liquids, do show enrichment in these elements *including* Nb (Tarney *et al.* 1979). However, the Sarmiento basalts, although enriched in light r.e.e., Ba and (in the fresher rocks) K and Rb, do *not* show enrichment in Nb. Instead Nb values are low and Zr/Nb ratios are notably high (Saunders *et al.* 1979). In this respect the Sarmiento basalts resemble those from the Scotia Sea, Bransfield Strait (and the Gulf of California), described above, in showing enrichment in light r.e.e. and l.i.l. elements to varying extents, but having low contents of h.f.s. elements such as Ta and Nb. These characteristics, as emphasized by Saunders *et al.* (1980), are typical of calc-alkaline magmas. It is therefore possible that the mantle source regions beneath the Andean margin have been enhanced in l.i.l. elements and light r.e.e., but not h.f.s. elements, perhaps derived from the downgoing slab at some earlier period. The tholeiitic trends exhibited by the Sarmiento basalts preclude high water pressures during magma genesis and fractionation, although the fact that plagiogranite is a notable feature of the Sarmiento complex (Saunders *et al.* 1979) suggests that the water content of the magmas may not have been insignificant, at least in the later stages of fractionation. Plagiogranites are a common feature of ophiolite complexes, which, if most represent obducted marginal basins, does permit more easily the involvement of water during magma genesis than with normal ridge basalts.

Western Pacific arcs and marginal basins

The western Pacific represents the classic area of arc and marginal basin development, and as such has received perhaps more detailed study from marine geophysicists and through dredging and deep sea drilling operations than any other marginal basin system. The tectonic evolution of the area has been discussed by Karig (1971, 1972, 1974, 1975*a*, *b*), Packham & Falvey (1971), Uyeda & Ben Avraham (1972), Hilde *et al.* (1977), Watts *et al.* (1977) and Uyeda & Kanamori (1979), among others. The basic geological features are shown in figure 3, where a series of basins, the West Philippine Basin, the Shikoku–Parece-Vela Basins and the

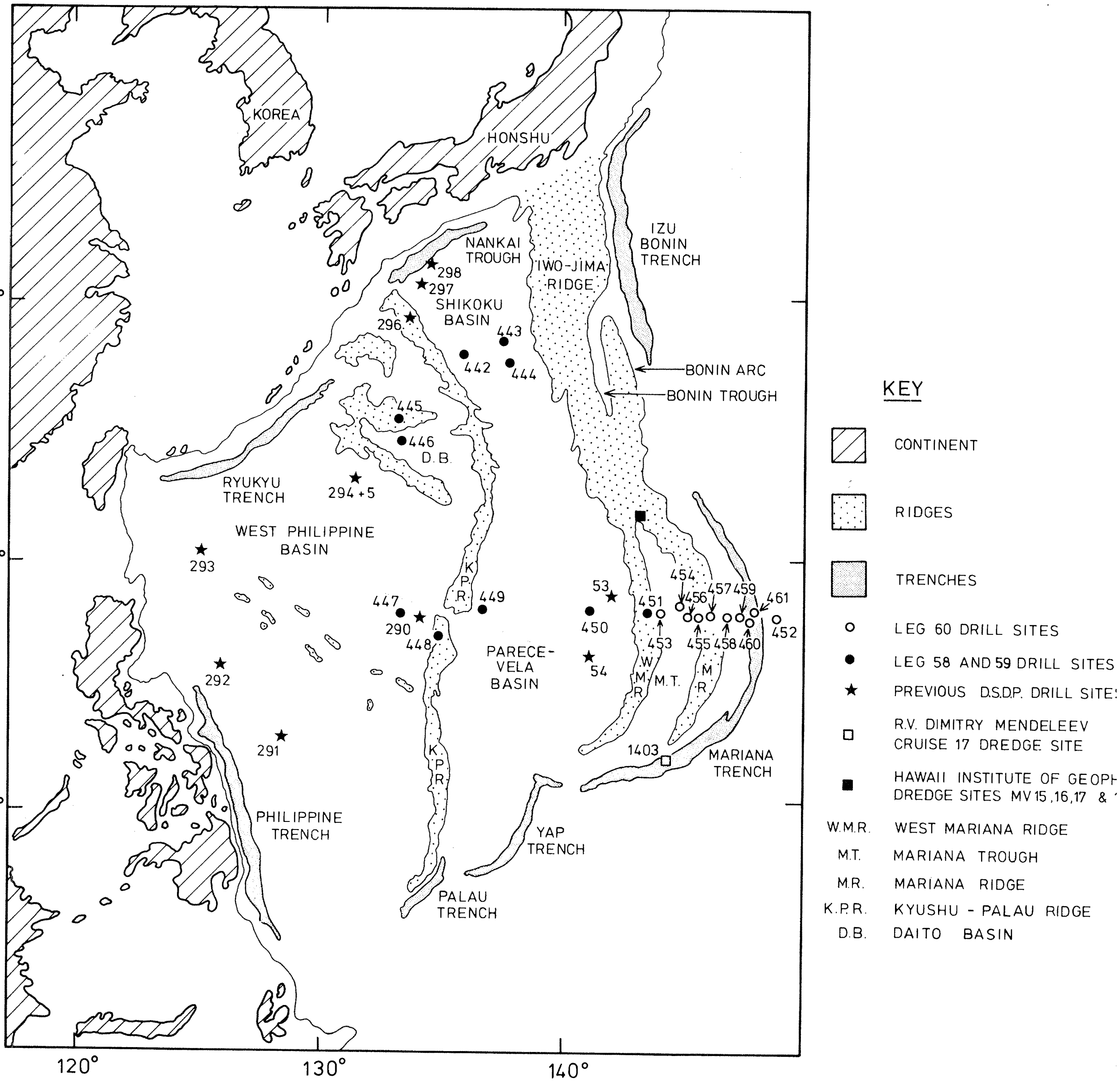

Figure 3. Sketch map of the Philippine Sea showing location of sites drilled by D.S.D.P. Legs 58, 59 and 60 in relation to the arcs, remnant arcs and marginal basins of the Mariana–Bonin arc system.

Mariana Trough respectively are separated by the submarine Kyushu–Palau and West Mariana Ridges and bounded to the west by the active Mariana–Bonin arc and trench. The submarine ridges were regarded by Karig (1971, 1972) as remnant arcs: original frontal arcs that had been split by mantle diapirism and separated by back-arc spreading from the currently active frontal arc. Recent deep sea drilling has recovered basement samples from most of the arcs and intervening basins, and our recent geochemical studies of these samples will be used as a basis for discussion.

(*a*) *The West Philippine Basin*

Our understanding of the West Philippine basin is still imperfect; it may in part be trapped in origin and pre-date the Kyushu–Palau Ridge. Magnetic anomalies (Louden 1976; Watts *et al.* 1977) suggest active spreading in the early Tertiary (62–40 Ma) with the NW–SE trending Central Basin Fault as the spreading centre (Ben Avraham *et al.* 1972). The Oki-Daito Ridge (a possible remnant arc? (Karig 1975)), in the northern West Philippine Sea, is aligned parallel to this feature. Andrews (1980) has suggested that the spreading direction may have changed 54 Ma ago from northeasterly to northerly. It is thus unlikely that the West Philippine Sea is related to the Kyushu–Palau remnant arc by normal back-arc spreading (Hilde *et al.* 1977).

The mineralogy, petrology and geochemistry of basalts from D.S.D.P. Site 447, located between the Central Basin Fault and the Kyushu–Palau Ridge, have been described by Mattey *et al.* (1980) and Wood *et al.* (1980*a*). They recognized two distinct magma types with different major element glass compositions and trace element ratios (e.g. Ti/Zr, Y/Zr) that appear to have evolved in separate magma chambers but are interlayered in the hole. However, the overall geochemical characteristics of these basalts (low K, Rb, Ba, Sr, low Nb and Ta, variable light r.e.e. depletion) are essentially similar to those of normal m.o.r.b. There are no obvious arc-related geochemical characteristics as observed for back-arc basalts in the Scotia Sea region. This would agree with the suggestion that the evolution of this part of the West Philippine Basin is unrelated to back-arc spreading.

