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EXPERIMENTAL CRYSTALLIZATION OF DECCAN BASALTS AT LOW PRESSURE: EFFECT OF CONTAMINATION ON PHASE EQUILIBRIUM

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ABSTRACT

Earlier studies have shown that Deccan tholeiites in general have undergone crystal sorting and magma mixing processes within the relatively shallow crust (~ 6 km; 2 kbar pressure). Many of the lavas have also been contaminated by the continental crust as reflected, for example, in their Srisotope ratio. Two Deccan lava formations from the type section of the Western Ghats that exhibit the extremes of isotopic contamination amongst the entire Deccan are the Ambenali (least contaminated: SiO_2 = 50%, $^{87}Sr/^{86}Sr$ = 0.704) and Bushe (most contaminated: SiO_2 = 54%, $^{87}Sr/^{86}Sr$ = 0.716) formations. It is somewhat peculiar that in spite of being most contaminated (isotopically) Bushe basalts are more "primitive" (i.e., greater Mg#) than the Ambenali formation. Here we report the results of an experimental crystallization study at 1 atmosphere under controlled oxygen fugacity (QFM buffer) on two representative samples from Bushe and Ambenali formations. Our goal was to evaluate the effect of contamination on the liquid line of descent for these spatially related Deccan tholeiites. We additionally selected an intermediate starting material from the Neral formation, which is moderately contaminated (SiO_2 = 51.5%, $^{87}Sr/^{86}Sr$ = 0.708). The chosen starting materials are either aphyric (Bushe1), or sparsely phyric with less than 5% phenocrysts (Neral: Amb005; Ambenali: CAT36). The sequence in which various crystalline phases appear in the experiments are sharply different between Bushe (pigeonite àpigeonite + olivine+augite+plagioclase àpigeonite+augite+plagioclase), Neral (olivine àolivine + augite àolivine+ augit + plagioclase), and Ambenali (plagioclase àplagioclase+pigeonite+augite àplagioclase + augite). The new data allow the construction of a phase diagram olivine augite silica (projected from plagioclase), in which the pigeonite liquidus field is significantly expanded relative to previous experimental studies on tholeiitic basalts or basaltic andesites. In this diagram Bushe and Ambenali lavas plot in distinct fields with Bushe plotting inside the pigeonite liquidus field, whereas Ambenali lavas plotting along olivineplagioclaseaugite pseudocotectic curve. Bushe lavas are generally aphyric or have rare pigeonite microphenocrysts. Although the Neral starting material is aphyric, many Neral lava flows do contain plagioclase + altered olivine phenocrysts. Combining this lava information with experimental liquidus and/or phase appearance temperatures, we surmise that the lavas in general erupted at temperatures of 1130 1160°C. The conformity of the phases found in Ambenali and Neral experiments with the lavas supports the hypothesis that these lavas have undergone effective crystalliquid sorting/mixing

processes in the shallow crust. However, Bushe's plotting inside the pigeonite field requires that these melts never "saw" the low pressure pseudocotectic curves. Occurrence of only pigeonite on the liquidus of Bushe lavas, their aphyric nature, greater silica and Mg# (relative to Ambenali) suggest that the contamination process was responsible for driving Bushe magmas inside the pigeonite liquidus. Based on our phase equilibrium study we conclude that Bushe parent magmas were contaminated with a silicic melt within the shallow crust (620 km) so that its compositions fell inside the pigeonite field. The absence of phenocrysts in Bushe lavas could suggest rapid rise of these lavas following contamination, perhaps using a completely different plumbing system (than the other Deccan formations) so that distinctive pigeonite phenocrysts never had a chance to form.

INTRODUCTION

Two large features that immediately stand out in the geologic map of the Indian subcontinent are the Deccan Trap flood basalts, which cover much of the peninsular India [Fig. 1], and the Himalayan mountain belt. De (1964 to 1994) made some outstanding contributions to the study of the Deccan that spanned over four decades, which included the discoveries of upper mantle xenoliths and silicate liquid immiscibility in the Deccan. He was also the first one to speculate that the extreme fractionation in the famed Skaergaard intrusion may have resulted from late stage twoliquid immiscibility between a Ferich and an alkalirich silicate liquids (De 1974). This was verified and substantiated by laboratory experiments and geochemical analyses by McBirney (1975).

Two factors about the Deccan lava province make its study particularly attractive: First is its enormous volume the original volume of the erupted lavas could have exceeded 2 million cubic kilometers. Second is the timing of their eruption: the bulk of the lavas erupted at the K/T stratigraphic boundary [cf. Hofmann et al. 2000]. Deccan is one of several flood basalt eruptions on continents that have punctuated the earth's geological history. Many speculations and hypotheses have been offered in the literature as to their effect on global climate and mass extinctions and about the probable events that led to such large scale melting in the mantle that generated their parent magmas [Caldeira and Rampino 1990]. One model that appears to have gained popular support

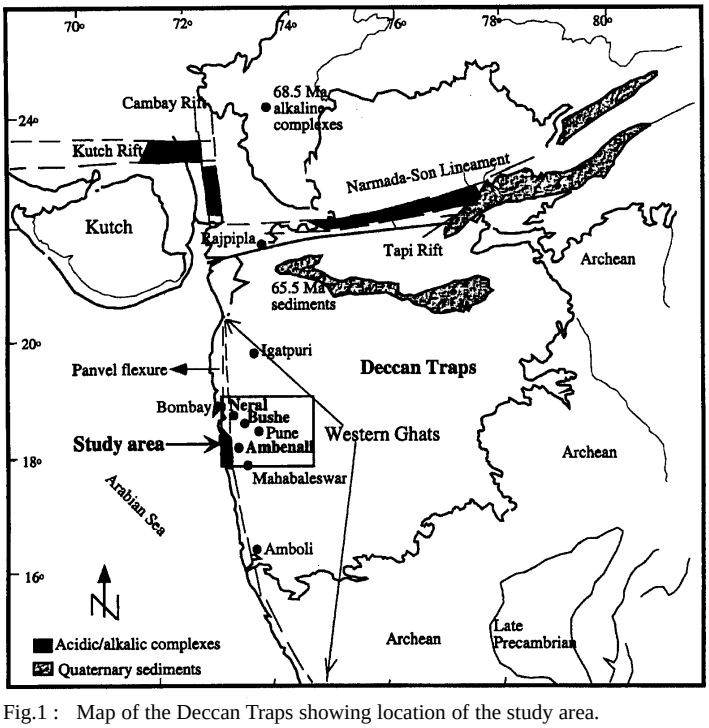

Fig.1 : Map of the Deccan Traps showing location of the study area.

