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ARTICLES

Pb–Sr isotope variation in Indian Ocean basalts and mixing phenomena

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Pb and Sr isotopic compositions from the Indian Ocean (active ridges, old ocean floor and aseismic ridge samples) confirm the characteristic nature of the mantle record in this region. The results emphasize the importance of mixing processes between the lower mantle (oceanic-island basalt source), and the upper mantle (ridge-basalt source). The isotopic characteristics of the Indian Ocean islands seem to be in agreement with the hypothesis of the reinjection of sediments into the mantle.

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SINCE the first studies of Schilling and co-workers, it has become clear that chemical and isotopic variations occur along the North Atlantic Ridge[1-4]. Schilling interpreted these variations as the result of injections of lower mantle material (hotspot) into the upper mantle which is the 'usual' source of oceanic lithosphere. Langmuir *et al.*[5] have shown that such a bipolar mixing process is insufficient to explain the observed variations and that a multipolar mixing process is necessary. A simple way[6] of multipolar mixing is to mix two reservoirs which are themselves chemically and isotopically heterogeneous.

This kind of mixing process could explain the negative correlation between the Nd and Sr or the positive correlation between the Sr and Pb isotopic compositions of ridge basalts[7-10]. However, the isotopic variations observed along a ridge or within a mid-oceanic ridge basalt (MORB) population can also be interpreted in terms of local mantle heterogeneity created by various phenomena such as continental crust extraction, sediment reinjection and basalt extraction, all of them operating long before the time of ridge genesis.

It is, therefore, possible to define two contrasting models. Model 1 consists of an isotopically homogeneous and well-mixed upper mantle reservoir, which is the source of normal MORB, and of an underlying isotopically heterogeneous lower mantle reservoir, which could be the source of oceanic islands. Blobs injected from the lower mantle reservoir at the ridge crest would mix with the upper mantle reservoir and, in such conditions, it is difficult to sample non-contaminated parts of the upper mantle reservoir because ridge crest basalts are 'polluted' to various degrees. In model 2, the upper mantle reservoir is isotopically heterogeneous and this heterogeneity has been created over a long period of time by various phenomena (one of which could even be the injection of sediments in the upper mantle). Thus, when we analyse ridge basalts we observe this heterogeneity directly.

To test these models, we have analysed a series of samples from the Indian Ocean. This study was undertaken because preliminary analyses of samples from Kerguelen[11] and Reunion[12] yielded peculiar compositions reflected in the isotopic Sr–Pb correlation diagram. We first had to verify whether these anomalies were small-scale or regional phenomena. After verifying that Indian Ocean island anomalies were actually regional, we decided to test our two models by analysing them. In model 1, a mixing of a normal component with abnormal blobs should yield abnormal variations in ridge basalts whereas in model 2, the Indian Ocean ridge basalts should belong to the common array, particularly in the Sr–Pb correlation diagram.

In looking for the causes of the variations along the ridges, we shall also discuss various explanations of the specific characteristics of some islands of the Indian Ocean.

Results

The Sr and Pb isotopic composition of these basaltic rocks were analysed using techniques described previously[13,14]. The results and blanks measured during this study are reported in Table 1.

(1) Oceanic Islands: We first analysed basalts from different islands including Kerguelen, Reunion, Comores, St Paul, Amsterdam and Crozet (sample locations are indicated in Fig. 1). For Kerguelen we analysed only two samples for Pb isotopes, and used data taken from the study by Dosso *et al.*[11]. We added to this data set, the analyses of samples from the Ninetyeast Ridge. Basalts from this aseismic ridge are chemically very similar to those of the oceanic islands and we shall consider these data as a whole.