Basalts recovered from Site 446 in the Daito Basin, between the Daito and Oki–Daito Ridges (figure 3) are very different. They occur as a series of sills of post-Early Eocene age (Marsh *et al.* 1980). There are two distinct types of basalt, one rich in kaersutitic hornblende, the other hornblende-free. Both types have high contents of titanium (up to 4.9% TiO_2) and incompatible elements and have strongly fractionated r.e.e. patterns (Ce_N/Yb_N = 3–6). These features are not unlike 'enriched' m.o.r.b. from Iceland or from 45° N in the Mid-Atlantic Ridge (Wood *et al.* 1979*a*, *b*), although the latter are not Ti-rich. The high Nb content of these basalts contrasts with the low Nb contents of the marginal basin basalts described so far and it is clear that they have no arc-related geochemical characteristics. The basement age at this site (53 Ma; Klein *et al.* 1980) pre-dates the development of the Kyushu–Palau arc.

(*b*) *The Parece-Vela and Shikoku Basins*

Recent studies of magnetic anomaly patterns in the Parece-Vela Basin indicate spreading between 30 and 17 Ma (Mrozowski & Hayes 1979), while equivalent studies in the Shikoku Basin (see, for example, Watts & Weissel 1975; Shih 1980), though resulting in some minor differences in interpretation, suggest spreading between *ca.* 26 and 15 Ma. In general this agrees with basement ages derived from deep sea drilling, although the presence of basaltic sills at several sites suggests that off-axis magmatic activity may have been more prolonged than at normal mid-ocean ridges and the spreading process less regular (cf. Lawver & Hawkins 1978).

Assuming that the subduction that led to the development of the Kyushu–Palau Arc began about 40 Ma (Hilde *et al.* 1977; Shih 1980), then back-arc spreading in these basins began about 10 Ma later, as predicted by the model of Toksöz & Bird (1977).

Basalts from Sites 449 and 450, located either side of the original spreading axis (the IPOD Trough) in the Parece-Vela Basin, have been described by Mattey *et al.* (1980) and Wood *et al.* (1980*a*). There are small but significant differences in the compositions of basalts from the two sites, but essentially both groups have the low incompatible element contents and element ratios characteristic of m.o.r.b. with flat to slightly depleted r.e.e. patterns.

Three sites have been drilled in the Shikoku Basin: Site 442 (50 km west of the axial zone) and Sites 443 and 444 (*ca.* 100 km east of the axis). All penetrated sills or massive flows and only at Site 442 was true pillowed basement reached. Many of the basalts are notably vesicular, suggesting high volatile contents during eruption. Different aspects of the petrology and geochemistry of these basalts have been described by Marsh *et al.* (1980), Wood *et al.* (1980*b*) and Dick *et al.* (1980). Geochemical variations can be ascribed to within-sill crystal settling, fractional crystallization in magma chambers and differing degrees of partial melting. Most of the basalts from the three sites are similar in composition to those from the Parece-Vela Basin. R.e.e. patterns are flat and incompatible element levels are low, but not as impoverished as in normal (N-type) m.o.r.b. Zr/Nb ratios are, however, high (more than 20). An exception is the upper sill at Site 444, which has much more fractionated r.e.e. patterns ($\mathrm{Ce_N/Y_N} \approx 2.5$), significantly higher levels of Nb and other incompatible elements and low Zr/Nb ratios (*ca.* 7). It is compositionally similar (figure 4) to enriched (E-type) basalts from the Mid-Atlantic Ridge (Wood *et al.* 1979*b*), and demonstrates that basalts with alkalic tendencies can be generated during back-arc spreading.

(*c*) *The Mariana Trough*

Lying between the West Mariana Ridge and the crescent-shaped Mariana Arc, the Mariana Trough (1500 km long and a maximum of 250 km wide) is characterized by rough topography (Hart *et al.* 1972; Karig *et al.* 1978) and high heat flow (Sclater 1972) and is underlain by a zone of high seismic wave attenuation (Barazangi *et al.* 1975). There is general agreement that the Trough has opened relatively recently (less than 6 Ma ago) by back-arc spreading, though magnetic lineations are poorly developed and estimates for the spreading rate vary from 2 cm/a (Hussong *et al.* 1978) to 4 cm/a (Karig *et al.* 1978).

Three sites have been drilled in the Mariana Trough. The petrology and chemistry of the basement rocks have been described by Wood *et al.* (1981). Site 453, 120 km west of the central graben and close to the West Mariana Ridge, drilled igneous and metamorphic breccias (older than 5.4 Ma) composed of metabasalts, gabbros and anorthositic cumulates. The compositions of the basalts are similar to those of the adjacent West Mariana Ridge lavas (see below and figure 4) in having high Sr and Ba but low Ta, Nb, Cr and Ni contents and moderately fractionated r.e.e. patterns ($\mathrm{Ce_N/Y_N} \approx 2$). The breccias may have been derived from the adjacent Ridge during splitting of the arc at the start of back-arc spreading, although it is difficult to exclude the possibility that magmas of this composition were generated during the early stages of back-arc spreading (their compositions indeed are broadly similar to Bransfield Strait lavas).

Sites 454 and 456 were drilled 28 km west and 37 km east of the central graben respectively and many of the recovered basalts are notably vesicular. Moreover, although some of the

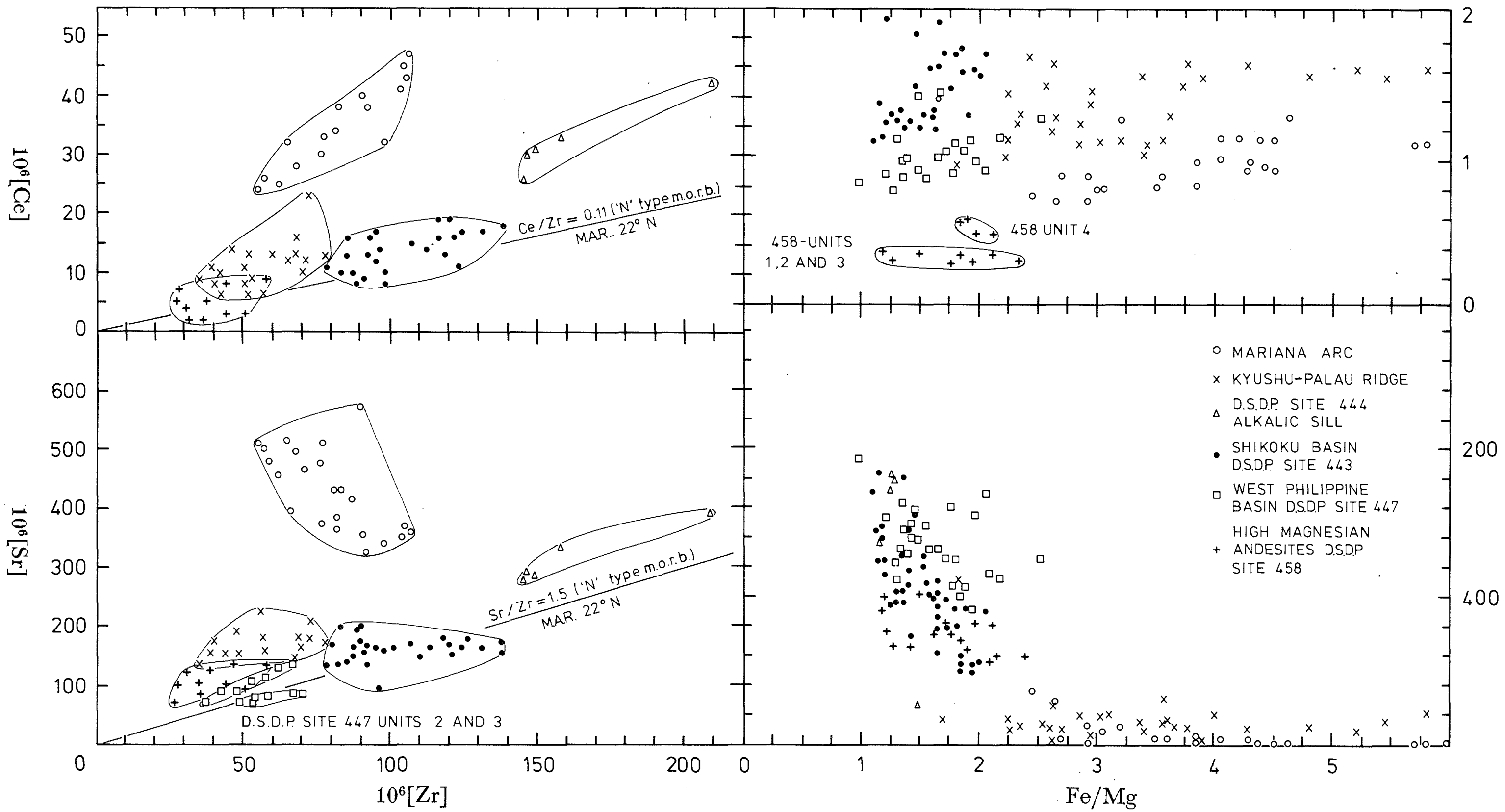

FIGURE 4. Biaxial plots of representative marginal basin and island arc samples from the western Pacific illustrating minor and trace element differences between the Kyushu–Palau and Mariana arc lavas and between the arc and basin basalts. Data from Marsh *et al.* (1980), Mattey *et al.* (1980) and Wood *et al.* (1981). Data points for the West Mariana Ridge (not shown for clarity) plot with the Mariana Arc lavas.

