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Olivine Compositions in Picrite Basalts and the Deccan Volcanic Cycle

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Olivine phenocryst compositions and whole-rock chemical compositions are used to identify primitive picrite basalts from widely separated parts of the Deccan flood basalt province. Overall, primitive picrites constitute a significant volume of rocks within the province. Most were probably emplaced along deep faults in the Cambay graben and Narmada rift regions. We combine mineral composition data on previously described samples from boreholes at Dhandhuka, Wadhwan and Botad with information on new finds of picritic basalts at Paliad, Anila, Pawagarh, Kawant and Ambadongar to help delineate the petrogenesis of these mafic rocks, and we also examine the nature and probable origin of picrite basalts from other regions of the Deccan, such as the Western Ghats. The combined data suggest that the incidence of high-MgO lavas decreased with time during the Deccan volcanic cycle.

KEY WORDS: *Deccan Traps; olivine composition; picrite basalts; volcanic cycle*

INTRODUCTION

The petrogenesis of flood basalt lavas, particularly their often iron-rich character, was a long-term interest of Keith Cox (e.g. Cox, 1980; Cox & Hawkesworth, 1985; Cox & Mitchell, 1988; Scarrow & Cox, 1995). Recognition that the earliest liquids produced during partial melting of peridotite are Mg rich, combined with the widespread but volumetrically minor occurrence of picritic rocks in flood basalt provinces, provides an important basis for the discussion of basalt genesis in these settings. In this study we examine picritic rocks from the Deccan flood basalt province from the point of view of their olivine phenocryst compositions, and use these mineralogical data to infer the mode of origin of these rocks and their place in the overall cycle of Deccan volcanism. This work builds on the earlier investigations of Krishnamurthy & Cox (1977), who examined picritic basalts from boreholes in the Cambay graben area (see Fig. 1).

In the IUGS classification scheme (Le Bas, 1999) a picrite or picrite basalt contains ≥12% MgO, <52% SiO_2 and >3% $Na_2O + K_2O$. Picrobasalts have compositions intermediate between basalts and picrites as defined here. Thus in a suite of mafic rocks, a spectrum of compositions may occur, ranging from primitive picrite basalts to picrobasalts and basalts. Rocks with picritic chemical characteristics can arise in a variety of ways; for example, as primitive picritic liquids that are little-modified melts of upper-mantle peridotite, by accumulation of early formed olivines from such primary picritic liquids, or by accumulation of olivines from 'normal' basaltic magmas. Under equilibrium conditions, olivine compositions will reflect the composition of the magma from which they crystallize; thus the composition of olivine phenocrysts in picrites is a valuable clue to their petrogenesis. This is the approach used by Krishnamurthy & Cox (1977), who examined a suite of mafic lavas recovered from boreholes in Western India that were first described by West (1958). The present study is an extension of Krishnamurthy & Cox's work to samples from additional occurrences of picritic rocks in the Deccan, collected in part during a joint project between the Physical Research

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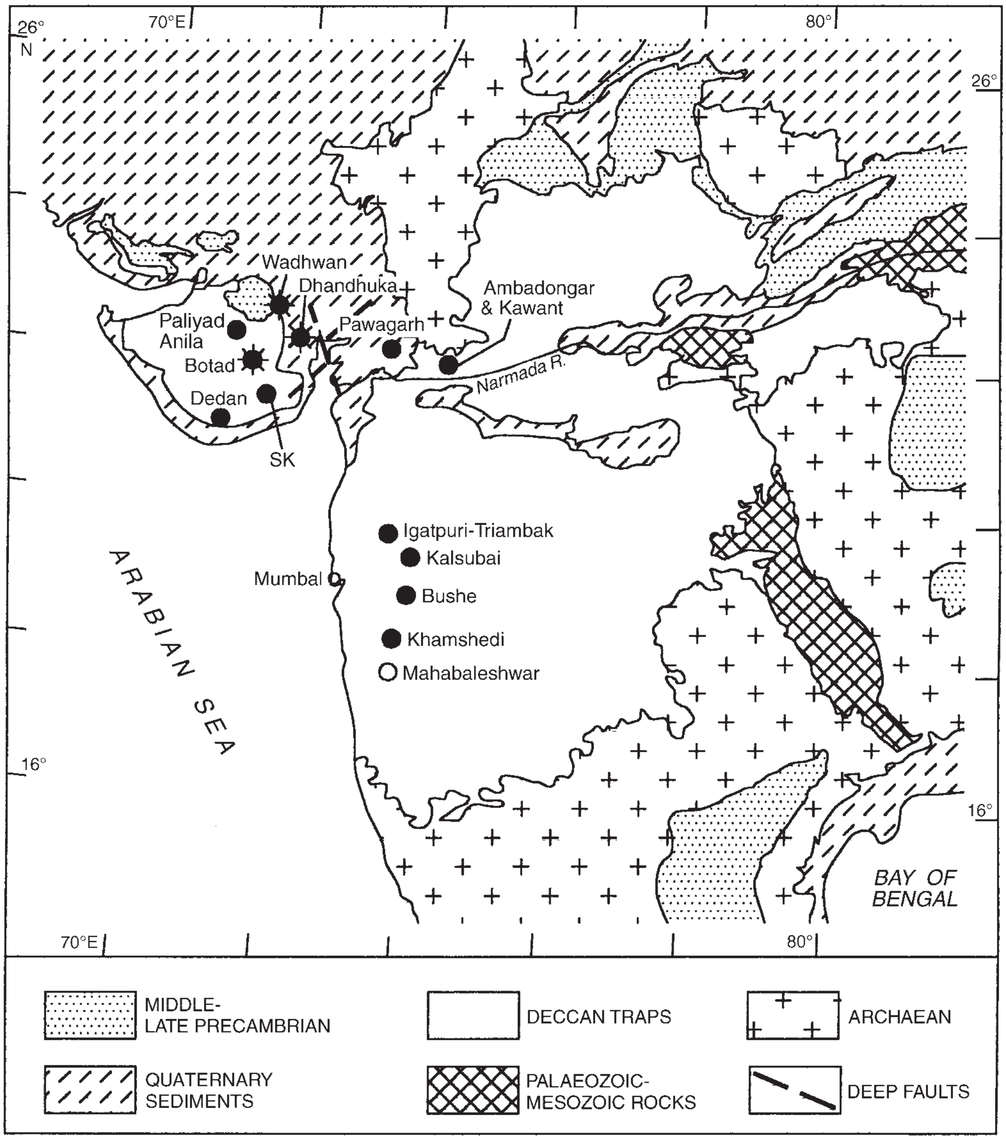

Fig. 1. Simplified geological map of the Deccan Traps (white) and adjacent areas showing the locations of picrite basalts. Filled circles with spikes show the borehole localities studied earlier by West (1958) and Krishnamurthy & Cox (1977). New localities examined in this work include those north of the Narmada rift (Pawagarh, Ambadongar and Kawant), in Saurashtra (Anila and Paliyad), and in Kathiawar (dykes around Dedan). SK, picrite basalts reported in south Kathiawar by Melluso *et al.*, (1995). Locations to the north of Mahabaleshwar in the Western Ghats represent picrite and picrobasalt flows encountered in various formations and include Poladpur (Cox & Hawkesworth, 1985), Bushe, Thakurvadi, Neral and Igatpuri (Beane & Hooper, 1988; Deshmukh, 1988; present work). Geology and deep faults around Cambay are from Roy (1963).

Laboratory, Ahmedabad, and the Scripps Institution of Oceanography, to study Deccan basalts.

FIELD RELATIONS

Known occurrences of flows and dykes with picritic compositions within the Deccan province are shown in Fig. 1. Among these the volumetrically most significant are those encountered in the borehole sequences at Dhandhuka, Wadhwan Junction and Botad (Krishnamurthy & Cox, 1977), and the surface occurrences in adjoining areas such as Anila and Paliyad. Taken together, these comprise a significant areal extent of picrite basalts. Perhaps of similar magnitude is the Pawagarh occurrence north of the Narmada River, although here the exposed thickness is minor ($\sim$75 m). However, a flow forming the base of Pawagarh Hill may be extensive; its dimensions are unknown because of alluvium and soil cover.

