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The Relative Roles of Crust and Upper Mantle in the Generation of Oceanic Island Arc Magmas [and Discussion]

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The relative roles of crust and upper mantle in the generation of oceanic island arc magmas

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The oceanic island arcs should represent the least complicated type of subduction related magmatism. Theoretically they represent an environment in which contamination by continental crustal materials does not occur.

Basaltic lavas from most island arc systems have Sr, Nd and Pb isotope characteristics that do not deviate substantially from the normal arrays of mantle derived magmas. However, their distinctive trace element geochemistry requires a distinctive mantle source composition which is most readily achieved by metasomatism of the lherzolite of the mantle wedge by fluids ascending from the upper surface of the subducted slab. Such fluids may be variably enriched in $^{87}Sr/^{86}Sr$, in which case they will induce deviations from the Nd–Sr mantle array.

In marked contrast, a range of basic to intermediate lavas from the Sunda–Banda arc of Indonesia and the Lesser Antilles island arc have a significant continental fingerprint to their isotopic compositions and show marked deviations from the Sr–Nd and Pb isotope mantle arrays. These data could be explained by the involvement of a terrigenous sedimentary component in the genesis of the slab derived fluids. However, they could equally reflect high level contamination of the ascending magmas by sediments *in situ* at the base of the island arc crust.

1. Introduction

Theoretically, the oceanic island arcs should represent the products of the least complicated type of subduction related magmatism, specifically one in which contamination of ascending magmas by continental crustal components should be eliminated. Magma generation in this tectonic setting is a multistage, multi-source phenomenon (Hawkesworth & Powell 1980; Barsdell *et al.* 1982; Dupuy *et al.* 1982; Sekine & Wyllie 1982) involving permutations and combinations of the following sources (see figure 1).

(*a*) *The mantle wedge above the subducted slab*

This consists of two components:

(i) a 40–70 km thick section of oceanic lithosphere;

(ii) a zone of asthenospheric upper mantle of varying thickness depending upon the specific arc geometry.

(*b*) *The oceanic crust*

This also consists of two main components:

(i) variably metamorphosed ocean floor basalt;

(ii) oceanic sediments, ranging from pelagic clays and carbonate oozes to terrigenous clastic sediments.

The oceanic crust can be involved in the magma generation process in two distinct environments:

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(i) the upper parts of the subducted oceanic lithosphere;
(ii) the base of the island arc volcanic sequence.

(*c*) *Seawater*

Seawater could become indirectly involved in the generation of island arc magmas as a result of:

(i) hydrothermal alteration of the subducted oceanic crust during ocean floor metamorphism;
(ii) circulation of seawater within the island arc crust.

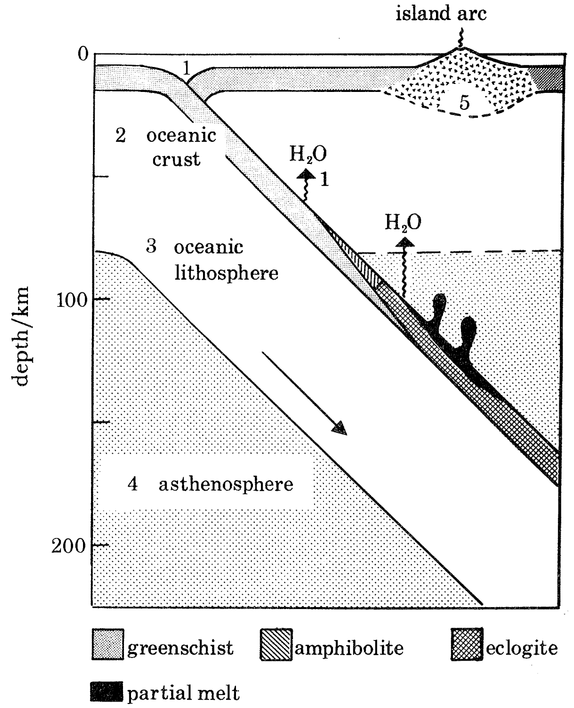

FIGURE 1. Potential source regions involved in island arc magma genesis, after Wyllie (1982). 1: seawater; 2: oceanic crust; 3: mantle of the oceanic lithosphere; 4: asthenospheric upper mantle; 5: oceanic crustal rocks depressed at the base of the island arc crust. Progressive metamorphism of the oceanic crust is shown from greenschist through amphibolite to eclogite facies. Dehydration reactions should release aqueous fluids into the mantle wedge at shallow depths. At greater depths hydrous partial melting of eclogite produces H_2O rich intermediate to acid partial melts which then rise into the mantle wedge.

This paper represents an attempt to review the relative importance of these various potential magma source components in a variety of oceanic arc systems with particular emphasis on the extent of involvement of sedimentary materials ultimately derived from the continental crust.

2. CLASSIFICATION OF OCEANIC ISLAND ARC MAGMAS

Figure 2 shows the distribution of the major oceanic island arc systems in the Pacific and Atlantic oceans and Indonesia. In table 1 these are subdivided into three groups based on convergence rate, crustal thickness and chemical characteristics of the erupted magmas.

(*a*) *Classification based on major element data*

Some confusion has marked attempts to classify the spectrum of magmas erupted in island arcs. The eruptive products typically have been subdivided into three major magma series, tholeiitic, calc-alkaline and alkaline, each series spanning the compositional range from basalt to rhyolite (Baker 1982). Much of the confusion over classification has arisen due to the use of different geochemical criteria by different authors. Following Gill (1981) two simple diagrams can be used to provide an adequate framework for classification.