basalts have compositions with 'depleted' characteristics similar to N-type m.o.r.b., other flow units interlayered with them have significantly higher Sr, Ba, Th and light r.e.e. relative to Zr, Ti and Y, but lower Ta and Nb. Note too that dredged basalts from the Mariana Trough described by Hart *et al.* (1972) have higher l.i.l. element and light r.e.e. contents and higher $^{87}Sr/^{86}Sr$ ratios than normal m.o.r.b.

It appears, then, that basalts with transitional arc-like trace element characteristics are well represented in the Mariana Trough, but, on present evidence, are uncommon in the Parece-Vela and Shikoku Basins. To understand the significance of this it is necessary to examine the way in which the accompanying arc magmatism has evolved during the same period.

(*d*) *The Kyushu–Palau Ridge*

Rising up to 2000 m above the adjacent basin floors, the Kyushu–Palau Ridge is over 2000 km long (figure 3). At Site 448 over 600 m of volcanic basement consisting of lava flows, dykes and sills interbedded with volcanoclastic breccias were penetrated below middle Oligocene oozes. Like dredged samples from this locality (Anon. 1977), the basalts are frequently highly vesicular. Mattey *et al.* (1980) have described the petrology and geochemistry of the arc lavas, all of which conform to the island arc tholeiite series of Jakeš & Gill (1970). They are readily separated from the marginal basin basalts on geochemical grounds (figure 4): Cr (20–50 μg/g) and Ni (0–20 μg/g) are significantly lower than in the basin basalts.

The Kyushu–Palau rocks are quartz-normative tholeiites and basaltic andesites with 48–56% SiO_2, 13–17% Al_2O_3 and 10–15% iron as total FeO. FeO/MgO ratios range from 1.5 to over 4.0, much higher than most m.o.r.b. or the marginal basin basalts, implying that they may have suffered considerable crystal fractionation. The most popular model for the origin of the island arc tholeiite series (cf. Ringwood 1974) is that they are generated through hydrous melting of the mantle wedge above the subducting slab, and have suffered extensive fractionation en route to the surface to explain the wide range of Fe/Mg ratios and low Cr and Ni contents (figure 5). Mattey *et al.* (1980) noted, however, that the concentrations of many incompatible elements in the Kyushu–Palau lavas, and especially the r.e.e., Zr, Nb and Ta, were much lower than in m.o.r.b. with equivalent Fe/Mg ratios, and that these did not increase systematically with Fe/Mg ratio. Moreover they distinguished several petrographic types (ol.–plag., opx.–cpx.–plag. and cpx.–plag. phryic) that had distinctive trace element ratios and that could not be related to each other by fractional crystallization. Mattey *et al.* (1980) considered that an alternative mechanism for the generation of the Kyushu–Palau arc tholeiites, namely melting of the basaltic ocean crust in the downgoing slab, could not be excluded by the geochemical data. Although thermal models for steady-state subduction zones (Anderson *et al.* 1978) tend not to favour melting of the subducted ocean crust, it is to be remembered that the Kyushu–Palau Ridge developed rapidly following the *start* of subduction beneath the West Philippine Sea. It is conceivable that, during the first few million years of subduction into hot mantle, high degrees of partial melting of ocean crust are possible. This would readily account for the consistently high Fe/Mg ratios and low Cr and Ni contents of the arc tholeiites. R.e.e. data (Mattey *et al.* 1980; Wood *et al.* 1980*a*; Scott 1980) show that the arc tholeiites have light r.e.e. depleted patterns, similar to normal m.o.r.b., that would be consistent either with derivation of arc tholeiite magmas from a 'depleted' mantle source or through high degrees of melting of normal m.o.r.b. or m.o.r.b. cumulates at depths shallower than the basalt–eclogite transition. Nonetheless, the arc tholeiites have higher contents of l.i.l.

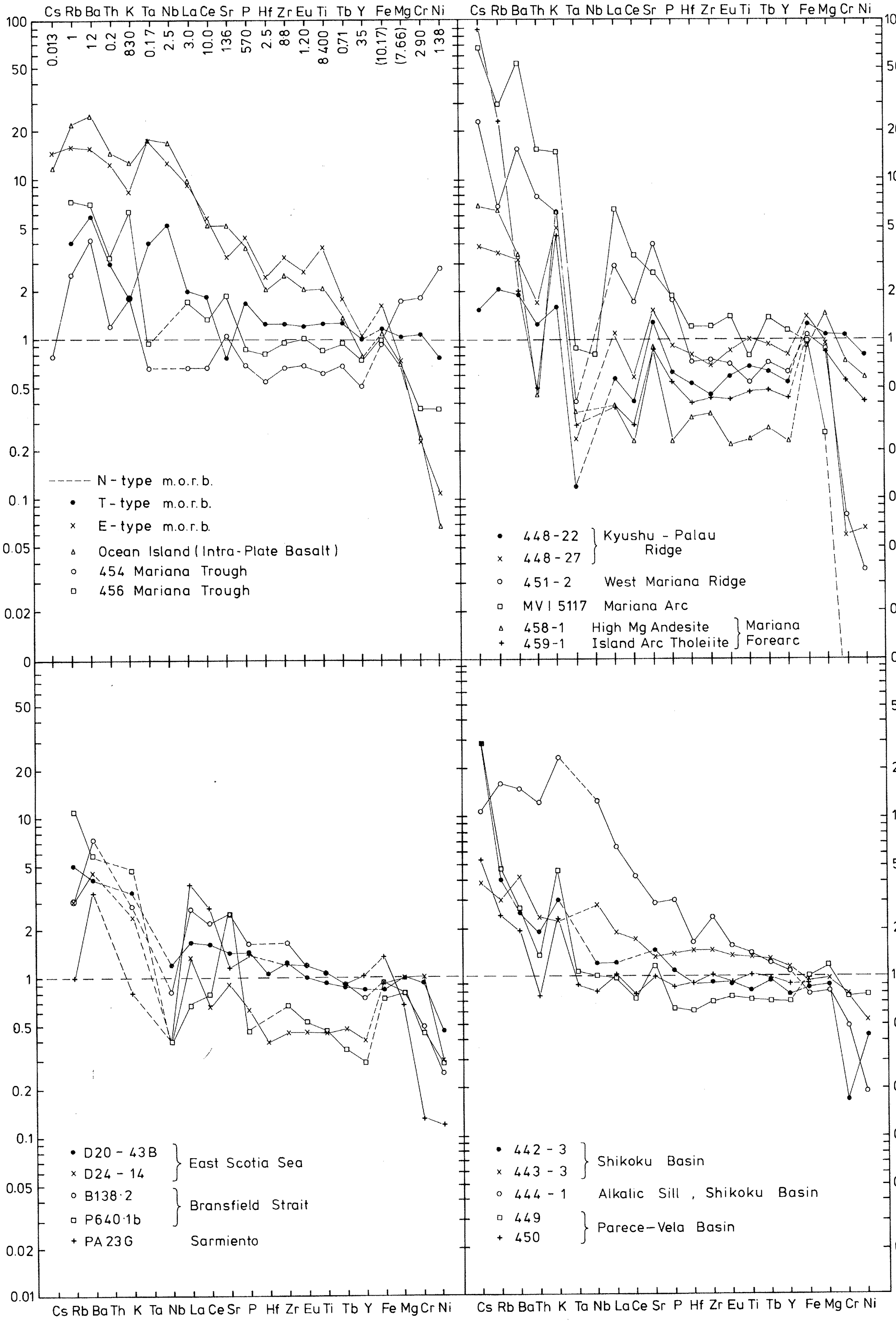

FIGURE 5. For description see opposite.

elements (K, Rb, Ba, Sr, Th, Pb) and lower contents of h.f.s. elements (Ta, Nb, Zr, Hf, Ti) than normal m.o.r.b. (figure 4), features typical of most arc lavas.