Picrite basalts and picrobasalts also occur within the thick Deccan basalt sequences of the Western Ghats. They have been reported from the Igatpuri, Neral, Thakurvadi, Bushe and Poladpur formations (see Fig. 1 for locations), constituting somewhat less than 10% of the total volume (Beane & Hooper, 1988). Some of these are porphyritic units in compound flow sequences showing clear evidence of crystal fractionation and accumulation (Mishra, 1971; Beane & Hooper, 1988; Deshmukh, 1988).

Picrodolerite dykes and picrite basalts also occur in southern Kathiawar. The dykes at Dedan (Fig. 1) are 10–15 m thick and can be traced over distances of >2 km. They exhibit clear flow differentiation features (Krishnamacharlu, 1972). The picrite basalt flows of southern Kathiawar (SK in Fig. 1) have only recently been described; they further enlarge the known area of occurrence of such rock types in the northern Deccan (Melluso *et al.*, 1995). Picritic dykes, including ankaramites, are also found together with rocks of the carbonatite–alkaline complex in the Ambadongar and Kawant areas (Nageshwara Rao, 1975; Simonetti *et al.*, 1995; present work).

METHODS

Olivine analyses were obtained using an automated CAMEBAX electron microprobe at the Scripps Institution of Oceanography. Standards included Smithsonian mineral standards and pure metal oxides. Based on repeated analyses of the Smithsonian San Carlos olivine standard (Jarosewich *et al.*, 1980), relative analytical uncertainty is <1% for the major elements and <16% for minor elements. Further details of the experimental methods have been given by Bloomer *et al.* (1982).

RESULTS

Olivine compositions and variations

Representative olivine compositions for samples from the various picrite localities are given in Table 1, and the ranges of MgO concentrations at each location are summarized in Fig. 2. Figures 3 and 4 provide further details of the range of compositions encountered, including CaO and NiO concentrations.

The primitive picrite basalts sampled from the borehole cores at Dhanduka, Wadhwan Junction and Botad, as well as the surface samples at Anila, Paliyad (Saurashtra region), Pawagarh, Ambadongar and Kawant (Narmada region), all contain forsteritic olivine phenocrysts. The cores of these olivines exhibit limited chemical variability (Fo_{92-86}; see Fig. 3) although the phenocryst rims are generally more iron rich. In a few cases the core-to-rim variability is large, such as in the sample from Kawant (ANK), where rim compositions reach Fo_{60}. The compositions of groundmass olivines that we analysed from this primitive picrite basalt range from Fo_{84} to Fo_{72}, which is within the range of phenocryst rim compositions observed.

The picritic flow from Botad quarry (sample SK/5/83 in Table 1) lacks the forsteritic olivines found in the Botad borehole sequence (e.g. sample 110 in Table 1) but exhibits considerable variation between phenocrysts ($\sim Fo_{83}$) and groundmass olivines (Fo_{64}). Given the close proximity, this flow may be derivative from the more primitive lavas sampled from the borehole. A picritic dyke at Dedan shows very limited variation in olivine composition (Fo_{80-77}) and appears to be an intrusion of a crystal-laden magma with clear flow differentiation features (Krishnamacharlu, 1972).

The picrite basalts and picrobasalts from the Western Ghats also lack forsteritic olivines, and they exhibit the maximum chemical variation observed among the analysed olivines. Compositions range from Fo_{84} to Fo_{43}, with virtually this entire range observed in a single crystal from a flow at Igatpuri (sample IG-68, Table 1). Olivines from Kalsubai samples (e.g. KB-88, Table 1) show the least variation ($\sim Fo_{80-78}$) whereas those from Triambak (e.g. TRB-5, Table 1) have a somewhat larger range ($\sim Fo_{80-67}$). The data in Fig. 3 suggest that there are minor compositional gaps among the analysed samples, but these may simply be the result of the relatively small number of grains analysed. The wide range of olivine compositions observed cannot be in equilibrium with a single magma type. They probably reflect the enrichment of Fe in residual melts during crystal fractionation, or mixing of evolved and less-evolved magmas, or both. Intra-flow differentiation within a compound lava flow, as observed by Deshmukh (1988), might also be responsible for some of the large compositional variations.

Variations in minor element compositions

Minor and trace elements such as Ca, Mn and Ni show significant variations among the analysed olivines. There is a general positive correlation between Ni and forsterite contents (Fig. 4a), with NiO reaching as high as 0·4 wt % for the most forsteritic olivines, although there is a significant range in Ni at a given olivine composition.

CaO also shows wide variations. Forsterites from the primitive picritic basalts of Dhanduka, Wadhwan, Botad, Paliyad, Anila and Kawant in Saurashtra contain distinctly higher CaO (0·4–0·5% CaO) than those from Pawagarh and Ambadongar along the Narmada rift (~0·25%; see Table 1). The Saurashtra flows are mildly alkalic and have higher CaO, TiO_2, K_2O and P_2O_5 contents than those from the Narmada rift (Table 2). There is also a negative correlation between CaO and

Table 1: Olivine analyses from picrite and picrobasalts of the Deccan Traps, India (all data in wt %)

Area:	Pawagarh							Kawant				Ambadongar			
Sample:	PB-39				PB-52			ANK				355			
Spot:	7P	13C	14C	14R	10P	12C	13R	8P	11C	12R	19Gm	7C	6R	8Gm	13Gm
SiO_2	40·14	40·78	39·89	39·42	40·11	40·05	38·49	40·03	39·30	35·40	37·79	39·87	39·07	38·91	37·89
FeO	7·82	7·72	11·39	19·48	11·34	12·55	21·18	11·17	13·10	33·39	21·60	11·03	15·78	19·28	25·42
MgO	50·18	50·92	47·83	41·96	47·93	47·07	40·12	47·23	45·94	28·40	38·19	47·92	44·27	41·75	36·81
NiO	0·40	0·38	0·29	0·25	0·31	0·22	0·16	0·17	0·14	0·04	0·11	0·31	0·30	0·22	0·17
MnO	0·06	0·05	0·06	0·10	0·05	0·07	0·11	0·06	0·08	0·22	0·12	0·05	0·06	0·11	0·13
CaO	0·26	0·25	0·47	0·39	0·25	0·30	0·31	0·41	0·42	0·66	0·68	0·28	0·29	0·29	0·32
Total	98·86	100·10	99·93	101·60	99·99	100·26	100·37	99·07	98·98	98·11	98·49	99·46	99·77	100·56	100·74
Forsterite (mol %)															
Fo	91·53	91·76	87·91	79·05	87·97	86·73	76·92	88·32	86·22	60·30	75·96	88·58	83·39	79·45	72·06
Fa	8·47	8·24	12·09	20·95	12·03	13·27	73·08	11·68	13·78	39·70	24·04	11·42	16·61	20·55	27·94

Area:	Igatpuri		Triambak		Kalsubai					Botad Q		Dedan	
Sample:	IG-68		TRB-5		KB-88					SK/5/83		SK/9/83	
Spot:	13C	14R	7C	8R	5P	6Gm	15	9C	10R	2P	3Gm	380/P2	380/P1
SiO_2	38·65	33·84	38·91	38·23	38·56	36·86	37·91	38·93	38·93	39·63	36·95	38·56	39·05
FeO	16·36	45·51	18·20	20·83	18·55	29·39	22·26	15·81	18·18	16·07	31·12	20·89	18·72
MgO	43·14	19·17	42·07	39·98	41·35	33·12	38·60	44·03	42·75	44·63	32·05	40·66	42·85
NiO	0·14	0·08	0·10	0·09	0·13	0·08	0·12	0·28	0·19	0·16	0·09	0·13	0·11
MnO	0·05	0·32	0·08	0·09	0·07	0·14	0·09	0·02	0·09	0·23	0·75	0·34	0·28
CaO	0·33	0·40	0·36	0·36	0·33	0·30	0·23	0·30	0·32	0·45	0·38	0·32	0·32
Total	98·67	99·32	99·72	98·58	98·99	99·89	99·21	99·37	100·46	101·17	101·34	100·90	101·33
Forsterite (mol %)													
Fo	82·28	42·68	80·31	76·96	79·91	66·73	75·54	83·24	80·24	82·86	64·11	77·23	79·98
Fa	17·72	57·32	19·69	23·04	20·09	33·27	34·46	16·76	19·24	17·14	35·89	22·77	20·02