is the "plume head" model, which suggests that throughout earth's history deep mantle plumes have episodically come up from the coremantle boundary and produced flood basalt eruptions. As a plume rises it develops a large "head" and a long "tail" [Richards et al. 1989]. As the plume head approaches the lithosphere it melts and produces flood basalt magmas, and the tail produces a chain of hot spot generated volcanoes on a moving lithosphere. Variations on this model have suggested the plume initiation source area to be the lower mantle or the transition zone. An alternative model to this plume head hypothesis is the shallow melting hypothesis led by D.L. Anderson [Anderson et al. 1992, Sheth 1999], which suggests that any large continental lithospheric plate is an effective insulator and can effectively shield heat from escaping from the mantle, forcing heat to build up in a zone below the lithosphere. Eventually such heat buildup leads to melting and splitting of continents. Several hypotheses have also appeared in the literature as to the nature of the source materials (eclogite ± lherzolite, recycled slab materials etc.) and the processes [hydrous, H_2O+CO_2 bearing vs. volatile free melting, Gallagher and Hawkesworth 1992; White and McKenzie 1995; Takahashi et al. 1998].

The large volume and predominantly tholeiitic composition of the lavas are two common characteristics to almost all of the flood basalt provinces; however, there are significant differences between these provinces in terms of their erupted products and eruption styles for example, picritic basalts that are common in the lower part of the Deccan are essentially absent in the Columbia River Basalt Group [CRBG] of northwestern United States [Hooper 1990]. Also, basalts belonging to the latter province are predominantly basaltic andesites.

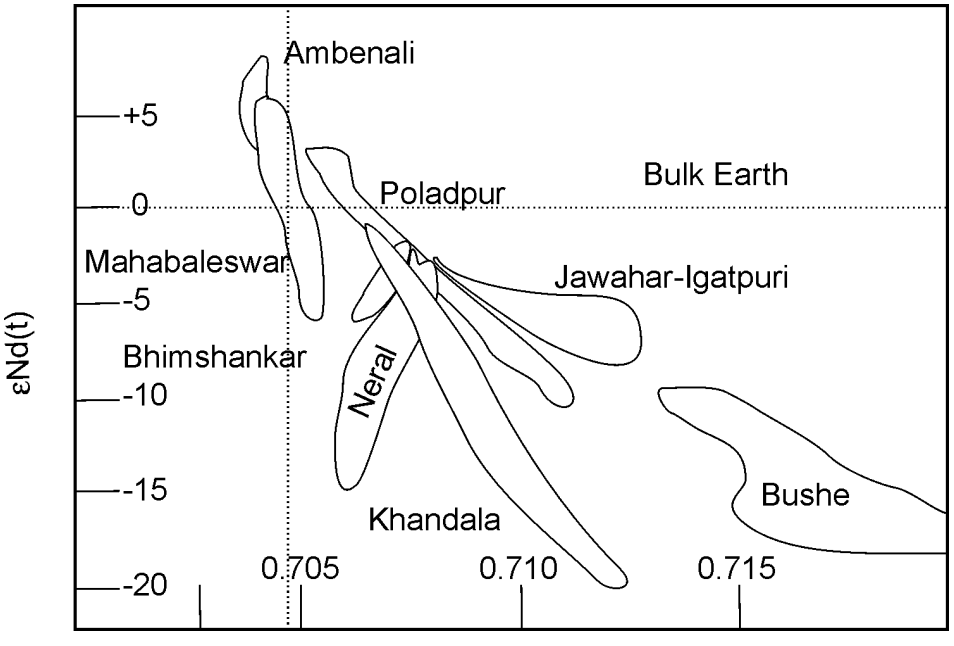

Fig. 3 : Sr-Nd isotope relations between various Deccan basalt formation of the Western Ghats (refs. cited in the text).

Fig. 2. Simplified stratigraphic subdivisions and geochemical characteristics of the western Deccan flows (compiled from Peng and Mahoney (1998) and Beane et. al. (1986))

Subgroups	Formations	Phenocrysts	Mg#[§]	TiO_2	Ba/Nb	$^{87}Sr/^{86}Sr$
	Panhala (>175 m*)	?				
Wai	Mahabaleswar (280 m)	ol[¥], cpx, pl	~ 0.45	2.75 - 1.65		0.7055 - 0.7060
	Ambenali[†] (500 m)	ol, cpx, pl	0.39-0.52	2.75 - 1.65	4.75-12.86	0.7040 - 0.7050
	Poladpur (375 m)	ol, cpx, pl	0.38-0.49	2.75 - 1.65		0.7060 - 0.7100
Lonavala	**Bushe** (325 m)	ol, plag, rare cpx	0.51 - 0.65	0.90 - 1.65	25 - 38	> 0.7100
	Khandala (140 m)	alternate aphyric and phyric (ol, pl ; very rare cpx)	0.38 - 0.59	highly variable; most commonly 1.65 2.75		commonly 0.7060 - 0.7100
	Bhimashankar (140 m)	ol, pl	0.40 - 0.45	1.65 2.75 (Up. Fms.??)	0.7100	0.7060 -
	Thakurvadi (650 m)	ol, cpx (Up. Fm.) ol, pl (L. Fm.)	0.29 - 0.63	1.65 - 2.75		0.7060 - 0.7100
Kalsubai	**Neral** (100 m)	aphyric, in some rocks mostly ol; sometimes with cpx and pl; rare opx	0.43 0.61	most commonly 0.90 1.65	8.4 - 18	0.7060 - 0.7100
	Igatpuri (?)	ol ± pl	0.35 0.57	2.75 3.60 (Up. and L. Fms)		> 0.7100
	Jawahar (>700 m)	ol ± pl	~ 0.37	0.90 1.65 (Up. Fm.) and 2.75 - 3.60 (L. Fm.) 0.9 1.65 (M. Fm.)	0.7055 - 0.7060	

* The values in parantheses are maximum thicknesses.

† Samples collected for the present study are from the formations in bold.