(*e*) *The West Mariana Ridge*

Like the Kyushu–Palau Ridge, the West Mariana Ridge has been interpreted by Karig (1972, 1975) as a remnant arc left behind during the opening of the Mariana Trough; it is shallower than the Kyushu–Palau Ridge, usually less than 2000 m below sea level. Drilling at Site 451 penetrated 930 m of volcanoclastic material, the breccia fragments being composed mainly of basalts and basaltic andesites with rare andesites and having phenocrysts of plagioclase ± clinopyroxene ± orthopyroxene ± olivine ± magnetite (Mattey *et al.* 1980).

Chemically these lavas have low contents of Cr, Ni, Zr, Nb and Ta (Mattey *et al.* 1980; Wood *et al.* 1980*a*) (figure 4) like the Kyushu–Palau arc tholeiites, but in other respects they are very different. They have low Fe/Mg ratios (1.0–2.0) (figure 5), are lower in both FeO and MgO, have much higher Al_2O_3 (18–20%) and CaO (9–13%) and a wider range of SiO_2 (45–58%). There are larger trace element differences. La/Zr and Ce/Zr ratios (figure 5) are higher and r.e.e. patterns more fractionated, with $Ce_N/Y_N \approx 2$. Concentrations of Ba (110–450 μg/g) and Sr (450–600 μg/g) (figure 5) and other l.i.l. elements are notably higher than in the arc tholeiites or in normal m.o.r.b. These characteristics are those of calc-alkaline rather than those of island arc tholeiite magmas and clearly mark a very significant temporal change in the magmatic evolution of the Mariana Arc system.

(*f*) *The Active Mariana Arc and fore-arc*

The northern section of the Mariana Arc, with a steeply dipping Benioff zone and seismic activity down to at least 600 km, is also the most volcanically active sector with at least ten volcanic islands and additional seamounts. Recent studies of the northern Mariana Arc (Stern 1978, 1979; Dixon & Batiza 1979; Chow *et al.* 1980) and our own data (reported in Wood *et al.* 1981) indicate that the erupted lavas are mainly basalts, basaltic andesites and andesites. The lavas lack a strong trend of iron enrichment (Stark 1963). Their geochemical characteristics are closely similar to the lavas of the West Mariana Ridge and are essentially calc-alkaline rather than island arc tholeiite. The observed concentrations of l.i.l. elements such as Sr and Ba display a greater range, with Ba in particular reaching higher levels; the r.e.e. patterns are also more variable and in many cases more fractionated (Ce_N/Y_N up to 4.0). This may be due

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FIGURE 5. Comparative element abundances in representative basalt samples from the marginal basin and arc samples discussed in the text, all normalized to N-type m.o.r.b. Normalizing values (listed on top left-hand abscissa) based on N-type m.o.r.b. from M.A.R. 22° N by using data from Bougault *et al.* (1978) and Rhodes *et al.* (1978) but with values for Cs, Rb, Ba, Th and K in fresh N-type m.o.r.b. as estimated by Mattey *et al.* (1980).

Samples as follows: T-type m.o.r.b., Reykjanes Ridge (409–3; Wood *et al.* 1979*b*); E-type m.o.r.b. Iceland (ISL 79; Wood *et al.* 1979*a*); ocean island basalt, Fayal, Azores (FA47; J.-L. Joron, personal communication); 454 and 456, Mariana Trough (454A-5-4, 15–18 cm and 456-13-1, 23–26 cm; Wood *et al.* 1981). Kyushu–Palau Ridge (448A-36-7, 130–133 cm and 448A-41-4, 6 cm), West Mariana Ridge (451-46-1, 24–30 cm) Mariana Arc (MV1 5117) and Mariana fore-arc (458-28-1, 58–64 cm and 459B-61-1, 115–118 cm) from Wood *et al.* (1980*a*, 1981). East Scotia Sea dredge samples (D20-43B, D24-14) from Saunders & Tarney (1979), Bransfield Strait samples (B138.2 Deception; P640.1b Bridgeman) from Weaver *et al.* (1979) and Sarmiento samples (PA 23G) from Saunders *et al.* (1979). Shikoku Basin samples (442B-16-1, 111–114 cm; 443-58-2, 99–101 cm and 444A-20-1, 73–77 cm) from Wood *et al.* (1980*a*); Parece-Vela Basin samples (449-15-2, 11–13 cm; 450-36-3, 7–9 cm) from Wood *et al.* (1980*a*).

in part to the greater extent of low pressure crystal fractionation, but may also reflect higher l.i.l. element contents in the source. Isotopic studies (Meijer 1976; DePaolo & Wasserburg 1977; Stern 1979; Dixon & Batiza 1979) place limits on the extent to which a component from the subducted slab is involved in the petrogenesis of the Mariana Arc lavas.

Deep sea drilling in the fore-arc region (Sites 458–461) penetrated only island arc tholeiites and high magnesian andesites (boninites) of late Eocene age. The island arc tholeiites are similar in age and composition (though not so iron-rich) to the arc tholeiites of the Kyushu–Palau Ridge, and it is clear that the fore-arc region represents the frontal half of the original Kyushu–Palau Arc, which was split during the formation of the Parece-Vela Basin and, subsequently, the Mariana Trough. The 'boninites' form the upper part of the section at Site 458. Apart from one sample they are not as Mg-rich as many boninites recently described from the Bonin Islands or dredged from the Mariana trench (cf. Kuroda & Shiraki 1975; Dietrich *et al.* 1978; Sun & Nesbitt 1978; Sharaskin *et al.* 1980). Nevertheless they have essentially the same mineralogical, petrological and geochemical characteristics (cf. Cameron *et al.* 1979) and can be regarded as less primitive members of the boninite group. The high MgO, Cr and Ni, but low r.e.e. Ti, Zr, Nb and Ta contents of the boninites (Wood *et al.* 1981) are consistent with high degrees of mantle melting, yet the contents of l.i.l. elements and SiO_2 are much higher than would be expected from such degrees of mantle melting. Rare earth patterns of Site 458 boninites (Hickey & Frey 1979, 1981) show progressive, though moderate, light r.e.e. depletion, although those from the Bonin Islands (Sun & Nesbitt 1978) have a dished shape with significant light r.e.e. enrichment. Element ratios such as Ta/Zr, Y/Zr and Ba/Zr, moreover, do not indicate a normal 'depleted' mantle source. It is possible that the mantle source of boninites may have been depleted by previous melting events (basalt extraction), but variably re-enriched, perhaps through the agency of fluids derived from the subducting slab (cf. Sun & Nesbitt 1978). The high vesicularity of many boninite pillow lavas and the high water content of glass rich samples (2–3% H_2O) indicates a high primary water content and it seems likely that hydrous conditions may have permitted high degrees of mantle melting, perhaps of a harzburgitic source.

Although intimately associated with island arc tholeiites in the fore-arc region, the element ratios in boninites (low Ti/Zr, Y/Zr, etc.) are so different from those in the arc tholeiites that it seems unlikely they are comagmatic or could have been derived from the same source. We note, however, that the combination of low r.e.e. and other incompatible elements plus high SiO_2 seen in boninites is also mirrored, to a less marked degree, in the dredge 24 basalts from the Scotia Sea and in the Bridgeman lavas of Bransfield Strait.

(*g*) *Evolution of the Mariana Arc system*

Three magma types (boninite, island arc tholeiite and calc-alkaline) have been generated during the evolution of the Mariana Arc, all of which must somehow be reconciled with models of subduction zone magmatism. The first two were produced during the initial formation of the Kyushu–Palau Arc, apparently with boninitic magmas being extruded on the trench side of the arc. The arc tholeiite lavas erupted on the trench side are also less iron-rich. Subsequent arc magmatism was calc-alkaline in nature.