The Pb isotopic results are reported in the binary diagrams ($^{206}Pb/^{204}Pb$ plotted against $^{207}Pb/^{204}Pb$) and ($^{206}Pb/^{204}Pb$ plotted against $^{208}Pb/^{204}Pb$) on Fig. 2. For Kerguelen, Crozet, Amsterdam and St Paul islands, values of the $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios are larger than those of North Atlantic and Pacific islands, but are similar to those of Tristan da Cunha and Gough islands in the South Atlantic and similar to the Walvis Ridge[15] (comparisons are made using Sun's compilation[12]). In

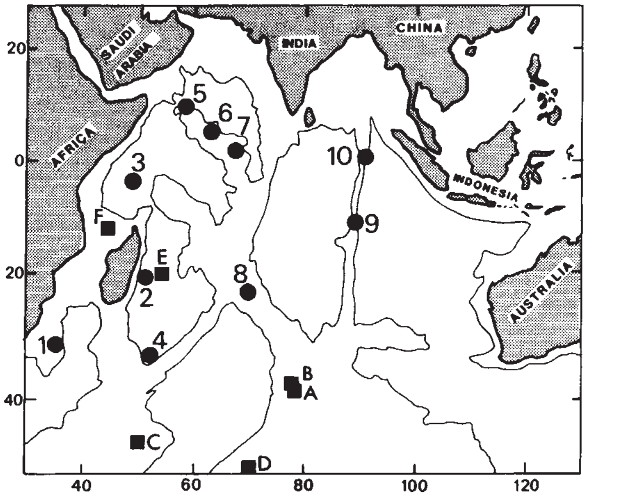

Fig. 1 Location map for the different samples from the Indian Ocean. Numbers and letters are as used in Table 1.

contrast, the Comores data do not show any $^{207}Pb/^{204}Pb$ or $^{208}Pb/^{204}Pb$ anomalies. They are very similar to data obtained on lavas from Kenya[16]. The isotopic data for La Reunion are intermediate between these two populations.

The Sr isotopic composition for the Indian Ocean islands appears to be very radiogenic (0.7035–0.7054) and supports the early suggestions of Hedge *et al.*[17]. The coupled Pb–Sr results, plotted in Fig. 2, reveal that in contrast with the North Atlantic and Pacific trend, the Indian Ocean islands define a negative trend with two endmembers: Kerguelen (for which the $^{206}Pb/^{204}Pb$ values are the lowest and the Sr values the highest) and Comores islands. This negative correlation had been suggested first by Vidal and Dosso[18] who considered it to be general at the scale of the world and, from it, suggested a global extraction model with separation of a sulphide phase going into the core. This model does not agree with the North Atlantic[12] and East Pacific[19] islands data which display a positive Pb–Sr correlation.

Note that in every diagram the Ninetyeast Ridge basalts behave exactly like Indian Ocean island basalts; considering the fact that they were very close to Kerguelen in the past, this result is not surprising. The isotopic identity between the Ninetyeast Ridge and the Kerguelen islands has already been noted[20,21] for Sr.

(2) Oceanic crust basalts: We have also analysed samples collected on ancient oceanic crust during the *Glomar Challenger* (Leg 25)[22] programme as well as very fresh glasses from young samples of the Indian Ridge; their location is given in Fig. 1. We also use data obtained by Cohen *et al.*[10] and Sun[12]. Pb isotopic values of samples from the Rodriguez triple junction and from the Carlsberg Ridge yield very low $^{206}Pb/^{204}Pb$ (17.35–18.30).

NOAA 3–10 and MO 23 DRO2 give the least radiogenic values for the $^{206}Pb/^{204}Pb$ ratio that have been observed on a ridge and plot within the field relative to the present-day geochron. If such samples were to be considered to be the most representative of the upper mantle (because they are the least contaminated by oceanic-island basalts), this reservoir should be considered as being slightly in the B field. Therefore, the extraction of continental crust should leave a residual (depleted) upper mantle with B type characteristics. This position should not be considered as abnormal as the continental crust on average is in the J field. However, these samples yield $^{208}Pb/^{204}Pb$ ratios that are larger than those obtained on other ridges for similar $^{206}Pb/^{204}Pb$ ratios. The results obtained by Cohen *et al.*[10] on the Indian southeastern ridge do not show such an unusual character and plot within the normal Atlantic–Pacific trend. Therefore these characteristics seem to be specific

Table 1 Sr and Pb isotopic compositions determined for the samples studied: blanks were less than 200 pg for Sr and 0.8 ng for Pb

