Geochemistry and strontium isotopic composition of basalts from the Eastern Deccan volcanic province, India

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SUMMARY. Ten rather uniform tholeiitic basalt flows totalling a thickness of 190 m from Sagar, India, contain two stratigraphical breaks. Major element variation allows the flows to be grouped into two eruption cycles. Due to intraflow variation, however, chemical composition is unlikely to be useful in widespread correlation of flow sequence. The initial $^{87}Sr/^{86}Sr$ ratios vary from 0·7039 to 0·7084 with Rb and Sr averaging 6·5 and 184 ppm respectively and Rb/Sr ratios ranging from 0·002 to 0·224, with no systematic relationship between the initial $^{87}Sr/^{86}Sr$ ratios and other chemical parameters. Bulk crustal contamination is considered unlikely; selective introduction of ^{87}Sr from the granitic basement is postulated.

THE DECCAN is one of the largest continental basaltic provinces with an area of about 10×10^5 sq. km. The rocks are uniform in mineralogy and chemistry over most of the area, being tholeiitic, but diverse types are present in the western part of the province. Consequently, geochemical studies have been carried out in the isolated centres in the western part (Chatterjee, 1964; Krishnamurthy, 1974; Sukeshwala and Poldervaart, 1958; West, 1958). The basalt thickness in the eastern part is only about 100 to 200 m, increasing westward to more than 2000 m (Bose, 1972). Although Sr isotope studies have established similarity or otherwise of the Mesozoic tholeiites of Tasmania, Antarctica, South America (Compston et al., 1968), such data are rare from the Deccan rocks (Faure and Hurley, 1963). The present work reports on ten lava flows sampled from three boreholes around Sagar (fig. 1), and is the first study of its kind on the lava sequence of the eastern Deccan volcanic province.

Stratigraphy. The Deccan traps have been divided into Lower, Middle, and Upper Groups (Wadia, 1957). The volcanicity occurred between the upper Cretaceous and upper Eocene, becoming younger from west to east.

The flows around Sagar (23° 56' N:78° 38' E), in the NE of the volcanic province (fig. 1), are simple, consisting of single flow units in contrast to compound flows of western India (Walker, 1972). At least ten flows can be recognized in the field; most of them are uniformly horizontal, with dips up to 2°. Individual flows may vary considerably in thickness, e.g. the second flow (fig. 3) varies from 20 to 50 m within a small distance.

The samples studied came from three boreholes (BH) that together penetrate the entire thickness of the lava pile. BH 1 encountered six flows with an intertrappean limestone; BH 2 penetrated four flows, two of which are also present in BH 1; BH 3 has the two lower flows. In BH 1 and BH 2, flows rest on Vindhyan Sandstone (Precambrian), while in BH 3 they overlie Lameta sandstone and limestone (upper Cretaceous). A composite stratigraphical column of the flow sequence has been constructed from the three borehole data (fig. 3). Correlation of the individual flows is primarily on comparable height, a valid assumption because of the closeness of the borehole locations. Two sedimentary horizons in the lavas divide them into three stratigraphical groups; a lower group comprising flows 1 to 4; a middle group, flow 5; and an upper group with flows X, 6, 7, 8, and 9. Flow X is present only in BH 1.

