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Relative contribution of crust and mantle to flood basalt magmatism, Mahabaleshwar area, Deccan Traps

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The 1200 m section of flat-lying basalts in the Mahabaleshwar area is divided into three formations on the basis of the trace elements Sr, Ba, Rb, Zr and Nb. The lowermost unit, the *Poladpur Formation*, is characterized by high Ba, Rb, and Zr/Nb, and low Sr. These features are accompanied by high K and Si, high and variable $^{87}Sr/^{86}Sr$ initial ratios (0.7043–0.7196), and low and variable ϵ_{Nd} values (+2.6 to −17.4). The formation is interpreted as having developed by contamination of the overlying Ambenali magma-type with ancient granitic crust, with simultaneous fractionation of a gabbroic mineral assemblage. The more basic members of the formation are found towards the base of the succession and are more contaminated than the upper flows. The succeeding *Ambenali Formation*, characterized by the Ambenali magma type, has low Ba, Rb, Sr and Zr/Nb, and low and rather uniform $^{87}Sr/^{86}Sr$ initial ratios (0.7038–0.7043) coupled with high and relatively uniform ϵ_{Nd} (+4.7 to +6.4). It is interpreted as being essentially uncontaminated and derived from a mantle source with a history of slight trace-element enrichment relative to m.o.r.b.-source. The uppermost group of flows, the *Mahabaleshwar Formation*, is, like the Poladpur, enriched in Ba, Rb, K and Si relative to the Ambenali, but has lower Zr/Nb and higher Sr. $^{87}Sr/^{86}Sr$ initial ratios (0.7040–0.7056) are slightly higher than in the Ambenali, and ϵ_{Nd} lies in the range +7.1 to −3.0.

In this formation Sr correlates *positively* with the other incompatible elements and with $^{87}Sr/^{86}Sr$ initial ratios. This is in strong contrast to the relations observed in the Poladpur, and we believe that the behaviour of Sr may be a simple pointer to the distinction between mantle and crustal contributions. Assuming that late-stage crystal fractionation processes can be allowed for, if Sr correlates positively with elements such as K, Rb and Ba then mantle enrichment processes are clearly implied. Conversely, as for example in the Poladpur, if the correlation is negative, crustal contamination is suspected because Sr is unlikely to behave as an incompatible element in most crustal derived melts or fluids because of buffering by residual plagioclase. Furthermore, the relative uniformity of the Mahabaleshwar Formation, the position on the Sr and Nd isotope diagram close to the 'mantle array', the fact that in terms of both incompatible element concentrations and isotopes the rocks are similar to tholeiites from oceanic islands such as Hawaii and Kerguelen, are all factors that reinforce the conclusion that these are mantle derived magmas which have suffered insignificant crustal contamination. They are, however, derived from a mantle which is trace-element enriched relative to the Ambenali source. Thus in the succession as a whole the crustal contribution appears to be small. Maximum amounts of contamination in the Poladpur Formation are difficult to determine but the *average* amount is probably in the region of 6–12 percentage mass. The whole sequence therefore contains a crustal contribution of about 2–3 %.

INTRODUCTION

Continental flood basalt provinces, because of their characteristically wide extent, constitute one of the more important potential sources of information about the nature of the subcontinental mantle. Most of the rocks in such provinces are, however, far from being primary mantle melts, having undergone quite extensive degrees of crystal fractionation en route to the surface, and in some cases clearly also having become contaminated by the crustal materials through which they have passed. In the study of these rocks it thus becomes of prime importance to develop criteria by which crustal contamination may be identified, and if possible quantified, so that distinctions may be drawn between those aspects of the geochemical evolution that have taken place in the mantle and those that may have taken place at a later stage. The present study is concerned with part of the Deccan Trap sequence of the very extensive Cretaceous–Tertiary province of peninsular India. The lava flows are almost horizontal over large areas and are superbly exposed in the cliff sections of the Western Ghats, an escarpment which parallels the west coast and is particularly well developed in the area south of Bombay. Around Mahabaleshwar, a hill town lying 150 km south of Bombay, the escarpment reaches its maximum height within the basalt terrain, and the geological structure is of maximum simplicity since the flows appear on first inspection to be plumb horizontal, and there are no faults nor even any dykes. This area is thus ideal for the study of ways in which basaltic evolution might vary with time, and has as a consequence been the subject of several recent studies. In this contribution we present conclusions drawn from the most complete set of analytical data yet obtained on a sequence which has been interpreted as showing the effects of both crustal contamination and the influence of different mantle sources.

Recent workers are in agreement about the contamination of the lower flows by material variously regarded as 'granitic' (Najafi *et al.* 1981; Cox & Clifford 1982) or as 'continental crust' (Mahoney *et al.* 1982). The main lines of evidence on which these conclusions were based are:

(*a*) the distinct division of incompatible and semi-incompatible elements into two independent groups. K, Rb, and Ba correlate well with each other but not with Ti, P, Zr and Nb. This was interpreted as the influence of a granitic contaminant by Najafi *et al.* (1981). Cox & Clifford, who considered relatively phenocryst-poor samples and whose data set was therefore biased towards the lower part of the sequence, showed that Si also correlated positively with the K, Rb, Ba group.

(*b*) Mahoney *et al.* (1982) demonstrated that both Sr and Nd isotopes were consistent with the assimilation of old continental crust.

The upper part of the sequence, however, remained somewhat problematical. Najafi *et al.*, noting many geochemical similarities with the lower part (but not considering isotopic data), concluded that contamination had also been operative here. Nevertheless, because of changes in inter-element ratios such as Zr/Nb they also postulated that contamination was superimposed on magmas that varied systematically with time because of changing source characteristics.

Mahoney *et al.* clarified the picture by showing that the isotopic compositions of the lower and upper parts of the sequence were in fact quite distinct. They regarded the contaminant evident in the lower part of the sequence as continental crust because of the inferred combination of high initial $^{87}Sr/^{86}Sr$ with low (negative) $_{\mathrm{JUV}}(\mathrm{T})$ values for the Sm/Nd system. The nature of the contaminant in the upper part of the sequence was left open, with both trace-element depleted crust and enriched mantle as possibilities.