Available evidence suggests that subduction at the Kyushu–Palau trench may have been initiated at a major N–S transform fault (Hilde *et al.* 1977) some 40 Ma ago, probably after a change in Pacific Plate motion (Jurdy 1979). At this time spreading was still actively taking place in the West Philippine Sea, so that the Pacific ocean crust was subducting beneath unusually hot, young lithosphere (with m.o.r.b.-like geochemical characteristics). It could be argued that under such favourable thermal conditions, dehydration of the slab could occur at relatively shallow depths with the released fluids, permitting high degrees of melting in the overlying mantle wedge and generation of boninitic magmas. Melting of the basaltic ocean crust would also be possible, at least during the early stages of subduction, and could potentially give rise to large volumes of island arc tholeiite magmas, leading to rapid development of the Kyushu–Palau Ridge. This model provides for the two contrasted magma types; the alternative of deriving them both from the mantle wedge would necessitate two separate mantle sources.

About 10 Ma after the start of subduction, mantle diapirism led to splitting of the Kyushu–Palau arc and formation of the Parece-Vela and Shikoku basins by back-arc spreading. As emphasized by Sharaskin *et al.* (this symposium), periods of back-arc spreading then appear to alternate with periods of arc volcanicity.

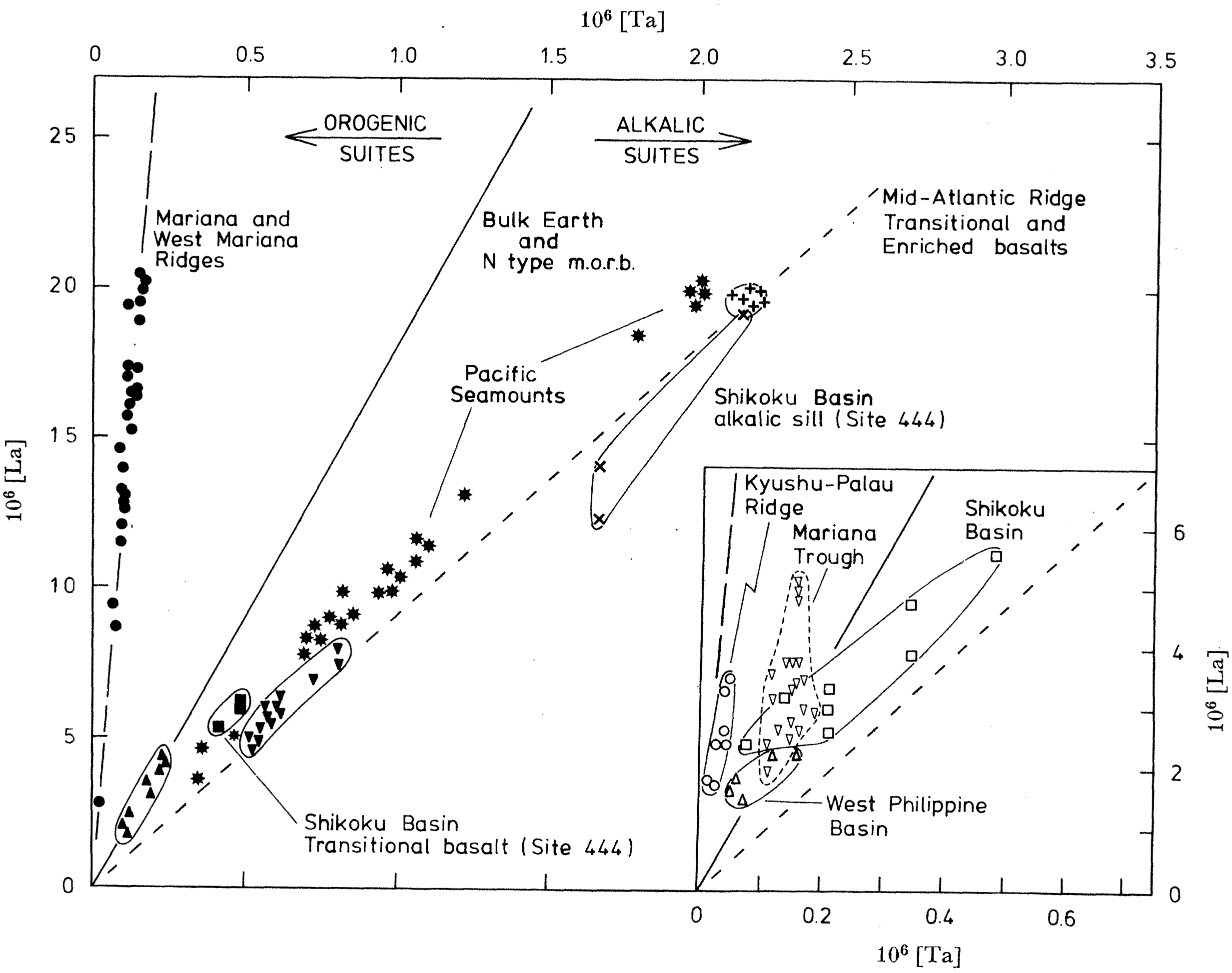

FIGURE 6. La versus Ta for western Pacific arc and basin lavas. For reference, data for Atlantic N-type m.o.r.b. (filled triangles), T- and E-type m.o.r.b. (inverted filled triangles, FAMOUS basalts; crosses, M.A.R. 45° N) and Pacific seamounts (stars) are also shown. (Note: Ta values for Shikoku Basin samples were estimated from Nb data of Marsh *et al.* (1980), assuming a constant Nb/Ta ratio of 14.4.) Sources of data: Wood *et al.* (1980*a*, *b*, 1981), Bougault *et al.* (1978) and Cambon *et al.* (1980).

With falling thermal gradients in the vicinity of the downgoing slab, it is likely that further arc magma production could only take place in the overlying mantle wedge, melting being induced by fluids derived through dehydration of the downgoing slab. It is clear, however, that by the time volcanicity occurred at the West Mariana Ridge and the currently active Mariana Arc, the mantle source in this mantle wedge had 'enriched' geochemical characteristics (enhanced in light r.e.e. and l.i.l. elements). It is difficult to see how this could occur through uprise of a deep mantle plume (Dixon & Batiza 1979) since there has been no essential change in geometry of the mantle wedge. There is no evidence for such a plume during the development of the Parece-Vela Basin (itself resulting from back-arc diapirism), and in any case 'plume-type' mantle sources are normally rich in Nb and Ta whereas the arc lavas are notably impoverished in these two elements (see figures 4 and 6). Rather we consider that the fluids themselves may have been the agency for enrichment (*a*) by transporting the more mobile l.i.l. elements and silica from the subducting slab, and (*b*) by causing incipient melting in the mantle wedge (probably over a considerable depth range) producing upward percolating l.i.l. and r.e.e. enriched liquids that vein and metasomatize the mantle wedge (cf. Saunders *et al.* 1980), and providing an enriched source for subsequent calc-alkaline magmas.

This enriched source clearly had developed by the time the lavas building up at least the upper part of West Mariana Arc were erupted. Moreover, during the formation of the Mariana Trough by splitting of the West Mariana Arc and separation of the frontal arc from the remnant arc by back-arc spreading, these same arc-like characteristics are seen in many of the marginal basin basalts, especially during the early stages of spreading. Evidently this enriched mantle source was, at least in part, being fed to the back-arc spreading centre. The mantle wedge remaining under the Mariana frontal arc would have been subjected to further metasomatism before generation of the present arc lavas, which may explain why some basaltic lavas have even higher l.i.l. element contents than those of the West Mariana Ridge. Note, however, that, taken as a whole, the active Mariana lavas show more variability in l.i.l. element contents and in their r.e.e. patterns (Dixon & Batiza 1979; Chow *et al.* 1980; Wood *et al.* 1981) than the West Mariana Ridge lavas. While this may be fortuitous and a function of limited sampling, it could indicate a more variable mantle source under the active frontal arc after the splitting of the West Mariana Arc.

The above model also accounts for the absence of arc-like characteristics in the Shikoku and Parece-Vela basin basalts. The lavas making up most of the Kyushu–Palau Ridge are arc tholeiites with low l.i.l. element contents and light r.e. depleted r.e.e. patterns. There is thus no evidence in the lava compositions of any immediately preceding phase of mantle wedge enrichment by l.i.l. elements; melting seems to be dominant over metasomatism by hydrous slab-derived fluids. Hence, during the back-arc spreading that followed splitting of the Kyushu–Palau arc, no l.i.l. element enriched mantle source had developed that could contribute towards an 'arc' geochemical characteristic in the erupted back-arc basalts.