§ Molar Mg number calculated as $Mg/(Mg + Fe^{2}+)$.

¥ Abbreviations are listed under List of Abbreviations (Page xiii).

Δ Up., L. and M. Fm indicate upper, lower and middle formations respectively.

Similarly, the Siberian Traps contain many tuffaceous layers and a special type of hydrous biotitebearing lava (meimechites, Arndt et al. 1995), while such things are absent in both Deccan and the CRBG. Therefore, it would not seem appropriate to group all flood basalt provinces into one and expect a single petrogenetic scheme to explain all the petrologic features of all of them. The case for the involvement of water and hydrous phases is particularly strong for the Siberian case, whereas, volatiles may not have played as significant a role in the origin of Deccan tholeiitic magmas [e.g., Sen 2001].

The thickest sequence of Deccan Trap lavas occurs in the Western Ghats area (1.2 km, Fig. 2) near Mumbai. A significant number of geochemical, isotopic and petrologic studies have been carried out on the Western Ghats (cf. Sukheswala and Poldervaart 1951; Deshmukh et al. 1977; Najafi et al. 1981; Mahoney et al. 1982; Cox and Hawkesworth 1985; Beane et al. 1986; Sen 1986; Subbarao 1988; Sethna and Sethna 1988; Lightfoot et al. 1990; Peng et al. 1994). These previous studies have shown that the Deccan basalts at the Western Ghats have been variably contaminated by the continental crust as indicated by the large variations in isotope ratios of Sr, Nd, and Pb [Fig. 3]. Among the various formations, Ambenali and Bushe formations are particularly interesting: while the voluminous Ambenali formation lavas (SiO_2 = 4950 wt%, $^{87}Sr/^{86}Sr$ = 0.704) do not appear to be contaminated, Bushe lavas are characterized by maximum contamination, as

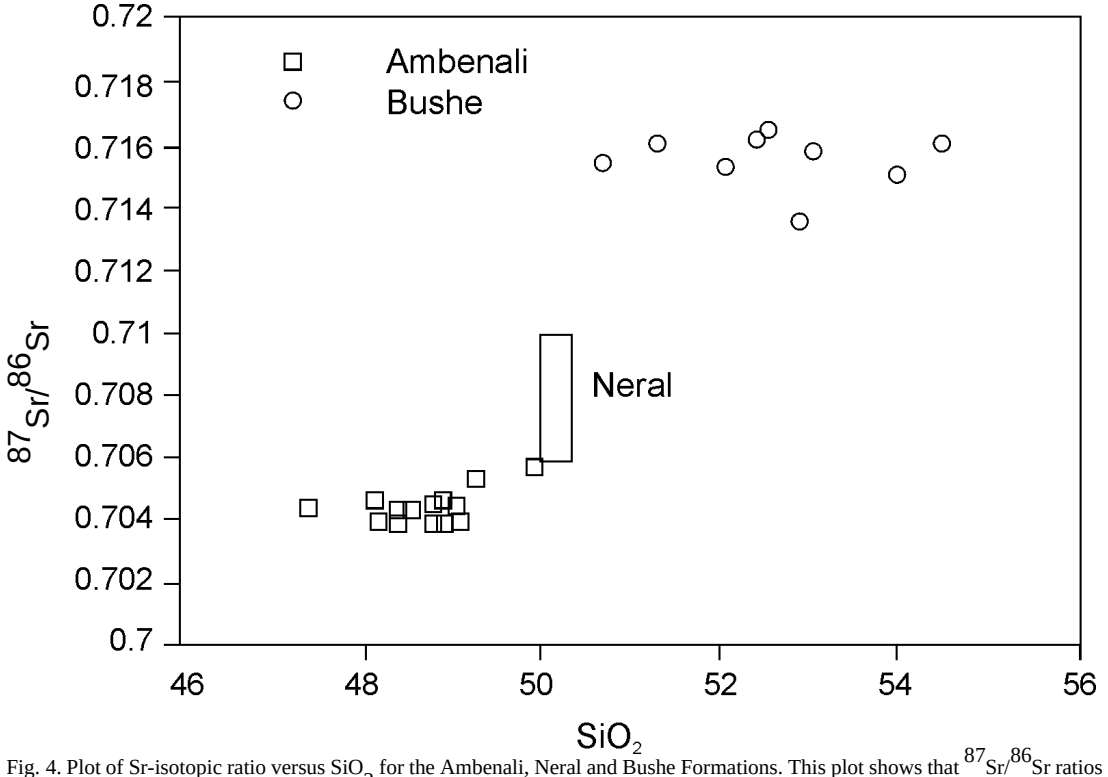

Fig. 4. Plot of Sr-isotopic ratio versus SiO_2 for the Ambenali, Neral and Bushe Formations. This plot shows that $^{87}Sr/^{86}Sr$ ratios progressively increase with increasing SiO_2 content. The field of Neral is plotted based on data from Beane (1986).

indicated by their high SiO_2 content (5354 wt%)and unusually high $^{87}Sr/^{86}Sr$ (0.716; Fig. 4; Cox and Hawkesworth 1985; Beane et al. 1986; Lightfoot and Hawkesworth 1988; Peng et al. 1994). One particularly intriguing aspect of the Western Ghats lavas, including those belonging to Bushe and Ambenali, is that there is a positive correlation between contamination indicators (such as, $^{87}Sr/^{86}Sr$, Ba/Zr, K) with such compositional parameters as Ni and Mg/Fe ratio, which decrease with increasing differentiation (e.g., Mahoney et al. 1982; Mahoney 1988; Sen 1986; Devey and Cox 1987). This is opposite of what would be expected in a typical AFC (assimilation coupled with fractional crystallization) process, if all these magmas had a common parent magma. Two studies specifically explored the reasons for such compositional peculiarity of the Deccan because of its potential significance in the Deccan "plumbing system" (Devey and Cox 1987; Sano et al. 2001).

Here we report an experimental crystallization study of starting materials from Bushe and Ambenali at 1 atmosphere pressure and under controlled oxygen fugacity (QFM buffer). We also included in our study a starting material from the Neral formation that falls in the middle between Bushe and Ambenali in terms of their isotopic rations and overall geochemistry (e.g., Cox and Hawkesworth 1985). Our results show that the liquidus field for pigeonite is expanded for the Deccan basalts with Bushe compositions distinctly falling inside it. We favor a model in which the Bushe parent magmas underwent contamination and fractional crystallization in deeper crust and rapidly ascended the surface while fractionating olivine.