The present study is aimed at the resolution of some of the outstanding ambiguities by the search for systematic criteria by which crustal contamination and mantle heterogeneity can be distinguished, and if possible quantified. It is based on the 33 analysed samples of Najafi *et al.* and 73 new analyses.

Table 1. Average analyses of rocks classified according to magma type

	Poladpur	Ambenali	Mahabaleshwar
SiO_2	49.98	48.78	49.15
TiO_2	2.05	2.24	2.66
Al_2O_3	13.90	13.92	13.87
Fe_2O_3	14.70	15.46	15.18
MnO	0.18	0.20	0.22
MgO	6.12	6.25	5.86
CaO	9.96	10.39	9.79
Na_2O	2.37	2.35	2.57
K_2O	0.48	0.19	0.39
P_2O_5	0.23	0.19	0.27
Rb	16	4	10
Ba	142	71	158
Sr	206	217	266
Zr	144	133	168
Nb	10	10	18
Y	36	35	37
Zn	96	100	110
Cu	176	199	233
Ni	100	86	92
$^{87}Sr/^{86}Sr_I$	0.7078	0.7042	0.7047
M'	29.9	29.3	28.2

Poladpur: 21 samples, 20 for isotopes;
Ambenali: 28 samples, 8 for isotopes;
Mahabaleshwar: 31 samples for trace elements, 27 for majors, 7 for isotopes.
M' is molecular $100\,\mathrm{Mg}/(\mathrm{Mg}+\mathrm{Fe}'')$ with the assumption that 85 % of Fe is Fe″.

STRATIGRAPHY

Because it is evident that petrogenetic processes affecting these lavas change with time, high priority in the present studies has been given to the establishment of a reliable stratigraphy. So far, however, it has not proved possible to subdivide the sequence on field criteria and stratigraphy is thus based on trace element compositions. The Mahabaleshwar succession is divided into three formations which are termed the Poladpur (below), Ambenali, and Mahabaleshwar (above). These are essentially the same as the three groups of flows defined by Najafi *et al.* A *formation* is defined as a packet of flows characterized by, though not necessarily entirely made up of, a given *magma type*. The simple criteria adopted for the definition of magma types are as follows:

Poladpur magma type	$Sr < 240$ µg/g, $Ba > 100$ µg/g, $Rb > 8$ µg/g, $Zr/Nb > 11$;
Ambenali magma type	$Sr < 240$ µg/g, $Ba < 100$ µg/g, $Rb < 8$ µg/g, $Zr/Nb > 11$;
Mahabaleshwar magma type	$Sr > 240$ µg/g, $Ba > 80$ µg/g, $Zr/Nb < 13$.

Average analyses of magma types are given in table 1.

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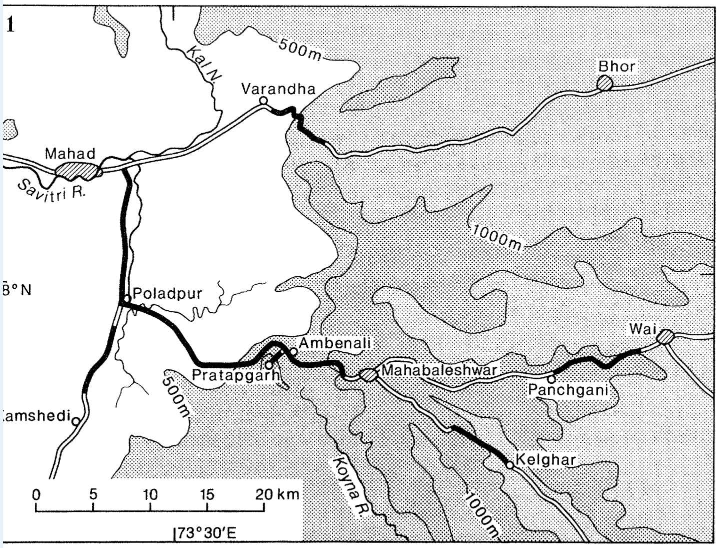
The locations of the sections so far studied are given in figure 1, and the provisional stratigraphy in figure 2. The relations illustrated imply a southerly regional dip of about 0.5°.



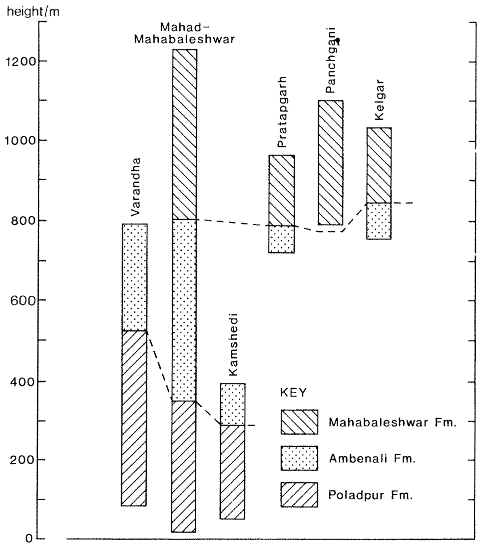


Figure 1. Location map for the Mahabaleshwar area with topography indicated. Road sections sampled shown in black.

Figure 2. Provisional stratigraphy of the Mahabaleshwar area showing sections as in figure 1. Vertical scale is height above sea level.