Area:	Dhandhuka		Botad		Anila		Wadhwan		Paliyad	
Sample:	244	292	110		SK/3/83		380		SK/39/83	
Spot:	244P	Gm	110P	110Gm	19P	23Gm	380/P2	380/P1	31	Gm
SiO_2	40·76	40·92	40·24	40·32	40·54	39·77	40·32	39·74	40·65	40·15
FeO	12·02	13·15	11·21	14·50	11·01	14·77	9·41	13·36	10·22	13·61
MgO	46·68	45·53	47·75	44·20	48·26	45·67	48·92	45·78	49·06	46·66
NiO	0·33	—	0·31	—	0·20	0·19	0·39	0·28	0·20	0·19
MnO	—	—	—	—	0·20	0·25	—	—	0·20	0·24
CaO	0·46	0·41	0·44	0·45	0·49	0·33	0·40	0·36	0·43	0·41
Total	100·25	100·01	99·95	99·47	100·70	100·98	99·44	99·52	100·76	101·26
Forsterite (mol %)										
Fo	87·40	87·10	88·35	84·40	88·29	84·26	90·30	86·00	89·17	85·55
Fa	12·60	12·90	11·65	15·60	11·71	15·24	9·70	14·00	10·83	14·45

C, Core; R, rim; P, phenocryst; MP, microphenocryst; Gm, groundmass.

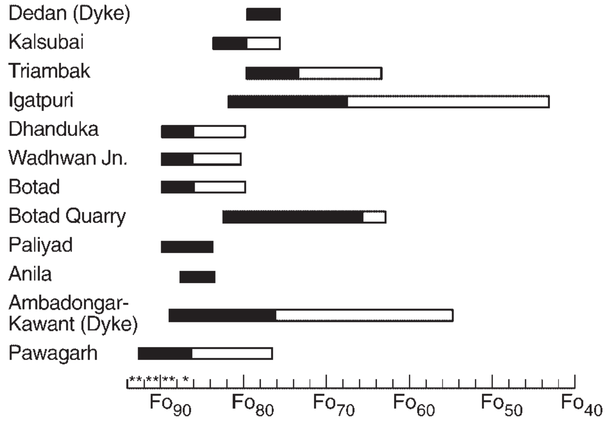

Fig. 2. Compositional range of olivines from picrite basalts of the Deccan. Filled bars, phenocrysts and phenocryst cores; open bars, rim and groundmass compositions; *, olivine compositions from peridotitic sources (Cox, 1980).

forsterite content for the Saurashtra samples. In general, phenocryst rim and groundmass olivine CaO contents are higher for olivines from samples with higher whole-rock CaO contents. There is a conspicuous absence of olivines with <0·1% CaO, perhaps not surprising as such low CaO contents are characteristic of olivines from deep-seated plutonic complexes and ultramafic inclusions (Simkin & Smith, 1970). However, taken together with the lack of features such as kink bands, this suggests that the phenocrysts in the Deccan picrite basalts are mainly of low-pressure origin and are not xenocrysts.

MnO contents in general are consistently low in forsteritic olivines (<0·1%), except for samples from Paliyad, Anila and Botad quarry (see Table 1). There is a general positive correlation between MnO and iron content.

Whole-rock chemistry and olivine compositions

Representative whole-rock analyses of picrite basalts from the Deccan province are given in Table 2. Computed equilibrium olivine compositions and the observed (maximum) forsterite contents within the studied samples or associated lavas are also listed.

Figure 5 shows mole percent forsterite in the analysed olivines vs *mg*-number of the host rock. These data can be used to examine the mode of origin of these picrites. A number of the samples with forsteritic olivine, such as those of Dhandhuka (D-12), Botad (B-6), Ambadongar and Kawant, show a fairly close correspondence between estimated equilibrium olivine compositions and those observed in the samples. This suggests a primitive status for these picrites. As noted above, phenocryst rim compositions are often much more Fe rich and therefore not in equilibrium, indicating evolution of the liquid compositions during petrogenesis of these rocks. In a few of the picrite basalts, olivine compositions show relatively minor deviations from the equilibrium field; for example, the reader is referred to the data for samples from Pawagarh (PB-39 and PB-52) and Wadhwan (W-1). The latter may have accumulated some forsteritic olivine as suggested by its high MgO content. Thus, broadly, these picrites must have formed from little-modified magma compositions, similar to those observed in anhydrous melting studies of upper-mantle peridotite.

In contrast to those just described, the picrite basalts of the Western Ghats contain relatively iron-rich olivine phenocrysts, typically $Fo_{80 \pm 2}$. In some samples (e.g. IG-68 and TRB-5) the phenocryst compositions are close to estimated equilibrium olivine compositions, but in others there are large deviations (e.g. samples JEB 291, SAM-017 and JEB-116; see Table 2 and Fig. 5). In most cases these rocks probably acquired their high MgO contents by olivine accumulation.

DISCUSSION AND CONCLUSIONS

Until recently, known Deccan province localities with primitive picrite basalts were confined to the borehole sequence in Saurashtra described by Krishnamurthy & Cox (1977). Here we have described additional occurrences at Pawagarh, Ambadongar and Kawant, all to the north of the Narmada rift zone (see Fig. 1). In addition, the presence of surface outcrops in the vicinity of the borehole localities, for example, at Anila and Paliyad, as well as those reported by Melluso *et al.* (1995) in southern Kathiawar suggest that picrite basalt flows may originally have had a large areal extent in this part of the Deccan province. The geographic and stratigraphic positions of these rocks may be related to the overall operation of the Deccan volcanic cycle, similar to the situation outlined by Cox (1972) for the Karroo province.

Compositional diversity among the Deccan picrite basalts

The data in Table 2 suggest that, in terms of chemical composition, there are at least two groups of Deccan picrite basalts, and that there is some overlap between them. They include (1) a mildly alkalic or transitional type rich in TiO_2 (>1·8% TiO_2), K_2O and P_2O_5, and (2) a tholeiitic type, poorer in TiO_2 (<1·8%), K_2O and P_2O_5. We will refer to these subsequently as Type 1 and Type 2. The former is mainly confined to areas north of the Narmada rift and west of the Cambay graben, e.g. Dhandhuka, Wadhwan, the Botad borehole sequence, Anila, Paliyad and Ambadongar. The second group occurs primarily in southern Kathiawar and the Western Ghats. The sample from Kawant is somewhat anomalous,

