PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Geochemistry and Timing of the Marginal Basin and Arc Magmatism in the Philippine Sea [and Discussion]

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Geochemistry and timing of the marginal basin and arc magmatism in the Philippine Sea

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Available data enable the recognition of three periods of back-arc crustal generation and three pulses of volcanic activity along the associated island arcs of the Philippine Sea. The geochemistry of the basalts from the back-arc basins of different ages indicates that in most cases they are identical to mid-ocean ridge basalts, and therefore should have similar sources and origins. In contrast, the island arc rock composition is variable in space and time, reflecting the different source and more complex nature of corresponding magmatism. Geomagnetic studies and recent Deep Sea Drilling Project results suggest an alternate sequence of back-arc and arc magmatic cycles. Both geochemical and geological observations provide important constraints on models of magmatism and extensional tectonics at convergent plate boundaries.

Introduction

The south Philippine Sea seems to present the most suitable region to elucidate some important peculiarities of the tectonics and magmatic activity during formation of complex arc–marginal basin systems of the western Pacific. Three parts of basins and adjacent arcs of the area have been studied recently in more detail then anywhere else.

Reviewing the progress in study of active marginal systems, Uyeda (1977) pointed out many unsolved problems. In this paper we wish to attract attention to the contrast in geochemistry of some incompatible trace elements in island arc and marginal basin rocks, and to the alternate character of back-arc spreading and arc volcanic episodes, features not previously recognized. Whatever their cause, these regularities are important constraints to be considered in possible models of the convergent plate boundaries.

General features of the area

Being surrounded by the chain of mature island arcs in the west and by the Izu–Bonin–Mariana arc–trench system in the east, the Philippine Sea encloses three marginal basins separated by remnant arcs. From west to east these are: the West Philippine Basin, the Palau–Kyushu Ridge, the Shikoku–Parece Vela Basin, the West Mariana Ridge and the Mariana Trough, terminated by the active Mariana arc (figure 1).

Results of multiple geological and geophysical surveys of the area have been reported by Ben-Avraham *et al.* (1972), Peive *et al.* (1980), Fisher *et al.* (1971), Karig (1971, 1974), Karig *et al.* (1975), Klein & Kobayashi (1978), Kobayashi & Isezaki (1976), Kroenke & Scott (1978), Louden (1976), Mrosowski & Hayes (1979), Murauchi *et al.* (1968), Sclater *et al.* (1976), Uyeda & Ben-Avraham (1972), Hussong *et al.* (1978), Watanabe *et al.* (1977) and Watts & Weissel (1975). The most important features of the area are outlined below.