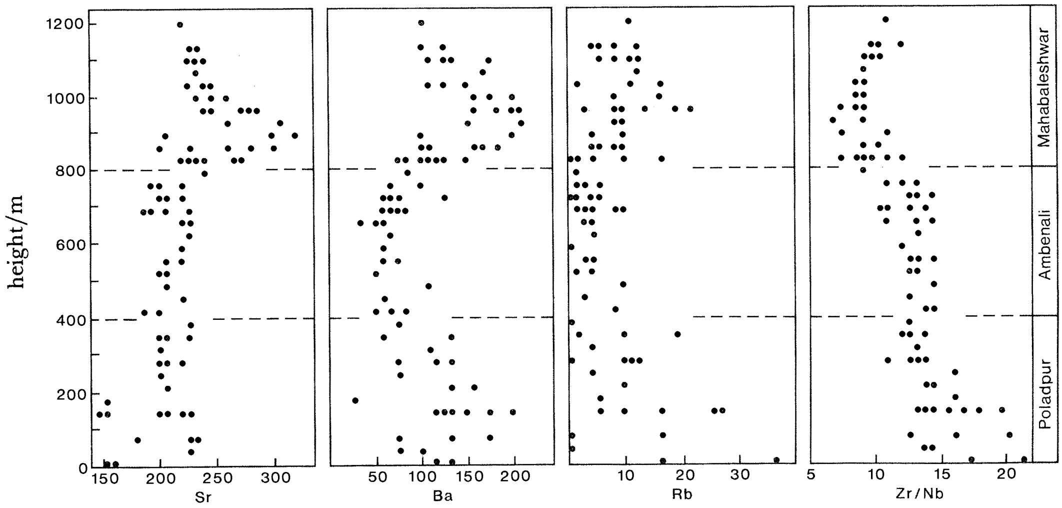


Figure 3. Classificatory parameters used in assigning samples to magma types plotted against height above sea level.

The classificatory parameters are plotted against topographic height in figure 3, but no allowance has been made here for possible differences in elevation of the top of the Poladpur Formation in different sections. Boundaries between formations are gradational or arbitrary in the sense that subjective decisions have been made about the levels in each section at which a particular magma type becomes dominant. Additionally, somewhat over 10 % of the analysed samples show transitional characteristics and have not therefore been classified. However within the Mahabaleshwar and Ambenali formations as shown in figure 2 more than 80% of the samples are classified as the magma type appropriate to the formation concerned, the majority of the remainder being unclassified. The Poladpur Formation is distinctive in containing several flows of Ambenali magma type, interbedded with a majority of Poladpur-type flows.

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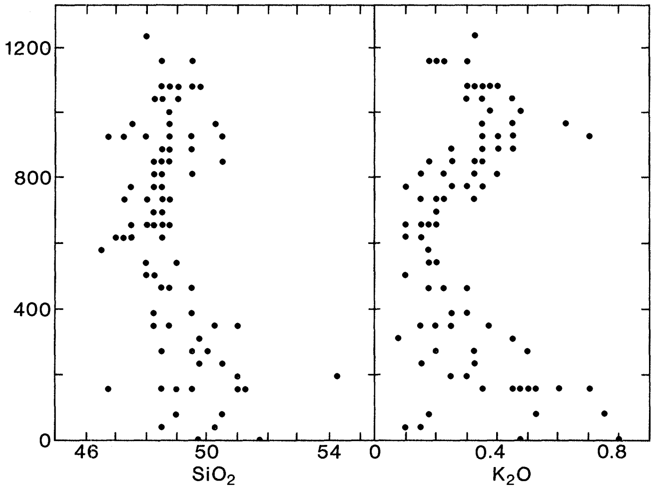

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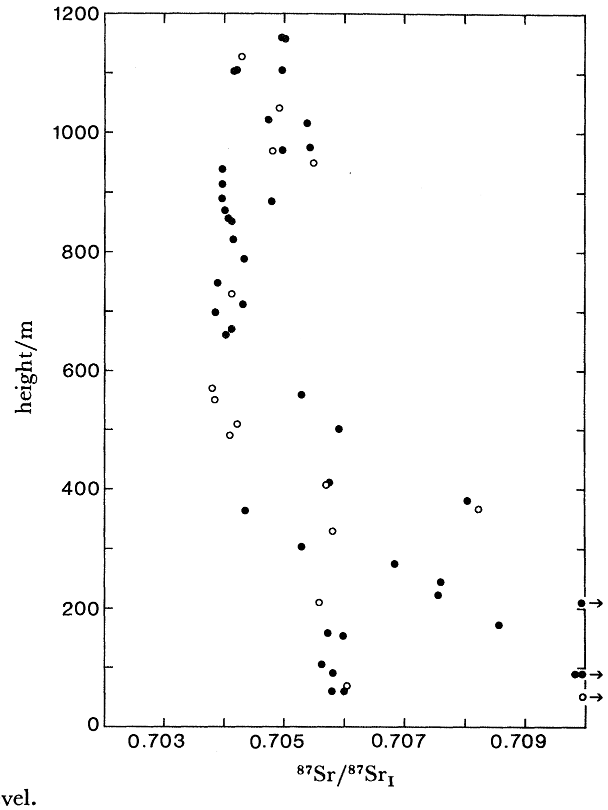

FIGURE 4. SiO_2 and K_2O plotted against height above sea level.

FIGURE 5. Initial $^{87}Sr/^{86}Sr$ ratios (at 60 Ma) plotted against height above sea level. The samples are not all from the same section, and so rocks from different formations occasionally plot at the same height (compare the Varandha and Mahad-Mahabaleshwar sections in figure 2). Solid symbols: data from present study; open symbols: from Mahoney *et al.* (1982); all normalized to NBS 987 = 0.71015.

The average analyses of magma types given in table 1 show some additional important differences between the magma types, which we do not at present include within the classificatory scheme. The Poladpur and Mahabaleshwar magma types are enriched in SiO_2 and K_2O relative to the Ambenali (see figure 4). As a consequence, the uppermost and lowermost parts of the sequence show many geochemical features in common. The Poladpur and Mahabaleshwar samples both tend to have higher initial $^{87}Sr/^{86}Sr$ ratios than those of the Ambenali, although the range of data is much greater in the Poladpur rocks (0.7043–0.7196, figure 5). Other important differences lie in the Zr/Nb ratios (lower at the top of the sequence) and in the Sr contents (high at the top of the sequence). Apart from this there are obvious differences in the relative behaviour of Sr and Nd isotopes as noted by Mahoney *et al.*, and here amplified by additional data (see figure 12).

In the following discussion we are mainly concerned with the proposition that the Ambenali magma type is essentially mantle-derived and uncontaminated with crustal materials, the

Poladpur magma type is a crustally contaminated version of the Ambenali, and the Mahabaleshwar magma type is uncontaminated by crust but contains a component derived from a mantle source enriched in trace elements relative to the Ambenali source.