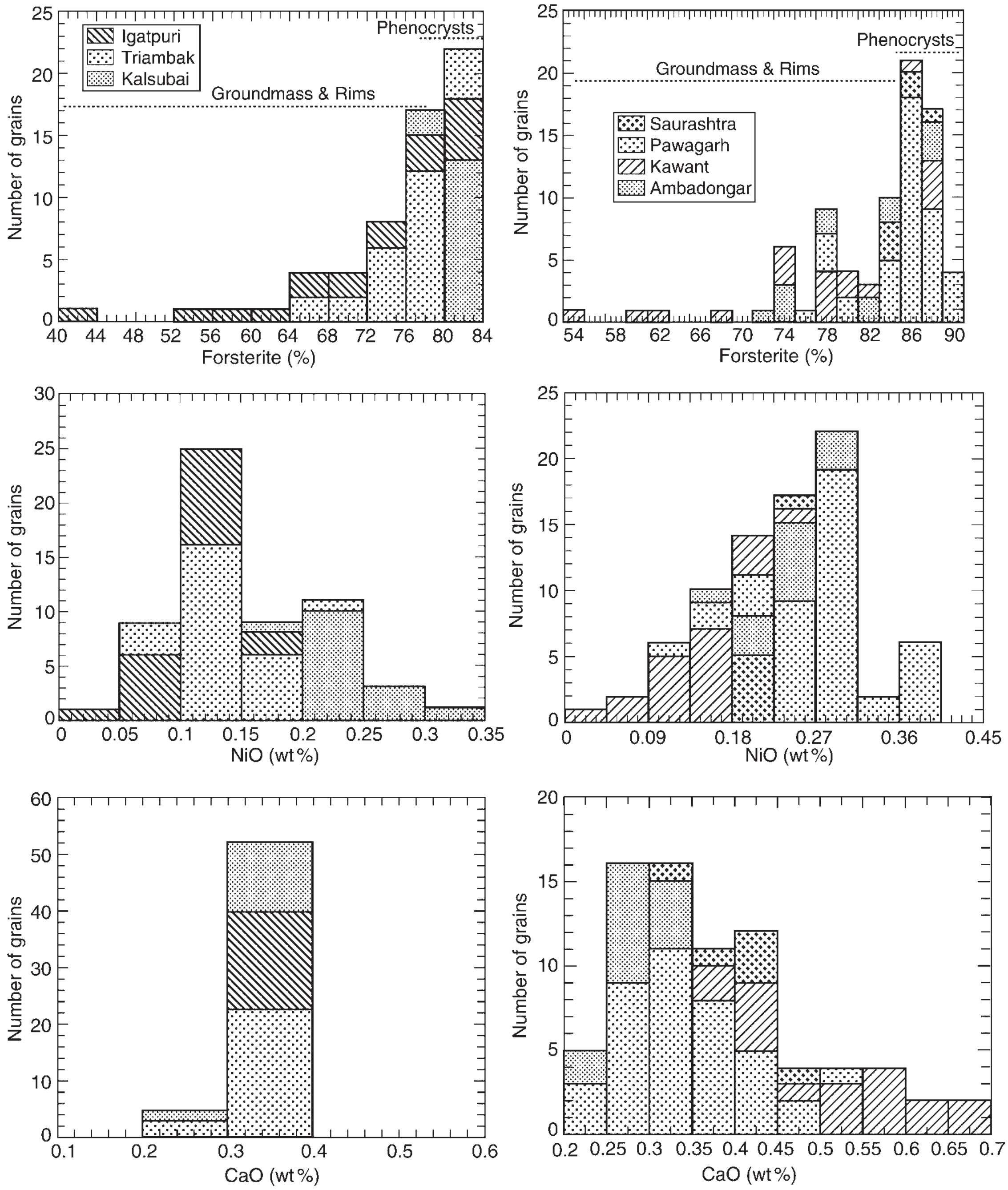

Fig. 3. Histogram showing the forsterite, NiO and CaO contents in olivines from picrite basalts of the present study.

having low TiO_2 but high K_2O and P_2O_5. Lavas of both types, as well as some that appear to be transitional, occur at Pawagarh (see Tables 2 and 3).

Primitive picrites and derivative basalts

The search for parental magmas and an understanding of Deccan basalt petrogenesis has been a continuing task for many investigators (e.g. Krishnamurthy & Cox, 1977, 1980; Krishnamurthy & Udas, 1981; Beane *et al.*, 1986; Lightfoot & Hawkesworth, 1988; Lightfoot *et al.*, 1990; Melluso *et al.*, 1995; Greenough *et al.*, 1998). These studies have identified a variety of magma types, but among them tholeiitic and mildly alkalic lavas are the predominant groups. Distinct from these, and not considered here, are strongly alkalic types, which include the spinel

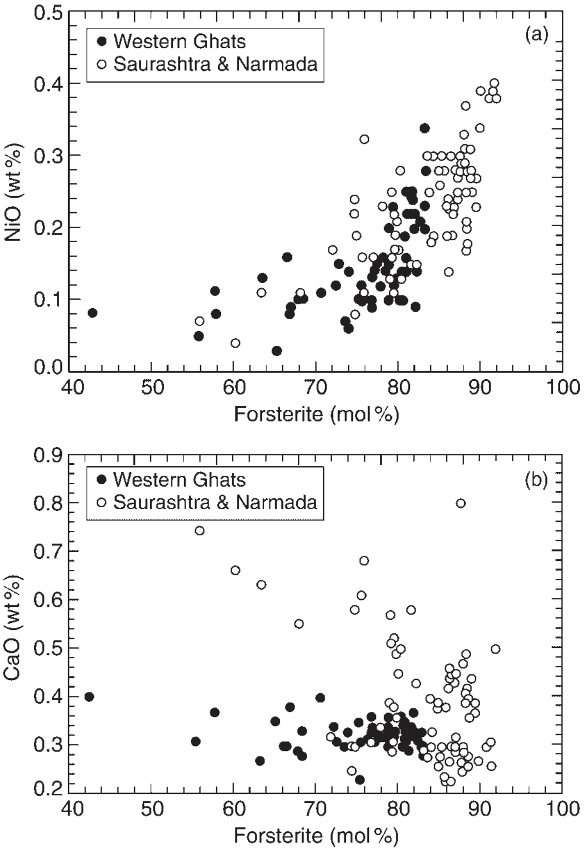

Fig. 4. Variation of forsterite content vs NiO (a) and CaO (b) in the olivines analysed in this study.

peridotite bearing basanites and olivine nephelinites of Kutch [Krishnamurthy *et al.* (1999) and references therein], and the phono-nephelinites and carbonatites of Ambadongar (Simonetti *et al.*, 1995).

Krishnamurthy & Cox (1977) showed that the bulk compositional characteristics and variability of the primitive picrite basalts from the borehole sequence at Botad, Dhandhuka and Wadhwan could be generated by fractionation of olivine and chromite from an Mg-rich parent. Fractionation of olivine + clinopyroxene from evolved picrite basalts could give rise to basalts of the mildly alkalic type. Krishnamurthy & Cox (1977) interpreted the significant degree of equilibrium crystallization inferred for many of the primitive picrite basalts in terms of compensated crystal settling. However, more recent work suggests that magmatic turbulence in hot, MgO-rich magmas during rapid emplacement may be a better explanation (Huppert & Sparks, 1985). The estimated MgO content for the magmas parental to the picrite basalts of the borehole sequence is at least 16%.

Picrite basalts and picrobasalts of the Western Ghats and olivine compositions

The nature of the parental magmas for the more common tholeiitic lavas that occur in the thick flow sequences of the Western Ghats and elsewhere in the Deccan is more problematic. However, picrite basalts from these sequences, and their olivine compositions, can provide some clues. Such rocks are found in several formations of the Kalsubai and Lonavala subgroups. These include, from base upwards, the Igatpuri, Neral, Thakurvadi, Bushe and Poladpur formations. Representative whole-rock and mineral analyses are given in Tables 1 and 2, and Figs 3 and 5. According to Beane & Hooper (1988), the olivine-rich flows constitute <10% of the total exposed volume of the lava sequence. Two important features emerge from the olivine composition and olivine–whole-rock data. The first is the absence of any samples bearing equilibrium forsteritic olivines, and the second is that for those few samples that do contain equilibrium olivines, even the most magnesian phenocrysts are relatively iron rich ($Fo_{80\,\pm\,2}$). The large differences in compositions between phenocryst cores and rims, or groundmass, are noteworthy.

Beane & Hooper (1988) used the compositions of olivine from mafic lavas of the Western Ghats to infer parental magma compositions. Some of their data are included in Tables 2 and 3. On the basis of the most magnesian olivine cores (Fo_{84}) they analysed from a phenocryst-poor flow from the Thakurwadi Formation (see data for sample SAM-018 in Table 3), Beane & Hooper estimated the MgO content of the equilibrium liquid to be $10{\cdot}3 \pm 0{\cdot}2\%$. According to those workers, such a liquid probably represents the most mafic primitive liquid supplied to the volcanic substratum in the Western Ghats. However, the most iron-rich olivine phenocryst cores from some Type I picrite basalts of the Narmada and Saurashtra regions reach Fo_{86}, and thus are little different from the most magnesian values in the Type 2 samples from the Western Ghats, such as SAM-018. Olivine composition alone may not be a sufficient indicator of parental liquid composition, as source peridotite composition, as well as magmatic processes during fractionation and differentiation, also play a role in determining phenocryst compositions. Other mineralogical evidence may also be important; for example, the presence of magnesian ilmenite (Murari *et al.*, 1993), or chrome–spinel inclusions in olivine (Krishnamurthy & Cox, 1977; Bell & Williamson, 1994). Chromite inclusions are present in some of the olivines analysed in this work. Sample KB-88 from Kalsubai has phenocryst olivines containing chromite with the approximate composition (in weight percent): Cr_2O_3, 44·11; Al_2O_3, 17·30; MgO, 10·96; FeO, 25·34; TiO_2, 1·55.