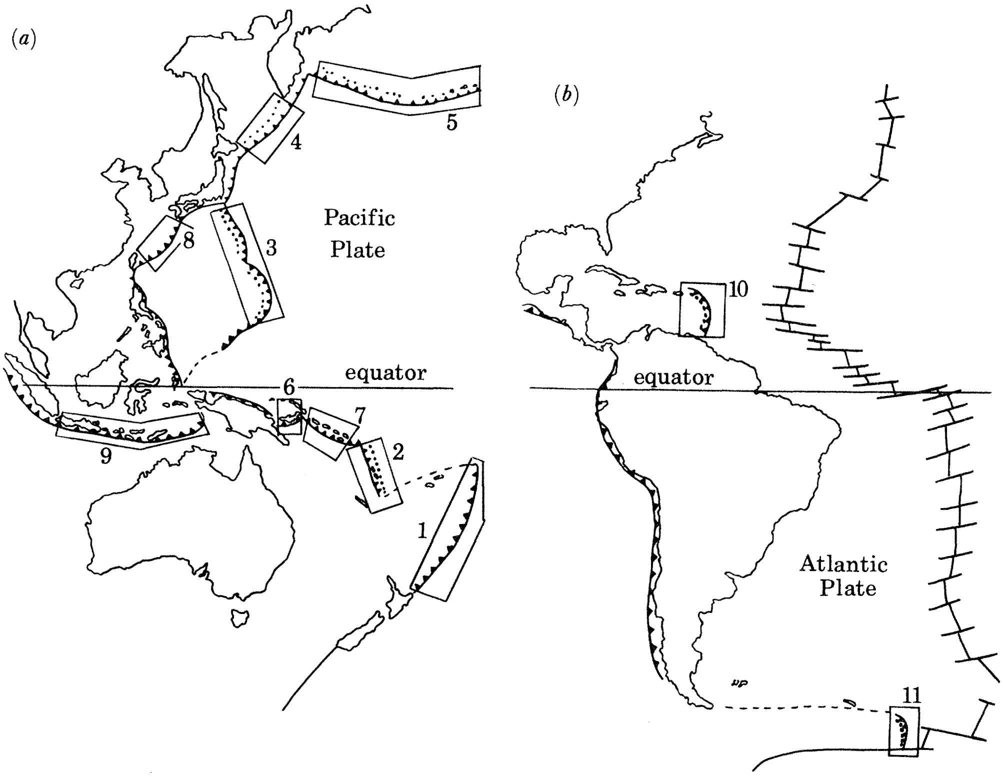

FIGURE 2. Distribution of the major currently active oceanic island arc systems in (*a*) the Pacific ocean and Indonesia and (*b*) the Atlantic. Numbered areas are as follows: 1, Tonga–Kermadec; 2, New Hebrides (Vanuatu); 3, Marianas–Izu; 4, Kuriles; 5, Aleutians; 6, New Britain; 7, Solomons; 8, Ryukyu; 9, Sunda–Banda; 10, Lesser Antilles; 11, South Sandwich.

(i) K_2O *against* SiO_2

With this simple Harker diagram, figure 3, the island arc volcanic suites can be subdivided into four major magma series:

A, low K series;
B, calc-alkaline series;
C, high K calc-alkaline series;
D, shoshonitic series.

Within each of these series the relative proportion of basalt varies widely with respect to more evolved magma types (Baker 1982). For example the low K series typically has a superabundance of basalts and basaltic andesites when compared with the calc-alkaline series.

(ii) FeO^*/MgO *against* SiO_2

The low K series of figure 3 can be equated with the tholeiitic magma series which is characterized by marked Fe enrichment in the early stages of fractionation (Gill 1981). A plot of FeO^*/MgO against SiO_2 (Miyashiro 1974) can be used to differentiate such tholeiitic trends from the typical calc-alkaline trend of no iron enrichment.

Figure 3 shows an array of apparent evolutionary trends from different oceanic island arc systems. Of particular note are the divergent trends displayed by volcanics within both the Aleutian and South Sandwich arcs, which must reflect varying conditions of low pressure fractionation. The South Sandwich lavas (Luff 1982) define both a calc-alkaline and a low K series. However in terms of FeO^*/MgO against SiO_2 both series display tholeiitic characteristics. This highlights one of the major sources of confusion in attempting to classify magmas as either tholeiitic or calc-alkaline: that magmas with higher K_2O contents than the low K series can still fractionate along Fe enrichment trends. Such trends are probably more closely

TABLE 1. SUBDIVISION OF THE OCEANIC ISLAND ARCS ACCORDING TO CONVERGENCE RATE, CRUSTAL THICKNESS AND CHEMISTRY OF THE ERUPTED MAGMAS (AFTER GILL 1981)

1		convergence rate > 7 cm a^{-1} crust < 20 km thick
	A	$> 40\,\%$ of volcanoes CA
		Solomons Aleutians
	B	$> 80\,\%$ of volcanoes Th
		Tonga–Kermadec Mariana–Izu South Sandwich
2		convergence rate > 7 cm a^{-1} crust 30–40 km thick 30–70 % of volcanoes Th
		New Britain Kuriles New Hebrides Sunda (Java)
3		convergence rate < 7 cm a^{-1} crust > 30 km thick $< 50\,\%$ of volcanoes Th
		Lesser Antilles Ryukyu

related to differing a_{O_2}/a_{H_2O} conditions during high level fractionation than to any fundamental differences in the chemistry of the parent magmas.

Although such classification schemes are necessary for ease of communication, they are essentially rather arbitrary divisions of a continuous spectrum of magma compositions. Linear trends on diagrams such as figure 3 are often composites of data from several distinct volcanic centres spanning a range of ages. In such cases, linearity does not necessarily imply consanguineity, and Sr isotopic analysis of the samples often reveals significant differences in $(^{87}Sr/^{86}Sr)_0$ which preclude a direct genetic relation.