CRYSTAL FRACTIONATION

The present detailed study confirms the original observation by Najafi *et al.* that plagioclase phenocrysts are ubiquitous and are accompanied in most cases by smaller amounts of clinopyroxene and by minor amounts of olivine, the latter invariably completely altered. The fractionation of the gabbroic assemblage olivine + clinopyroxene + plagioclase has been proposed by both Najafi *et al.* and Mahoney *et al.* as a major factor controlling compositional variation. Crustal contamination may, however, have noticeable effect on major element analyses and we have therefore selected a group of rocks from the lower half of the sequence for which $^{87}Sr/^{86}Sr$ initial ratios are below 0.706, and we believe are thus relatively little contaminated. Rocks from the upper part of the sequence have been excluded because of the suspicion that they may have been derived from a different source, and we have also excluded rocks with $MgO > 7\%$. The latter exclusion is made because of the possibility of fractionation controlled by ferrogmagnesian minerals only, rather than by gabbro. Variation diagrams for the selected group prove to be highly typical of gabbro fractionation (i.e. olivine + clinopyroxene + plagioclase). Major elements behave similarly to those of the idealized trends modelled by Cox (1980). Trace elements not highly susceptible to contamination (e.g. Zr, Nb, Sr, Zn, Cu, Y) all show appropriate enrichment effects and the constant behaviour of Sr is particularly notable, giving excellent confirmation of plagioclase fractionation. It is also important to note that rocks within the selected group show almost no variation in SiO_2.

Within the Mahabaleshwar Formation we have not been able at present to confirm the importance of gabbro fractionation because of the dominance of porphyritic types.

Changes of fractionation stage with time

In order to monitor the progress of fractional crystallization it is essential to select a parameter which is insensitive to contamination. The best choice is some form of the Fe/Mg ratio, and in figure 6 we illustrate the parameter M′ plotted against topographic height. M′ is defined as $100\,Mg/(Mg+Fe^{2+})$ on the assumption that 85% of the Fe in each sample is in the ferrous state. The range of M′ shown by the samples is approximately 22–40. Insensitivity to contamination by granitic materials can be illustrated by comparing this range with M′ for granites and allied rocks. The average granite and granodiorite of Le Maitre (1976) for example have M′ values of 23 and 30 respectively.

Figure 6 thus illustrates a number of important features of the sequence. It is notable that with the exception of a group of high-M′ samples at *ca.* 900 m there is a general drift towards more fractionated types with time. This is similar to the trend found in the 1500 m sequence of horizontal Karoo basalts in Lesotho (Cox & Hornung 1966; Marsh & Eales 1983). However, at any particular restricted stratigraphic level a large range of M′ values is found.

The most primitive rocks, with the exception of the 900 m samples, are mainly concentrated towards the base of the sequence. We know from seismic data (Kaila *et al.* 1981) that the Deccan Traps are likely to extend for another 0.5–1 km below sea level in this general area, and thus a considerable part of the section is unexposed at Mahabaleshwar. If the trend noted above is continued, primitive rocks are expected to become more important in the unexposed part of the section. Ankaramitic flows are exposed in the Igatpuri area about 200 km north of Mahabaleshwar (Mishra 1969) and it is interesting to speculate that these may prove to be stratigraphically lower than the lowest part of the Mahabaleshwar section when sufficient detailed information has been gained.

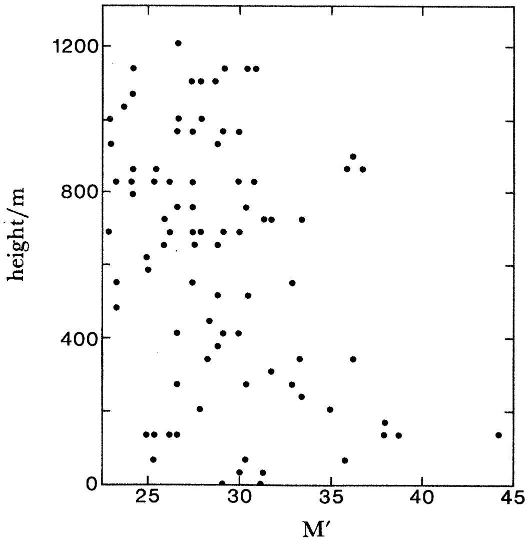

FIGURE 6. M′ values plotted against height above sea level.

CRUSTAL CONTAMINATION IN THE POLADPUR FORMATION

We have attempted to define the details of the contamination process by studying individual samples, but relations have an apparently random element which is difficult to interpret. The criteria established by previous work imply that, relative to uncontaminated magma, contaminated magma should be enriched in SiO_2, K_2O, Rb, Ba and ^{87}Sr relative to ^{86}Sr, and it is also likely to be depleted in Fe_2O_3 and TiO_2. The most obvious effects are expected to be visible in the behaviour of elements such as K, Rb, and Ba which are so abundant in potential contaminants such as granite that increases consequent upon contamination will much outweigh variation induced by gabbro fractionation. However, because SiO_2 is almost constant during fractionation, contamination effects should also be evident for it. The behaviour of Fe_2O_3 and TiO_2 is more difficult to judge because neither is constant during fractionation nor very strongly affected by contamination.

Nevertheless, all the effects noted above can be seen in their generalized form by a comparison of the average Ambenali and Poladpur magma types in table 1. In detail however individual analyses rarely show all the expected effects. Poladpur samples suspected of being contaminated all show inflated Rb and Ba contents but some fail to show significant concommitant increases in either K_2O or SiO_2. Similarly, most of these samples have high $^{87}Sr/^{86}Sr$ but a few do not. The reasons for these discrepancies are not at present known. The behaviour of SiO_2 may well be caused by analytical problems since a relatively very high precision is required here. We can not comment on the other discrepancies until we know to what extent the flows are homogeneous with regard to the critical elements. The effect may be a consequence of the heterogeneity of contaminants, or it may be the result of alteration or other processes.