Sample no.		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{87}Sr/^{86}Sr$	
1	249–33.3	18.133	15.537	38.53		Tholeiites
	249–33.2	18.148	15.552	38.54	0.70 361±8	
2	239–21.1 113–119	17.717	15.426	37.24		
	Leaching	17.837	15.454	37.39	0.70 362±9	
3	240–71 126–134	18.679	15.518	38.14	0.70 397±9	
4	245–19–1	18.03	15.57	37.93		
	145–15.0 glass	17.921	15.556	37.79	0.70 287±7	
5	NO AA 3–10 9°49.5′N 57°56.7′E	17.353	15.425	37.19	0.70 262±3	
6	NOAA 6–9 glass 3°47′N 63°52′E	17.994	15.490	37.80		
7	NOAA 9–96 glass 1°395′N 67°46.4′E	17.985	15.446	37.77	0.70 279±4	
8	MO 23 DR 02 glass	17.541	15.423	37.42	0.70 332±5	
	MO 23 DR 04 glass	17.790	15.434	37.55		
9	214 481 7683 DSDP	18.367	15.607	38.84	0.70 461±5	Ninetyeast Ridge
10	216 22 373 DSDP	17.93	15.553	38.71	0.70 543±6	
A	St Paul 12	18.684	15.653	39.05	0.70 358±6	Islands
B	Amsterdam NA 23	19.170	15.708	39.81	0.70 386±6	
C	Crozet	18.913	15.679	39.29	0.70 411±8	
D	Kerg 15 G 16	18.477	15.604	39.20		
	Kerg 15 233	18.037	15.540	38.92		
E	Re 50 Reunion	18.938	15.604	39.03	0.70 409±3	
	Re 56 Reunion	18.874	15.575	38.92	0.70 417±4	
F	MI 40 Comores	19.359	15.583	39.41	0.70 369±3	
F	MI 159 Comores	19.249	15.515	39.19	0.70 367±4	

The standard deviation for lead isotopic ratio is given as:

$$\sigma = (\sigma_{mes}^2 + R_m^2 \times \delta_m^2 \times \sigma_\varepsilon^2)^{1/2}$$

σ_{mes} = statistical error of the run; σ_ε = error on the mass discrimination factor estimated from the SRM 981 reproductibility; δ_m = mass difference of the measured ratio R_m. The major factor of uncertainty comes from σ_ε. Typical uncertainties (1σ) are 0.012 for $^{206}Pb/^{204}Pb$, 0.014 and 0.03 for $^{208}Pb/^{204}Pb$.

to the Carlsberg Ridge. The results obtained by Cohen and O'Nions[23] on two samples located at 61° 50′E and 59°52.4′E on the Indian Ridge are very similar to ours, although small differences between the different oceans may be noted when the whole data[12,20,23] are considered.

Results of the analysis of ancient oceanic crust samples obtained by the IPOD drilling programme are identical to those for young ridges (Site 249 and Site 245) and for typical 'normal ridge' (Site 240). Values for Site 240 (north of the Comores) are similar to those of the Comores islands.

As previously outlined[24], the Sr isotopic ratios are higher for the Indian Ocean ridge basalts than for those of the other oceans. This is true for raw data obtained after strong leaching experiments as well as for young or old oceanic crust, and when these results are reported on the Pb–Sr isotopic correlation diagram, they all plot slightly above the trend found for the Atlantic and Pacific oceans[6,9,10,13]; this observation remains true even when considering the young fresh glasses only. Such a position in the Pb–Sr diagram clearly indicates that the Indian Ocean ridge samples have the lowest values for Pb isotopes, but this is not true for the $^{87}Sr/^{86}Sr$ ratios.

Discussion

The isotopic results obtained for the Indian oceanic crust are clearly different from those of the Pacific or the North Atlantic oceans and a choice between the two models proposed can be made: model 1 seems to give the best explanation of our data.