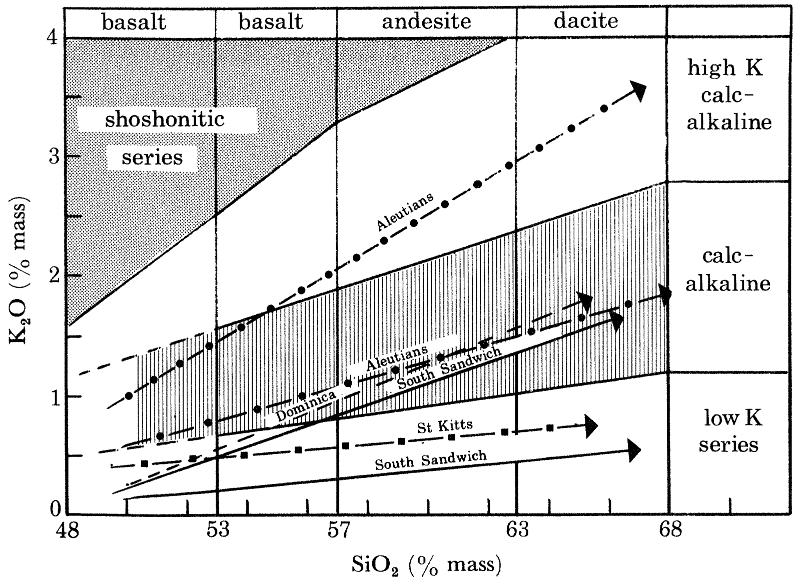

FIGURE 3. Plot of percentage mass K_2O against percentage mass SiO_2 showing the major subdivisions of the island arc volcanic series (after Basaltic Volcanism Study Project 1981). Data sources: Aleutians (Marsh 1982); Dominica (Wills 1974); St Kitts (Smith *et al.* 1980); South Sandwich (Luff 1982).

(*b*) *Identification of primary magma compositions*

In those arcs in which basalt forms a significant percentage of the eruptive products, candidates for primary magmas are sought among those basalts with $100\ (Mg/(Mg+Fe^{2+})) = 70\text{–}74$, $Ni = 250\text{–}300\ \mu g/g$ and $Cr = 500\text{–}600\ \mu g/g$ (Perfit *et al.* 1980). Generally such compositions are rare in island arc volcanic suites. Nevertheless, petrological and geochemical evidence frequently suggests the development of the basalt–andesite–dacite–rhyolite suites by low pressure fractionation of such primary magmas, (Foden 1983; Meijer & Reagan 1981).

In some arcs, however, individual volcanic centres are composed dominantly of andesitic–dacitic material. A major problem in these cases is whether the primary magma is also andesitic or basaltic andesitic in composition, implying a different source region–magma generation process. Hawkesworth & Powell (1980) in a detailed isotopic study of contrasting basic and andesitic centres from Dominica, Lesser Antilles, concluded that both types probably had a similar basaltic parent. Differences in the SiO_2 content of the eruptive products were accounted for in terms of differences in subvolcanic plumbing systems. Further studies are required before such conclusions can be considered generally applicable. However, if correct, this stresses the importance of detailed geochemical studies of the most primitive basaltic compositions in island arc volcanic suites as petrogenetic indicators.

(c) *Trace element characteristics of island arc basalts*

Island arc basaltic rocks are typically characterized by selective enrichment of incompatible elements of low ionic potential (Sr, K, Rb, Ba, ± Th) and low abundances of elements of high ionic potential (Ta, Nb, Ce, P, Zr, Hf, Sm, Ti, Y, Yb, Sc, Cr). The low ionic potential elements are those most readily mobilized by a fluid phase and their enrichment has been attributed to metasomatism of the mantle source region of the basalts by hydrous fluids derived from the subducted oceanic crust. The low abundances of the high ionic potential elements have been variously attributed to (Pearce 1982):

(i) high degrees of melting of the mantle source;
(ii) stability of minor residual phases in the source region, e.g. rutile, zircon, sphene;
(iii) remelting of a depleted mantle source.

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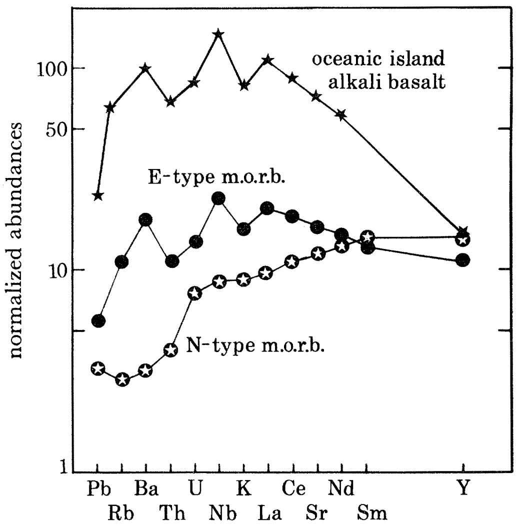

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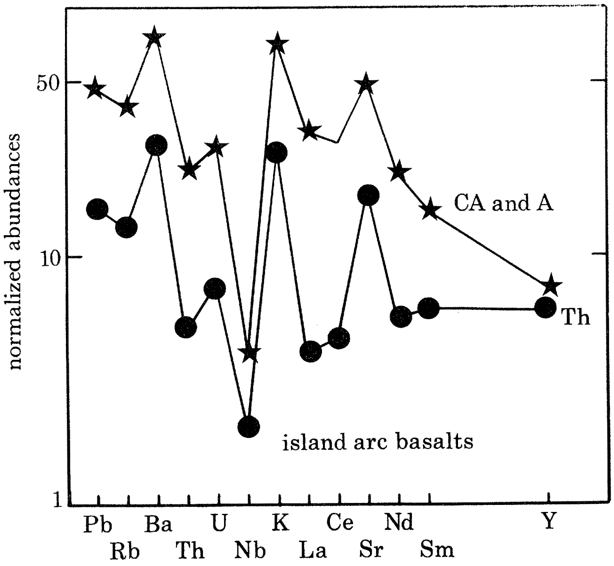

FIGURE 4. Incompatible element abundances, normalized to primordial mantle values, in mid ocean ridge and oceanic island basalts (after Sun 1980).