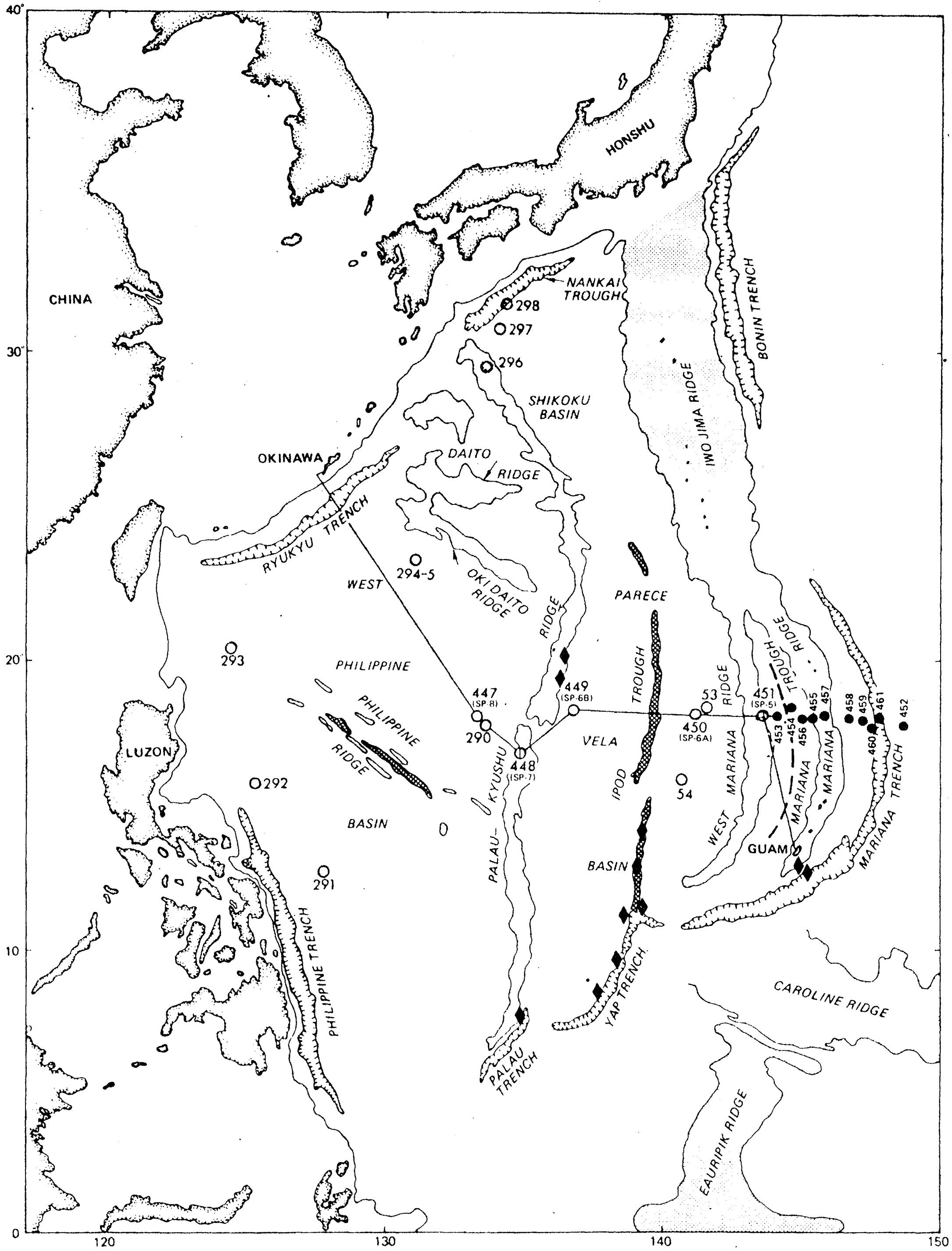

FIGURE 1. Structural sketch map of the Philippine Sea and location of D.S.D.P. sites (circles) and *Dm. Mendeleev* Leg 17 dredging stations (diamonds).

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The marginal basin topography of the Philippine Sea is characterized by the presence of contrast relief zones in its central part, namely the Philippine Ridge (or Central Basin Fault), IPOD Trough and the axial high in Mariana Trough (figure 1). Weak magnetic anomalies running parallel to these zones allow us to interpret them as extinct or (in the last case) active spreading centres. The crust beneath the basins is about 5–7 km thick and has a normal oceanic-type structure. It is up to three times thicker under the remnant and active arcs, but still is free of any possible equivalent of the seismic 'granitic layer'. The total heat flow through the area is high (nearly 2 h.f.u. (2.32 mW m^{-2})), being highest in the Shikoku and east Parece Vela basins, and in the axial zone of the Mariana Trough.

The estimated lithosphere thickness of the Philippine Sea plate is 35–40 km (Abe & Kanamori 1970; Seekens & Teng 1977), i.e. 20–30 km less thick than the adjacent part of the Pacific plate. The presence of a low Q, high seismic wave attenuation zone in the upper mantle behind the Izu–Bonin and northern Mariana arc was inferred by Barazangi *et al.* (1975), based upon a wave propagation study.

A thin hemipelagic sedimentary cover overlies the marginal basins in areas remote from the Palau–Kyushu and West Mariana ridges. The sedimentary sections adjacent to these regions on their western side consist of thick volcanoclastic aprons produced by island arc volcanic activity and subsequently buried under the younger marine sediments. Aphyric to phyric pillow-lavas cored or dredged from marginal basin floors are similar both in mineralogy and in bulk chemical composition to ocean-floor tholeiites (Hart *et al.* 1977; Ridley *et al.* 1974; Zakariadze *et al.* 1980). D.S.D.P. Site 293 in the western Philippine basin encountered tectonized and metamorphosed basalts, diabases and coarse-grained gabbroic rocks. The same rock association together with serpentinized ultramafics was dredged from IPOD Trough zone in the Parece Vela basin (Sharaskin & Bogdanov 1979), providing further evidence for a similarity between marginal basin and oceanic crust composition.