Table 2: Whole-rock analyses of picrite and picrobasalts from the Deccan Traps (all data in wt %)

Location:	Wadhwan	Dhandhuka	Botad	Pawagarh	Pawagarh	Kawant	Ambadongar	Dedan	Dedan	Dedan
Flow:	W-1	D-12	B-6	20	28	Dyke	Dyke	Dyke	Dyke	Dyke
Sample:	380[1]	244[1]	110[1]	PB-39	PB-52[1]	ANK[1]	355[1]	A-78K[1]	A-64[1]	TK/A-31[1]
SiO_2	46·93	47·41	46·20	48·70	47·26	46·13	48·03	48·37	49·29	49·87
TiO_2	1·53	2·00	2·08	1·76	1·71	1·18	1·92	1·00	1·30	0·96
Al_2O_3	6·75	10·07	11·33	10·09	9·99	12·90	11·70	11·62	12·51	10·69
FeO^t	10·67	11·11	10·90	10·29	11·23	9·43	10·89	11·57	11·51	10·65
MnO	0·20	0·14	0·17	0·17	0·19	0·17	0·18	0·19	0·17	0·19
MgO	23·78	13·20	14·02	14·78	17·49	12·30	12·65	16·09	13·31	13·22
CaO	8·85	13·19	12·08	11·76	9·81	15·04	12·00	8·93	10·01	12·34
Na_2O	0·68	1·65	1·83	1·49	1·54	1·71	1·76	1·59	1·52	1·02
K_2O	0·43	0·92	1·03	0·68	0·52	0·82	0·57	0·52	0·22	0·89
P_2O_5	0·18	0·31	0·36	0·28	0·26	0·32	0·30	0·12	0·16	0·17
mg-no.	0·82	0·70	0·72	0·74	0·76	0·72	0·70	0·73	0·70	0·71
Fo(calc)	93·6	88·7	89·5	90·5	91·1	89·6	88·5	90·2	88·4	89·1
Fo(max)	90·3	87·4	88·3	91·7	87·9	88·3	88·6	77·2	79·9	80·0

Location:	Igatpuri	Triambak	Kalsubai	Khamshedi	Water Pipe	Thakurwadi	Bushe
Flow:	IG-12	TRB-2	KB-13	—	—	—	—
Sample:	IG-68[2]	TRB-5[2]	KB-88[2]	ABC-29[3]	JEB-291[4]	SAM-017[4]	JEB-116[5]
SiO_2	47·94	49·76	47·22	47·63	53·19	49·00	50·44
TiO_2	2·18	1·76	1·56	1·41	1·02	1·71	1·14
Al_2O_3	11·96	12·26	12·56	10·97	8·21	10·17	11·77
FeO^t	13·16	12·18	12·91	13·79	9·39	13·91	10·54
MnO	0·14	0·13	0·14	0·19	0·18	0·21	0·16
MgO	9·32	10·26	14·68	12·20	13·14	15·87	12·17
CaO	12·69	11·34	9·11	11·48	12·65	7·17	10·95
Na_2O	1·79	2·08	1·31	1·74	1·65	1·24	2·31
K_2O	0·41	0·26	0·32	0·46	0·46	0·56	0·41
P_2O_5	0·18	0·29	0·32	0·13	0·11	0·16	0·11
mg-no.	0·55	0·63	0·69	0·70	0·74	0·69	0·70
Fo(calc)	80·5	85·8	88·2	88·4	90·2	88·3	88·4
Fo(max)	82·2	83·0	83·0	82·0	83·0	84·0	84·0

All analyses are recalculated to 100% on water-free basis; FeO^t, total iron as FeO.; *mg*-no. = molar Mg/(Mg + Fe), after assigning 10% of total FeO to Fe_2O_3; Fo(calc), olivine composition estimated from the *mg*-number value assuming $K_D = 0{\cdot}3$ (Roeder & Emslie, 1970); Fo(max), maximum forsterite content observed in the sample or in associated lavas (see Basaltic Volcanism Study Project, 1981, table 1.42.1, p. 413).
[1]Krishnamurthy (1974) and Krishnamurthy & Cox (1977); [2]Deshmukh (1979, 1988); [3]Cox & Hawkesworth (1985); [4]Beane & Hooper (1988); [5]Beane *et al.* (1986).

Magma chamber processes and their influence on olivine compositions

It has been claimed by a number of workers that in the Western Ghats extensive gabbroic fractionation produced basalts with MgO contents in the range of 7% or less, and that an initial stage of olivine ± aluminous clinopyroxene accumulation resulted in samples with >7·5% MgO (Sen, 1988, 1995; Cox & Mitchell, 1988; Lightfoot *et al.*, 1990). However, Cox & Hawkesworth (1985) questioned an accumulative origin (which had been based solely on olivine compositions) for some mafic lavas, such as the Khamshedi picrite basalts. According to Cox & Hawkesworth, the Khamshedi rocks could be primitive picrites erupted at the beginning of a new compositional cycle. They overlie the Fe-rich flows of the Lower Poladpur Formation, and although the magma may initially have

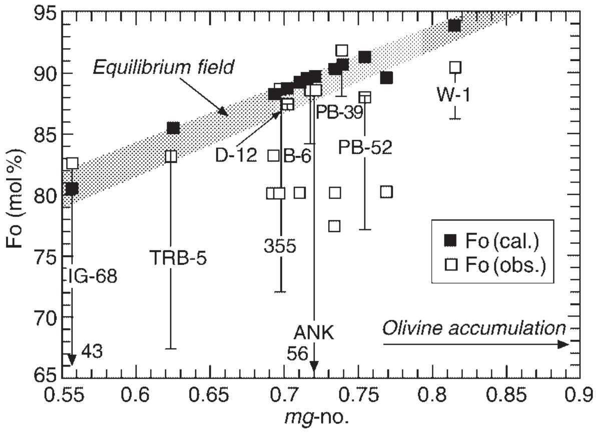

Fig. 5. Plot of whole-rock *mg*-number [molar Mg/(Mg + Fe^{2+})] vs percent forsterite in olivine phenocryst cores for selected picrite and picrobasalts of the Deccan. Data include those of the present study plus data from Beane *et al.* (1986) and Beane & Hooper (1988). Vertical lines with arrows show compositional variation observed in the phenocrysts (core and rim) and groundmass as indicated (see also Table 1). The equilibrium field (grey band) is based on Fe/Mg for olivine/whole rock = 0·30 ± 0·03 after Roeder & Emslie (1970) and Garcia (1996, fig. 5).

been trapped in a magma chamber because of its high density, it could have mixed with evolved, Fe-rich magmas of the previous cycle before eruption. Hybrid magmas of this sort would be anomalously rich in iron and Mg poor compared with the original picrite liquid (note that the Khamshedi lavas contain ~15% Fe_2O_3). Crystallizing olivines would also be relatively Fe rich. Thus picritic basalts of the Khamshedi type may derive from true picrite magmas, in spite of the presence of low-Mg olivine phenocrysts. The establishment of well-developed magma chambers, and the operation of RTF (replenished, trapped, fractionated) type processes (O'Hara & Mathews, 1981) may ensure that unmodified primitive picrite basalts are not erupted directly (Huppert & Sparks, 1980, 1985). In the Deccan, the restriction of most primitive picritic lavas to the early parts of the sequence may at least in part be related to the fact that such magma chambers were not established until later in the volcanic cycle.

