Low-pressure fractional crystallization origin of the tholeiitic basalts of the Deccan plateau, India

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Petrographic descriptions and mineralogical data have been presented together with analytical results of major and trace elements for tholeiitic picritic basalt - ferrobasalt suite from the Deccan plateau, India. The compositional relation between coexisting augite and pigeonite was elucidated. Wide variations of incompatible element abundances were recognized among the samples but their patterns of relative enrichments parallel one another. The rock suite was probably produced by partial melting of mantle peridotite with abundances of incompatible elements rather close to primordial abundances. However, the Sr isotopic abundances were highly variable in the source, as also were alkali and alkali earth elements to a lesser extent. Fractional crystallization under low-pressure conditions was a major process in the evolution of this rock sequence. Olivine (Fe_{85-90}) was predominant in the differentiation and plagioclase was probably also involved together with augite.

Keywords: Deccan plateau, Tholeiitic basalt, Incompatible element, Sr isotope, Fractional crystallization

I. Introduction

Basaltic rocks forming the vast Deccan plateau are distributed over an area of 6.5×10^5 km² in the western India subcontinent. Their volume total is about 5×10^5 km³ equivalent to the volume of other continental flood basalts such as Columbia River basalt, Stormberg basalt, and Parana basalt. The eruption of the Deccan basalts started in Late Cretaceous and ceased by Early Tertiary (100~60 Ma), while it was more than 70 Ma ago when the majority erupted (Kaneoka, 1980). According to Alexander (1981), however, some of the flows may be

as young as 30 Ma. The lava pile reaches approximately 2,000 m thick in the west Deccan plateau, whereas the accumulation is 100-200 m in the east. The thickness of particular flows is variable; some are less than 1 m, others are nearly 70 m. Their estimated average thickness is 30 m. Most of the Deccan basalts are tholeiitic but 5% or less are alkalic: they are alkali basalt, mugearite, nephelinite, ankaramite, trachyte, and other differentiated rocks.

Boss (1972) summarized the petrographical and geochemical characteristics of the Deccan basalts in a compilation of data available before 1970. Since then, Alexander and Gibson

Fig. 1. Map showing the distribution and sample locality of Deccan basalts.

BO, Bombay island; PN, Thana-Khopoli; IG, Igatpuri; GI, Junagadh.

(1977) reported trace element data for some Deccan basalts, a number of geochemical data including Sr and Nd isotope ratios have been published (Alexander and Paul, 1977; Kurasawa *et al.*, 1982; Mahoney *et al.*, 1982; Paul *et al.*, 1984). However, to date, no study has produced a systematic set of petrographical and geochemical data for the Deccan basalts obtained on the same sample. Therefore, in this paper we report the results of a detailed petrography and mineralogy, together with major and trace element data for the picritic basalt - ferrobasalt association of a representative tholeiitic suite of the Deccan plateau.

II. Sample Localities

The Deccan basalts are distributed in the area shown in Fig. 1 and the investigated samples are from Bombay and its environ (Bombay island, BO; Thana-Khopoli, PN; Igatpuri, IG; Junagadh, GI). All the samples are tholeiitic basalts or tholeiitic dolerites. The Deccan basalts have been severely altered and fresh olivines and glasses were difficult to obtain. The alteration is especially conspicuous in the

lavas. Therefore, less altered samples have been selected for the analysis through thin section examinations but some of them contain serpentinized olivines. They are picritic basalts - ferrobasalts and picritic dolerites - ferrodolerites; the latter were from dykes intruded into the lavas.

III. Summary of Petrography

We classified the samples using Mg-value; picritic basalt > 60, basalt 60-30, ferrobasalt < 30. The samples with an ophitic texture are regarded as being dolerites.

The phenocryst usually make up less than 10% for the rocks and some rock are nearly aphyric (less than 1-2%), while a few contain abundant phenocrysts that is up to 20%. The phenocrysts are olivine, augite, and plagioclase. All the samples include olivine phenocryst shorter than 2 mm, but some olivine phenocrysts are as long as 4 mm. Plagioclase phenocrysts can be found in almost all the samples as well. Although most of them are shorter than 5 mm, some are longer than 15 mm. By contrast, augite phenocrysts are less frequently found.