Arc-tholeiites are the dominant rock types among the island arc volcanics of the Philippine Sea. Calc-alkaline andesites and related rocks are rare but nevertheless present both in Cainozoic and Recent volcanic series (Meijer 1978; Tarney *et al.* 1978; Saunders *et al.* 1978; Stern 1979; Dixon & Batiza 1979). The peculiar boninites and related rocks were erupted only during the Oligocene period of arc volcanism and appear to be preserved now in the fore-arc region of the Izu–Bonin–Mariana arc system (Sharaskin *et al.* 1980).

Trace elements in arc and basin lavas

The incompatible trace elements have been shown to be most useful in assessing the probable nature of magma sources and the fractional crystallization history of volcanic rock series. Unfortunately, many of these elements, including K, Rb, Cs, Th, U, Sr, Ba and some rare earth elements (r.e.e.) are highly mobile during the secondary processes, which are common, variable and not always recognized. This may lead to erroneous results.

Because many of the Philippine Sea rocks studied are weathered, or have suffered hydrothermal and low-grade metamorphic alteration, we concentrated our attention on the geochemistry of another group of incompatible elements, namely Ti, Zr and Y. These elements are insensitive to secondary processes (Pearce & Cann 1971, 1973) and also contain important information on magma genesis and evolution (Bougault *et al.* 1978; Pearce & Norry 1979; Wood *et al.* 1979). Here they were used together with Cr, which is similarly immobile but has a geochemical trend opposite to the previous group and appears to improve the discrimination of ocean floor and island arc basalts (Pearce 1975).

Available data for the Philippine Sea show the perfect separation of island arc and marginal basin lavas on a diagram of Ti against Cr (figure 2). There is no difference between basalts from all three marginal basins; they overlap each other in composition, plotting as a compact group in the m.o.r.b. field. The compositions of island arc rocks are more variable, reflecting

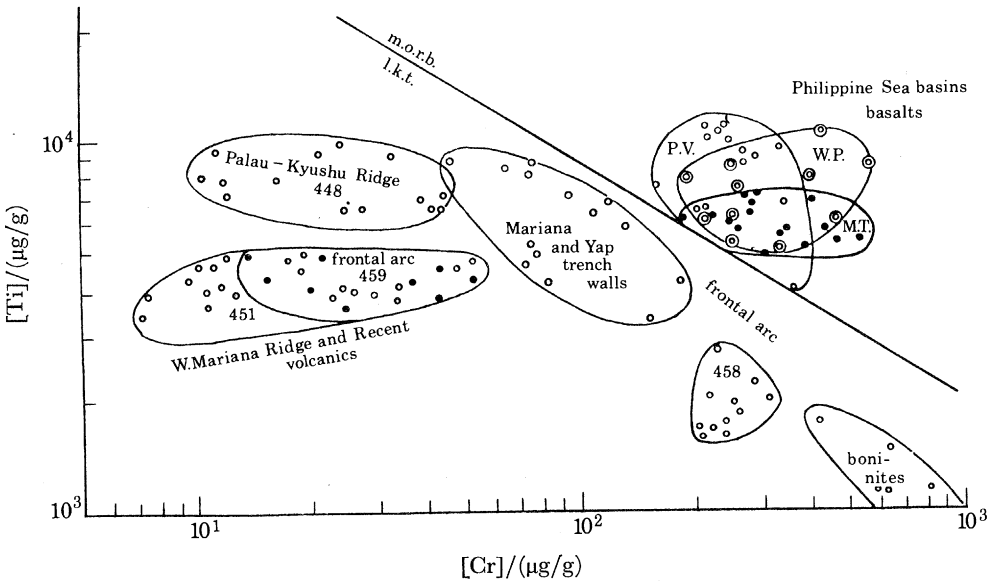

FIGURE 2. Ti–Cr diagram for the Philippine Sea arc and basin lavas. Subdivision line after Pearce (1975), W.P., W. Philippine basin; P.V., Parece Vela basin; M.T., Mariana Trough. Here and later data sources: Dixon & Batiza (1979), Stern (1979), Sharaskin *et al.* (1980), Sharaskin (1980), Zakariadze *et al.* (1980), Tarney *et al.* (1980), J. A. Pearce (personal communication), Scott *et al.* (1980).