The model also agrees with our observations in the Scotia Sea region. The Bransfield Strait and the Sarmiento–Tortuga marginal basins are both situated in areas with a previous history of calc-alkaline magmatism. The marginal basin magmas generated during the early stages of extension have a strong 'arc' imprint. In the South Sandwich back-arc basin this 'arc' imprint is minor and essentially restricted to one dredge haul (D24) in the southern half of the East Scotia Sea. The associated arc is a young arc, erupting island arc tholeiites, and is no older than the marginal basin itself. It is possible that this mild 'arc' imprint may have been conveyed by fluids derived from the subducted slab. Alternatively it is to be remembered that an earlier arc (the Discovery Arc) existed in the southern part of the East Scotia Sea a few million years previously (Barker & Hill, this symposium).

Conclusions

The following features may characterize ocean crust formed as a result of back-arc spreading.

1. There appears to be a higher incidence of sills in back-arc basins, perhaps in part due to the high sedimentation rate in some basins, but probably also reflecting less regularity in the spreading process. The poor magnetic anomaly record in some basins may be linked to the latter factor.

2. The range of basalt types in marginal basins appears to be just as diverse as that from normal mid-ocean ridges, and it may be inferred that the range of mantle sources and magma-generating processes are equally diverse. Nevertheless, on available evidence, there is a tendency for marginal basin basalts to be geochemically less 'depleted' in incompatible elements.

3. Marginal basin basalt glasses tend to have higher water contents and higher H_2O/CO_2 ratios than normal m.o.r.b. This is attributed to dewatering of the subducted slab and entry of fluids into the source regions of back-arc basalts.

4. Basalts from back-arc basins may have geochemical characteristics transitional toward arc magmas, particularly during the early stages of back-arc extension. This is manifest as higher ratios of l.i.l. (K, Rb, Ba, Sr, Th, U and light r.e.e.) to h.f.s. elements (Nb, Ta, Ti, Zr) and perhaps higher $^{87}Sr/^{86}Sr$ ratios. On the one hand this can be attributed to the hydrous environment in subduction zones enhancing the stability of minerals such as rutile or ilmenite, which retain h.f.s. elements, while on the other, hydrous fluids may transport l.i.l. elements into the back-arc mantle source regions, either from the slab, or via incipient melting within the mantle wedge itself.

In the western Pacific, where back-arc spreading has been initiated through splitting of the volcanic arc, the arc-like geochemical characteristics in the back-arc basalts are obvious only when the arc itself is calc-alkaline. The implication is that fluids derived from the downgoing slab are responsible for the incipient melting that leads to enrichment in l.i.l. elements and light r.e.e. (cf. Mysen 1979) and development of a calc-alkaline mantle source in the overlying mantle wedge. Isotopic data (Hawkesworth *et al.* 1977; Hawkesworth 1979; DePaolo & Wasserburg 1977; DePaolo & Johnson 1979) may permit, but do not always require, an added geochemical component from the subducted slab. No doubt as spreading continues this source will in part be dissipated, and as the back-arc spreading centre becomes separated from the volcanic arc, the 'arc' geochemical component will diminish. Where the frontal arc is erupting arc tholeiite magmas, as with the Lau Basin (Gill 1976; Hawkins 1976) and the East Scotia Sea, the 'arc' component in the back-arc basalts may be minor or absent. Ophiolite complexes that represent obducted marginal basin floor may, or may not, therefore have an 'arc' geochemical signature (cf. Miyashiro 1973, 1975; Smewing *et al.* 1975; Pearce, this symposium).

The ultimate cause of back-arc spreading may depend on absolute and relative plate motions (Chase 1978; Uyeda & Kanamori 1979) but it appears from the geological and geochemical data that when the mantle beneath the volcanic arc is weakened by continual magmatism, diapiric activity is initiated and concentrated along this weak zone.

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References (Tarney *et al.*)

Anderson, R. N., Delong, S. E. & Schwarz, W. H. 1978 *J. Geol.* **86**, 731–739.
Anon. 1977 *Ofioliti* **2**, 137–168.
Andrews, J. E. 1980 *Geology* **8**, 140–143.
Ashcroft, W. A. 1972 *Br. Antarct. Surv. sci. Rep.* **66**, 1–43.
Baker, P. E. 1978 *Br. Antarct. Surv. sci. Rep.* **93**, 1–34.
Barazangi, M., Pennington, W. & Isacks, B. L. 1975 *J. geophys. Res.* **80**, 1078–1092.
Barker, P. F. 1972 *Earth planet. Sci. Lett.* **15**, 123–132.
Barker, P. F. 1976 In *Andean and Antarctic volcanology problems* (ed. O. Gonzalez-Ferran), pp. 330–346. Rome: IAVCEI.
Barker, P. F. & Griffiths, D. H. 1972 *Phil. Trans. R. Soc. Lond.* A **271**, 151–183.
Barker, P. F. & Hill, I. A. 1980 *Nature, Lond.* (In the press.)
Barker, P. F., Hill, I. A., Weaver, S. D. & Pankhurst, R. J. 1980 In *Antarctic geoscience* (ed. C. Craddock). Madison: University of Wisconsin Press. (In the press.)
Ben-Avraham, Z., Bowin, C. & Segawa, T. 1972 *Nature, Lond.* **240**, 453–455.
Bougault, H., Treuil, M. & Joron, J. L. 1978 In *Init. Rep. Deep Sea Drilling Project* **45**, 439–506. Washington, D.C.: U.S. Government Printing Office.
Bruhn, R. L. & Dalziel, I. W. D. 1977 In *Island arcs, deep sea trenches and back arc basins.* (Maurice Ewing Series, vol. 1) (ed. M. Talwani & W. C. Pitman), pp. 395–406. Washington, D.C.: American Geophysical Union.
Bruhn, R. L., Stern, C. R. & de Wit, M. J. 1978 *Earth planet. Sci. Lett.* **41**, 32–46.
Cambon, P., Joron, J.-L., Bougault, H. & Treuil, M. 1980 In *Init. Rep. Deep Sea Drilling Project* **55**, 585–597. Washington, D.C.: U.S. Government Printing Office.
Cameron, W. E., Nisbet, E. G. & Dietrich, V. J. 1979 *Nature, Lond.* **280**, 550–553.
Chase, C. G. 1978 *J. geophys. Res.* **83**, 5385–5388.
Chow, T. J., Stern, R. J. & Dixon, T. H. 1980 *Chem. Geol.* **28**, 111–121.
Dalziel, I. W. D., de Wit, M. J. & Palmer, K. F. 1974 *Nature, Lond.* **250**, 291–294.
Davey, F. J. 1972 In *Antarctic geology and geophysics* (ed. R. J. Adie), pp. 39–45. Oslo: Universitetsforlaget.
DePaolo, D. J. & Johnson, R. W. 1979 *Contr. Miner. Petr.* **70**, 367–379.
DePaolo, D. J. & Wasserburg, G. J. 1977 *Geophys. Res. Lett.* **4**, 465–468.
Dewey, J. F. 1976 *Tectonophysics* **81**, 93–120.
de Wit, M. J. 1977 *Tectonophysics* **37**, 53–81.
de Wit, M. J. & Stern, C. R. 1978 *J. Volcan. geotherm. Res.* **4**, 55–80.
Dick, H. J. B., Marsh, N. G. & Bullen, T. D. 1980 In *Init. Rep. Deep Sea Drilling Project* **58**, 843–872. Washington, D.C.: U.S. Government Printing Office.
Dietrich, V., Emmerman, R., Oberhänsli, R. & Puchetl, H. 1978 *Earth planet. Sci. Lett.* **39**, 127–144.
Dixon, T. H. & Batiza, R. 1979 *Contr. Miner. Petr.* **70**, 167–181.
Duncan, R. A. & Green, D. H. 1980 *Geology* **8**, 22–26.
Elthon, D. 1979 *Nature, Lond.* **278**, 514–518.
Elthon, D. L. & Stern, C. R. 1978 *Geology* **6**, 464–468.
Garcia, M. D., Liu, N. W. K. & Muenow, D. W. 1979 *Geochim. cosmochim. Acta* **43**, 305–312.
Gill, J. B. 1976 *Bull. geol. Soc. Am.* **87**, 1394–1395.
Green, D. H. 1973 *Tectonophysics* **17**, 285–297.
Hart, S. R., Glassley, W. E. & Karig, D. E. 1972 *Earth planet. Sci. Lett.* **15**, 12–18.
Hawkesworth, C. H. 1979 In *Origin of granite batholiths: geochemical evidence* (ed. M. P. Atherton & J. Tarney), pp. 76–89. Orpington: Shiva Press.
Hawkesworth, C. J., O'Nions, R. K., Pankhurst, R. J., Hamilton, P. J. & Evenson, N. M. 1977 *Earth planet. Sci. Lett.* **36**, 253–262.
Hawkins, J. W. 1976 *Earth planet. Sci. Lett.* **28**, 283–297.
Hawkins, J. W. 1977 In *Island arcs, deep sea trenches and back arc basins* (Maurice Ewing Series, vol. 1) (ed. M. Talwani & W. C. Pitman), pp. 366–375. Washington, D.C.: American Geophysical Union.
Hickey, R. & Frey, F. A. 1979 *Eos, Wash.* **60**, 413.
Hickey, R. & Frey, F. A. 1981 In *Init. Rep. Deep Sea Drilling Project* **60**. Washington: U.S. Government Printing Office. (In the press.)
Hilde, T. W. C., Uyeda, S. & Kroenke, L. 1977 *Tectonophysics* **30**, 145–165.