The groundmass is composed of plagioclase, olivine, clinopyroxene, and iron oxides (titanomagnetite and ilmenite) and a little apatite. Small to trace amounts of quartz, cristobalite, and alkali feldspar are observed in some samples. Brown glasses are observed even in the holocrystalline groundmasses. The groundmass olivine is not in reaction relation with pigeonite which appears with augite in some differentiated basaltic rocks. A trace amount of hornblende is found in a few samples. The mesostasis among the groundmass minerals in the coarse-grained ferrobasalts and ferrodolerites are filled with the light brown glasses that carry needle-shape plagioclase, fayalitic olivine, ferroaugite, ferropigeonite, titanomagnetite, ilmenite, alkali feldspar, quartz, and apatite.

Table 1. Major and trace element analyses of Deccan tholeiitic basalts

Sp. No. Rock name*	1 GI-69 A O dol.	2 GI-67 O dol.	3 GI-68 O dol.	4 GI-66 O dol.	5 GI-70 O dol.	6 PN-27 O bas.	7 BO-21 O A bas.	8 PN-21 F. dol.	9 PN-26 F. dol.	10 PN-30 O f. dol.	11 PN-28 F. dol.	12 PN-23 F. bas.	13 IG-04/D F. bas.	14 BO-30 F. dol.	15 PN-22 F. dol.
SiO ₂	46.80	44.90	49.81	49.10	49.36	46.43	48.67	48.35	47.78	48.82	49.03	49.51	49.96	50.87	50.08
TiO ₂	1.06	1.17	1.22	1.31	1.25	1.41	1.98	2.57	3.04	2.16	2.79	3.01	2.70	2.52	3.70
Al ₂ O ₃	13.48	16.04	13.70	13.91	15.37	15.62	14.04	13.28	13.63	12.77	13.11	12.15	12.63	13.22	11.88
Fe ₂ O ₃	2.51	2.37	2.04	2.49	2.23	5.49	5.12	2.28	2.56	3.50	3.58	3.97	2.48	3.41	3.85
FeO	9.27	9.05	8.65	9.56	8.64	5.62	6.75	11.90	11.41	11.29	10.92	11.50	12.60	11.09	11.47
MnO	0.19	0.19	0.18	0.18	0.19	0.18	0.16	0.24	0.20	0.24	0.22	0.25	0.22	0.22	0.26
MgO	12.66	11.15	8.51	8.54	6.94	7.67	7.00	6.21	6.20	5.93	5.85	5.27	4.80	4.38	4.15
CaO	9.12	10.03	10.60	10.52	11.06	9.92	11.21	11.37	10.61	10.38	10.60	10.41	9.02	8.44	9.34
Na ₂ O*	1.69	1.99	1.39	2.08	2.14	2.13	2.22	2.25	2.45	2.27	2.33	2.33	2.64	2.70	2.45
K ₂ O	0.43	0.41	0.69	0.50	0.57	0.49	0.20	0.56	0.69	0.45	0.63	0.65	0.54	0.98	1.24
P ₂ O ₅	0.11	0.13	0.12	0.12	0.09	0.13	0.23	0.19	0.28	0.20	0.27	0.26	0.28	0.38	0.41
H ₂ O*	2.35	1.51	1.45	1.09	1.66	1.32	1.02	0.66	0.98	0.82	0.73	0.71	0.73	0.77	0.68
H ₂ O*	0.43	0.35	0.51	0.29	0.62	2.38	1.43	0.50	0.49	0.94	0.61	0.87	0.91	1.20	1.02
Total	100.10	100.00	99.47	99.79	100.66	100.79	100.03	100.36	100.32	99.77	100.67	100.89	99.51	100.18	100.53
Ba ppm	119	90	143	202	139	214	159	110	188	120	204	167	340	475	252
Ce	12.7	14.4	22.5	22.2	19.1	18.5	27.5	20.8	41.1	25.2	29.6	35.0	45.9	64.6	62.1
Cu	66.3	68.7	49.9	53.9	46.5	65.6	46.2	54.5	49.0	52.8	48.5	47.5	49.3	46.7	43.9
Cr	408	406	329	296	248	74.2	286	74.6	242	52.4	87.4	69.6	79.7	32.5	56.6
Cs	0.07	0.31	0.45	0.46	0.37	-	-	-	0.22	-	-	-	1.55	0.56	-
F	158	137	235	227	156	-	229	222	357	254	281	381	405	414	521
Nb	5.0	5.8	6.3	6.1	4.9	5.2	9.6	9.9	23.9	10.9	13.2	14.5	13.3	29.4	20.3
Rf	374	356	140	109	105	205	116	85.6	122	59.4	91.1	48.5	56.5	27.6	43.3
Rb	13.4	10.5	25.2	18.9	12.4	7.3	2.5	11.6	12.8	7.2	13.8	17.0	18.7	20.3	24.1
Sc	25.6	24.9	29.4	35.1	34.0	26.1	30.4	44.9	41.8	35.5	38.5	41.1	40.2	26.3	46.5
Sr	105	156	131	153	165	174	211	177	270	186	194	175	233	299	211
Y	208	294	-	-	254	-	344	438	371	382	-	-	363	427	420
Y	21.6	23.3	22.6	24.9	25.5	22.2	28.3	30.1	32.3	23.7	34.4	37.6	44.2	37.7	47.8
Zn	98	69	81	97	66	94	96	106	134	162	139	148	132	166	162
Zr	76.8	80.1	85.8	87.0	89.0	81.8	124	122	171	128	154	184	190	193	270
(⁸⁷ Sr/ ⁸⁶ Sr) _i **	0.70915	0.70587	0.71779	0.71486	0.70941	0.70989	0.70646	0.70443	-	0.70599	0.70463	0.70671	0.70864	0.70562	0.70764