The importance of mixing processes in the petrogenesis of Western Ghats basalts is corroborated by the mineral and melt inclusions present in zoned plagioclase phenocrysts from the 'giant phenocryst' basalts of the region (Pankov *et al.*, 1994). These flows are typically relatively Fe rich and occur at the close of recognizable cycles,

Table 3: Representative samples of primitive picrite basalts and postulated parental and primary compositions from Deccan Traps, India (all data in wt %)

Locality:	South Kathiawar		Pawagarh	Botad	Thakurwadi	Deccan Traps*	
Sample:	D-57†	D-56†	D-97†	129‡	SAM-018§	DEC-Melt-1 Parent	DEC-Melt-1 Primary
SiO_2	46·61	47·17	46·32	46·10	49·04	51·39	50·57
TiO_2	0·80	1·06	2·43	1·62	2·32	1·31	0·87
Al_2O_3	14·39	15·72	13·48	10·49	15·05	13·54	12·67
FeO	10·96	11·99	11·52	10·85	13·02	11·34	10·88
MnO	0·18	0·19	0·15	—	0·19	—	—
MgO	14·31	10·20	13·20	16·52	6·89	7·70	13·96
CaO	10·19	10·93	9·97	11·91	10·92	12·05	9·13
Na_2O	1·85	2·35	1·77	1·41	1·90	2·67	1·96
K_2O	0·35	0·42	0·80	0·55	0·40	—	—
P_2O_5	0·10	0·12	0·35	0·25	0·26	—	—
mg-no.	0·72	0·63	0·70	0·75	0·51	0·57	0·73
Fo(calc)	89·6	84·9	88·4	90·9	77·9	81·8	89·4
Fo(obs)	75	91·0	88·0	—	84·	—	—

*Parent and primary melt compositions computed from Sen (1995, tables 1 and 2). Other details as in Table 2.
†From Melluso *et al.* (1995, table 7).
‡From Krishnamurthy (1974, table 4-3).
§Western Ghat sample from Beane & Hooper (1988, table 3).

particularly in the Kalsubai subgroup, which contains numerous picrite and picrobasalt horizons (see Beane *et al.*, 1986). In some giant phenocrysts, pyroxenes and/or olivines (Fo_{40-32}) of varying compositions are included within the same plagioclase zone, and in addition, Mg-rich olivines have been observed in the rim zones of plagioclases that contain Fe-rich olivines in their cores. Geochemical data for lavas from the Western Ghats also provide evidence for mixing of primitive and evolved magmas (Cox & Hawkesworth, 1985; Mahoney, 1988).

Primitive picrite basalts and stratigraphic considerations

Volumetrically significant occurrences of primitive picrite basalts in the Deccan appear to be confined to areas north of the Narmada rift, west of the Cambay graben, or southern Kathiawar (Fig. 1). This spatial distribution may be related to stratigraphic position within the Deccan flood basalt sequence. If the Reunion-plume model for Deccan volcanism is valid, areas of northwest India along the plume-axis trace should have encountered the plume first, and should therefore contain the oldest members of the sequence (Cox, 1983). That this is the case is supported by several pieces of evidence. First, to the north of the Narmada rift the flow sequence exhibits a normal–reversed–normal magnetic stratigraphy, with the lower normal representing the older Narmada Formation (Sreenivasa Rao *et al.*, 1985). The Western Ghats sequences to the south reveal only a single reversal. Second, detailed stratigraphic correlations in the Western Ghats indicate that the flow sequence there exhibits a very low (<0·5°) southerly dip, so that the oldest formations occur to the north (Beane *et al.*, 1986). Third, older plutonic and sub-volcanic complexes related to the Deccan, such as Mundwara (68·5 Ma; Basu *et al.*, 1993) occur in the north. The Pawagarh hill flow sequence is an erosional outlier. Thus the picrite-containing effusive sequences in Saurashtra and north of the Narmada appear to be early members of the Deccan volcanic sequence.

The primitive picrite localities are also in close proximity to the Narmada and Cambay rift zones (Fig. 1), which apparently provided pathways for rapid transport and eruption. Lacking such conduits, such dense magmas may pond at the crust–mantle boundary (Herzberg *et al.*, 1983). Eruption of fairly large volumes of high-Mg primitive picrites may also have been facilitated early in the Deccan cycle by the high temperatures of parts of the plume head (Campbell & Griffith, 1990). The paucity of such primitive picrite basalts in the stratigraphically younger sequence of the Western Ghats may be attributed to the general decrease of thermal energy later in the volcanic cycle, and the development of steady-state magma chambers and magmatic plumbing systems in which ponding and mixing of dense picritic magmas occurred, as described above.

Picrite basalts and the Reunion plume

Campbell & Griffith (1990) have argued that primary picritic lavas represent high-degree melts from the high-temperature part of a plume head. Combined Sr–Nd–Pb systematics for the primitive picrite basalts of the Dhandhuka–Wadhwan–Botad borehole sequence support this idea, as they suggest a present-day Reunion type plume source for some of the early picrite basalts (Peng & Mahoney, 1995), although other isotopic components are also present. The situation for other Deccan picrite basalts is less clear. On geochemical grounds, a deep ocean-island basalt type mantle source has been suggested for the high-TiO_2, large ion lithophile element (LILE)-enriched suite at Pawagarh and Rajpipla (Melluso *et al.*, 1995; Greenough *et al.*, 1998), and Melluso *et al.* (1995) also postulated a high field strength element depleted mantle source for the low-TiO_2 suites in southern Kathiawar.

The depths and extents of melting necessary to generate some of the primitive picrite basalt compositions have been dealt with in two recent publications. Sen (1995) postulated a depth range of 100–60 km (garnet to spinel lherzolite field) with 11–18% melting for the primary magmas. For the low-TiO_2 picrite basalts of south Kathiawar, Melluso *et al.* (1995) found a slightly shallower but overlapping depth range (80–40 km). Peng & Mahoney (1995) used LILE abundances to argue that the picrite basalts result from smaller degrees of melting than the Ambenali type basalts of the Western Ghats. However, especially in a plume-influenced environment, LILE abundances may be affected by a variety of processes.

Mantle metasomatism by plume-derived or plume-related fluids can provide a rich source of LILE. In the Deccan region, alkaline and ultra-alkaline rocks such as the carbonatites of the Narmada zone have been attributed to mantle metasomatism and enriched mantle sources (Krishnamurthy & Udas, 1981; Simonetti *et al.*, 1995). Metasomatism has also been implicated in the genesis of the potassium-rich alkaline suite of the Rajpipla area, on the basis of Sr and Nd data and geochemical decoupling between tholeiitic and alkali basalts (Mahoney *et al.*, 1985). Mantle enrichment has also been suggested to explain some aspects of the Mahabaleshwar lavas of the Western Ghats (Cox & Hawkesworth, 1984). Cryptic metasomatism of the sub-Deccan mantle has been inferred from Sr and Nd isotopic studies of spinel peridotite nodules from alkali basalts in Kutch (Krishnamurthy *et al.*, 1988; Pande, 1988), and from the presence of sodian–ferrian in diopsides in the same nodules (Murari, 1993). Recently the low-pressure, low-temperature, orthopyroxene–rutile–spinel intergrowths that occur in spinel peridotite xenoliths from Mt Sayala Devi in Kutch have been ascribed to mantle metasomatism (Karmalkar *et al.*, 1999). Thus throughout the northern parts of the Deccan a variety of mineralogical and geochemical features point to mantle metasomatism, probably the result of complex interaction between the Reunion plume and the lithospheric mantle.

An additional aspect of this discussion concerns the Fe content of the source as inferred from primitive picrite basalts. It has been postulated (e.g. Francis, 1985; Melluso *et al.*, 1995; Scarrow & Cox, 1995; Francis *et al.*, 1999) that intraplate or plume-related picrites show an inverse relation between Si and Fe that indicates Fe-rich sources. As has already been discussed, the Fe content of the source influences both initial magma compositions and the compositions of early formed olivines. Thus source composition is important for understanding picrite basalt petrogenesis.