Table 1 : Representative bulk chemical data obtained through EPMA and XRF data[&] reported from Washington State University in bracket [ ].

	CAT 036	AMB005	Bushe-1
SiO_2	49.61 [50.19]	51.53 [49.38]	53.89
TiO_2	2.96 [2.65]	3.34 [3.000]	1.08
Al_2O_3	13.70 [13.86]	11.97 [14.36]	15.07
FeO	13.97 [13.91[§]]	14.81 [14.54[§]]	10.31
MnO	0.22 [0.23]	0.22 [0.23]	0.19
MgO	5.67 [5.65]	5.05 [5.58]	7.43
CaO	10.98 [10.27]	9.34 [9.18]	9.64
Na_2O	2.48 [2.51]	2.19 [2.29]	2.32
K_2O	0.26 [0.33]	0.89 [0.97]	0.81
P_2O_5	0.22 [0.25]	[0.31]	
Total	100.06 [99.85]	99.34 [99.84]	100.73

§ The original XRF data (having both FeO and Fe_2O_3) were recalculated to FeO as total Fe on the basis of FeO (as total Fe) = FeO + 0.8995 * Fe_2O_3.

& Complete bulk chemical analyses for CAT 036, AMB005 and Bushe1 are presented in Appendix VII.

EXPERIMENTAL AND ANALYTICAL TECHNIQUES

Our starting materials were either totally aphyric (Bushe1) or moderately phyric (~ 1% phenocrysts). We first performed petrography and electron probe analysis of the minerals in each starting rock sample, using standard procedures outlined in Sen and Presnall (1984). The freshest cmsized chips were ground to a fine powder first in a tungsten carbide ball mill and then in acetone in an agate mortar. They were stored in a drying oven at 110°C for later use in experiments. Major element analyses (Table 1) of the starting materials were obtained by an electron microprobe following techniques of Gangopadhyay (2000).

The crystallization experiments were performed in a Ptwound, one atmosphere gasmixing furnace housed in the Experimental Petrology Laboratory at Florida international University. The furnace was calibrated against the melting temperature of diopside taken to be 1391.5, although diopside shows a small melting loop. A Pt/Pt$_{87}$Rh$_{13}$ thermocouple was used and the temperature was controlled within +/ 1°. The hot spot was also calibrated; and the radial temperature gradient (i.e., T_{center} T $_{inner}$ edge / tube radius) ranged within +/ 2°C. For each experiment an optimum amount of rock powder (0.19 g) was compressed into a pellet, which was then hung from a Pt wire (0.05 mm thick) loop centered at the hot spot of the furnace. Each run was performed in two steps: first it was held at about 100° above the liquidus for an hour and then the temperature was reset to the desired run temperature and held there for the duration of the run. Oxygen fugacity was controlled using appropriate mixtures of high purity CO_2 and H_2 gases (details in Gangopadhyay 2000). Oxygen fugacity during a run was monitored with a zirconiumtipped (type DL) oxygen fugacity sensor (manufactured by Australian Oxytrol Systems^{TM}). Runs were quenched in distilled water, and the charges were mounted on a slide, polished, and inspected first with a reflected light microscope and then with the electron microprobe (first with our ARL SEMQ and later reanalyzed with the JEOL 8900R Superprobe located at FCAEM). As pointed out by Grove (1981) and others, Feand Naloss during a run are potentially difficult problems in this type of experiments. On the other hand, Presnall and Brenner (1974) considered such Feloss due to solid solution with Pt is generally insignificant in wire loop techniques. In all our runs, we monitored the loss of Fe and Na by (1) comparing microprobe analysis of the fused glass with ICPES and XRF bulk analyses (Gangopadhyay 2000). Following Yang et al. (1996), we used larger amount of the sample (150200 mg), relatively lower rate of gas flow (~0.1 ml/sec) and reasonably short run durations to minimize sodium volatilization. We found that Na loss was highly variable in our runs. We also made multiple runs at the same T and fO_2 conditions to evaluate the extent of Fe and Na losses. The use of extremely thin Pt wire loop allowed us to constrain the extent of Feloss to the Pt. However, in some extreme cases we noticed that as much as 8% (relative) Fe was lost, only a very small part of which could be attributed to analytical uncertainty.

Electron probe analytical conditions were: 15 kV accelerating potential, 25 nA beam current, 1 μm beam diameter, and 15 secs counting time. Standards used were: BHVO1 (for glass), Lake County plagioclase (USNM# 11590), San Carlos olivine (USFHCJ), synthetic TiO_2 and MnO, enstatite, augite (USNM#117733), chromite (UC, Berkeley,

Table 2a. : Details of experimental conditions and mineral crystallization sequence with phase proportions for basalt from the Ambenali Formation (CAT036)

Run#	Temperatures (°C)		Run duration (hours)	fO_2	Phases present[§]	Phase proportions[¥]
CAT036						
	8	1165	14	QFM	gl	
- - - - - - - - - - Liquidus (~1160°C) - - - - - - - - - -						
	15	1155	9. 1	QFM	gl, pl	99:tr
	5	1150	3.1	QFM	gl, pl	98:2
	14	1145	15.1	QFM	gl, pl	95:5
	33	1141	11.8	QFM	gl, pl	94:6
	31	1139	10.2	QFM	gl, pl	92:8
	30	1137	10.8	QFM	gl, pl	91:9
	12	1135	2.4	QFM	gl, pl	90:10
	32	1133	6.7	QFM	gl, pl	90:10
	28	1131	10.8	QFM	gl, pl	88:12
	27	1129	11.5	QFM	gl, pl, pig, aug	87:12:tr:tr
	26	1127	4. 5	QFM	gl, pl, pig, aug	83:13:2:2
	9	1125	11.9	QFM	gl, pl, pig, aug	81:13:3:3
	6	1100	18.5	QFM	gl, pl, aug	74:18:8
	10	1075	11.7	QFM	gl, pl, aug	68:20:12

[§]Abbreviations used: gl = glass, pl = plagioclase, pig = pigeonite, aug = augite, tr = trace amounts.
[¥]Visual estimation using SEM

#5239), and orthoclase (Ingamells). We took BSE pictures of the charges first, and then analyzed multiple spots on each phase in a given run and from different parts of the charge

Tests for Equilibrium.