FIGURE 5. Incompatible element abundances, normalized to primordial mantle values, in island arc basalts (after Sun 1980). (CA: calc-alkaline; A: alkaline; Th: Tholeiitic.)

Following Sun (1980) figures 4 and 5 compare incompatible element abundances normalized to primordial mantle values for magmas erupted in arc and non-arc settings. Figures 6, 7 and 8 show similar data for basalts from the New Britain, South Sandwich and Lesser Antilles island arcs. Despite variations in tectonic setting and in major element chemistry from tholeiitic to alkaline all the basalts show the characteristic 'spiked' island arc signature. This must have fundamental implications for models of magma generation.

Rare earth element patterns for the above basalts vary from flat to light rare earth depleted to strongly light rare earth enriched. In general, the relative magnitude of the Sr, K and Ba spikes appears to correlate with the degree of light r.e.e. enrichment. The characteristic island arc signature can be accounted for by the addition of a component rich in Sr, Ba, K, Pb and light r.e.e., presumably derived from the subducted lithospheric slab, to the lherzolite of the mantle wedge. Variations in parental basalt compositions from tholeiitic to calc-alkaline to alkaline must then reflect the relative proportions of this l.i.l. (large-ion lithophile) enriched component and mantle lherzolite phases entering subsequent partial melts.

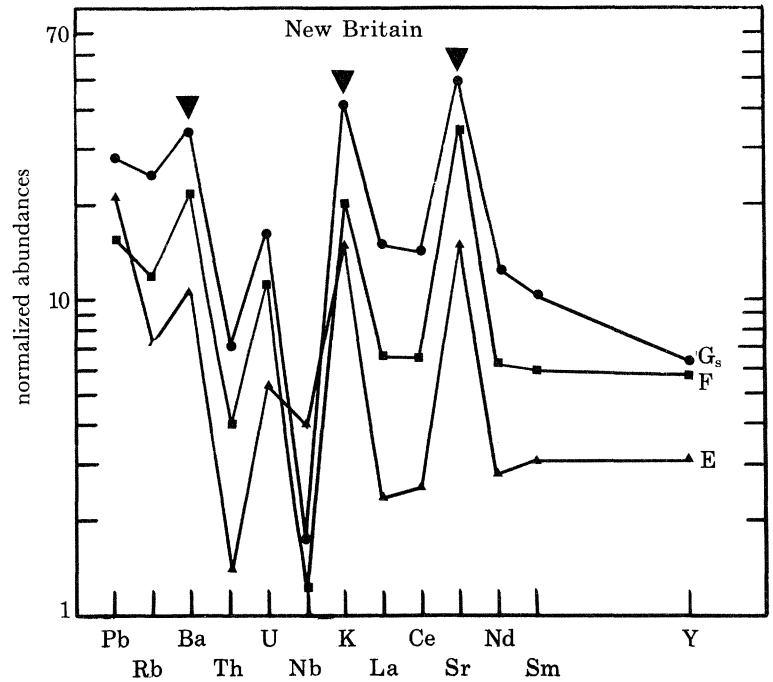

Figure 6. Normalized incompatible element abundances in basalts from the New Britain island arc. Arrows indicate the positions of the Sr, K and Ba 'spikes'. Data from Basaltic Volcanism Study Project (1981). Samples E, F, G_8 come from sites with increasing depths to the Benioff Zone.

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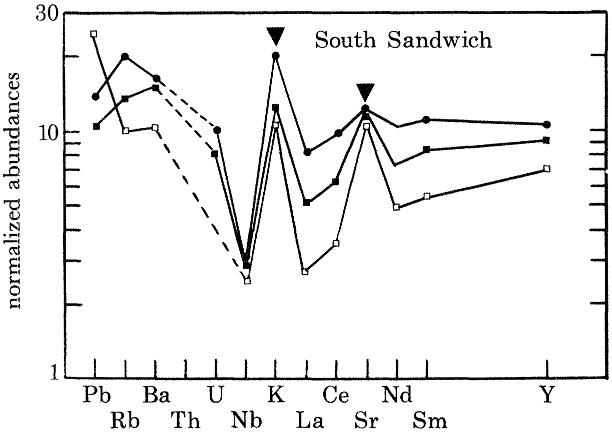

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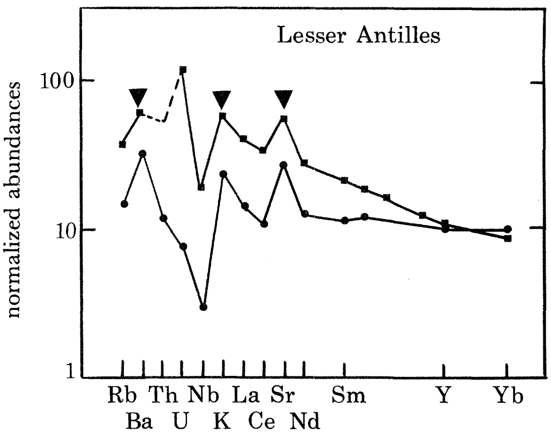