* A, augite; O, olivine; bas., basalt; F.dol., ferrodolerite; F.bas., ferrobasalt. ** Kurasawa et al., 1982.

IV. Chemistry

Analytical methods: Major element compositions were determined by conventional wet chemical methods for silicate analysis, combined with flame photometric and atomic absorption spectroscopic techniques. Most of the trace elements were determined by non-destructive photon activation analysis with gamma ray spectrometry at the Laboratory of Nuclear Science, Tohoku University. Detailed procedures and accuracy of the analysis are given by Yoshida *et al.* (1981, 1986). Fluorine was determined using a selective ion-electrode method (Kanisawa, 1979) adapted from the procedure outlined by Ingram (1970) and Kesler *et al.* (1973). The Sr isotopic ratios were determined by a solid-source mass spectrometer (VG 354) at Geological Survey of Japan.

Major elements: Table 1 gives the major and trace elements abundances and Sr isotopic ratios for fifteen representative samples. A narrow range in SiO₂ is one of the characteristic chemical features of flood basalts. The analytical results of SiO₂ are between 45.8 and 52.8 wt% (water-free basis); these samples are not exceptional. The other major elements vary greatly among the samples. We used the SiO₂ - Na₂O + K₂O diagram to classify the samples in this study. All the analytical results plot in Fig. 2 where the boundaries between alkali and high-alumina basalts (Al₂O₃ > 16.5%) or high-alkali tholeiite (Al₂O₃ < 16.5%), and between high-alkali tholeiite and low-alkali tholeiite are shown (Kuno, 1966). Most of the samples plotted in the high-alumina basalt field, and the basaltic rocks should belong to either high-alkali tholeiite series or high-alumina

Fig. 2. Total alkali-silica diagram. a, boundary between alkali and high-alumina basalt series; b, boundary between high-alumina basalt and tholeiite series (Kuno, 1966).

basalt series.

A few of the samples contain normative olivine, however, normative quartz (up to 10%) was calculated in most of the samples. Recalculation on the assumption that $\text{FeO}/(\text{FeO} + \text{Fe}_2\text{O}_3)$ ranged from 0.10–0.15 before alteration, demonstrates that most of these rocks are olivine normative. Although a few of them are still quartz normative, the calculated Q no longer exceeds 5%.

The Mg-value is used as an index of the degree of differentiation since the SiO_2 contents very little. The relations between the major oxides and the Mg-value are shown in Fig. 3. Their TiO_2 , FeO^* ($\text{FeO} + 0.9\text{Fe}_2\text{O}_3$), Na_2O , and K_2O contents gradually increase with the decreasing Mg-value while the MgO content decreases. The CaO content initially increases but starts decreasing after passing the Mg-values of 50. The SiO_2 and Al_2O_3 values are rather constant through the entire range of Mg-values.

Trace elements: The trace element abundances are plotted against the Mg-value in Fig. 4. The compatible elements (Cr and Ni) decrease rapidly while Mg-value is between 70 and 50 and parallel to the trend of gradually as

another compatible element, Co after 50. Gradual and systematic increases are characteristic of such incompatible elements as Ce, F, Sc, Sr, V, Y, and Zr. Although Ba and Rb increase, they show much scatter at high Mg-values.