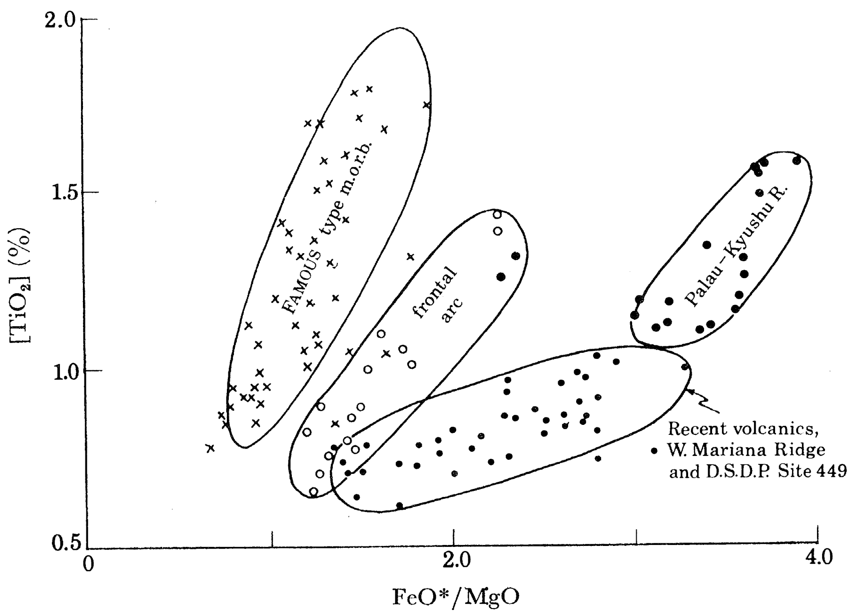

FIGURE 3. Ti–FeO*/MgO diagram for the Philippine Sea arc (circles) and basin (crosses) lavas.

the more fractionated nature of corresponding volcanic series. In general they display the negative correlation of these two elements, when only low-Cr (i.e. more evolved) arc lavas have Ti concentrations comparable with those of m.o.r.b. This Ti depletion of arc volcanics is also illustrated on a Ti–FeO/MgO diagram (figure 3), where the marginal basin basalts are again identical to m.o.r.b.

A recent comprehensive study of m.o.r.b. revealed three geochemically different types of these rocks. Based on their r.e.e. patterns, these rocks were subdivided into 'depleted' (in light r.e.e. relative to chondrites), 'enriched' and 'transitional' types (Schilling 1975). The subdivision was proved by study of other incompatible elements and radiogenic Sr and Pb distributions in m.o.r.b. (see, for example, Sun *et al.* 1975, 1979). Being the most widespread (accordingly called normal), the 'depleted' m.o.r.b. magmatism is most characteristic of the crustal generation process along the mid-oceanic ridges. There are several important regularities in the geochemistry of Ti, Zn and Y in relevant rocks. All these elements have extremely low and nearly equal mineral–liquid distribution coefficients for olivine and plagioclase, the main phases involved in the fractional crystallization of basaltic magmas. The recommended values of coefficients for both minerals are between 0.01 and 0.04 (Pearce & Norry 1979). Being therefore unaffected by magmatic differentiation, these element ratios are supposed to be characteristic of the source material, whereas their absolute abundances should increase in evolved rocks relative to primary magmas.

In fact, there are some variations of Ti/Zr ratios in m.o.r.b., mainly caused by interlaboratory discrepancies and to some extent by clinopyroxene fractionation at the advanced stage of the magmatic differentiation. Nevertheless the plotting of available data for normal m.o.r.b. on a Zr–TiO_2 diagram forms a general linear array with zero intercept, which corresponds to Ti/Zr ratios slightly lower than chondritic. This generalization, first inferred by Hubbard (1969), remains unchanged, even if recent results are taken into account.