Attempts to quantify the contamination process are fraught with difficulty but if we average all Poladpur analyses which satisfy all the contamination criteria we obtain 50.93 % SiO_2 and 0.73 % K_2O. Using the first of these values, a starting material of average Ambenali magma type, and a granitic contaminant of 70 % SiO_2 we calculate that the amount of contamination is 10 %. With the K_2O values and assuming the contaminant has 4 % K_2O we obtain an alternative value of 14 %. Using an average contamination of 12 % we can then calculate the Rb and Ba contents of the contaminant as 170 and 920 μg/g respectively, values that are obviously plausible for granite.

Table 2. Mixing calculation relating average Poladpur and Ambenali magma types

input data, oxide (% mass)

	weight	Poladpur	gabbro	granite	Ambenali
SiO_2	1	49.98	49.37	71.3	48.78
TiO_2	1	2.05	0.25	0.31	2.24
Al_2O_3	1	13.90	17.63	14.32	13.92
Fe_2O_3	1	14.70	5.31	3.01	15.46
MgO	1	6.12	10.13	0.39	6.25
CaO	1	9.96	16.04	1.14	10.39
Na_2O	1	2.37	1.35	3.55	2.35
K_2O	5	0.48	0.03	4.30	0.19

solution

	weight	Ambenali	calculated	difference	difference (%)
SiO_2	1	48.78	48.64	0.14	0.28
TiO_2	1	2.24	2.18	0.06	2.88
Al_2O_3	1	13.92	13.84	0.08	0.57
Fe_2O_3	1	15.46	15.52	−0.06	−0.38
MgO	1	6.25	6.45	−0.20	−3.13
CaO	1	10.39	10.46	−0.07	−0.69
Na_2O	1	2.35	2.31	0.05	1.93
K_2O	5	0.19	0.24	−0.05	−28.04

sum of squares: 0.0813952

solution

Poladpur	107.183
gabbro	−0.882034
granite	−6.30082

To extend this calculation to take into account the additional fractionation effects we have attempted to match the average Ambenali magma type by subtracting the average granite of Le Maitre (1976) and the average gabbro derived from earlier calculations of fractionation processes. The precise results obtained depend upon the weighting technique used for individual elements in the mixing calculation (Wright & Doherty 1970) and the result given in table 2 is a compromise obtained by giving extra weight to K_2O. The correspondence between the calculated and actual Ambenali analyses is excellent, and indicates, with rearrangement of the figures, that the average Poladpur magma type can be made by adding together the Ambenali type, gabbro, and granite in the proportions 93 : 1 : 6. This suggests that approximately 6 % of the substance in the *average* Poladpur magma is of granitic origin, i.e. about half that calculated for more extreme samples above.

Relation between contamination and fractionation

Mahoney *et al.* noted that there appeared to be a negative correlation between the degree of fractionation and the amount of contamination shown by their samples. Cox & Clifford (1982) observed that the most basic rocks were apparently over-represented among the most contaminated samples, so that positive correlations appeared between Ni and K and Rb. The present study shows that this is indeed the case. For example in figure 7 the good positive correlation between M′ and SiO_2 in samples from the lowermost 400 m of the section (essentially the Poladpur Formation) indicates quite clearly the Si-rich nature of the more primitive samples. Since we have argued that M′ is not sensitive to contamination while SiO_2 is not sensitive to gabbro fractionation the conclusion that the more primitive rocks are more contaminated is difficult to escape. We agree with Mahoney *et al.* (1982) that the most likely explanation of this relation is that conduits through the crust, or the walls of magma chambers, became more insulated with solidified basalt as time progressed. However, since we do not believe that the upper part of the sequence (Mahabaleshwar Formation) is contaminated by crustal material at all (see later discussion) we would extend the above argument to the *whole* sequence in the Mahabaleshwar area. The Poladpur Formation is essentially contaminated, though we note something that we might expect to be characteristic of crustal contamination, that is that *some* flows of Ambenali type lie within it and there is a considerable scatter in the initial $^{87}Sr/^{86}Sr$ ratios (figure 5); thus the amount of contamination in flows within restricted stratigraphic ranges can be very variable. However, we also note the tendency for the most contaminated rocks to be found in the lower part of the formation. Conversely, once the top of the Poladpur Formation is reached, no further flows which we would regard as significantly contaminated are found at higher levels.

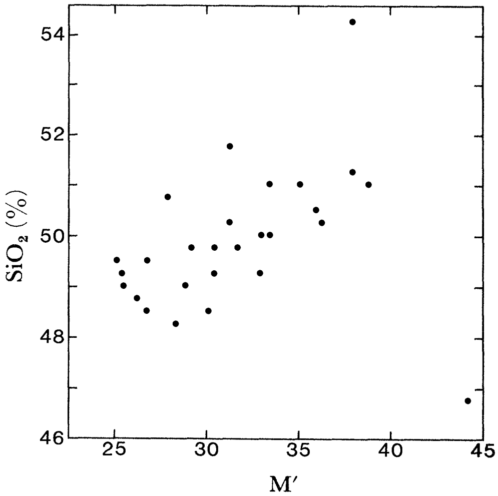

FIGURE 7. SiO_2 against M′ for samples between 0 and 400 m above sea level. This effectively restricts the diagram to the Poladpur Formation.

Comparison of the Mahabaleshwar and Poladpur magma types

The base of the Mahabaleshwar Formation is located at approximately 800 m above sea level. At this point the Zr/Nb ratio of the flows begins to decrease gradually upwards (see figures 3 and 4) while K_2O, SiO_2, Rb, Ba and Sr all begin to increase. The behaviour of Zr/Nb, Ba and Sr is particularly clear, and shows a peaking of the changes at about 900 m, followed by a gradual reversal of the trends. The detailed work of Najafi *et al.* indicates that all these changes take place within approximately 15 successive flows.