Most of the major and trace element data seem indicative of either a simple fractional crystallization from a primary magma or a different degree of partial melting of mantle material under common conditions as the cause of the diversity of the samples. However, mantle heterogeneity and/or crustal contamination might have been responsible for the scattered abundances of K, Rb, and Ba in the picritic to basaltic rocks and the Sr isotopic data may also require either or both of the processes.

V. Mineralogy

Eight representative rocks, which are medium- to coarse-grained and holocrystalline with trace to negligible amounts of pale brown glass in groundmass, were selected for mineral analysis: one picritic dolerite, one basalt, one dolerite, and five ferrodolerites. Mineral compositions were determined with an electron microanalyzer according to our routine procedure (Fujimaki and Aoki, 1980). The selected analytical results are given in Tables 2 to 5.

Plagioclase: Plagioclases are zoned normally and their composition ranges from An_{79} – An_{32} . The Or contents are 0.5–1% for An_{79} – An_{70} and they slowly increase with a decrease in An component; plagioclase of An_{50} has 2% Or content and plagioclase of An_{35} has 6%. The compositional range of the plagioclase as well as its Or component are comparable to those of basalts and ferrobasalts of the other tholeiitic suites elsewhere. Note an increase in Ab content (Fig. 5) with differentiation from picritic dolerite to ferrodolerite. The most sodic compositions and the narrowest ranges in

Fig. 3. Major oxides - Mg-value variation diagram.

composition are characteristic of the plagioclases occur in the mesostasis in the ferrodolerites; such compositions are comparable to those of the outermost margins of the groundmass plagioclases. Alkali feldspar can be identified but it is too small to be analyzed.

Olivine: Individual analyses of olivine in the samples are plotted in Fig. 6 in terms of atomic percent Ca, Mg, and Fe together with coexisting clinopyroxene. The range of olivine composition is much broader (Fa_{14} - Fa_{95}) than for the other minerals. Although CaO wt% is within 0.2-0.5 for the phenocryst olivines as well as groundmass ones regardless of Fa content, the fayalitic olivines in the mesostasis are rather enriched in CaO (0.5-0.6 wt%). The MnO contents range from 0.25-1.5 wt%; they positively correlate with Fa component. The most magnesian olivine was found in a picritic dolerite sample (GI-67). Its phenocryst olivines have a range of Fa_{14-21} and the groundmass ones Fa_{21-48} . The NiO content in the olivine of Fa_{14} is 0.37 wt% but since it rapidly decreases with an increase in Fa component, the NiO content is 0.1 wt% or less in the

olivines of Fa_{30} . The chemical composition of the phenocryst and groundmass olivines varies gradually from Fa_{14} in the picritic basalt to Fa_{88} in the ferrobalt. The most fayalitic olivines were observed in the mesostasis of some ferrodolerites; they appear as microlites whose composition ranges from Fa_{77} , which is equivalent to the outermost margins of the most fayalitic groundmass olivine, to Fa_{95} in a ferrodolerite (PN-30).

Clinopyroxene: The Mg-value of the most magnesian diopsidic augite ($Wo_{42}En_{46}Fs_{12}$) is 80 that is rather smaller than the 86 of olivines. The diopsidic augites contain 0.4-1.1 wt% Cr_2O_3 but the chromium content decreases rapidly with an increase in FeO. The Mg-Fe substitution changes clinopyroxene compositions in the picritic basalt and dolerite along the CaMg-CaFe line. The Ca-Fe substitution takes over the Mg-Fe substitution in a basaltic composition: the crystallization trend of clinopyroxene seems subparallel to the CaFe-Fe join. The ferrobalts and ferrodolerites include Fe-rich augite as well as pigeonite. The modal abundance in the groundmass of the latter is as

Fig. 4. Trace elements-Mg-value variation diagram.

small as 1/10 of the former. The most Fe-rich clinopyroxene appears in the mesostasis with fayalitic olivine. Abundant ferroaugite (Mg-value=28-39) coexists with less abundant pigeonite (Mg-value=50-55) in the mesostasis of a ferrodolerite PN-30, while no ferroaugite was recognized in a ferrodolerite PN-22. Instead, PN-22 contains the most Fe-rich clinopyroxene which is ferropigeonite (Mg-value=62-65). No orthopyroxene was found in the samples from the Deccan tholeiitic suite.