Similarly it was noted that normal m.o.r.b. from fast spreading ridges have the same range of Zr/Y ratios as basalts from slow spreading ridges (Pearce & Norry 1979). However, in contrast to previous element pairs, these elements' ratios show systematic variations, becoming higher in evolved rocks, enriched in both elements. This correlation may be attributed to the higher distribution coefficients for Y in plagioclase and clinopyroxene, compared with Zr. On the Zr–Y diagram the normal m.o.r.b. trend has also a linear character, but intersects the chondrite reference line in such a manner that the Zr and Y-poor (i.e. most primitive) basalts have Zr/Y ratios lower than chondritic.

The Zr–Ti diagram for the Philippine Sea rocks (figure 4) illustrates that marginal basin basalts do plot along the m.o.r.b. trend (figure 4*a*). The island arc lavas (figure 4*b*) show entirely different regularities, being highly variable in Ti/Zr ratio. The main trend for these rocks coincides with the chondritic one, but there are some distinct deviations. For example, volcanics from O-Shima, Iwo-Jima Islands (J. A. Pearce, personal communication) have remarkably higher Ti/Zr ratios than contemporaneous Mariana Arc lavas, which have Ti/Zr ratios somewhat lower than the m.o.r.b. trend. The boninite-type rocks from the D.S.D.P. Site in the Mariana fore-arc zone form another separate trend with extremely low Ti/Zr ratios. Plotted on the Zr–Y diagram, marginal basin basalts form an array again orientated along the normal-type m.o.r.b. trend (figure 5*a*). The vast proportion of island arc rocks, in contrast, have Zr/Y ratios close to the chondritic, except in the high-Ti rocks of D.S.D.P. Site 448 (figure 5*b*) on the Palau–Kyushu Ridge.

Whatever the cause for variation of Ti/Zr and Zr/Y ratios in island arc lavas, it is important to note that many of them are significantly depleted in Ti, Zr and Y relative to the marginal basin basalts, having at the same time lower Cr concentrations (figure 1) and higher FeO/MgO ratios (figure 2). This diversity cannot be explained by any simple model of magmatic evolution and may indicate a different source for both magma types.

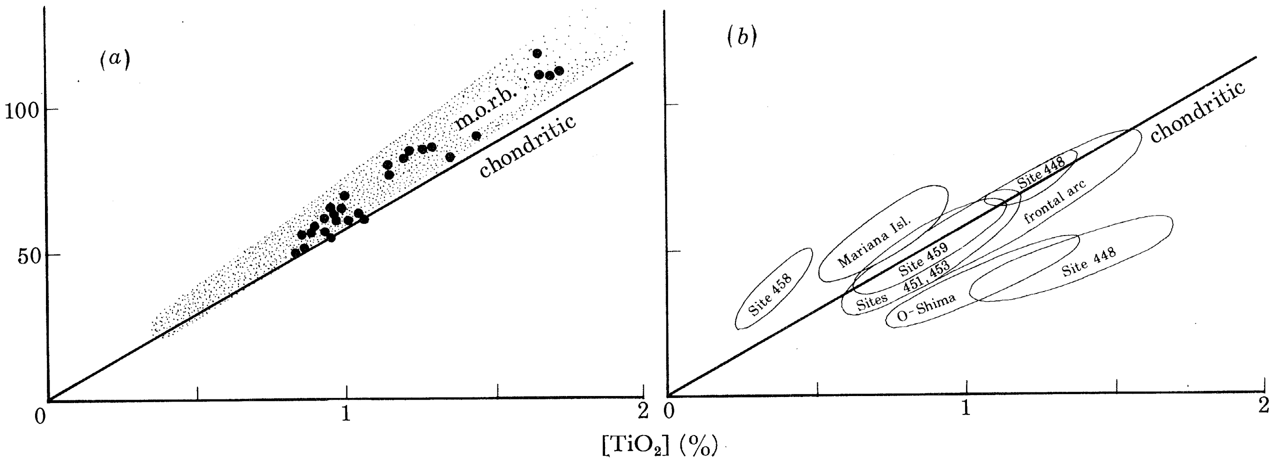

FIGURE 4. Zr–TiO_2 diagram for the Philippine Sea basin (*a*) and arc (*b*) lavas. Shaded area, normal m.o.r.b. trend; reference line, Ti/Zr ratios in chondrites.