The runs made are all synthesis runs and reversal experiments were not done. At any rate, in a multivariate system equilibrium cannot be unequivocally established. Given that background, we believe that equilibrium was achieved in the runs listed here (Table 2) for the following reasons: (1) Phases were homogenous (within analytical uncertainties; Fig. 5), with the exception of augite, which showed some zoning in Al. In one run zoned pigeonite (B13) was present. (2) The sequence in which various phases appeared and their modal proportions were all internally consistent. (3) Partition coefficients for Fe

Table 2b. : Details of experimental conditions and mineral crystallization sequence with phase proportions for basalt from the Neral Formation (AMB005)

Run#	Temperatures (°C)	Run duration (hours)	fO_2	Phases present[§]	Phase proportions[¥]
AMB005					
1	1180	11.3	QFM	gl	
9	1165	21.7	QFM	gl	
2	1155	20.5	QFM	gl	
7	1145	22.8	QFM	gl	
3	1135	23.8	QFM	gl	
8	1130	37.1	QFM	gl	
			————————Eruption temperature ??1127°C ---		
- Liquidus temperature (~1127°C) - - - - - -					
4	1125	23.1	QFM	gl, ol	96:4
5	1115	18.7	QFM	gl, ol	94.6
6	1100	21.7	QFM	gl, ol, aug	86:8:6
10	1075	20.7	QFM	gl, ol, aug	80:10:10
11	1050	21	QFM	gl, ol, aug	65:20:15

[§]Abbreviations used: gl = glass, ol = olivine, pl = plagioclase, aug = augite
[¥]Visual estimation using SEM

←→Mg exchange for Aug/L and Pig/L and for Ca ←→Na exchange for Plag/L were within expected equilibrium values (cf. Thy et al. 1999; Durand and Sen 2003).

RESULTS

Phase Appearance

Ambenali (CAT 36 starting material): We estimate the liquidus temperature for this starting material to be 1160° (+/ 4°)C (Table 2a). This is identical to the liquidus temperature obtained by Sano et al. (2001) for a more magnesian starting material (MAW25, MgO = 6.7 wt%) from the Ambenali formation. Plagioclase is the liquidus phase that makes its appearance at 1155°C and at 1129°C, a multiphase assemblage L+pl+pig+aug appears in our experiments at QFM buffer. This phase appearance sequence is significantly different from that in Sano et al.'s experiments that were also run at FMQ buffer, in which the assemblage ol+pl+aug appears at the liquidus. While the difference in phase assemblages between the two sets of experiments can be explained in terms of different degrees of "primitiveness" (e.g., Mg#) of the starting materials, the difference in the liquidus temperature is not easily understood. It is possible that the starting material we used actually represents a slightly plagioclaseenriched composition (i.e., exotic

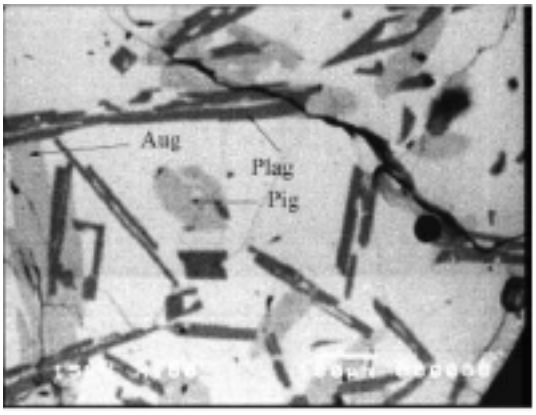

Fig. 5. Back scattered electron image of a charge (scale shown in bottom right of the picture). It contains largely melt (glass) with abundant plagioclase (dark, long crystals), augite (large, prismatic crystals), and pigeonite (short, subprismatic crystals).

plagioclase accumulated composition), which would account for the high liquidus temperature and also for having plagioclase as the only liquidus phase with an extended crystallization interval. Plagioclase phenocrysts are highly heterogeneously distributed in the erupted lavas of Ambenali (e.g., Beane 1986). It is possible that the rock powder we prepared from a 10 g rock chip may have contained "extra" plagioclase. We checked the three separate thin sections of this rock, and two of them were aphyric whereas the third one contained a plagioclase phenocryst. Thus, we feel that the liquidus temperature obtained by Sano et al. is more appropriate for the average eruption temperature of the aphyric lavas of Ambenali.

Neral Formation (AMB 005): The liquidus temperature of this starting material is established at 1127°C (+/2). The liquidus phase is olivine, quickly followed by augite (Table 2b). Surprisingly, in contrast to Ambenali and Bushe, the Neral starting material did not crystallize plagioclase even at a temperature of 1050°C. Olivine and augite had a large temperature interval.

Erupted lavas belonging to the Neral formation are generally aphyric; however, in some lavas olivine (altered), augite and plagioclase microphenocrysts are rarely found. Thus, our experiments would suggest that aphyric Neral formation lavas erupted at a temperature above ~1130°C.

Bushe Formation (Bushe1) : We did not obtain a tight constraint on the liquidus temperature of this starting material, which is estimated to be 1167° C(+/12°C). Here, pigeonite+olivine are the liquidus phases. Augite joins the crystallization sequence, followed by plagioclase (Table 2C). The large range in temperature over which the two pyroxenes appear is remarkable.

Phase Diagram

Phase analyses of selected runs are presented in Table 3. We note that plagioclase in all runs was homogeneous but both and pigeonite were found to be heterogeneous with respect to Alcontent. As indicated earlier, some of our experimental melts suffered significant Feloss (as much as 8%) and therefore could not use those runs for constructing an appropriate phase diagram for Deccan basalts. We screened the analyses in order to test for chemical equilibrium between glass and mineral phases, glass analyses in a series of runs that provide an appropriate liquid line of descent, and homogeneity of the glass in general.