In Fig. 7, the averaged compositions of clinopyroxenes in the samples, including those in the mesostasis of a ferrodolerite PN-22, were shown with the averaged composition of groundmass clinopyroxenes of tholeiitic suites from Izu-Hakone region and Nasu volcanic zone, Japan for comparison. It is well recog-

nized that clinopyroxene crystallization trends in alkalic suites are parallel or subparallel to the CaMg-CaFe join. By contrast, Kuno (1955) emphasized that the Ca-Fe substitution turned toward ferrosilite in tholeiitic suites. Note a more clearly defined crystallization trend from diopside toward ferrosilite has been determined for the Deccan tholeiitic suite than that of Izu-Hakone tholeiitic suite in Fig. 7. Although Aoki (1967) discovered that augite was the first pyroxene phase in the groundmass of the olivine tholeiitic suite and pigeonite started crystallizing side by side with augite with further crystallization, the nature of the relationship between the pyroxenes has long been in doubt: as no one knew the composition of the clinopyroxene when pigeonite starts crystallizing. The present study has established that as

Table 2. EPMA analyses of representative plagioclases

Sp. No.	1	2	3	4	5	6	7	8	9	10
	GI-67		PN-21		PN-30		PN-22		PN-22	
	Gr-C	Gr-R	C	R	C	R	M	C	R	M
SiO ₂	47.98	55.52	49.98	60.16	51.25	59.50	60.19	53.54	57.72	59.66
Al ₂ O ₃	32.42	27.53	31.33	24.78	30.30	25.12	24.88	28.88	25.81	24.78
Fe ₂ O ₃	0.61	1.06	0.70	0.48	0.57	0.70	0.76	0.80	0.63	0.71
CaO	16.32	10.31	14.78	6.56	13.63	7.37	7.04	11.82	7.97	6.56
Na ₂ O	2.35	4.99	2.81	7.42	3.70	6.54	6.85	4.53	6.28	6.84
K ₂ O	0.09	0.51	0.09	0.56	0.35	0.58	0.57	0.48	0.78	0.88
Total	99.77	99.92	99.69	99.96	99.90	99.81	100.29	100.05	99.19	99.43
An mol %	78.9	51.7	73.9	31.8	65.7	37.0	35.0	57.4	39.4	32.8

Ph, phenocryst; Gr, groundmass; C, core; R, rim; M, mesostasis.

long as the atomic Ca of clinopyroxene $[100 \text{ Ca}/(\text{Ca} + \text{Mg} + \text{Fe})]$ is more than 35, no pigeonite crystallizes. When the atomic Ca decreases less than that, pigeonite starts crystallizing. In the groundmass of the tholeiitic suite of Izu-Hakone region, augite and pigeonite coexist; both have the atomic Ca less than 35. Pigeonite precedes augite crystallization in the groundmass of the tholeiitic suite of Nasu zone. The atomic Ca is less than 25 for both. The pyroxene compositional relation can be summarized as follows: Augite alone crystallizes when its atomic Ca is more than 35 and pigeonite should precede augite when the atomic Ca is less than 25. Either pigeonite or augite precedes the other when the Ca is between 35 and 25. This is consistent with the experimental phase relation between augite and

pigeonite; Kushiro (1972) demonstrated the existence of the cotectic line in the center of the pyroxene quadrilateral at the magnesian side.

Iron oxides: The titanomagnetites included consist of a series of ulvospinel-magnetite solid solution (98-95%) and the spinel-hercynite component ranges for 5-2%. Their picrochromite-chromite component is hardly more than 0.4%. Most of the titanomagnetites are enriched in TiO₂ and their ulvospinel moles are for 76-60%, while a few of them have 55-27%. The maximum amounts of MgO and MnO are 1.7 and 1.4 wt%, respectively. Commonly they carry between 0.2-0.8 wt% MgO. The chemical compositions of the titanomagnetites seem independent of the coexisting mafic minerals. Ilmenites are rather depleted in hematite mole (8-3%) and contain minor amounts of MnO