Primitive picrite basalts and the volcanic cycle

The primitive picrite basalts identified in the Deccan can be examined in terms of Cox's volcanic cycle model for the Karoo (Cox, 1972). According to this model, the volcanic cycle has a very early low-degree-of-melting stage, characterized by alkaline and ultra-alkaline rocks, followed by a thermal peak (the culmination stage) that is represented by high-Mg primitive picritic basalts. The thermal peak is followed by a steady-state stage during which basalts constituting the bulk of the province erupt. These typically have fairly uniform major element chemical compositions. A crustal stage, dominated by rhyolitic rocks, may closely follow or be coeval with the basalts. The end of the cycle is again characterized by alkaline and acidic rocks produced as low-degree melts.

Broadly speaking, volcanism in the Deccan appears to have followed a similar pattern. Among the oldest known Deccan rocks are alkaline complexes at Sarnu (68·5 Ma) and Mundwara (68·5 Ma) in the north, representing the very early, low partial melt stages (Basu *et al.*, 1993). This is probably followed by the sequences found in Kutch, Saurashtra and Narmada. In Kutch, tholeiitic and ultra-alkaline rocks are almost synchronous, giving ages of 67–64 Ma (Pande *et al.*, 1988). Field evidence appears to place the primitive picrite basalts of the borehole sequence, as well as those of Pawagarh, below the tholeiites of the Western Ghats in the stratigraphic sequence. The primitive picrites would thus represent the culmination stage in Cox's model, and probably originated in the high-temperature Reunion plume head. Deep-seated faults along the Narmada rift and Cambay graben aided rapid transport of these dense magmas to the surface. The predominant evolved tholeiitic basalts of the Deccan province, well represented in the Western Ghats, were erupted during the steady-state phase of the volcanic cycle. Cox (1980) envisioned sill-like complexes of ponded, picritic magmas in the lower crust, or at the crust–mantle boundary, from which such lavas evolved. The bulk of the tholeiitic lavas probably erupted near 65 Ma (Duncan & Pyle, 1988; Venkatesan & Pande, 1996). The Deccan volcanic cycle apparently closed with late-stage alkaline complexes such as Phenaimata (65·0 Ma; Basu *et al.* 1993) and Ambadongar (65·0 Ma; Ray & Pande, 1999).

CONCLUSIONS

On the basis of olivine phenocryst compositions (Fo_{92-86}) and whole-rock chemical compositions, primitive picrite basalt flows and dykes have been identified from widely separated parts of the Deccan flood basalt province. These include localities in Saurashtra (Anila and Paliyad) and north of the Narmada rift (Pawagarh, Ambadongar and Kawant). These occurrences, together with those reported earlier from borehole cores of Dhandhuka, Wadhwan and Botad, constitute significant quantities of primitive picrite basalts. They were probably emplaced early in the Deccan volcanic cycle, along deep faults in the Cambay graben and Narmada rift regions.

Picrite dykes from South Kathiawar (near Dedan) and flows at Botad, contain less magnesian olivine phenocrysts (Fo_{83-77}). The former is olivine rich, probably as a result of flow differentiation, and the latter may be derivative from the geographically adjacent primitive picrite flows sampled at the Botad borehole locality.

Picrite basalts of the Western Ghats lack forsteritic olivines and exhibit a large range of olivine compositions. They apparently originated from more primitive picritic magmas through fractionation and mixing processes within the crust.

We suggest that the volumetrically significant primitive picrite basalts of the Narmada and Saurashtra regions can be linked to an early stage of Deccan volcanism and thus conform to the type of volcanic cycle envisioned by Cox (1972) for the Karroo flood basalts. Similarly, the less primitive picrite basalts of the Western Ghats appear to fit the 'steady-state' stage of Cox's ideal volcanic cycle.

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REFERENCES

Basaltic Volcanism Study Project. (1981). *Basaltic Volcanism on the Terrestrial Planets*. New York: Pergamon Press, p. 1286.

Basu, A. R., Renne, P. R., Das Gupta, D. K., Teichman, F. & Poreda, R. J. (1993). Early and late alkali igneous pulses and a high ^{3}He plume origin for the Deccan flood basalts. Science 261. *Geological Society of India, Memoir* **10**, 117–133.

Beane, J. E. & Hooper, P. R (1988). A note on the picritic basalts of the Western Ghats, Deccan Traps, India. *Geological Society of India, Memoir* **10**, 117–133.

Beane, J. E., Turner, C. A., Hooper, P. R., Subba Rao, K. V. & Walsh, J. N. (1986). Stratigraphy, composition and form of the Deccan basalts, Western Ghats, India. *Bulletin of Volcanology* **48**, 61–83.

Bell, B. R. & Williamson, I. T. (1994). Picritic basalts from the Palaeocene lava field of west–central Skye, Scotland: evidence for parental magma compositions. *Mineralogical Magazine* **58**, 347–356.

Bloomer, S., Melchior, J., Evans, C. & Francis, R. D. (1982). Techniques for the chemical analysis of igneous rocks at the Scripps Institution of Oceanography. La Jolla, CA: Scripps Institution of Oceanography, Reference 82-7, **510**, p. 68.

Campbell, I. H. & Griffith, R. W. (1990). Implications of mantle plume structure for the evolution of flood basalts. *Earth and Planetary Science Letters* **99**, 79–93.

Cox, K. G. (1972). The Karroo volcanic cycle. *Journal of the Geological Society, London* **128**, 311–336.

Cox, K. G. (1980). A model for flood basalt volcanism. *Journal of Petrology* **21**, 629–650.

Cox, K. G. (1983). The Deccan Traps and the Karroo; stratigraphic implications of possible hot spot origins. Abstracts, XVIII General Assembly of the International Union of Geodesy and Geophysics. Hamburg: IUGG, p. 96.

Cox, K. G. & Hawkesworth, C. J. (1984). Relative contribution of crust and mantle to flood basalt magmatism, Mahabaleshwar area, Deccan Traps. *Philosophical Transactions of the Royal Society of London, Series A* **310**, 627–641.

Cox, K. G. & Hawkesworth, C. J. (1985). Geochemical stratigraphy of the Deccan Traps at Mahabaleshwar, western Ghats, India, with implications for open system magmatic processes. *Journal of Petrology* **26**, 355–377.

Cox, K. G. & Mitchell, C. (1988). Importance of crystal settling in the differentiation of Deccan Trap basaltic magmas. *Nature* **333**, 447–449.

Deshmukh, S. S. (1979). A critical petrological study of the Deccan basalts and associated high level laterites in parts of the Western Ghats, Maharashtra State. Ph.D. thesis, Nagpur University.

Deshmukh, S. S. (1988). Petrographic variations in compound flows of Deccan Traps and their significance. Deccan Flood Basalts. *Geological Society of India, Memoir* **10**, 305–319.

Duncan, R. A. & Pyle, D. G. (1988). Rapid eruption of the Deccan flood basalts, Western India. *Geological Society of India, Memoir* **10**, 1–10.

Francis, D. (1985). The Baffin Bay lavas and the value of picrities as analogues of primary magmas. *Contributions to Mineralogy and Petrology* **89**, 144–154.

Francis, D., Ludden, J., Johnstone, R. & Davis, W. (1999). Picrite evidence for more Fe in Archaean mantle reservoirs. *Earth and Planetary Science Letters* **167**, 197–213.

Garcia, M. O. (1996). Petrography and olivine and glass chemistry of lavas from the Hawaii Scientific Drilling Project. *Journal of Geophysical Research* **101**, 11701–11713.

Greenough, J. D., Hari, K. R., Chatterjee, A. C. & Santhosh, M. (1998). Mildly alkaline basalts from Pawagarh Hill, India: Deccan flood basalts with an asthenospheric origin. *Mineralogy and Petrology* **62**, 223–245.

Herzberg, C. T., Fyfe, W. S. & Carr, M. J. (1983). Density constraints on the formation of the continental Moho and crust. *Contributions to Mineralogy and Petrology* **84**, 1–5.

Huppert, H. E. & Sparks, R. J. (1980). The fluid dynamics of a basaltic magma chamber replenished by influx of hot, dense ultrabasic magma. *Contributions to Mineralogy and Petrology* **75**, 279–289.