Figure 6 shows an oxygennormalized diagram cpx+ol+qz (plagioclase saturated) based on selected glass analyses from our runs. The olivine+augite (+plag) pseudocotectic curve is based on our Neral experiments. The

Table 2c. : Details of experimental conditions and mineral crystallization sequence with phase proportions for basalt from the Bushe Formation (Bushe1)

Run#	Temperatures (°C)	Run duration (hours)	fO_2	Phases present§	Phase proportions¥
Bush1					
7	1180	14.8	QFM	gl	
- - - - - - - - - - - -				Liquidus (~1167°C) - - - - -	
8	1155	16.7	QFM	gl, pig	95:5
9	1145	27.8	QFM	gl, pig, aug	93:7:tr
10	1135	17.3	QFM	gl, pig, ol, pl	90:9:tr:tr
15	1130	65.4	QFM	gl, pig, aug, ol, pl	87:10:2:tr:1
		——Eruption temperature (11271140°C)——			
11	1125	16.8	QFM	gl, pig, pl	85:11:4
14	1118	49.3	QFM	gl, pig, aug, pl	80:12:2:6
12	1115	18.3	QFM	gl, pig, aug	79:12:7
13	1105	21.8	QFM	gl, pig, aug, pl	70:13:7:10

§ Abbreviations used: gl = glass, ol = olivine, pig = pigeonite, pl = plagioclase, aug = augite, Ti-mgt = titanomagnetite.

¥ Visual estimation using SEM

augite+pigeonite (+plag) curve is based on We compare our phase diagram with the well known diagram presented earlier by Grove and Baker (1984). Our experiments indicate that the pigeonite liquidus field is somewhat more expanded for the Deccan basalts. Although we have made some repeat runs, we did not actually "reverse" any experiment in the sense we did not approach a particular run temperature form both superliquidus and subsolidus directions.We also note that in a multicomponent system with so many variables, it is not reasonable to trulty reverse any equilibrium reactioh. Neverthless, based on internal consistency in phase appearance, particularly, systematic behaviour of pigeonite, we think that the expansion of pigeonite+ liquid field for the Deccan bgasalts is real.

DISCUSSION AND CONCLUSION

Sen (1995) pointed out that Bushe (most contaminated) and Ambenali (least contaminated) basalts plot in distinct fields when projected form plagioclase on to the triangle cpx- o1- qz. figure 6 shows this distinction,with Ambenali (and Neral) basalts falling outside the pigeonite liquidus field, overlapping the ol+aug+plag+liq pseudocotectic curve.The spread in the Ambenali field could be a result of several things - analytical uncertainty (particularly in

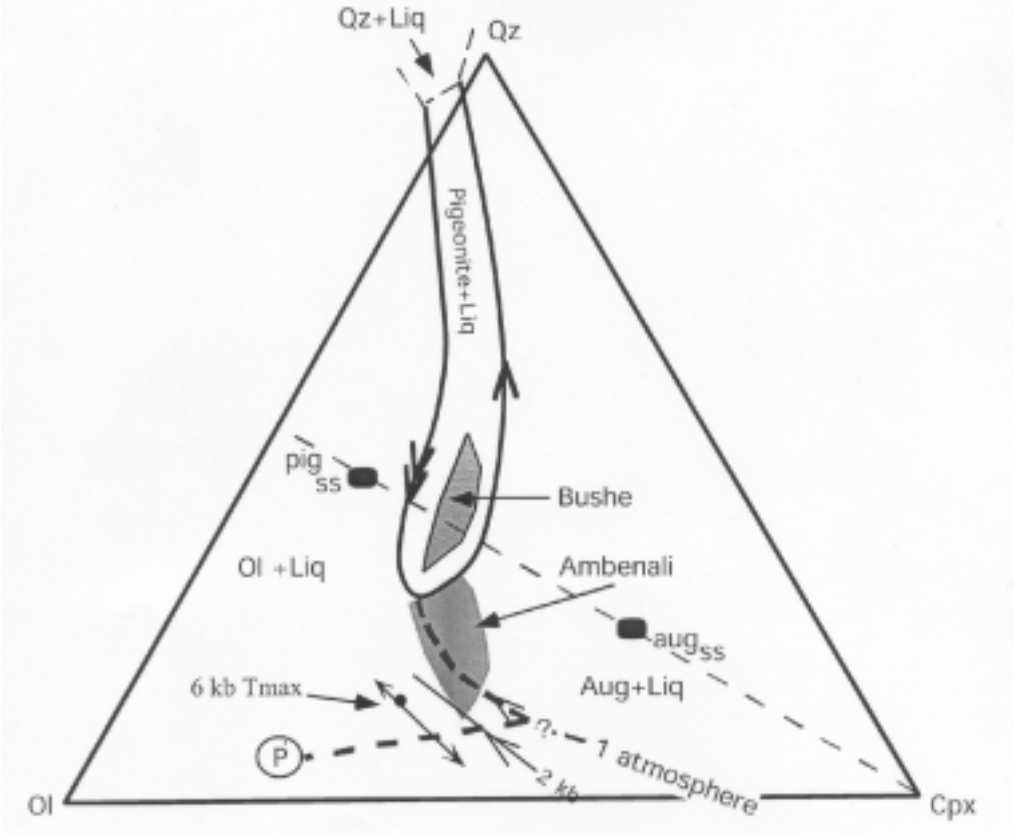

Fig 6. Olcpxqz (mole% oxygen normalized) diagram showing the pigeonite liquidus field based on pigeonite+augite+(plagioclase)saturated glass compositions in Bushe runs. This diagram shows that Bushe and Ambenali lavas plot in distinctively different fields. Ambenali lavas may be explained by low pressure (< 2 kbar) fractionation and mixing of melts derived from a more primitive magma "P". However, the Bushe plot requires a more complex expanation (see fig. 7).

Na and Si), mixing between ol+aug+plag saturated melts and differentiated melts saturated with aug+pig+plag. We show an example of aprimitive, olivihne-saturated, Ambenali magma [**P**] reaching shallow crustal chamber and differentiating via crystallization. this magma would first "drop off" crystals of olivine (±plag), followed by ol+aug+plag crystals. As the evolved melt reaches the pigeonite liquidus field, olivine would dissolve due to the reaction relation o1+liq→pig, as a result of which the differentiated liquid that is only satuated with pig+aug+plag would be free to move down the curve aug+pig+plag+liq. Mixing between such melts that have evolved to various degrees along such a liquid line of descent and less differentiated melts along the curve o1+aug+plag+liq could generate the entire field of ambenali in fig.6.