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Petrography. Petrographically the flows are uniform throughout the sequence. The principal constituents are 20 to 60% plagioclase (An_{50}), 25 to 40% augite, 6 to 14% magnetite and titano-magnetite. Most of the flows are fine to medium grained with sub-ophitic texture and 3 to 10% glass. Olivine is present only in flows 2 and 5, which is unusual as abundant olivine pheno-crysts occur elsewhere in the Deccan province (West, 1958). The major phenocrysts of the sub-porphyritic flows are plagioclase with an average grain size of 2 mm. Amygdules of calcite, zeolites, and altered glass occur in some flows. Flows 1 and 6 contain the largest plagioclase phenocrysts whilst flow 5 is the finest grained.
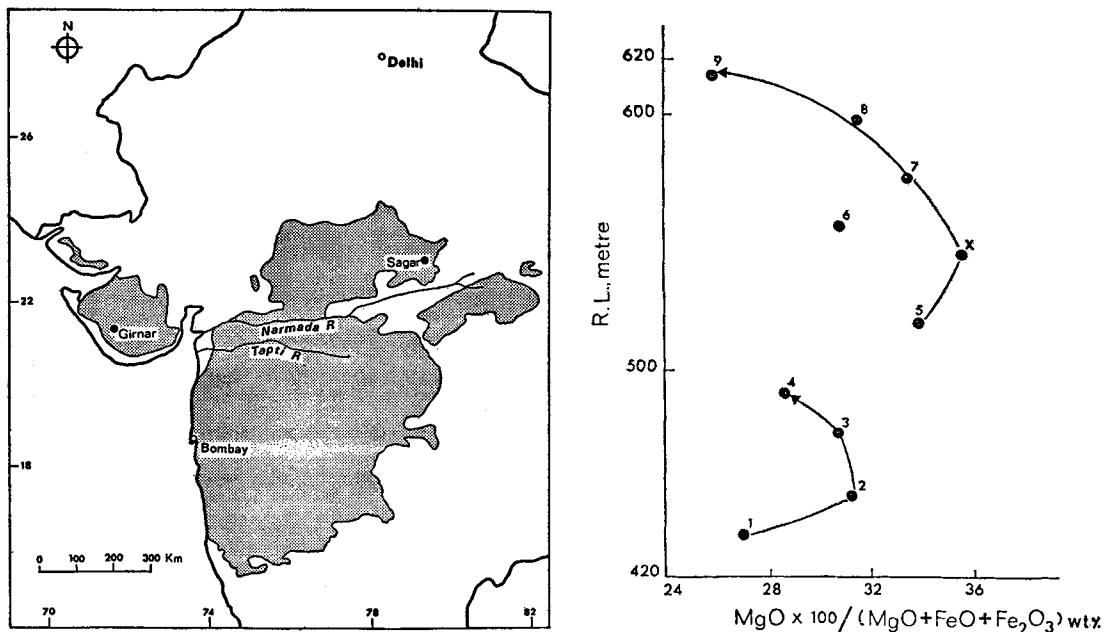
FIGS. I and 2: FIG. I (left). Distribution of Deccan basalts in India showing the location of the present study. FIG. 2 (right). Variation of Fe/Mg index $(MgO \times 100)/(MgO+FeO+Fe_2O_3)$, wt. %, in the lava column around Sagar. Numbers refer to the flow sequence. R.L. = Reduced level.

Chemistry. A total of 36 samples was analysed by a combination of X-ray fluorescence and wet-chemical (Fe^{2+} and water) methods. A minimum of three samples was analysed from each flow with the exception of flow 7 where only one was analysed. The average composition of each of the ten flows is given in Table I.

On the basis of the presence of hypersthene in the CIPW norms, and plots on the alkali–silica diagram of Macdonald and Katsura (1964) (not shown), the flows are classified as tholeiitic basalt, as are the Deccan volcanics. The compositional range is narrow, but enrichment in Fe and Ti is found in all the Sagar flows. In fact, Ti is high for tholeiitic basalt (Chayes, 1965), as in the Deccan basalts of the Mahabaleshwar area in western India (Konda, 1971). TiO_2 is plotted against solidification index $(MgO \times 100/(MgO+FeO+Fe_2O_3+Na_2O+K_2O)$, Kuno *et al.*, 1957) for the present samples and some tholeiites from Japan, Hawaii, and the oceanic regions in fig. 5. It is evident that the Sagar tholeiites have a unique place on this diagram. Their high Ti content is matched only with some Hawaiian tholeiites.

When the Fe/Mg index, $(MgO \times 100/(MgO+FeO+Fe_2O_3)$, wt %) is plotted against strati-graphical sequence (fig. 2), a break between flows 4 and 5 subdivides the sequence into two

groups. For both groups, the Fe/Mg index follows a hyperbolic pattern in the ascending sequence. In the basal group, SiO_2 decreases upwards from 49·27 to 46·92 %, Na_2O+K_2O from 3·15 to 2·57 %, while $CaO+MgO$ increases from 14·64 to 15·71 % in flows 1 to 4 (fig. 3). In flows 5 to 9, SiO_2 ranges from 47·66 to 49·22 %, $FeO+Fe_2O_3$ behave sympathetically to silica, while TiO_2, K_2O, and P_2O_5 remain approximately constant in flows 5 to 8, but increase in the youngest flow 9. However, flow of any composition may occur in either group. Thus flows 1 and 9 have very similar composition, especially in their SiO_2 and alkali contents.