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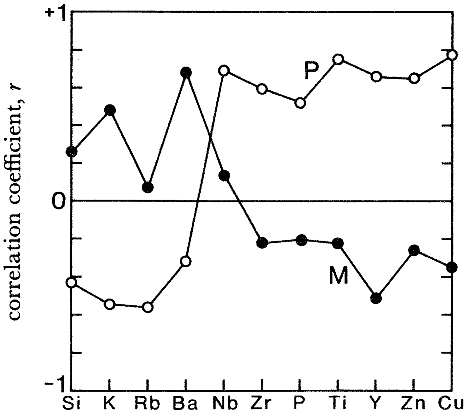

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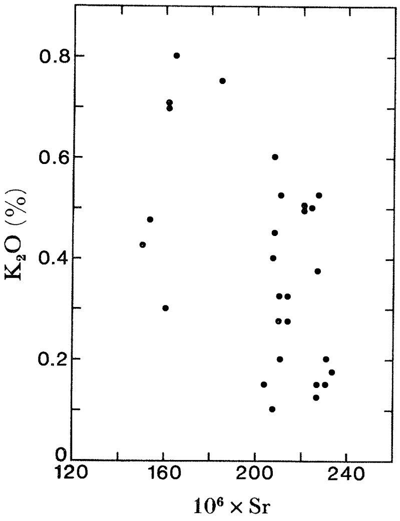

FIGURE 8. Correlation coefficients, *r*, for Sr against other elements. Open circles (P trend), lowest 400 m of section (= Poladpur Formation), solid circles (M trend), samples lying between 800 and 1200 m (= Mahabaleshwar Formation).

FIGURE 9. K_2O against Sr for samples between 0 and 400 m (Poladpur Formation).

There is however a great deal of similarity between the geochemistry of the Mahabaleshwar and Poladpur magma types. Relative to the Ambenali type both are on average enriched in SiO_2, K_2O, Rb and Ba, a feature which led Najafi *et al.* to postulate crustal contamination for both sequences. However, apart from isotopic considerations to be discussed later, there are several reasons why we no longer think that crustal contamination has been significant within the Ambenali Formation.

First, the trace element changes took place with extreme regularity as successive flows were erupted. The gradual change in Zr/Nb, which is more a consequence of increasing Nb than of changing Zr, is thus difficult to envisage in terms of a contamination model. The increase in Sr could at first sight be attributed to the accumulation of plagioclase phenocrysts, but the most Sr-rich samples are abnormally basic and contain few if any of them. Thus it seems likely that the Mahabaleshwar magma type is inherently Sr-rich compared with the Ambenali, a feature unlikely to be the result of contamination by crustal materials (Hawkesworth & Vollmer 1979). Studies of Karoo basalts have for example shown that magma enriched in K, Ba and Rb are also characteristically enriched in Sr and SiO_2 (Cox 1983). Enrichment in the latter is attributed to the effects of water on the melting of a trace-element enriched source (mica or amphibole-bearing), while enrichment in Sr presumably reflects the mobility of this element, along with K, Rb and Ba, in the mantle environment. Such mobility is not to be expected in the crust because of the presence of abundant plagioclase.

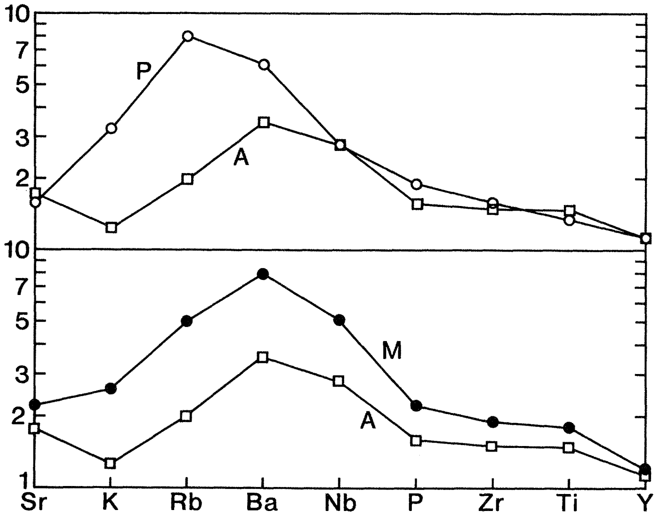

FIGURE 10. Trace and minor element concentrations in average magma types normalized against typical m.o.r.b. of Pearce *et al.* (1981). P: Poladpur; A: Ambenali; M: Mahabaleshwar. Normalization values (m.o.r.b.) are Sr: 120 μg/g; K_2O: 1.5 %; Rb: 2 μg/g; Ba: 20 μg/g; Nb: 3.5 μg/g; P_2O_5: 0.12 %; Zr: 90 μg/g; TiO_2: 1.5 %; Y: 30 μg/g.

The correlation behaviour of Sr is intriguingly different within the two formations, Mahabaleshwar and Poladpur. The previous study of Cox & Clifford was dominated by samples from the Poladpur and Ambenali formations and showed a pattern similar to that given for the Poladpur Formation in figure 8. The contrast between this and the Mahabaleshwar formation pattern is striking and shows a complete change of allegiances in the upper part of the sequence. Here Sr shows the positive correlations with K, Rb, Ba and Si characteristic of the Karoo rocks mentioned above. In the Poladpur, on the other hand, the positive correlations are with those elements that are not enriched, or are depleted, in the contaminant relative to the basalt magmas. Reference to the scattered relations between Sr and K_2O given in figure 9 leaves the Sr-content of the Poladpur contaminant open to some doubt, but a relatively high-K, low-Sr composition seems most likely.

We suspect that one of the most useful ways of distinguishing crustal contamination from the effects of enriched mantle sources lies in the study of the behaviour of Sr. When it correlates positively with Si, K, Rb and Ba a mantle explanation of the geochemical effects is indicated. When it shows behaviour as in the Poladpur pattern of figure 8, and correlates negatively with these elements, then crustal contamination by generally low-Sr materials such as granitic partial melts is a more likely explanation.