It is curious that Bushe basalts form a tight cluster well within the pigeonite liquids field. We note that the actual loocation of the curve aug+p8g+(Plag)+liq curve is not constrained by our experiments. Its location is based on Grove and Baker (1984). The phase apearance

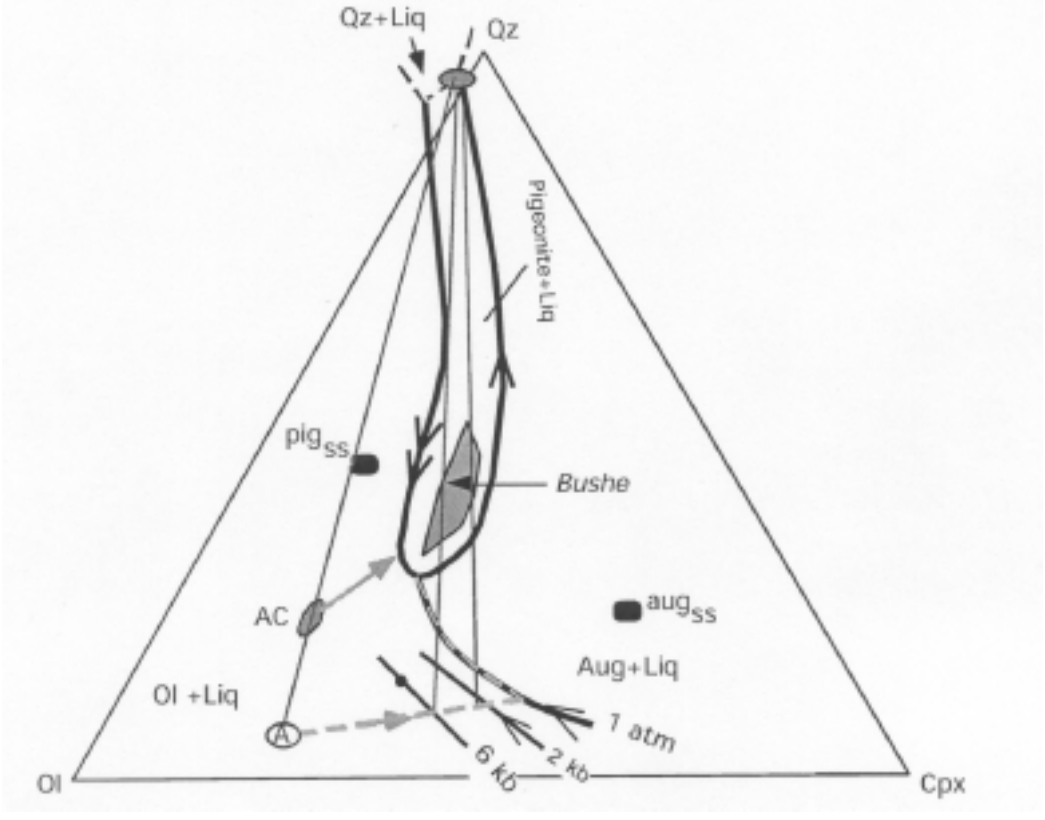

Fig. 7. Phase diagram depicting the effect of shallow contamination origin of the Bushe magmas. Note how the ol+aug+(pl) curve shifts toward olivine with increasing pressure. If the reasonable Deccan parent magma "A" is contaminated near the Moho (say, 15 kbar) by partially melting a lower crustal quartzgranulite (or other quartzbearing lithologies), then in such a scenario the contaminant melt would plot close to the quartzsaturated invariant point; and the contaminated Deccan magma (depending upon the nature of the mix of the contaminant vs. Deccan parent magma A) may plot at AC (or anywhere along that dashed line). This newly contaminated melt would fractionate olivine as it ascends toward the surface and eventually reach the saturation surface pig+ol+(pl). We noted that Bushe has only pigeonite as the sole liquidus phase, which is a severe constraint on its origin that certainly precludes such a lower crustal contamination scenario. By virtue of where Bushe lavas plot in this diagram, we can construct lower pressure scenarios in which the Deccan parent magmas fractionate olivine to about 6 2 kbar (upper crust) and are then contaminated by quartzsaturated contaminant melts (perhaps generated by partial melting of a granitic, sedimentary, or metasedimentary upper crust). Such contaminated magmas can actually fall within the pigeonite liquidus field if the proportion of the contaminant is approximately 3040% as shown. This is our preferred model.

sequence Liq→Liq2+Pig→Liq+Pig+Aug →Liq+Plag in our experiements is in accord with the observation that Bushe lavas cluster within the pigeonite liquidus field. Thus, the relative positions of the plagioclasesaturated curves aug+pig+liq and ol+pig+liq with respect to Bushe lavas are likely to be correct. The question then is: how did Bushe got to be that way? The evidence that Bushe parent magmas were strongly contaminated by the continental crust suggests that contamination may have had something to do with where they plot. We now explore various scenarios concerning contamination and differentiation.

Table 3a. : Representative microprobe analyses of glass and different phases appearing at different temperatures from starting material CAT36

Phases	n	SiO_2	TiO_2	Al_2O_3	FeO*	MgO	MnO	CaO	Na_2O	K_2O	Total
Run# 26 (1127°C)											
Gl	8	49.01 (0.98)	3.61 (0.3)	12.58 (0.31)	16.19 (0.82)	5.09 (0.34)	0.22 (0.01)	9.11 (0.34)	3.19 (0.11)	0.87 (0.02)	99.87
pl	2	53.49 (0.03)	0.18 (0.18)	30.32 (0.32)	1.51 (0.23)	0.23 (0.24)	-	11.7 (0.12)	3.36 (0.07)	0.08 (0.01)	100.9
pig	3	52.19 (0.51)	0.4 (0.09)	2.05 (0.21)	16.32 (0.87)	22.52 (0.45)	-	6.13 (0.27)	0.22 (0.03)	-	99.83
aug	4	50.56 (0.65)	1.22 (0.08)	3.05 (0.15)	12.24 (0.52)	18.7 (0.51)	-	13.8 (0.58)	0.11 (0.10)	-	99.68
Run#	9	(1125°C)									
gl	2	49.26 (0.76)	3.16 (0.08)	12.89 (0.82)	16.97 (0.06)	5.05 (0.60)	0.31 (0.02)	9.13 (0.23)	2.53 (0.17)	0.98 (0.05)	100.28
pl	6	51.79 (0.48)	0.11 (0.10)	28.56 (0.33)	1.35 (0.32)	0.14 (0.10)	-	13.34 (0.45)	4.58 (0.14)	0.12 (0.05)	99.99
pig	3	54.16 (0.71)	0.6 (0.32)	1.65 (0.26)	16.73 (0.67)	20.4 (0.57)	-	5.74 (0.19)	0.14 (0.08)	-	99.42
aug	3	51.29 (0.77)	0.98 (0.44)	3.41 (0.06)	11.89 (0.09)	16.44 (0.47)	-	15.71 (0.39)	0.30 (0.03)	-	100.02