Table 3. EPMA analyses of representative olivines

Sp. No.	1	2	3	4	5	6	7	8	9	10	11
	GI-67				PN-21		PN-30			PN-22	
	Ph-C	Ph-R	Gr-C	Gr-R	C	R	C	R	M	M	M
SiO ₂	39.96	38.32	36.74	34.97	37.78	33.27	36.30	31.62	31.70	29.92	30.64
FeO	13.48	21.11	31.33	39.59	25.41	50.24	30.71	57.38	57.30	65.15	64.27
MnO	0.26	0.37	0.60	0.80	0.39	0.87	0.47	1.11	1.08	1.49	1.26
MgO	45.56	39.63	31.13	24.08	36.02	15.64	31.36	9.40	9.85	2.27	3.59
NiO	0.37	0.14									
CaO	0.28	0.30	0.41	0.40	0.29	0.28	0.33	0.38	0.40	0.54	0.59
Total	99.91	99.87	100.21	99.84	99.89	100.30	99.17	99.89	100.33	99.37	100.35
Fo mol %	85.8	77.0	63.9	52.0	71.7	35.7	64.5	22.6	23.4	5.8	9.0

Table 4. EPMA analyses of representative clinopyroxenes

Sp. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	GI-67		PN-21				PN-30				PN-22			
	Gr-C	Gr-R	C	R	C	R	C	R	M	M	C	R	C	M
SiO ₂	49.64	48.62	50.77	49.74	51.90	51.04	52.07	49.97	48.09	50.97	49.69	49.66	52.50	48.46
TiO ₂	0.90	2.30	0.80	0.57	0.56	0.49	0.58	0.77	0.90	0.37	1.34	0.71	0.41	0.51
Al ₂ O ₃	4.89	3.41	3.07	1.16	1.36	1.03	2.12	1.36	1.46	0.79	3.27	1.54	0.97	1.00
Cr ₂ O ₃	0.89													
FeO	7.51	14.79	9.21	26.24	21.25	27.70	9.80	21.60	28.79	26.77	12.01	23.58	21.82	36.82
MnO	0.14	0.45	0.18	0.73	0.54	0.70	0.21	0.57	0.79	0.61	0.24	0.55	0.48	0.85
MgO	14.47	10.87	15.01	10.22	18.70	14.27	15.60	9.63	5.27	15.62	14.11	10.25	19.26	8.60
CaO	21.09	19.91	19.59	11.29	5.66	5.17	19.24	16.16	14.67	4.34	18.43	13.27	4.71	4.07
Na ₂ O	0.47	0.35	0.44	0.12	0.36	0.41	0.21	0.12	0.16	0.19	0.40	0.44	0.12	0.10
Total	100.00	100.70	99.07	100.07	100.33	100.81	99.83	100.18	100.13	99.66	99.40	100.00	100.27	100.41
Ca atom %	44.7	42.4	41.0	24.3	11.7	11.0	39.5	34.5	32.5	9.1	38.7	28.6	9.6	9.0
Mg	42.7	32.2	43.7	30.5	53.4	42.0	44.5	28.6	16.3	45.8	41.2	30.8	54.8	26.3
Fe	12.7	25.4	15.3	45.2	34.9	47.0	16.0	36.9	51.2	45.1	20.1	40.6	35.6	64.7

(0.5–0.9 wt%) and MgO (0.2–1.7 wt%).

Glass in mesostasis: Pale brown glasses, filling the mesostasis in the samples include Fe-rich mafic minerals and sodic plagioclase. Although the glasses are rather heterogeneous, they are rhyolitic; the average composition of the glass in PN-22 ferrodolerite is as follows: SiO₂, 72.42; TiO₂, 0.58; Al₂O₃, 14.69; FeO*, 2.04; MgO, 0.27; CaO, 1.11; Na₂O, 4.90; K₂O, 3.99. Rhyolitic lavas are very rare in the Deccan plateau but their compositions are quite similar to this. The similarity is indicative of

a crystallization differentiation from the associated olivine tholeiitic magma as a plausible mechanism for the origin of the rhyolitic liquid.

VI. Discussion

We summarized the petrographical, mineralogical, and geochemical features of the samples which represent the most abundant olivine tholeiite suites in the Deccan plateau basalt group as follows:

(1) Olivine is the commonest phenocryst and plagioclase is subordinate. Augite phenocrysts are rare. The major groundmass mineral assemblage is common for all the rock suite. Olivine coexists with augite in the groundmasses of all the samples and continuously changes in composition towards the Fe-rich end. Pigeonite crystallization is delayed and starts in an olivine basaltic composition. In the latest stage ferropigeonite cocrystallizes with fayalite but no ferroaugite appears. Plagioclase ranges in composition from calcic to sodic.