Huppert, H. E. & Sparks, R. J. (1985). Cooling and contamination of mafic and ultramafic magmas during ascent through continental crust. *Earth and Planetary Science Letters* **74**, 371–386.

Jarosewich, E. J., Nelen, J. A. & Norberg, J. A. (1980). Reference samples for electron microprobe analysis. *Geostandards Newsletter* **4**, 43–47.

Karmalkar, N. R., Duraiswami, R. A., Griffin, W. L. & O'Reilly, S. Y. (1999). Enigmatic orthopyroxene–rutile–spinel intergrowth in the mantle xenoliths from Kutch, India. *Current Science* **76**, 687–692.

Krishnamacharlu, T. (1972). Petrology of the picrodolerites from the Dedan cluster, Gujarat. *Journal of the Geological Society of India* **13**, 262–272.

Krishnamurthy, P. (1974). Petrological and chemical studies of Deccan Trap lavas from western India. Ph.D. thesis, University of Edinburgh.

Krishnamurthy, P. & Cox, K. G. (1977). Picrite basalts and related lavas from the Deccan traps of Western India. *Contributions to Mineralogy and Petrology* **62**, 53–75.

Krishnamurthy, P. & Cox, K. G. (1980). A potassium-rich alkalic suite from the Deccan Traps, Rajpipla, India. *Contributions to Mineralogy and Petrology* **73**, 179–189.

Krishnamurthy, P. & Udas, G. R. (1981). Regional geochemical characters of the Deccan Trap lavas and their genetic implications. *Geological Society of India, Memoir* **3**, 394–418.

Krishnamurthy, P., Pande, K., Gopalan, K. & Macdougall, J. D. (1988) Upper mantle xenoliths in alkali basalts related to Deccan Trap volcanism. *Geological Society of India, Memoir* **10**, 53–67.

Krishnamurthy, P., Pande, K., Gopalan, K. & Macdougall, J. D. (1999) Mineralogical and chemical studies on alkaline and basaltic rocks of Kutch, Gujarat, India. Deccan Volcanic Province. *Geological Society of India, Memoir* **43**, 757–784.

Le Bas, M. J. (2000). IUGS reclassification of the high-Mg and picritic volcanic rocks. *Journal of Petrology* (in press).

Lightfoot, P. C. & Hawkesworth, C. J. (1988). Origin of Deccan Trap lavas: evidence from combined trace elements and Sr-, Nd-, and Pb-isotope studies. *Earth and Planetory Science Letters* **91**, 89–104.

Lightfoot, P. C., Hawkesworth, C. J., Devey, C. W., Rogers, N. W. & Van Calsteren, P. W. C. (1990). Source and differentiation of Deccan Trap lavas: implications of geochemical and mineral chemical variations. *Journal of Petrology* **31**, 1165–1200.

Mahoney, J. J. (1988). Deccan Traps. In: Macdougall, J. D. (ed.) *Continental Flood Basalts*. Dordrecht: Kluwer Academic, pp. 151–194.

Mahoney, J., Macdougall, J. D., Lugmair, G. W., Gopalan, K. & Krishnamurthy, P. (1985). Origin of contemporaneous tholeiitic and K-rich alkalic lavas: a case study from the northern Deccan Plateau, India. *Earth and Planetary Science Letters* **72**, 39–53.

Melluso, L., Beccaluva, L., Brotzu, P, Gregnanin, A., Gupta, A. K., Morbidelli, L. & Traversa, G. (1995). Constraints on the mantle sources of the Deccan Traps from the petrology and geochemistry of the basalts of Gujarat states (Western India). *Journal of Petrology* **36**, 1393–1432.

Mishra, K. K. (1971). Petrology of the picrite basalt flows in the Igatpuri–Kalsubai area, Nasik district, Maharashtra. *Bulletin of Volcanology* **35**, 957–964.

Murari, R. (1993). Sodian–ferrian diopsides in ultramafic nodules from Kutch, Saurashtra. *Modelling in Earth Sciences with Special Reference to Tectonics and Volcanism in the Deccan Volcanic Province*. Group Discussion, National Geophysical Research Institute, Hyderabad, Abstract, 34.

Murari, R., Krishnamurthy, P., Tihonenko, P. I. & Gopalan, K. (1993). Magnesian ilmenites in picrite basalts from Siberian and Deccan Traps—additional mineralogical evidences for primary melt compositions (?). *Mineralogical Magazine* **57**, 733–735.

Nageshwara Rao, V. (1975). Petrology of igneous rocks around Kawant, Baroda district, Gujarat, India. Ph.D. Thesis, Saugar University.

O'Hara, J. M. & Mathews, R. E. (1981). Geochemical evolution in an advancing, periodically replenished, periodically tapped, continuously fractionated magma chamber. *Journal of the Geological Socciety, London* **138**, 237–277.

Pande, K. (1988). Isotopic and chemical studies of ultramafic nodules in alkali basalts from Kutch, Western India. Ph.D. Thesis, Physical Research Laboratory, Ahmedabad, p. 136.

Pande, K., Venkatesan, T. R., Gopalan, K., Krishnamurthy, P. & Macdougall, J. D. (1988). $^{40}Ar–^{39}Ar$ ages of alkali basalts from Kutch, Deccan volcanic province, India. *Geological Society of India, Memoir* **10**, 145–150.

Pankov, V., Oleinikov, B. V., Krishnamurthy, P., Murari, R. & Gopalan, K. (1994). Mineral and melt inclusions in the giant plagioclase phenocrysts of Deccan basalts, Western Ghats, India: some comparisons with plagioclases of intrusive Siberian Traps and implications on the physico-chemical conditions during magmatic evolution. In: Subbarao, K. V. (ed.) *Volcanism (Radhakrishna Volume)*. New Delhi: Wiley Eastern, pp. 187–200.

Peng, Z. X. & Mahoney, J. J. (1995). Drillhole lavas from the northwestern Deccan Traps and the evolution of Reunion hotspot mantle. *Earth and Planetary Science Letters* **134**, 169–185.

Ray, J. S. & Pande, K. (1999). Carbonatite–alkaline magmatism associated with continental flood basalts at stratigraphic boundaries: cause for mass extinction. *Geophysical Research Letters* **26**, 1917–1920.

Roeder, P. L. & Emslie, R. F. (1970). Olivine–liquid equilibrium. *Contributions to Minerology and Petrology* **29**, 275–289.

Roy, B. C. (1963). *Geological and Tectonic Maps of India*. Calcutta: Geological Survey of India.

Scarrow, J. H. & Cox, K. G. (1995). Basalts generated by decompressive adiabatic melting of a mantle plume: a case study from the Isle of Skye, NW Scotland. *Journal of Petrology* **36**, 3–22.

Sen, G. (1988). Possible depth of origin of primary Deccan tholeiite magma. *Geological Society of India, Memoir* **10**, 35–51.

Sen, G. (1995). A simple petrologic model for the generation of Deccan Trap magmas. *International Geology Review* **37**, 825–850.

Simkin, T. & Smith, J. V. (1970). Minor elements distribution in olivine. *Journal of Geology* **78**, 304–325.

Simonetti, A., Bell, K. & Viladkar, S. G. (1995). Isotopic data from the Ambadongar carbonatite complex, west Central India: evidence for an enriched mantle source. *Chemical Geology* **122**, 185–198.

Sreenivasa Rao, M., Ramasubba Reddy, N., Subbarao, K. V., Prasad, C. V. R. R. & Radhakrishnamurthy, C. (1985). Chemical and magnetic stratigraphy of parts of Narmada region, Deccan basalt province. *Journal of the Geological Society of India* **26**, 617–639.

Venkatesan, T. R. & Pande, K. (1996). A review of $^{40}Ar–^{39}Ar$ ages from the Western Ghats, Deccan Trap Province, India: implication for K/T events. *Gondwana Geological Magazine* **2**, 321–328.

West, W. D. (1958). The petrography and petrogenesis of forty eight flows of Deccan trap penetrated by borings in Western India. *Transactions of the National Institute of Science, India* **4**, 1–56.