TABLE I

Flows	1	2	3	4	5	X	6	7	8	9	Average
SiO_2	49.27	48.80	47.99	46.92	47.66	47.95	48.68	47.10	48.70	49.22	48.26
TiO_2	2.62	2.33	2.31	2.39	2.27	2.14	2.65	2.62	2.63	3.48	2.55
Al_2O_3	14.50	13.71	13.56	14.33	14.23	14.20	14.32	14.45	13.71	12.07	13.95
Fe_2O_3	2.76	3.21	4.57	5.81	4.12	3.65	4.70	1.85	3.43	3.48	3.84
FeO	9.95	10.57	8.96	7.11	8.66	8.47	8.89	9.96	10.20	10.96	9.32
MnO	0.20	0.21	0.22	0.24	0.20	0.19	0.22	0.21	0.27	0.23	0.22
MgO	4.66	6.23	6.00	5.16	6.57	6.57	5.98	5.92	6.19	5.00	5.84
CaO	9.98	10.79	10.49	10.55	11.04	11.40	10.52	9.13	10.63	9.63	10.38
Na_2O	2.58	2.30	2.30	2.36	2.26	2.24	2.38	2.53	2.66	2.45	2.40
K_2O	0.57	0.33	0.22	0.21	0.16	0.14	0.23	0.26	0.30	0.61	0.29
P_2O_5	0.29	0.23	0.22	0.23	0.22	0.21	0.25	0.27	0.28	0.38	0.25
H_2O^+	2.09	1.23	2.67	3.98	2.43	2.09	0.52	4.59	1.01	1.18	1.81
Others	0.25	0.36	0.34	0.43	0.31	0.18	0.67	0.82	0.08	0.02	0.42
Total	100.42	100.30	99.85	99.72	99.25	99.09	100.01	99.80	100.09	98.71	99.53
D.I.	28.89	23.35	24.81	26.74	22.41	22.07	25.77	24.37	25.34	29.95	25.41

C.I.P.W. norm:

	1	2	3	4	5	X	6	7	8	9	Average
Qz	3.69	1.94	4.05	5.53	2.34	2.29	4.28	1.42	1.06	5.62	3.39
Or	3.37	1.95	1.30	1.24	0.95	0.83	1.36	1.54	1.77	3.61	1.71
Ab	21.83	19.46	19.46	19.27	19.12	18.95	20.14	21.41	22.51	20.73	20.31
An	26.31	26.11	26.03	27.89	28.22	28.27	27.72	27.31	24.59	20.14	26.44
Di	17.66	21.33	20.02	18.43	20.40	21.87	18.56	13.56	21.60	20.78	19.16
Hy	14.88	18.30	14.45	8.75	15.57	15.08	14.34	20.98	16.86	14.10	15.31
Mt	4.0	4.65	6.63	8.42	5.97	5.29	6.81	2.68	4.97	5.05	5.57
Il	4.98	4.42	4.39	4.54	4.31	4.06	5.03	4.98	4.99	6.61	4.84
ap	0.68	0.54	0.52	0.54	0.52	0.58	0.59	0.64	0.66	0.90	0.59
H_2O	2.08	1.22	2.66	3.97	2.42	2.07	0.41	4.58	1.00	1.16	1.80
Total	99.47	99.94	99.51	99.29	99.82	99.23	99.97	98.89	100.01	98.69	99.11

D.I. = Differentiation Index

Fig. 4 shows the variation of some major oxides in three flow units. Obviously, the chemical variation in one flow is as large as between-flow variation. The chemical composition is therefore unlikely to be useful in stratigraphical correlation of the flows.