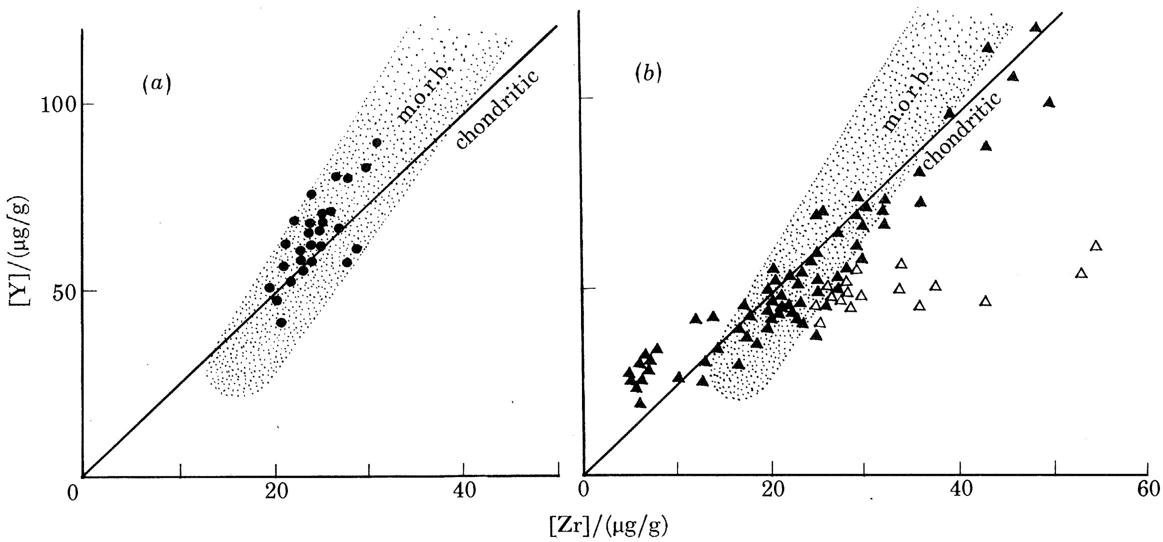

FIGURE 5. Zr–Y diagram for the Philippine Sea basin (*a*) and arc (*b*) lavas. Open triangles, D.S.D.P. Site 448 rocks; other symbols as in figure 4.

The strong similarity between m.o.r.b. and marginal basin basalts suggest the same source and origin for both, i.e. partial melting of the oceanic-type mantle and subsequent magma differentiation at higher level. The source for island arc volcanics is accepted to be either subducted oceanic crust transformed into quartz-eclogite (Green & Ringwood 1968), or hydrous melting in the mantle wedge overlying subducted lithosphere (Green 1973; Nicholls & Ringwood 1973; Yoder 1976). The latter process seems to be more realistic according to isotope constraints (Meijer 1976; De Paolo & Wasserburg 1976, 1977; Hawkesworth *et al.* 1977).

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Nevertheless, the depletion of island arc lavas in such refractory elements as Cr and simultaneously in incompatible Ti, Zr and Y may indicate significant differences in the composition between the mantle wedge beneath island arcs and the mantle source of m.o.r.b. or marginal basin basalts.

Timing of back-arc spreading and arc volcanism

Magnetic anomalies in the West Philippine Basin have been interpreted by Ben-Avraham *et al.* (1972) as Mesozoic. This interpretation grossly contradicts the D.S.D.P. results now available. Later magnetic anomaly identifications suggest that the anomalies are more recent. Louden (1976) suggests an age for the West Philippine basin of between 37 and 52 Ma, whereas Watts *et al.* (1977) estimate basin formation between 40 and 62 Ma. Palaeontological data on the basement age in this basin range between 53 Ma (Site 446; Klein & Kobayashi 1978) and older than 34 Ma (Scott *et al.* 1980), these results being in good agreement with available radiometric ages (Ozima *et al.* 1977).

Magnetic anomalies in the Parece Vela basin restrict the spreading period to between 30 and 18 Ma (Mrosowski & Hayes 1979). This timespan overlaps that predicted for the Shikoku Basin by Tomoda *et al.* (1975), Watts & Weissel (1975) and Shih (1978). Basement ages revealed by D.S.D.P. Sites in the Parece Vela Basin extend from 25 Ma (Site 449) to 17 Ma (Site 450) (Scott *et al.* 1980). The youngest basalts known were erupted in the Shikoku basin at about 15 Ma.