TRACE AND MINOR ELEMENT ENRICHMENT PATTERNS

Figure 10 shows the average analyses of the magma types (table 1) normalized against typical m.o.r.b. (Pearce *et al.* 1981). There is a good deal of similarity between the enrichment patterns of the Mahabaleshwar and Ambenali magma types, with the former showing greater degrees of enrichment. It is possible that these differences reflect variation in the degree of partial melting, but in that case very low-volume partial melts would have to be invoked in order to explain the changes in inter-element ratios (e.g. increases in Ba/Ti in the Mahabaleshwar relative to the Ambanali). However, since we know that the two magma types are *isotopically* different (see next section) it is more likely that two source components are involved, and they have inherently different trace element contents. At present we assume therefore that the observed patterns simply reflect those of their sources, as a consequence of the magmas having been derived by relatively high degrees of partial melting. The Ambenali pattern is almost identical to that figured for Hawaii by Pearce (1982, figure 1).

The Poladpur magma type pattern is distinctly different, and relative to the Ambenali, is enriched significantly in K, Rb, and Ba. These are clearly features that can be ascribed to contamination by granitic materials, as is the depletion in Ti. The slight enrichment in P remains at the moment unexplained.

ISOTOPES

Over sixty initial $^{87}Sr/^{86}Sr$ ratios are now available (Mahoney *et al.* 1982; and this work) and these are plotted against height above sea level in figure 5. We note the following.

(1) A third of the samples analysed exhibit a very restricted range in initial $^{87}Sr/^{86}Sr$ from 0.7038–0.7043, and these occur in the upper 800 m.

(2) Figure 5 includes rocks from several sections and some of the scatter is because rocks from different formations in different areas can occur at the same height above sea level (figure 2). For example, at 500–600 m the high $^{87}Sr/^{86}Sr$ samples are from the Poladpur Formation in the Varandha section, and the low initial $^{87}Sr/^{86}Sr$ samples are from the Ambenali Formation in the Mahad-Mahabaleshwar section.

(3) Comparison of figure 3 with 5 demonstrates that the $^{87}Sr/^{86}Sr$ results are broadly consistent with the trace element variations discussed above. The Poladpur Formation is characterized by very variable trace element and isotope compositions, but low Sr contents tend to be accompanied by high Rb, Ba and $^{87}Sr/^{86}Sr$. The Ambenali Formation has uniformly low Sr, Ba, Rb and ^{87}Sr abundances, and then the Mahabaleshwar Formation is marked by a coherent increase in, for example, Sr and $^{87}Sr/^{86}Sr$ (figure 11).

(4) Although the low Sr contents and high and variable $^{87}Sr/^{86}Sr$ ratios of some of the Poladpur rocks are entirely consistent with contamination by crustal material, half of the Poladpur rocks analysed have restricted $^{87}Sr/^{86}Sr$ ratios of 0.7056–0.7060. Further work is in progress to assess whether, as implied here, this just reflects remarkably similar degrees of crustal contamination, or whether the 'pre-contamination' magma in the Poladpur Formation was different from those now observed in the Ambenali Formation.

In summary the Ambenali Formation has uniform initial $^{87}Sr/^{86}Sr$ ratios of 0.7038–0.7043 consistent with its low average Rb/Sr ratio (0.018 table 1), and the Mahabaleshwar Formation has both higher $^{87}Sr/^{86}Sr$ ratios and Rb/Sr ratios (0.7047 and 0.038 respectively, table 1). Moreover, it is argued that these variations reflect mantle processes and that they therefore contrast with the high and variable ratios from the Poladpur rocks (average $^{87}Sr/^{86}Sr = 0.7078$, $Rb/Sr = 0.078$, table 1) which are due primarily to contamination with granitic crust.

The Nd-isotope results of this study confirm those reported previously by Mahoney *et al.* However, although they chose to maintain a two-fold division of the Deccan lavas, it is now clear that all the available Nd- and Sr-isotope data are entirely consistent with the three stratigraphic units described there (figure 12). The rocks of the Ambenali Formation have restricted ϵ_{Nd} and ϵ_{Sr} values of $+4.7$ to $+6.4$ and -4 to -11 respectively, and the two trends identified by Mahoney *et al.* are then defined by the rocks of the Poladpur and Mahabaleshwar Formations.

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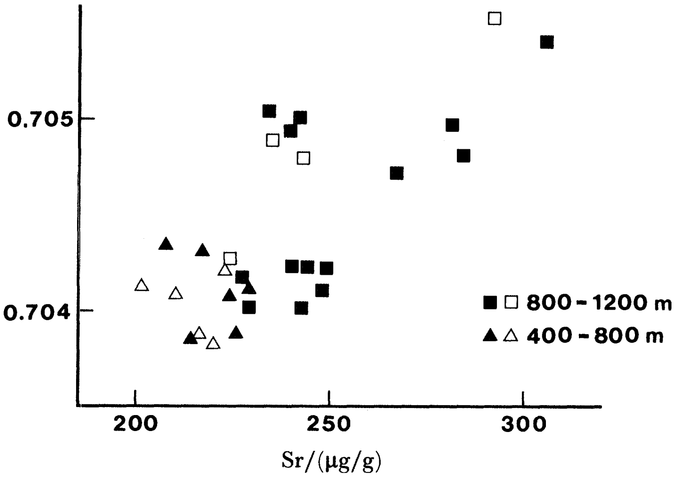

12

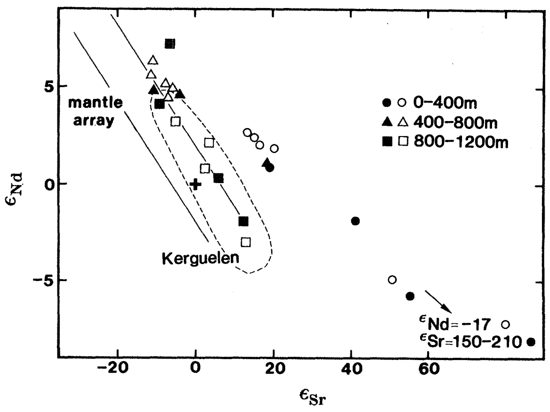

FIGURE 11. Initial $^{87}Sr/^{86}Sr$ ratios against Sr μg/g in Deccan basalts in the upper 800 m: 400–800 m corresponds to Ambenali Formation and 800–1200 m corresponds to the Mahabaleshwar Formation. Solid symbols: data from present study; open symbols: from Mahoney *et al.* (1982).