(2) Pigeonite geothermometry (Ishii, 1975) provides the pigeonite liquidus temperatures for the ferrobasalts and the rhyolitic mesos-

Table 5. EPMA analyses of representative iron oxides

Sp. No.	1	2	3	4	5	6	7
	GI-67		PN-21		PN-22		
	Mt	Mt	Il	Mt	Il	Mt-M	Il-M
TiO ₂	25.80	23.94	50.28	24.00	49.99	25.37	50.68
Al ₂ O ₃	2.01	1.13		1.79	0.12	1.71	0.15
Cr ₂ O ₃	0.25			0.24		0.23	
V ₂ O ₅	1.10	0.81		0.85	0.36	0.70	0.14
Fe ₂ O ₃ *	15.80	20.32	5.16	19.57	4.40	17.23	3.48
FeO*	51.88	51.85	41.26	52.65	42.95	53.72	43.77
MnO	0.59	0.76	0.63	0.33	0.60	0.31	0.63
MgO	1.73	0.42	1.86	0.43	0.78	0.55	0.65
Total	99.16	99.23	99.19	99.86	99.20	99.82	99.50

* Calculated as FeO and Fe₂O₃ assuming stoichiometry.
Mt, titanomagnetite; Il, ilmenite; M, in mesostasis.

Fig. 5. EPMA analyses of plagioclases in mole percent anorthite (An), albite (Ab) and orthoclase (Or).

Solid circle, phenocrystic and groundmass plagioclase; open circle, mesostasis plagioclase.

tasis; they are 1100°C and 930°C, respectively. Each of them is within an acceptable range. The temperature of the least differentiated picritic basalt magma must have been higher than 1100°C when it erupted.

(3) All the major elements vary gradually without any abrupt change.

(4) Most of the trace elements vary systematically and no sudden shift is recognized in their variation diagrams as well.

Previous geochemical investigations (Aramaki and Kohno, 1975; Alexander and Gibson, 1977; Alexander and Paul, 1977; Kurasawa *et al.*, 1982; Mahoney *et al.*, 1982; Paul *et al.*, 1984) revealed that the Deccan tholeiitic suites were highly enriched in LREE with La/Yb ratios of 3.86–6.33. Some of the basaltic rocks have either negative or positive Eu anomalies. Their Sr isotopic ratios vary between 0.70393–0.71972.

Recently, Norry and Fitton (1983), Cox (1983), and Thompson *et al.* (1983) proposed a new model to account for the diversity of conti-

nental flood basalts. According to them, the following four explanations are appropriate: 1) different degree of partial melting, 2) heterogeneity of upper mantle materials, 3) crystallization differentiation, and 4) crustal contamination.

Alexander and Paul (1977) and Kurasawa *et al.* (1982) noticed no positive correlation between Sr isotopic ratios and major element variations; accordingly, they rejected the idea of crustal contamination. Our data confirm the improbability of contamination as well (see Table 1). Some picritic basalts have very high Sr isotopic ratios and some differentiated ones have low ratios. If crustal contamination plays a significant role in generating diversity, a correlation between Sr isotopes and major elements should exist to some extent. Some one may propose selective transportation of Sr from basement granitic rocks but it is difficult to envisage a practical mechanism for doing this. Therefore, crustal contamination is not acceptable.

Fig. 6. EPMA analyses of olivine and clinopyroxene in atomic percent Ca, Mg and Fe+Mn. Solid square, phenocrystic and groundmass olivine; open square, mesostasis olivine; dotted area, estimated composition of altered groundmass olivine; solid circle, phenocrystic and groundmass clinopyroxene; open circle, mesostasis clinopyroxene.

Fractional crystallization is one of the best candidates for the cause of the diversity of flood basalts. We examine the possibility in a $\text{MgO}-\text{FeO}^*-\text{Na}_2\text{O}+\text{K}_2\text{O}$ diagram (Fig. 8). The differentiation trend is nearly parallel to the $\text{MgO}-\text{FeO}^*$ line and demonstrates a progressive iron enrichment. The variation corresponds to the beginning half of the Skaergaard trend, which is regarded as a result of crystallization differentiation under high temperature and low

oxygen partial pressure. We marked three points on the $\text{MgO}-\text{FeO}^*$ line in Fig. 8, that indicate the Mg/Fe ratios of Fo_{85} , Fo_{80} and Fo_{75} . An extrapolation of the variation trend crosses the line between Fo_{85} and Fo_{80} ; this is suggestive of an effective fractionation of olivine ($\text{Fo}_{85}-\text{Fo}_{80}$) in the differentiation. The petrographic and geochemical natures of the basaltic suite are well consistent with this estimation. The rapid decreases in Ni and Cr

Fig. 7. Average composition of groundmass and mesostasis clinopyroxenes. Solid circle, Deccan basalts; open circle, Izu-Hakone tholeiite (Kuno, 1955); open square, Nasu zone tholeiite (Aoki, unpubl.).