Magnetic patterns in the Mariana Trough are difficult to interpret, but the D.S.D.P. Leg 60 results (Hussong *et al.* 1978) indicate that spreading in this young basin started only 6–7 Ma ago, i.e. about 5 Ma before the last period of volcanic activity along the Mariana island arc.

The duration of previous island arc volcanic episodes can be measured from the stratigraphy of the Mariana Islands, recently reviewed by Ingle (1975). It may also be inferred from the ages of the volcaniclastic aprons penetrated by drill-holes west of the Palau–Kyushu and West Mariana ridges, during D.S.D.P. Legs 31 and 59 respectively (Karig *et al.* 1975; Scott *et al.* 1980).

A synthesis of the available data on the timing of back-arc spreading and arc volcanism in the Philippine Sea is shown in figure 6. It perfectly illustrates the periodicity in the tectonics and magmatism within the area, a feature first suggested by Karig (1975) on the basis of more limited data. However, the most important point of the present synthesis is the evidence for the alternate character of the back-arc and arc magmatic activity, which was not recognized by previous workers.

Discussion

Various models have been proposed for the origin of complex marginal systems of the western Pacific (Karig 1971; Matsuda & Uyeda 1971; Moberly 1972; Packham & Falvey 1971; Sleep & Toksöz 1971; Turcotte & Oxburgh 1969), with numerous recent modifications. They are mainly concerned with the thermomechanical aspects of lithospheric subduction and plate–asthenosphere interaction. These geophysical models, including numerical modelling (e.g. by Andrews & Sleep 1974), explain reasonably well the present state of convergent plate boundaries and consider the subduction process as the main factor in their development. However, tracing back the geological history of an area such as the Philippine Sea, we point out that the periodicity and alternate character of marginal basin and arc magmatism present one of the most intriguing problems to be solved. If subduction is a continuous process it is obviously possible to interpret the episodic evolution of the active margins in terms of abrupt changes in subduction rate, as suggested by Karig (1975). Variations in relative plate motions might be responsible for this (Jurdy 1979). If we admit this assumption we should expect a synchronous rather than an alternate manifestation of back-arc spreading and arc volcanic episodes. In fact the overlapping of these two processes seems to be insignificant and therefore the desirable model must be more sophisticated.

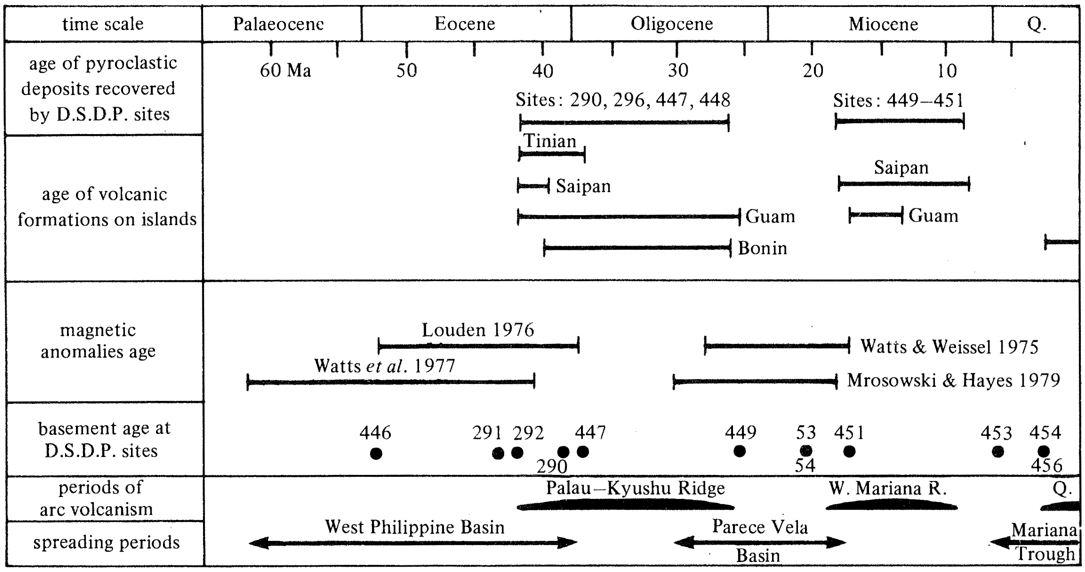

FIGURE 6. Time correlation diagram of back-arc spreading and arc volcanic cycles in the Philippine Sea areas (see text for explanation).