Hill, I. A. 1979 Ph.D. thesis, University of Birmingham.

Hill, I. A. & Barker, P. F. 1980 *Geophys. J. R. astr. Soc.* (In the press.)

Hussong, D. H., Uyeda, S. *et al.* 1978 *Geotimes* **23**(10), 19–22.

Jakeš, P. & Gill, J. 1970 *Earth planet. Sci. Lett.* **9**, 17–28.

Jurdy, D. M. 1979 *J. geophys. Res.* **84**, 6796–6802.

Karig, D. E. 1971 *J. geophys. Res.* **76**, 2542–2561.

Karig, D. E. 1972 *Bull. geol. Soc. Am.* **83**, 1057–1068.

Karig, D. E. 1974 *A. Rev. Earth planet. Sci.* **2**, 51–75.

Karig, D. E. 1975*a* *J. geophys. Res.* **76**, 2542–2560.

Karig, D. E. 1975*b* In *Init. Rep. Deep Sea Drilling Project* **31**, 857–879. Washington: U.S. Government Printing Office.

Karig, D. E., Anderson, R. N. & Bibee, L. D. 1978 *J. geophys. Res.* **83**, 1213–1226.

Klein, G. de V., Kobayashi, K. *et al.* 1980 *Init. Rep. Deep Sea Drilling Project* **58**. Washington, D.C.: U.S. Government Printing Office.

Kuroda, N. & Shiraki, K. 1975 *Rep. Fac. Sci. Shizuoka Univ.* **10**, 145–155.

Langmuir, C. H., Bender, J. F., Bence, A. E. & Hanson, G. N. 1977 *Earth planet. Sci. Lett.* **36**, 133–156.

Lawver, L. A. & Hawkins, J. W. 1978 *Tectonophysics* **45**, 323–339.

Louden, K. E. 1976 *Am. geophys. Un. Monogr.* **19**, 253–267.

Marsh, N. G., Saunders, A. D., Tarney, J. & Dick, H. J. B. 1980 In *Init. Rep. Deep Sea Drilling Project* **58**, 805–842. Washington, D.C.: U.S. Government Printing Office.

Mattey, D. P., Marsh, N. G. & Tarney, J. 1980 In *Init. Rep. Deep Sea Drilling Project* **59**. Washington, D.C.: U.S. Government Printing Office. (In the press.)

Meijer, A. 1976 *Bull. geol. Soc. Am.* **87**, 1358–1369.

Miyashiro, A. 1973 *Earth planet. Sci. Lett.* **19**, 218–224.

Miyashiro, A. 1975 *J. Geol.* **83**, 249–281.

Mrozowski, C. L. & Hayes, D. E. 1979 *Earth planet. Sci. Lett.* **46**, 49–67.

Muenow, D. W., Liu, N. W. K., Garcia, M. O. & Saunders, A. D. 1980 *Earth planet. Sci. Lett.* **47**, 272–278.

Mysen, B. O. 1979 *Am. Miner.* **64**, 274–287.

O'Hara, M. J. 1977 *Nature, Lond.* **266**, 503–507.

O'Nions, R. K., Hamilton, P. J. & Evensen, N. M. 1977 *Earth planet. Sci. Lett.* **34**, 13–22.

Packham, G. & Falvey, D. 1971 *Tectonophysics* **45**, 323–339.

Rhodes, J. M., Blanchard, D. P., Dungan, M. A., Rodgers, K. V. & Brannon, J. C. 1978 In *Init. Rep. Deep Sea Drilling Project* **45**, 447–459. Washington, D.C.: U.S. Government Printing Office.

Ringwood, A. E. 1974 *J. geol. Soc. Lond.* **130**, 183–204.

Saunders, A. D. & Tarney, J. 1979 *Geochim. cosmochim. Acta* **43**, 555–572.

Saunders, A. D., Fornari, D. J., Joron, J.-L., Tarney, J. & Treuil, M. 1981 In *Init. Rep. Deep Sea Drilling Project*, **64**. Washington, D.C.: U.S. Government Printing Office. (In the press.)

Saunders, A. D., Tarney, J. & Weaver, S. D. 1980*a* *Earth planet. Sci. Lett.* **46**, 344–360.

Saunders, A. D., Tarney, J., Marsh, N. G. & Wood, D. A. 1980*c* In *Proc. Ophiolite Conf., Cyprus, 1979*. (In the press.)

Saunders, A. D., Tarney, J., Stern, C. R. & Dalziel, I. W. D. 1979 *Bull. geol. Soc. Am.* **90**, 247–258.

Saunders, A. D., Tarney, J., Weaver, S. D. & Barker, P. F. 1980*b* In C. Craddock (ed.). *Antarctic geoscience* (ed. C. Craddock). Madison: University of Wisconsin Press. (In the press.)

Sclater, J. G. 1972 *J. geophys. Res.* **77**, 5705–5719.

Scott, R. B. 1980 In *Init. Rep. Deep Sea Drilling Project* **59**. Washington, D.C.: U.S. Government Printing Office. (In the press.)

Sharaskin, A. Y., Dobretsov, N. L. & Sobolev, N. V. 1980 In *Proc. Ophiolite Conf., Cyprus, 1979*. (In the press.)

Shih, T. 1980 In *Init. Rep. Deep Sea Drilling Project* **58**, 783–788. Washington, D.C.: U.S. Government Printing Office.

Smewing, J. D., Simonian, K. O. & Gass, I. G. 1975 *Contr. Miner. Petr.* **68**, 151–169.

Stark, J. T. 1963 *U.S. geol. Surv. prof. Pap.* no. 403–C. (32 pages.)

Stern, C. R. 1979 *Contr. Miner. Petr.* **68**, 243–258.

Stern, C. R. 1980 *J. geophys. Res.* **85**, 955–966.

Stern, C. R. & Elthon, D. L. 1979 *Tectonophysics* **55**, 179–213.

Stern, C. R., de Wit, M. J. & Lawrence, J. R. 1976 *J. geophys. Res.* **81**, 4370–4380.

Stern, R. J. 1978 *Bull. volcan.* **41**, 1–13.

Stern, R. J. 1979 *Contr. Miner. Petr.* **68**, 207–219.

Suarez, M. 1979 *Geol. Mag.* **116**, 181–190.

Sun, S.-S. & Nesbitt, R. W. 1978 *Geology* **6**, 689–693.

Tarney, J. & Windley, B. F. 1981 *Phil. Trans. R. Soc. Lond.* (In the press.)

Tarney, J., Dalziel, I. W. D. & de Wit, M. J. 1976 In *The early history of the Earth* (ed. B. F. Windley), pp. 131–146. London: Wiley.

Tarney, J., Saunders, A. D. & Weaver, S. D. 1977 In *Island arcs, deep sea trenches and back arc basins* (Maurice Ewing Series, vol. 1) (ed. M. Talwani & W. C. Pitman), pp. 367–377. Washington: American Geophysical Union.