(contained in spinel inclusion in olivine) abundances should be a proof of the significant olivine fractionation in forming the ferrobasalts from the picritic basalts as well.

The major constituents of the mantle peridotite may not contain significant amounts of such highly incompatible elements as K, Ba, Ce, F, Rb, Sr, and Zr. They may rather be included in some minor constituents like pargasite, phlogopite, and apatite. These elements should be selectively concentrated in a magma with melting and exclusively enriched in the residual liquid with fractional crystallization until some rare minerals, with which these elements are compatible, start crystallizing. Among them Sr also follows the scheme before sodic plagioclase crystallizes. Therefore, the enrichments in these elements should be parallel to the initial abundances in a parental magma during early to middle stage of fractional crystallization. The parallel increases in the incompatible elements in the samples are suggestive of homogeneous mantle sources of the parental magmas.

The abundance ratios (incompatible element/K) of the samples are restricted in narrow ranges with a few exceptional elements and so are those of the other Deccan basaltic rocks. The trace element abundance patterns of the samples normalized by an assumed

Fig. 8. $\text{MgO}-(\text{FeO}+\text{Fe}_2\text{O}_3)-(\text{Na}_2\text{O}+\text{K}_2\text{O})$ diagram.

primordial upper mantle are equivalent to those of the continental flood basalts (cf. Norry and Fitton, 1983; Cox, 1983; Thompson *et al.*, 1983; Yoshida and Aoki, 1986). They have neither strong positive Ba nor negative Nb anomaly common to the island arc tholeiite (Yoshida and Aoki, 1984). They show no such abrupt depletions in K, Nb, Ba, and Rb as MORB does. Accordingly, a particular heterogeneity is highly unlikely in the mantle source region of the basaltic rocks. However, no correlation between Sr isotopes and Rb/Sr ratios of the samples does require an extreme heterogeneity of Sr isotopic abundances in the source. In combination with the results of high-temperature and high-pressure experiments, we interpret the petrological and geochemical features of the picritic basalt and ferrobasalt suite as follows:

- 1) Picritic olivine tholeiite magma was produced by a partial melting of the upper mantle peridotite (possibly 50 km deep) which presumably had the trace element abundances rather close to the assumed primordial mantle. The mantle material might have been rather depleted in Sr and highly heterogeneous in

isotopic abundances.

2) The low-pressure fractional crystallization dominated by olivine, accompanied by augite and plagioclase to a lesser extent, produced the sequence of the picritic basalt - basalt - ferrobasalt from a parental olivine tholeiite magma.

Acknowledgements: The authors are indebted to Dr. S.S. Deshmuk, Geological Survey of India, Nagpur, India for his kind assistance with the field work. A part of expenses of this study was defrayed by a Grant-in-Aid for Overseas Scientific Survey (1973) and Scientific Research (No. 02453045) from the Ministry of Education, Science, and Culture of Japan.

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デカン高原、ソレライト質玄武岩の分別結晶作用について

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インド、デカン高原のソレライト質ピクライト玄武岩—鉄玄武岩の代表的な試料について、記載岩石学的性質を調べると共に、主成分・微量成分元素の定量とSr同位体比の測定を行った。かんらん石は早期から最晩期まで晶出(Fo_{88-95})する。一方単斜輝石は早期には普通輝石のみが晶出するが、分別作用が進むと普通輝石と共にピジョン輝石が出現し、最晩期には普通輝石は晶出せず、鉄ピジョン輝石のみとなる。

ピクライト質ソレライトマグマはその地球化学的性質から仮想的な初生マントルに近似した微量元素濃度をもったかんらん岩の部分融解によって生成したと推定される。ピクライト質玄武岩—玄武岩—鉄玄武岩の分化は低圧下における普通輝石と斜長石を伴う、主としてかんらん石の分別結晶作用によって生じた。