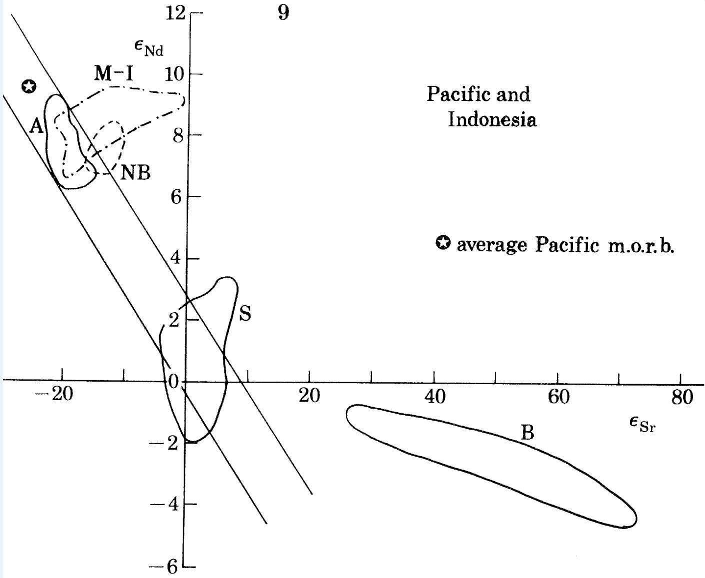
Figure 7. Normalized incompatible element abundances in basalts from the South Sandwich island arc. Data from Luff (1982) and Doherty (1981).

Figure 8. Normalized incompatible element abundances in basalts from the Lesser Antilles island arc. Circles represent a tholeiitic basalt from St Kitts (Hawkesworth & Powell, unpublished data); squares an alkali basalt from Grenada (Thirlwall, unpublished data).

3. Sr, Nd and Pb isotope systematics of island arc magmas

(a) Nd–Sr *data*

Recent Nd and Sr isotope studies have significantly increased the understanding of the origin of island arc magmas. In particular, they have demonstrated the involvement of both the subducted oceanic crust and the overlying mantle wedge (Hawkesworth & Powell 1980;



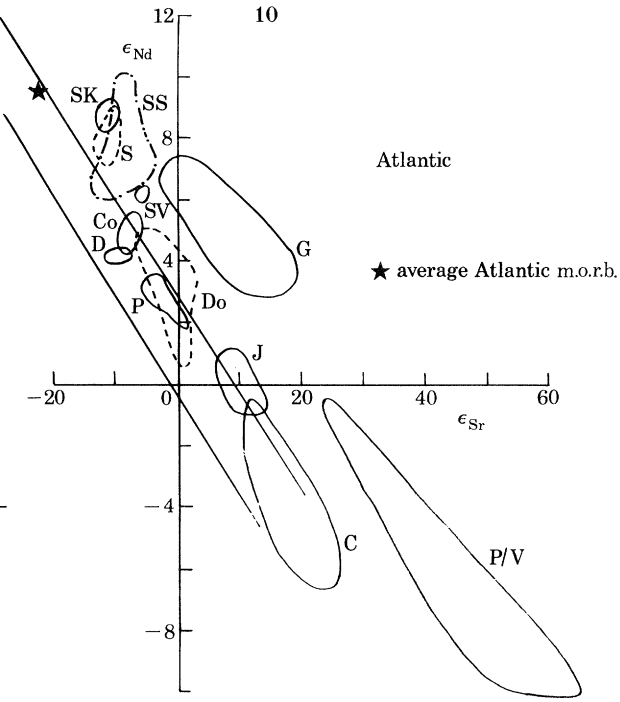


FIGURE 9. A plot of ϵ_{Nd} against ϵ_{Sr} for volcanic rocks from the Pacific and Indonesian oceanic island arcs, compared with the mantle array of Zindler *et al.* (1982). Data sources: A: Aleutians (McCulloch & Perfit 1981); NB: New Britain (DePaolo & Johnson 1979); Thirlwall, unpublished data; M–I: Mariana–Izu (Nohda & Wasserburg 1981; DePaolo & Wasserburg 1977); S–B: Sunda – Banda (Whitford *et al.* 1981).

FIGURE 10. A plot of ϵ_{Nd} against ϵ_{Sr} for volcanic rocks from the Atlantic oceanic island arcs, compared with the mantle array of Zindler *et al.* (1982). Data sources: Luff (1982); Hawkesworth (1977): SS, South Sandwich; Davidson, unpublished data; Hawkesworth & Powell (1980): SK, St Kitts; S, Statia; Do, Dominica; *Martinique centres*: D, Diamant; Co, Conil; P, Pelée; J, Jacob; C, Carbet; P/V, Pavillon/Vauclin; Thirwall (unpublished data): SV, St Vincent; Hawkesworth (1979): G, Grenada.

Whitford *et al.* 1981; DePaolo & Johnson 1979) in the magma generation process. Unfortunately these data cannot reveal the nature of the involvement of the subducted oceanic crust, that is whether the contribution is derived from melting of the slab or merely from fluids released during dehydration.

In figures 9 and 10, $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ data for a range of dominantly basaltic rocks from both arc and non arc environments are plotted in terms of ϵ_{Nd} and ϵ_{Sr}. The majority of recent mantle derived volcanic rocks from mid ocean ridges and continental and oceanic intraplate settings plot on a single broad negative trend, the mantle array. Volcanics from the oceanic island arcs however show variable displacements from this array and this has considerable petrogenetic significance.

The Pacific arc data, figure 9, show small but variable displacements in the direction of increasing ϵ_{Sr} from the mantle array. This has been attributed to the involvement of a component enriched in $^{87}Sr/^{86}Sr$, derived from the subducted oceanic crust, in the genesis of the magmas (DePaolo & Johnson 1979; Perfit *et al.* 1980).