The regional isotopic variations observed for the MORB closely follow the regional variations for the Indian Ocean islands. The island source material which disturbs the MORB reservoir can also be recognized through the variations measured in the oceanic crust basalts. With the additional constraint that the oceanic island source (lower mantle?) material composition must be heterogeneous, Schilling's interpretation remains basically correct, with the result that, in global evolution models of the crust–mantle system, if oceanic-island basalts came from the lower mantle, transfer of lower mantle material into the upper mantle must be considered as a fact.

If this interpretation was correct, the ridge basalts reservoir should be isotopically rather homogeneous on a world-wide scale. However, it is perturbed by the injection of blobs which are, in contrast, isotopically extremely heterogeneous. In this case, we can characterize the uncontaminated endmember by the intersection of such contamination lines with the Sr–Pb correlation found for the Atlantic and Pacific oceans. We thus obtain depleted mantle values: $^{87}Sr/^{86}Sr \sim 0.70200$; $^{206}Pb/^{204}Pb \sim 17.2$; $^{207}Pb/^{204}Pb \sim 15.4$; $^{208}Pb/^{204}Pb \sim 36.8$. Using the Nd–Sr correlation[7,8,25], these would correspond to an ε_{Nd} of +13. These values should be considered as the best estimate of the uncontaminated (upper mantle) composition.

The remaining, and much more difficult, problem is the cause of the isotopic heterogeneity of oceanic islands and, especially, that of the Indian Ocean. First, we should recall that in the Sr–Pb diagram, the Indian Ocean island data define a negative trend, and second, that in the Pb–Pb isotopic diagram, these islands define a trend roughly parallel to the usual MORB correlation but schifted towards higher $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values and, finally, that in the Nd–Sr diagram, the trend coincides with the mantle array although some values are higher than admitted for the bulk Earth[26]. We have no definitive answer to this problem and the following should be considered as a tentative explanation. We will thus consider the existence of two reservoirs which may be identified with the upper and the lower mantle.

Model A: lower mantle with pristine and depleted domains. The lower mantle is the source of blobs, but it is not convecting as a whole and therefore it is extremely heterogeneous. Parts of that lower mantle, that have an almost pristine composition for all elements, are the source of the Kerguelen volcanism. The $^{87}Sr/^{86}Sr$ (0.705) value is almost planetary whereas those for lead isotopes correspond to closed system values. Other parts of the lower mantle are extremely enriched in U/Pb as, for example, beneath the Atlantic. The Indian Ocean islands originate from sources which are a mixture of these two types of lower mantle.

Model B: contamination by continental crust material. Indian Ocean islands are abnormal because they have been contaminated by continental crust material. Numerous studies have shown (see the compilation of Doe and Zartman[27]) that the continental crust isotopic characteristics are different from those of the oceanic islands. Despite their great variety of isotopic compositions, nearly all the continental crust samples have radiogenic values for $^{87}Sr/^{86}Sr$, $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$. Contamination may have occurred locally because one may consider that the Kerguelen or the Ninetyeast Ridge are remnants of ancient continental crust. However, the geophysical data do not give a definitive answer to the problem of the nature of the basement underlying Kerguelen or the Ninetyeast Ridge[28]. Qualitatively the ^{87}Sr, ^{208}Pb and ^{207}Pb enrichment of these oceanic islands would suggest some kind of contamination by the continental crust.

Another way of contaminating the oceanic islands source would be the reinjection of sediments into the mantle. This has been already proposed[27,29,30] to explain the oceanic islands isotopic characteristics. This reinjection would create an enriched domain in the lower part of the upper mantle (or in the lower mantle) and this enriched domain may contaminate the hotspots when they rise towards the surface. (Here, we consider the fact that basalts from islands are more comtaminated than basalts from ridges.)

Figure 3 shows data for oceanic islands throughout the world and reveals that it is possible to define large-scale areas for which Nd–Sr–Pb isotopic compositions are roughly the same. The South Atlantic and the southern Indian oceans are quite different from the North Atlantic and the eastern Pacific oceans. This geographical mapping suggests that it is possible to define large-scale domains for the oceanic island source. More data are needed before the complex isotope chemistry of the Earth's mantle may be understood.