Another problem relevant to active margins is the diverse geochemistry of arc and back-arc basin lavas. The dynamics of this problem have not been considered. At present the most acceptable hypothesis for producing the island arc magmas is hydrous melting of the upper mantle wedge beneath the volcanoes, contaminated by volatile incompatible elements as a result of dehydration of the downgoing slab. The dominant island arc rocks in the Philippine Sea region are basalts or basaltic andesites of tholeiite or calc-alkaline series. In spite of the chemical and mineralogical differences between these series, they have distinctive and similar geochemical characteristics compared with marginal basin or ocean ridge tholeiites. Data presented here emphasize the general depletion of island arc volcanics in Cr, Ti, Zr and Y simultaneously. Trying to explain the depletion in Cr as a result of the intense fractional crystallization in island arc series, one should assume the high degree of partial melting in the mantle to understand the low Ti, Zr and Y contents in the same rocks. This assumption will immediately contradict the disproportionally high concentrations of other incompatible elements. The latter group includes some low mobile elements (e.g. Th and V), which can be hardly introduced into the mantle wedge from the crustal portions of the subducted oceanic slab.

Presented arguments indicate that all of the above mentioned processes, leaving significant imprints on geochemical characteristics of island arc volcanics, still cannot be responsible for the peculiar geochemistry of small ion lithophile elements, such as Ti, Zr and Y, in these rocks. Finally, we suggest a subtle but important difference between mantle sources for m.o.r.b. (or equally marginal basin basalts) and island arc magmas.

The Ti/Zr and Zr/Y ratios in island arc lavas, which are more chondritic than those in normal m.o.r.b. (as well as K/La and K/U ratios reported by Dixon & Batiza (1979)), permit an assumption that more primitive, undepleted mantle material might be involved in the magma generation process beneath the active arc volcanoes. There is some evidence that the mantle below 600 km may have a different composition, e.g. higher Fe/Mg ratio (Anderson 1967) and SiO_2 content (Burdick & Anderson 1975), and one can assume that its composition is less differentiated in other components as well. Being disturbed by the downgoing slab, this material may affect both the thermal state and the composition of the overlying zone. If these speculations should prove to be correct, they would have some important consequences for the currently accepted plate tectonics scheme for convergent plate boundaries.

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Discussion

M. F. Osmaston (*The White Cottage, Sendmarsh, Woking, Surrey, U.K.*). I have often wondered whether the complexity of the long-lived plate interaction zone between the Pacific and Asian plates might arise from its having acted as a take-up zone within which changes in the global balance of ocean floor genesis and consumption, occasioned by collisions or separations elsewhere, had been accommodated while the main Pacific floor convective overturn continued. The remarkable alternation of periods of sea-floor genesis and of island arc volcanism in the

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Philippine Sea region, to which the authors have drawn attention, is an exciting indication that this may indeed be the case. The overlap of the dated periods might reasonably be attributable partly to dating uncertainties and partly to the decay times to be expected for both processes after the tectonic régime has changed.

Do the authors accept that this interpretation is a possibility? If so, the precise dating of orogenic phases, in the Alpine belt for example, may acquire a new significance for the western Pacific, and *vice versa*.

A. Sharaskin. We have no objections to this suggestion, but we would point out that it is one of several possibilities. At any rate, the correlation of major phases of tectonic activity in the Alpine belt and the western Pacific seems to be a very important scientific goal. In *Geology of the Philippine Sea floor* (ed. A. V. Peive. Moscow: Nauka (1980)), we pointed out that the major tectonic events in the Philippine Sea do correlate roughly with early Senonian–pre-Oligocene and late Miocene orogenic phases in the Alpine Belt. Nevertheless, more detailed investigation of this problem is apparently required to establish the correlation more precisely.