Data from the Sunda–Banda arc of Indonesia (Whitford & Jezek 1982), however, show a completely different pattern, following a trend of increasing ϵ_{Sr} and decreasing ϵ_{Nd} away from the mantle array. Such a trend can be most easily accounted for by the involvement of a terrigenous sedimentary component. The Sunda arc specimens are from Java, which has a complex crustal structure transitional to a continental type. Whitford & Jezek assume that the Java ϵ_{Sr}–ϵ_{Nd} values represent the unmodified mantle composition field towards which the variably contaminated Banda arc samples project. If correct, this implies that the mantle wedge beneath this arc system had a highly enriched composition relative to m.o.r.b. sources before subduction. However, location of samples within the mantle array does not necessarily indicate that they are derived from unmodified mantle lherzolite. Mixing of a mantle component lying within the m.o.r.b. field of the mantle array with an appropriate slab derived component could very easily produce displacements of the source along the mantle array. Nd and Sr isotopic data alone are thus insufficient to identify pre-subduction mantle compositions and must be combined with other isotope systems, e.g. Pb.

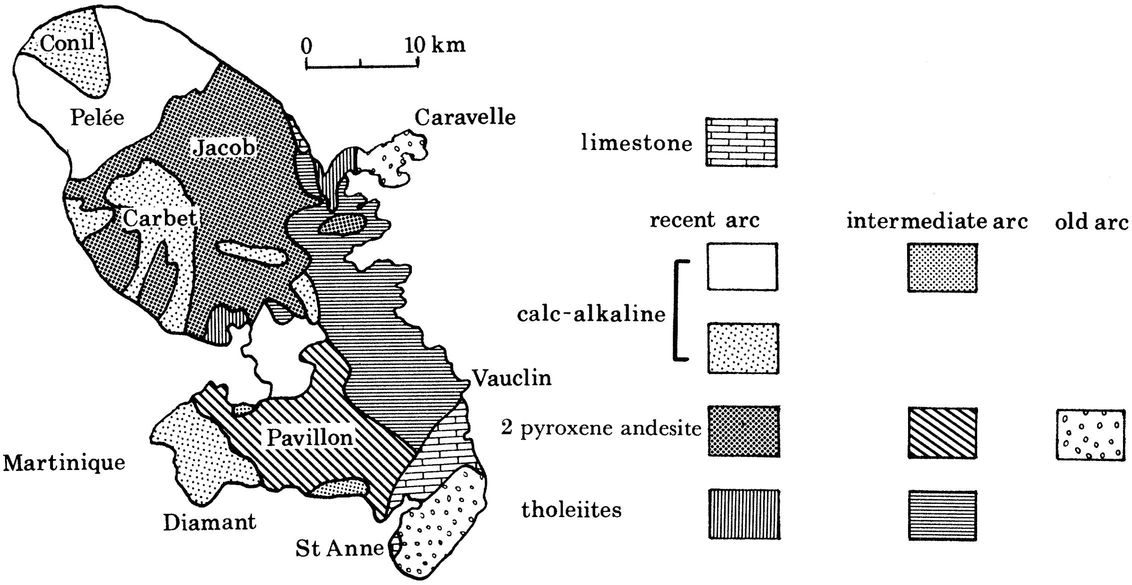


Figure 11. Geological map of Martinique after Westercamp & Tazieff (1980). Ages of the individual volcanic centres (Briden *et al.* 1979) are: Pelée 0.4 Ma, Conil 0.6 Ma, Carbet 1 Ma, Diamant 1–3.5 Ma, Jacob 2–7 Ma, Pavillon 5–10 Ma, Vauclin 10–15 Ma, older arc 15–36 Ma.

Within the Atlantic, data from the South Sandwich arc show a marked similarity to Pacific arc systems. In contrast, data from the Lesser Antilles show variable displacements from the mantle array (figure 10). The most northerly islands of the arc, Statia and St Kitts, plot in a similar field to the South Sandwich and Pacific data arrays. In contrast, volcanics from islands further to the south show the effects of a variable contamination process displacing the ϵ_{Nd} values to some of the lowest values recorded from island arcs.

Data from a series of andesitic volcanic centres from Martinique, figure 11, plot in an extensive trend within or close to the mantle array. These data could most simply be explained by derivation of the parent magmas from a markedly heterogeneous but enriched upper mantle source without necessarily involving any slab derived components. However Pb isotopic studies of the same specimens reveal that the actual process must be much more complex (§3*b*). Data from Grenada and the older Pavillon–Vauclin centres of Martinique are however displaced to higher ϵ_{Sr} values in trends subparallel to the mantle array, necessitating the involvement of slab derived fluids in this case.

The Sr–Nd isotope data for the different age volcanic centres of Martinique have considerable implications for the scale of mantle heterogeneity (either original or metasomatically induced) within the mantle wedge, with the assumption that the andesitic magmas are derived by fractionation of a basaltic precursor. Different centres less than 10 km apart display markedly different isotopic signatures, e.g. Pelée and Jacob. The time element however must not be overlooked in this case as the volcanic centres are of different ages. In figure 10 the rocks from the oldest Pavillon–Vauclin centres show the most extreme effects of contamination, while among the younger centres there is no systematic age progression.

The simplest explanation for all of the Lesser Antilles data involves partial melting of an originally fairly homogeneous source region close to the Atlantic m.o.r.b. field in ϵ_{Sr}–ϵ_{Nd} space which was progressively modified by interaction with a variety of slab derived fluids, involving in some cases a significant contribution from a terrigenous sedimentary component. The data cannot however eliminate the possibility of a significant pre-subduction mantle heterogeneity from north to south along the arc as originally suggested by Brown *et al.* (1977).