This isotopic similarity between the values of Tristan da Cunha, Gough and some of the islands of the Indian Ocean allows us to use the ^{3}He results of Kurz *et al.*[31] for these islands; their results favour model B.

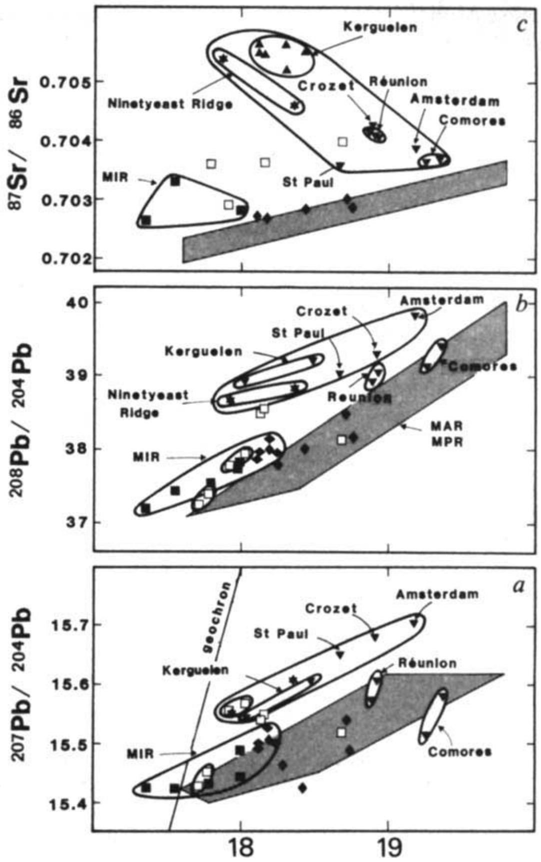

Fig. 2 Results for samples from Indian Ocean. *a*, $^{207}Pb/^{204}Pb$ plotted against $^{206}Pb/^{204}Pb$. ■, Samples from the Indian Ridge; □, old oceanic crust; ◆, results obtained by Cohen *et al.*[10,23]; ▼, results obtained by Sun[12]; ★, Ninetyeast Ridge. The left side of the geochron is labelled as B field, and the right side as J field. *b*, $^{208}Pb/^{204}Pb$ plotted against $^{206}Pb/^{204}Pb$. *c*, $^{87}Sr/^{86}Sr$ plotted against $^{206}Pb/^{204}Pb$. ▲, Data obtained by Dosso *et al.*[11]. The hatched area is the domain of MORB values for the Atlantic and Pacific oceans (refs 4, 9, 10, 12, 26 and B. Hamelin, B.D. and C.J.A., in preparation).

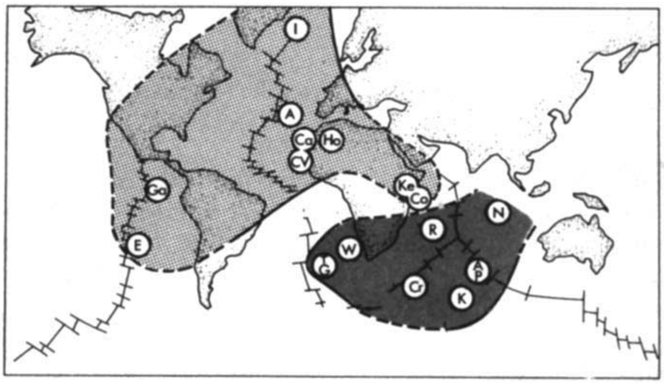

Fig. 3 General map indicating the large geographical domains with similar isotopic characteristics. I, Iceland; A, Azores; H, Hoggar; Ca, Canaries; Cv, Cape Verde; F, Fernando de Noronha; Ga, Galapagos Islands; E, Easter Island; Co, Comores; T, Tristan da Cunha; G, Gough; W, Walvis Ridge; Cr, Crozet; R, Reunion; K, Kerguelen; A, Amsterdam; P, St Paul; N, Ninetyeast Ridge; Ke, Kenya. Data are from refs 11, 12, 16, 19, 32 and this work.