Bushe magmas could not have evolved from parent magmas of Ambenali lavas at a low pressure, even if the latter magmas got severely contaminated by the crust (as is required by the isotopic compositions). This is because Bushe lavas have higher Mg# than Ambenali (cf. Cox and Hawkesworth 1985). That is because Assimilationfractional crystallization (AFC) processes show an inverse correlation between, say Srisotopic composition (a contamination indicator in this case) and Mg#, i.e., increasing $^{87}Sr/^{86}Sr$ should correlate with decreasing Mg#. Bushe has higher Mg# and higher $^{87}Sr/^{86}Sr$ than Ambenali lavas. Thus, a low pressure AFC model would not work for Bushe. By the same token, greater silica content of Bushe lavas relative to Ambenali lavas also needs to be explained.

Although we did not perform experiments at high pressures we can make reasonable guesses about what could have happened to Bushe parent magmas at greater depths. Based on many high pressure experiments by other authors, we can be confident about the fact that ol+aug+liq (±plag) shifts toward olivine

Table 3b. : Representative microprobe analyses of glass and different phases appearing at different temperatures from starting material Bushe1

Phases	n	SiO_2	TiO_2	Al_2O_3	FeO *	MgO	MnO	CaO	Na_2O	K_2O	Total
Run# 14 (1118°C)											
gl	3	52.64	1.87	13.81	13.74	3.87	0.23	9.18	3.08	1.17	99.59
		(0.49)	(0.05)	(0.44)	(0.27)	(0.25)	(0.02)	(0.34)	(0.20)	(0.03)	
pig	4	54.51	0.37	3.18	11.28	23.36	0.30	6.46	0.09	-	99.55
		(0.34)	(0.09)	(0.13)	(0.52)	(0.33)	(0.01)	(0.28)	(0.07)		
aug	2	53.66	0.73	5.47	11.84	14.64	0.35	12.43	0.59	0.10	99.81
		(0.88)	(0.09)	(0.34)	(0.11)	(0.13)	(0.03)	(0.59)	(0.43)	(0.14)	
pl	3	52.53	0.06	27.80	1.28	0.22	-	13.79	3.99	0.24	99.91
		(0.43)	(0.02)	(0.31)	(0.09)	(0.09)		(0.20)	(0.21)	(0.04)	
Run# 13 (1105°C)											
gl	3	54.34	2.65	12.10	14.04	3.67	0.20	8.23	2.48	1.61	99.12
		(0.24)	(0.09)	(0.29)	(0.35)	(0.17)	(0.05)	(0.17)	(0.16)	(0.04)	
pig	3	53.65	0.54	1.79	17.68	21.4	0.35	5.16	0.13	0.01	
100.71											
		(0.39)	(0.14)	(0.24)	(0.27)	(0.18)	(0.04)	(0.14)	(0.08)	(0.02)	
aug	3	50.42	0.77	6.32	12.43	12.73	0.28	16.55	0.24	-	99.74
		(0.82)	(0.15)	(0.08)	(0.35)	(0.10)	(0.04)	(0.46)	(0.01)		
pl	3	55.01	0.18	24.28	1.31	0.24	0.04	12.36	5.36	0.37	99.15
		(0.62)	(0.06)	(0.28)	(0.11)	(0.03)	(0.04)	(0.13)	(0.08)	(0.04)	

in the olcpxqz triangle. Simultaneously, the pigeonite field would shrink dramatically. This dual effect of increasing pressure on the evolution is important to understand. It is also important to point out that Bushe parent magmas were probably contaminated by very little amount of perhaps granitic melt generated from a very old crust (the strong isotopic contamination signal, high silica and high Mg#: cf. Sen 1995).

Figure 7 shows a schematic example in which the same magma P (uncontaminated, Ambenaliparent) is contaminated at high pressure by a siliceous melt, which shifts the bulk composition of the contaminated magma toward the quartz corner. This contaminated magma may undergo further crystallization at high pressure or rise to a shallow chamber where it would first fractionate olivine crystals and then reach the boundary ol+pig(+plag) curve. The fact that olivine never crystallized from the Bushe magma suggests that such a path is

not appropriate for Bushe. One could propose more complicated scenarios such as mixing between such evolved ol+plag+pig saturated melts with evolved Ambenali melts saturated with aug+pig+plag, which could produce mixed melts with bulk composition within the pigeonite liquidus field. However, we would see some evidence of magma mixing within Bushe lavas. More seriously, Bushe lavas are largely aphyric! We suggest that a primitive melt such as P was contaminated by a granitic melt, which drove the bulk composition of the contaminated melts to where the Bushe lavas plot. We also speculate that the contamination process also introduced sufficient amount of dissolved water into the melt, which would keep the melt at or close to its liquidus temperature. Such a hydrous, mixed, contaminated Bushe melt rose rapidly through the crust in order to avoid degassing (that would have forced crystallization) and erupted on the surface. Their plotting within the pigeonite liquidus field was a matter of chance!

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This paper is my humble tribute to the memory of the late Professor Aniruddha De. Prof. De taught me how a really unassuming rock such as basalt can be so charming in gently giving out secrets of the way earth works. He also introduced me to the Deccan Traps and gave me a problem (study of feeder intrusions), which became a lifelong fascination for me. I was fortunate to share a room with him during a Deccan workshop and also to host Prof. and Mrs. De in Miami during one of their visits to the U.S. He always served as an inspiration to me. I am thankful for having the good fortune to be taught by one of the best teachers in this field. I will sorely miss the long conversations we used to have.

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