Tarney, J., Weaver, S. D., Saunders, A. D., Pankhurst, R. J. & Barker, P. F. 1981 In *Orogenic andesites* (ed. R. S. Thorpe). London: Wiley. (In the press.)

Tarney, J., Wood, D. A., Saunders, A. D., Cann, J. R., & Varet, J. 1980 *Phil. Trans. R. Soc. Lond.* A **297**, 43–66.

Tarney, J., Wood, D. A., Saunders, A. D., Varet, J. & Cann, J. R. 1979 In *Results of deep sea drilling in the Atlantic* (Maurice Ewing Series, vol. 2) (ed. M. Talwani), pp. 285–301. Washington: American Geophysical Union.

Toksöz, M. N. & Bird, P. 1977 In *Island arcs, deep sea trenches and back-arc basins* (Maurice Ewing Series, vol. 1) (ed. M. Talwani & W. C. Pitman), pp. 379–393. Washington: American Geophysical Union.

Uyeda, S. 1977 In *Island arcs, deep sea trenches and back-arc basins* (Maurice Ewing Series, vol. 1) (ed. M. Talwani & W. C. Pitman), pp. 1–14. Washington: American Geophysical Union.

Uyeda, S. & Ben-Avraham, Z. 1972 *Nature, phys. Sci.* **240**, 176–178.

Uyeda, S. & Kanamori, H. 1979 *J. geophys. Res.* **84**, 1049–1062.

Watts, A. B. & Weissel, J. K. 1975 *Earth planet. Sci. Lett.* **25**, 239–250.

Watts, A. B., Weissel, J. K. & Larson, R. L. 1977 *Tectonophysics* **37**, 167–181.

Weaver, S. D., Saunders, A. D., Pankhurst, R. J. & Tarney, J. 1979 *Contr. Miner. Petr.* **68**, 151–169.

Weaver, S. D., Saunders, A. D. & Tarney, J. 1980 In *Antarctic geoscience* (ed. C. Craddock). Madison: University of Wisconsin Press. (In the press.)

Wood, D. A. 1979 *Geochim. cosmochim. Acta* **43**, 1031–1046.

Wood, D. A., Joron, J.-L., Marsh, N. G., Tarney, J. & Treuil, M. 1980*a* In *Init. Rep. Deep Sea Drilling Project* **58**, 873–894. Washington, D.C.: U.S. Government Printing Office.

Wood, D. A., Joron, J.-L., Treuil, M., Norry, M. J. & Tarney, J. 1979*a* *Contr. Miner. Petr.* **70**, 319–339.

Wood, D. A., Marsh, N. G., Tarney, J., Joron, J.-L., Fryer, P. & Treuil, M. 1981 In *Init. Rep. Deep Sea Drilling Project* **60**. Washington, D.C.: U.S. Government Printing Office. (In the press.)

Wood, D. A., Mattey, D. P., Marsh, N. G., Joron, J.-L., Tarney, J. & Treuil, M. 1980*b* In *Init. Rep. Deep Sea Drilling Project* **59**. Washington, D.C.: U.S. Government Printing Office. (In the press.)

Wood, D. A., Tarney, J., Varet, J., Saunders, A. D., Bougault, H., Joron, J.-L., Treuil, M. & Cann, J. R. 1979*b* *Earth planet. Sci. Lett.* **42**, 77–97.

Discussion

D. Roberts (*Geological Survey of Norway, Trondheim, Norway*). In dealing with the chemical characteristics of basalts erupted at back-arc spreading centres, Professor Tarney and colleagues have forwarded a fairly convincing explanation for l.i.l. enrichment in basalts extruded during the earliest stages of spreading, i.e. the influence of contaminants, fluids, etc., derived from the subducting oceanic crust. It was reported that in many cases these early-stage magmatic products show 'mixed' chemical signatures, transitional between ocean floor and calc-alkaline basalts.

It would be interesting to hear if this is considered to be a general feature of west Pacific intraoceanic basins, or is the reported early-stage, lithophile element enrichment a more noticeable characteristic of the *younger* basins developed, for example, by the splitting of established arcs with coeval oceanward migration of the Benioff zone? I should also like to query the very nature of this early-stage geochemical transition. How secure are the indications that this is an ocean floor basalt – calc-alkaline basalt (o.f.b.–c.a.b.) transition, rather than just a reflection of temporary alkaline tendencies during the incipient-spreading stage? Diagrams illustrating some of Professor Tarney's points showed marked Ti-enrichment relative to m.o.r.b., and also fairly high Zr/Y ratios, such that the hybrid o.f.b.–c.a.b. traits are open to question. However, the possibility of an o.f.b.–c.a.b. 'transition' in the younger basins, oceanward of remnant arcs, is a more likely proposition. Have Professor Tarney and his coworkers in fact detected noticeable temporal changes in the chemical characteristics of western Pacific marginal basin basalts – i.e. from the oldest basins in the west to the youngest in the east?

J. Tarney *et al.* The main points that we have tried to stress in our contribution are:

(1) that basalts from marginal basins show a range of trace element variation similar to that

of basalts from mid-ocean ridges, which presumably reflects a similar range of mantle source compositions, partial melting conditions and fractional crystallization, and

(2) that when back-arc spreading develops through splitting of a calc-alkaline volcanic arc, that marginal basin basalts have a transitional m.o.r.b.–calc-alkaline signature, particularly during the early stages of basin formation. This calc-alkaline signature is weaker when the associated arc is composed of island arc tholeiites.

With regard to whether this 'arc' signature is a *general* feature of western Pacific marginal basins, the answer is 'no'. It depends in each case how the basin has developed. It will not be present in 'trapped' basins, formed where a new intra-oceanic volcanic arc has developed in response to the start of subduction at, say, a major transform fault. The alkalic high Ti-basalts, with high concentrations of incompatible elements and high Zr/Y ratios, were from the Daito Basin in the West Philippine Sea. This is regarded as a 'trapped' basin, mostly older than the Kyushu–Palau volcanic arc, and not formed by back-arc spreading. Nonetheless, there is no reason why basalts with alkalic tendencies should not be erupted in basins formed by back-arc spreading (as at Site 444 in the Shikoku Basin).

The point about whether the basalts erupted during the early stages of back-arc spreading show alkaline rather than calc-alkaline tendencies needs further consideration. In terms of trace elements there are subtle differences between 'alkaline' and 'calc-alkaline' basalts. Both may have similar levels of r.e.e. and l.i.l. elements such as Sr and Ba. However, l.i.l. elements such as K, Rb and Cs are higher but h.f.s. elements such as Nb and Ta are significantly lower in calc-alkaline basalts. Possible reasons for this have been outlined by Saunders *et al.* (1980*a*). Note too that alkali basalts in island arcs tend to have much lower Nb and Ta contents than their within-plate (oceanic island or continental rift) equivalents. Back-arc basalts with an 'arc' signature always have low Ta and Nb contents. For this reason we prefer to consider them transitional to 'calc-alkaline' rather than 'alkaline' magmas.

There are temporal changes in the compositions of western Pacific marginal basin basalts, and indeed in some of the other marginal basin magmas too. These are outlined and discussed in the text.

L. Stegena (*Department of Cartography, Lorand Eötvös University, Budapest, Hungary*). Why do the authors not use the discrimination diagrams of Miyashiro (*Am. J. Sci.* (1974) **274**, 321–355)?

J. Tarney *et al.* In his paper, Miyashiro (1974) reviews and assesses major element data on destructive plate margin volcanic rocks belonging to tholeiitic, calc-alkaline and alkaline suites. He neither compares these data with data on ocean ridge or back-arc basins basalts, nor does he emphasize that his plots be used as discrimination diagrams. There are in addition several other reasons why these diagrams are of little value in the type of study that we have undertaken. First, the concentrations of the elements used in Miyashiro's study are susceptible to low temperature (K, Na) and hydrothermal (Si, Fe, Mg, Na) alteration by seawater. This would render any extrapolation of studies of fresh basalts from present-day tectonic régimes to studies of ophiolite complexes well-nigh useless. Secondly, the parameters used by Miyashiro are, we feel, not sufficiently sensitive indicators of igneous processes: trace elements are much more valuable in this respect, and have effectively superseded (or at least complement) major element discriminants. Thirdly, we would emphasize that in this paper we have described geochemical differences between basalts from different tectonic settings, and have attempted to assess how these differences may arise; we are *not* proposing that our diagrams be used as discrimination diagrams.