Strontium isotopes. Isotopic analyses were carried out on a modified AEI MS5 mass spectrometer the details of which and those of the chemical purification, analysis, and data processing are given by Burwell (1975). The measured $^{87}Sr/^{86}Sr$ ratio for the Eimer and Amend standard $SrCO_3$ was 0·7082±0·0002 (2σ). All $^{87}Sr/^{86}Sr$ ratios were normalized to a value of 8·375 for the $^{88}Sr/^{86}Sr$ ratio and to a value of 0·7080 for the Eimer and Amend standard. Rb and Sr concentrations were determined by X-ray fluorescence spectroscopy. Reproducibility for the Sr is ±10 % (2σ), but worse for Rb due to low concentrations.
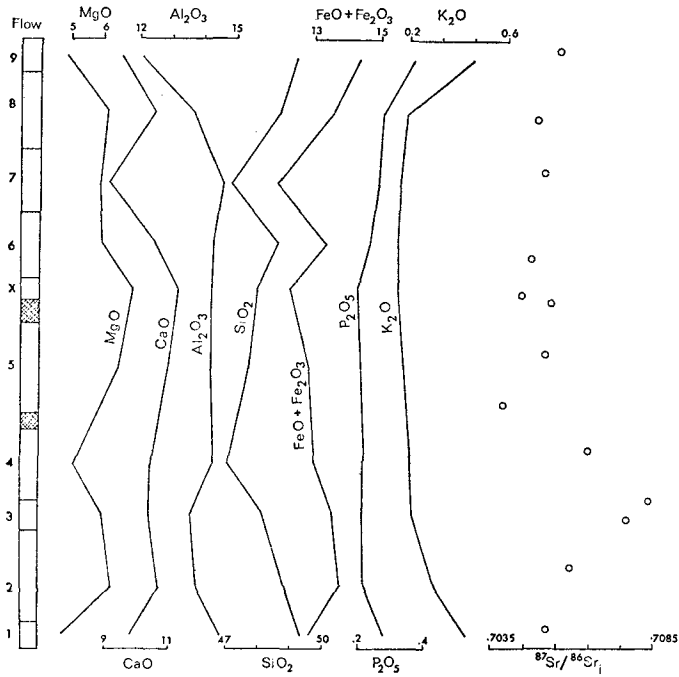
FIG. 3. Vertical variation of some major oxides (wt. %) and $^{87}Sr/^{86}Sr$ initial ratios in the lava pile around Sagar. Ornamentations in the flow column indicate intratrappean sedimentary formation.
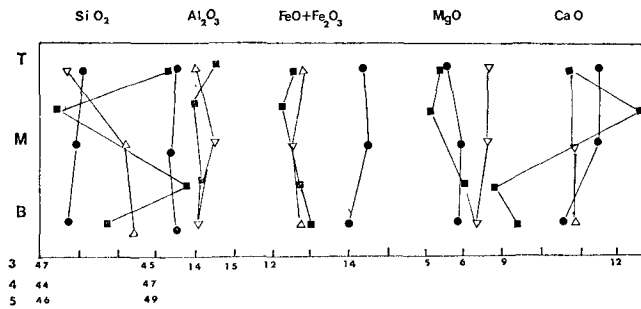

FIG. 4. Intraflow major element (wt. %) variation in three flows. T = Top, M = Middle, and B = Bottom of each flow. ●, flow 3; ■, flow 4; △, flow 5.

The average contents of Rb and Sr are 6·5 and 184 ppm respectively for the 10 lavas. Thus Rb (Table II) is low compared with other continental basalts (Hedge, 1966). The initial $^{87}Sr/^{86}Sr$ ratios, calculated assuming an age of 50 Myr (unpublished K–Ar data, P. O. Alexander), vary from 0·7039 to 0·7084 as in other continental basaltic rocks. The corrected Sr isotopic compositions of the Deccan traps analysed by Faure and Hurley (1963) are within the range reported here. Two samples from each of flows 4, 5, X, and 6 were analysed for possible intraflow variation. In three of these flows there is significant variation in the $^{87}Sr/^{86}Sr$ ratios outside the possible experimental error. The greatest variation is 0·002 found in flow 4. Such intraflow variation has also been reported elsewhere (Laughlin et al., 1972; Noble and Hedge, 1969).

In general, the $^{87}Sr/^{86}Sr$ ratios increase from flow 1 to 4, but vary within narrow limits in flows 5 to 9. This coincides with a stratigraphical break as shown by the presence of inter-trappeans. However, the chemistry does not show a higher break indicated by another inter-trappean formation (limestone). No pronounced correlation exists between the Sr isotopic
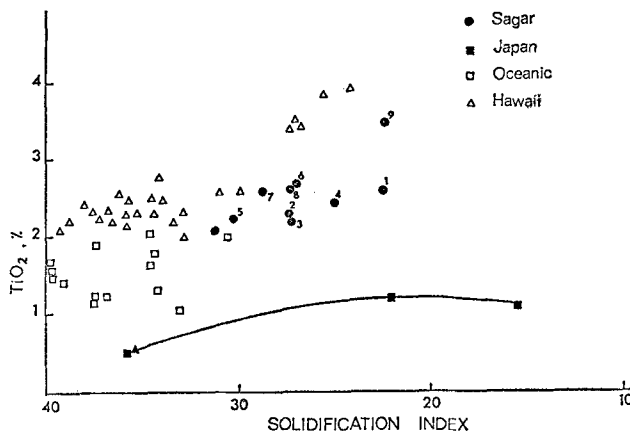

FIG. 5. Plot of TiO_2 against Kuno's (1957) solidification index $(MgO \times 100)/(MgO+FeO+Fe_2O_3+K_2O+Na_2O)$. Source of data: Japan, Kuno (1957); Hawaii, Macdonald and Katsura (1964); Oceanic, Miyashiro et al. (1969) and Engel et al. (1964).