FIGURE 12. Initial ϵ_{Nd} and ϵ_{Sr} variations in Deccan basalts. Present day CHUR, $^{143}Nd/^{144}Nd = 0.51264$ and $^{147}Sm/^{144}Nd = 0.1967$. $^{87}Sr/^{86}Sr$ results normalized to N.B.S. 987 = 0.71015. The height intervals of 0–400 m, 400–800 m and 800–1200 m broadly correspond to the Poladpur, Ambenali and Mahabaleshwar Formations; but note that the one high ϵ_{Sr} 400–800 m sample is from Varandha where the top of the Poladpur Formation is at least 150 m higher than in the other sections. Solid symbols: data from present study; open symbols: from Mahoney *et al.* (1982).

The Poladpur basalts exhibit a large range of initial ϵ_{Nd} ($+2.6$ to -17.4) and ϵ_{Sr} ($+13$ to $+213$) values and they tend to be displaced to relatively high ϵ_{Sr} compared with both the so-called 'mantle array' and other Deccan rocks (figure 12). Such trends often reflect contamination with continental crust (Carlson *et al.* 1981; Menzies *et al.* 1983), and at least along the southern margin Deccan lavas lie unconformably on Archaean granites and gneisses. Many solutions are possible and Mahoney *et al.* modelled these Poladpur rocks as mixtures of Indian Ocean basalt with 'm.o.r.b.-like' trace element contents, and high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ Archaean crustal material. However, their suggestions that the latter might contain three times more Sr than the mantle-derived end-member conflicts with the presence of low-Sr rocks in this formation (figure 3) and with the relatively high-K, low-Sr composition of the contaminant implied by figure 9. Moreover, the choice of m.o.r.b.-like Sr and Nd abundances in the uncontaminated magma proved difficult to reconcile with the higher concentrations in the Deccan basalts, a problem which is eased considerably by accepting that the Ambenali rocks are likely to represent uncontaminated mantle melts.

The calculations summarized in table 2 demonstrated that many aspects of the chemistry of the average Poladpur basalt can be produced by mixing 93 parts Ambenali basalt, 1 part gabbro, and 6 parts 'granite'. Isotopically, that is equivalent to 94 parts Ambenali basalt and 6 parts continental crust, and while in principle both the Nd- and Sr-isotope variations can be used to test that conclusion, in practice the calculations are very sensitive to the exact choice of input parameters, and often they are poorly known: for example, the average $^{87}Sr/^{86}Sr$ of the Poladpur Formation = 0.7078 (table 1), but one standard deviation is 0.0035.

Nonetheless if 0.7078 is adopted as the average initial $^{87}Sr/^{86}Sr$ ratio of the Poladpur Formation, the data array in figure 12 suggests that $\epsilon_{Nd} = -3.0$ (or $^{143}Nd/^{144}Nd = 0.51241$) is the equivalent initial Nd-isotope composition. The mantle end-member is represented by Ambenali type magma with average initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of 0.7042 and 0.51283, and assumed slightly lower than average Sr and Nd contents of 200 and 18 μg/g. Then if the model is constrained so that the average Poladpur basalt consists of 94 parts mantle end-member and 6 parts crust, and the latter contains less Sr than the mantle end-member, mixing calculations indicate a typical crustal component of $^{87}Sr/^{86}Sr = 0.78$, Sr = 156 μg/g, $^{143}Nd/^{144}Nd = 0.5110$ and Nd = 82 μg/g. The Nd-isotope ratio is consistent with 3.0 Ga continental crust with an average Sm/Nd = 0.19, but the estimated $^{87}Sr/^{86}Sr$ ratio implies an unusually high Rb/Sr ratio (0.64) over 3.0 Ga, and the Nd content is probably higher than expected for a crustal melt. Such an end-member is possible, but unlikely.

An alternative interpretation is to increase the crustal contribution to 12%, whereupon it has the more reasonable values of $^{87}Sr/^{86}Sr = 0.744$, Sr = 146 μg/g, $^{143}Nd/^{144}Nd = 0.5110$ and Nd = 39 μg/g, or perhaps the estimated average isotope compositions of the Poladpur Formation are simply biased to slightly high $^{87}Sr/^{86}Sr$ or low $^{143}Nd/^{144}Nd$ ratios. Whichever explanation is preferred the Nd- and Sr-isotope data on the Poladpur rocks are clearly in accord with models in which an Ambenali-type mantle-derived magma is variously contaminated by relatively small amounts of low Sr crustal material of Archaean age.

One of the perplexing aspects of the Ambenali results is their position slightly to the right of the mantle array at high ϵ_{Nd} values (figure 12). Similar compositions are observed in destructive plate margin volcanic rocks but the Deccan lavas do not, for example, exhibit the relatively low Nb abundances (or high Ba/Nb ratios) supposedly characteristic of rocks generated in that environment. Moreover, the average Rb/Sr (0.018) and Sm/Nd (*ca.* 0.285) of the Ambenali rocks are such that if similar ratios were also present in their mantle source regions, they would have plotted at even higher ϵ_{Sr} and ϵ_{Nd} values further back in time.

Finally, the basalts of the Mahabaleshwar Formation define the second, much steeper trend on figure 12, with $\epsilon_{Nd} = +7.1$ to -3.0. This change in isotope ratios at the top of the sequence (see also figure 5) is accompanied by higher incompatible element abundances and positive correlations between Sr and Si, K, Rb, Ba and $^{87}Sr/^{86}Sr$ (figures 8 and 11) which are arguably indicative of mantle processes. Moreover, this is supported by the ϵ_{Nd}, ϵ_{Sr} results since the observed trend is similar to those reported from many oceanic islands, and in particular to that from Kerguelen (Dosso & Murthy 1980; White & Hofmann 1982). Such isotope trends may reflect either comparatively recent mixing events, or long-term chemical variations or both in their mantle source regions. There is still little clear evidence from the Deccan, but whereas the low ϵ_{Nd} Mahabaleshwar basalts have low Sm/Nd and slightly high Rb/Sr consistent with their isotope ratios, no such simple relation is observed in the Ambenali rocks, suggesting that they at least have had their isotope systems disturbed by some recent event.

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