(*b*) Pb *isotope data*

Figures 12 and 13 show the variation in $^{207}Pb/^{204}Pb$ against $^{206}Pb/^{204}Pb$ for the Pacific, Indonesian and Atlantic oceanic island arcs. The Pacific data (New Britain, Aleutians and Marianas) plot essentially within the mantle array of Cohen & O'Nions (1982). Minor displacements from this array for some of the Aleutian lavas could indicate limited involvement of Pacific sediments with a terrigenous component. The Sunda arc (Java) data show a much more significant displacement to higher $^{207}Pb/^{204}Pb$ values indicating the involvement of Pb from a much older terrigenous sedimentary source. This exemplifies the need for caution in the interpretation of the Sr–Nd isotope data for the Java lavas. In view of the Pb isotope data the ϵ_{Sr} and ϵ_{Nd} values cannot be taken as indicative of unmodified mantle values beneath the Sunda – Banda arc.

Data for the Lesser Antilles, figure 13, (Grenada and Martinique only) show similar displacements to the Sunda arc data again indicating the involvement of an old continental crustal component. In contrast, data for the South Sandwich island arc plot essentially within the mantle array.

The Pb isotope data for the various volcanic centres of Martinique support a model for the generation of the trend of data points within the Nd–Sr mantle array by mixing between an unmodified lherzolite composition close to the m.o.r.b. field and a slab derived fluid involving in some cases a substantial contribution from terrigenous sediments.

4. MODELS FOR MAGMA GENERATION IN ISLAND ARCS

It is generally accepted that the basaltic magmas erupted in island arcs have to be generated by partial melting of the mantle wedge above the subducted lithospheric slab (Wyllie 1982; Mysen 1982; Green 1982). In most circumstances it is the asthenospheric part of this mantle wedge which is most likely to melt, the overlying lithospheric mantle having already been rendered significantly refractory by previous partial melting events associated with the generation of mid ocean ridge basalts. This asthenospheric mantle component could show substantial pre-subduction isotopic heterogeneity. In addition, it is a source which can be potentially

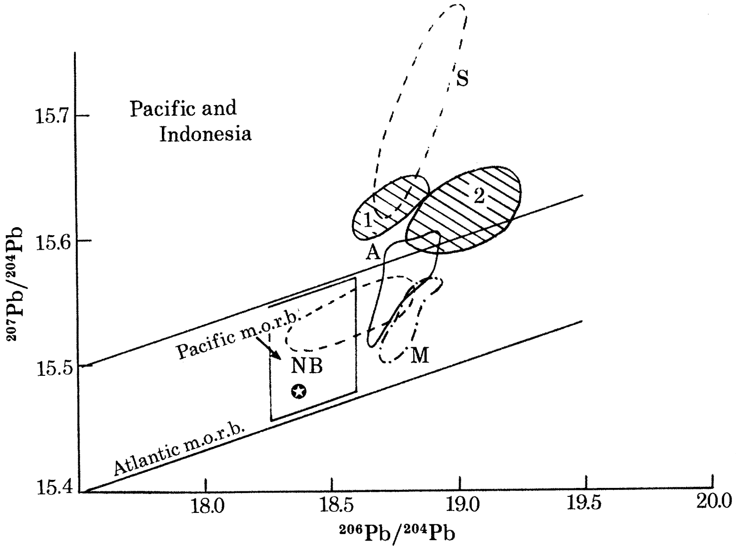


FIGURE 12. Variation of $^{207}Pb/^{204}Pb$ against $^{206}Pb/^{204}Pb$ for the Pacific and Indonesian oceanic island arcs. The 'mantle array' is taken from the data of Cohen & O'Nions (1982). Data sources: A: Aleutians (Kay *et al.* 1978); M: Marianas (Meijer 1976; Meijer & Reagan 1981); NB: New Britain (Thirlwall, unpublished data); S: Sunda arc (Whitford & Jezek 1982). Fields 1 and 2 show the approximate fields of Pacific clay sediments after Sun (1980). 1: N Pacific pelagic sediments; 2: NE Pacific oceanic sediments composed of continental detritus.

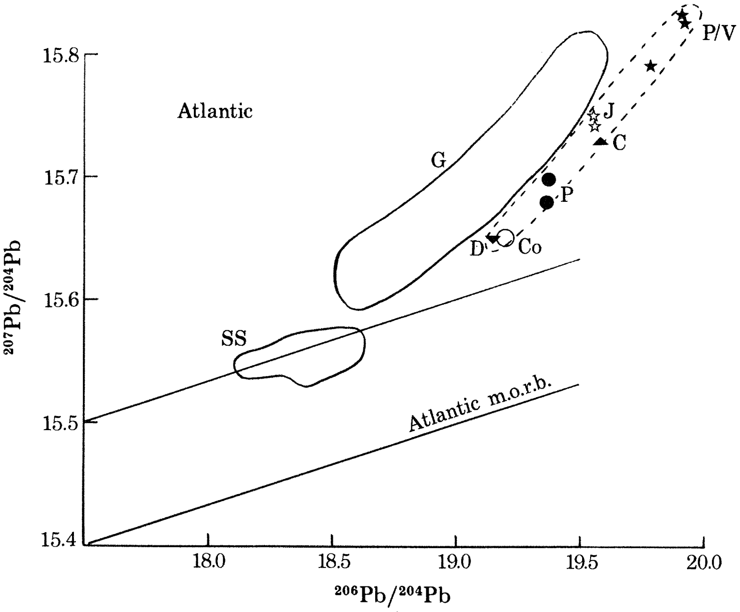


FIGURE 13. Variations of $^{207}Pb/^{204}Pb$ against $^{206}Pb/^{204}Pb$ for the Atlantic island arcs. The mantle array is as in figure 12. Data sources: SS: South Sandwich (Doherty 1981); G: Grenada (Thirlwall, unpublished data); D, Co, P, J, C, P/V; various volcanic centres from Martinique as in figure 12 (Davidson, unpublished data).

replenished by convective overturn related to instabilities generated by the subduction of cold oceanic lithosphere.