TABLE II

Sample	Flow	Height	Rb ppm	Sr ppm	Rb/Sr	$^{87}Sr/^{86}Sr$ measured	$^{87}Sr/^{86}Sr$ initial
Z/88	9	183	14.2	197.6	0.072	0.7058	0.7057
Z/72	8	163	28.7	128.1	0.224	0.7054	0.7050
Z/62	7	147	3.6	205.3	0.017	0.7052	0.7052
Z/46	6	120	3.3	214.5	0.016	0.7048	0.7048
Z/27	6	108	2.1	65.0	0.032	0.7048	0.7048
Z/40	x	109	—	176.0	—	0.7045	0.7045
Z/38	x	107	2.3	193.5	0.012	0.7054	0.7054
Z/25	5	90	0.5	220.8	0.002	0.7052	0.7052
Z/20	5	75	4.1	73.2	0.055	0.7040	0.7039
Z/18	4	61	7.3	201.29	0.036	0.7065	0.7064
Z/13	4	46	1.1	222.0	0.004	0.7084	0.7084
Z/10	3	40	4.9	200.6	0.024	0.7077	0.7077
Z/8	2	25	7.0	204.2	0.035	0.7060	0.7059
Z/3	1	6	12.4	269.9	0.046	0.7053	0.7052

The height is measured in metres above the base. Initial $^{87}Sr/^{86}Sr$ has been calculated assuming an age of 50 Myr (unpublished age data, P. O. Alexander).

composition and the major oxides (fig. 3). A weak correlation ($r = 0.57$), however, occurs between the Sr isotopic ratios and the differentiation index (Thornton and Tuttle, 1960). Sample Z/13 has the highest ^{87}Sr content, although it is little different from the others in major element chemistry except for a high Fe_2O_3/FeO ratio.

Discussion and conclusions

Our chemical and isotopic data are in general agreement with results for other continental basalts. The variations in the $^{87}Sr/^{86}Sr$ ratios obviously could not have been produced by

fractional crystallization under closed conditions. Furthermore, duplicate analyses from the same flow indicate within-flow variation.

Taylor and Forrester (1971) have shown that hydrothermal alterations may disturb the Sr and Pb isotopic composition of rocks. Mineralogical evidence of such alteration was not found in the present samples. In the Girnar complex on the western margin of the Deccan volcanic province (fig. 1), the $^{87}Sr/^{86}Sr$ ratios in the constituent rock types of gabbro, lamprophyre, diorite, and syenite vary from 0·7051 to 0·7080, but the $\delta^{18}O$ values remained almost constant around 6 ‰ (Paul et al., in prep.), suggesting that hydrothermal alteration has not been responsible for variations of the Sr isotopic ratios.

These basalts are believed to have erupted through a continental crust of about 41 km (Bose, 1972). Contamination with crustal Sr is thus possible. The mixing of mantle-derived basaltic magma with a crustal end-member having different $^{87}Sr/^{86}Sr$ ratios and Sr contents results in a hyperbolic relation. No correlation is observed between the $^{87}Sr/^{86}Sr$ values and Rb, Sr, or SiO_2 (Tables I and II). Distinct relationships between these parameters occur in many basalts where mixing of crustal rocks is believed to have taken place (e.g. Faure et al., 1974). Few data exist on the isotopic composition of Sr in the Deccan basement. One sample from the Precambrian basement granite gave a $^{87}Sr/^{86}Sr$ ratio of 0·7101 and a Sr content of 668 ppm (Paul et al., in prep.). If bulk crustal contamination was responsible for the observed variation of Sr isotopic ratios in these basalts, a significant assimilation of crustal rocks is required. The petrological and geochemical data do not support this.

In a bulk contamination mechanism, the samples with low Sr content would have their $^{87}Sr/^{86}Sr$ ratios most affected, provided there is significant difference between the host and the contaminant. In Sagar flows this is clearly not the case. For example, sample Z/20 has the lowest Sr but the Sr isotopic composition is not much different from the average. It is suggested therefore that radiogenic Sr has been selectively introduced into the basaltic magma by wall-rock reaction, perhaps by an analogous mechanism to that proposed by Green and Ringwood (1967). The erratic distribution of the $^{87}Sr/^{86}Sr$ ratios in the lava pile and also the intraflow variations suggest that such selective introduction must have occurred locally.

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