Indeed, a very important difference between He isotopic values and those of the other radiogenic tracers Sr, Pb and Nd can be found in their position relative to the main endmembers considered in present models (the MORB source mantle, the virgin primitive mantle, the continental crust and sediments). For Sr, Nd and Pb, the virgin mantle has values intermediate between those for the residual mantle (MORB source) and those for the continental crust and sediments. Thus, values similar to those of the virgin mantle may be interpreted either as actually originating from 'primitive' portions of the mantle, or resulting from the mixing of the two extreme reservoirs (MORB and sediments). For He in contrast, the virgin mantle values are not intermediate between those for the two other endmembers. This results from the fact that the complementary reservoir of the mantle for the rare gases is not the continental crust but the atmosphere (in the case of He the atmosphere is a leaky reservoir). This difference will thus enable a choice to be made between the various models.

The $^3He/^4He$ values for Gough and Tristan da Cunha are more radiogenic than the MORB values[31], themselves being more radiogenic than the pristine value. These results thus exclude the primitive mantle interpretation for these islands, as well as for the Kerguelen islands, which have similar Sr, Nd and Pb characteristics. In contrast, mixing with sediments may explain all the isotopic data.

Conclusions

Some Pb–Sr isotopic results obtained on islands of the Indian Ocean are similar to those of the North Atlantic Ocean (Comores, for example) and others are similar to those of the South Atlantic (Kerguelen, for example). These Pb–Sr–Nd isotopic similarities on a large geographical scale suggest a broad cartography of large domains with specific characteristics: North Atlantic and West Pacific on the one hand, and South Atlantic and Indian Ocean on the other.

The Pb, Nd, Sr and He characteristics of the endmembers represented by Gough, Tristan da Cunha and Kerguelen are interpreted by the mixing of lower mantle material with subducted sediments.

The isotopic peculiarity of the Indian Ocean islands is also found, with less intensity, in the Indian Ridge tholeites. This confirms the hypothesis of mixing between the oceanic islands source and the ridges tholeiites source.

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Small-angle X-ray scattering from myosin heads in relaxed and rigor frog skeletal muscles

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Low-angle X-ray diffraction patterns from relaxed and non-overlap rigor muscles show a central region of diffuse scattering (disk) which is circularly symmetrical, behaves as solution scattering and comes predominantly from myosin heads. In full-overlap rigor the disk is compressed in the diagonal direction, indicating that the myosin heads have a bent shape and a preferred orientation consistent with a 45° angle of attachment to actin.

DURING muscular contraction, interdigitating arrays of actin and myosin filaments slide further into each other[1,2]. The required energy release takes place between the two types of filament and involves a cyclical action of 'cross-bridges'[3]. The central problem is to understand the relationship between chemical, structural and mechanical aspects of the cross-bridge cycle. Here we describe a new approach to the study of the structural behaviour of the cross-bridges.

Cross-bridges can be seen in the electron microscope as projections from the surface of the myosin filaments[4–6]. They are largely composed of the S-1 and S-2 subfragments of the myosin molecule, two globular S-1 heads being joined to one double α-helical S-2 rod[7]. The latter connects the heads to the double α-helical light meromyosin rods which in vertebrate striated muscle form the backbone of the filament and constitute the third major component of the myosin molecule[7].

X-ray diffraction has been extensively used to obtain structural information about the cross-bridge cycle mainly because it can be applied to the living system. Experience from crystallography naturally led to the choice of muscles such as the striated frog sartorius which produce relatively sharp peaks[8]. However, a full interpretation presented difficulties which, besides the usual cylindrical mixing of intensity about the fibre axis, arose partly from lattice sampling on the meridional peaks[9] and partly from the presence of various types of disorder[10]. Consequently, even the configuration of the projections in the relaxed muscle is not fully understood. Nevertheless, recent time-resolved studies of the sharp peaks during contraction have given very interesting results[11–13]. Thus, it was shown that myosin heads move towards actin slightly ahead of tension rise, whilst their three-dimensional order breaks down and their axial repeat becomes more prominent; furthermore, rapid

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