If no additional components were involved in the magma generation process then the major and trace element characteristics of the resultant partial melts should be broadly similar to the range of mid ocean ridge and oceanic island basalts. However the distinctive trace element characteristics of arc basalts, figure 5, requires distinctive source characteristics unique to the subduction zone environment. These characteristics can most readily be achieved by metasomatism of the lherzolite of the mantle wedge by fluids ascending from the subducted oceanic lithosphere.

(*a*) *Nature of the slab derived fluids*

Satisfactory interpretation of the trace element and Sr, Nd and Pb isotope geochemistry of island arc lavas requires the involvement of a component derived from the subducted oceanic crust. Such a component could be either a hydrous fluid or a partial melt and could have variable Sr, Nd and Pb isotopic ratios depending upon the extent of ocean floor metamorphism of the subducted oceanic crust and the extent of involvement of subducted sedimentary components.

Sekine & Wyllie (1982) have attempted to model the metasomatic effects of slab derived fluids on the lherzolite of the mantle wedge by experimentally investigating the system granite–peridotite–H_2O. The most significant feature of these experiments is the demonstration that olivine can be eliminated as a residual phase during partial melting of the metasomatized mantle, thus facilitating the generation of basaltic andesite and andesite primary partial melts.

Wyllie (1982) stressed that aqueous fluids derived from dehydration reactions within the subducted oceanic crust must contain considerable proportions of dissolved silicates at the pressures involved. It is therefore likely that there is a continuous spectrum of fluid compositions generated within the slab, ranging from aqueous SiO_2 rich fluids to hydrous andesitic partial melts.

(*b*) *The role of sedimentary components*

Basaltic island arc magmas ranging in chemistry from low K to high K and showing variable displacements from the mantle arrays in Sr, Nd and Pb isotope systems all show the same characteristic spiked trace element patterns, figures 6, 7 and 8. This suggests that the trace element and isotope systems can become variably decoupled during the magma generation process.

It is suggested here that all island arc magmas are ultimately related to a parental partial melt of mantle lherzolite metasomatized to varying degrees by an isotopically heterogeneous slab derived fluid.

In most of the arc systems studied so far, evidence for the involvement of sedimentary components is minimal and this may provide indirect evidence for the non-subductibility of oceanic sediments. However, Sr, Nd and Pb isotopic data from the Sunda–Banda and Lesser Antilles island arcs indicate substantial involvement of terrigenous sediments derived from an old continental crustal terrain. Such sediments probably represent clastic wedges developed at passive continental margins during the early stages of ocean opening.

A major and as yet largely unresolved problem is the site at which such sediments become involved in the magma generation process. Thus far, it has been implicitly assumed that it is the slab derived fluids that carry the ancient continental crustal signature. However, many authors have refuted the physical possibility of significant sediment subduction and thus indirectly the involvement of partial melts of subducted sediments to account for the isotopic data. Alternatively, mantle derived magmas could become contaminated by terrigenous sediments *in situ* in the base of the island arc crust. The results of such contamination would be isotopically indistinguishable from the former model. Detailed oxygen isotope studies of selected suites could resolve this problem, (James 1981).

(*c*) *Contamination of magmas within the island arc crust*

There must be substantial circulation of seawater in the crust during the early submarine stages of arc development. This provides a potential reservoir of hydrothermally altered volcanic rocks enriched in $^{87}Sr/^{86}Sr$ which could contaminate magmas stored in high level chamber systems during the later stages of arc development. Isotopically the effects of such contamination might be difficult to distinguish from those of aqueous fluids ascending from the subducted oceanic crust. Oxygen isotope studies may be of crucial importance in resolving the effects of such high level contamination.

(*d*) *Processes responsible for the generation of evolved magma compositions*

The compositions of evolved magmas, e.g. andesites, erupted in island arcs are sufficiently diverse that no single magma generation process is capable of explaining the range of geochemical characteristics. Crystal fractionation of plagioclase–olivine–clinopyroxene–orthopyroxene–magnetite ± amphibole from basaltic parent magmas is probably the major process (Powell 1978). However from the experiments of Sekine & Wyllie (1982) generation of magmas more SiO_2 rich than basalt from a highly metasomatized mantle source remains a possibility. In addition, high level contamination of basaltic magmas by terrigenous sediments in the base of the island arc crust could generate more acidic magmas.

This work represents a synthesis of data and ideas collected over a considerable period of time at Leeds University involving M. Wilson, J. P. Davidson, M. Thirlwall, R. A. Cliff, C. J. Hawkesworth, I. Luff and M. Doherty.

Dr M. Thirlwall kindly made available his unpublished Sr, Nd and Pb isotopic data on Grenada and New Britain samples which are gratefully acknowledged.

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Discussion

H. Colley (*Department of Geology and Physical Sciences, Oxford Polytechnic, Oxford OX*3 0*BP, U.K.*). Dr Powell* has mentioned that magmas rising beneath island arcs may be subject to high-level crustal contamination. I would suggest that such contamination may be caused by an aqueous phase. The volcanic pile forming the arc would contain a considerable amount of seawater and at the elevated temperatures in the lower part of the pile (10–20 km) rock–water interactions could give an aqueous fluid containing significant SiO_2, Ca, Sr; Ba, K, Cu and possibly the l.r.e.e. Would Dr Powell care to comment on the possibility of such contamination?

Marjorie Powell. High level contamination of ascending magmas by hydrothermally altered volcanics in the base of the island arc crust is a distinct possibility but one whose effects would be difficult to distinguish isotopically.

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* Now Dr Wilson.