Enigmatic iron oxide-rich rinds in columnar basalts of Deccan Trap near Chincholi, Beed District, Maharashtra and their origin

The tholeiite lavas of Deccan Trap are in general sub-aerially emplaced in 92% geographical area of Maharashtra. It is a known fact that the lower part of the Deccan Trap stratigraphy consists predominantly of compound pahoehoe flows and the upper part consists of simple flows that are emplaced as flood lavas[1]. Distinct spatial distribution of the two lava types is also recognized across the main Deccan Volcanic Province (DVP)[2]. The compound pahoehoe flows are exposed in a roughly oval area between Pune–Dhule–Aurangabad–Ahmednagar, and the peripheral parts of the main DVP expose the simple flows[3,4]. In the west-central part of Maharashtra, pahoehoe flows are overlain by the simple flows. Such a scenario is seen in Beed District, Maharashtra, where six basaltic lava flows have been recorded[5]. Out of the six flows, the lowermost flow is pahoehoe and the remaining five flows are 'aa' flows. According to the Geological Survey of India, most of these flows belong to the Indrayani Formation of Sahyadri Group.

The study area lies in the eastern peripheral part of Chincholi village, Beed District (Figure 1). The basaltic flows here are of simple type, mostly dominated by thick massive cores. Within the cores of the basaltic lava flows, fairly regular cooling joints have developed and these have given rise to columnar structures. In plan, these columns show a zoned pattern with development of enigmatic circular or oval, highly oxidized reddish-brown rinds. The diameter of individual blocks from the inner core (of grey basalt) to the peripheral reddish rind varies from 3.5 to 17 cm (Figure 2).

Thin-section studies reveal that the basalt is composed of olivine, plagioclase, clinopyroxene, opaque minerals and glass. It is a fine to medium-grained basalt showing predominantly glomeroporphyritic texture. Glomeroporphyritic aggregates of olivine pseudomorphically replaced by iddingsite are seen in close association with clinopyroxene phenocrysts throughout the rock. Rarely fresh olivine grains are preserved. At places, glomeroporphyritic aggregates of phenocrysts of clinopyroxene and plagioclase are observed. The groundmass of the basalt is glassy to fine-grained and shows intersertal and intergranular textures. Glass in the groundmass shows devitrification. Olivine crystals are generally oval or elongated with characteristic cracks. Wherever the olivine is altered to iddingsite, fine, dusty opaques are found. The plagioclase phenocrysts are 0.5 mm to nearly 2 mm long with straight boundaries and show polysynthetic twinning. The plagioclase laths show no strain effects, except for a few irregular cracks. Some large phenocrysts show fine, dusty inclusions in the core. The clinopyroxene phenocrysts are large and appear to be sub-calcic augite (?) or piegonite. Most opaque mineral grains exhibit skeletal forms. They are evenly distributed throughout the basalt. A few large phenocrysts of opaques are also seen in the rock. They show plagioclase and orthopyroxene (?) inclusions. Thus, there appears to be two generations of opaques in the rock: one formed during magmatic crystallization and the other that got released during the replacement of olivine by iddingsite.

In the red-coloured rind portion, the minerals are stained reddish-orange (Figure 3). Observations under high magnification show an intricate network of

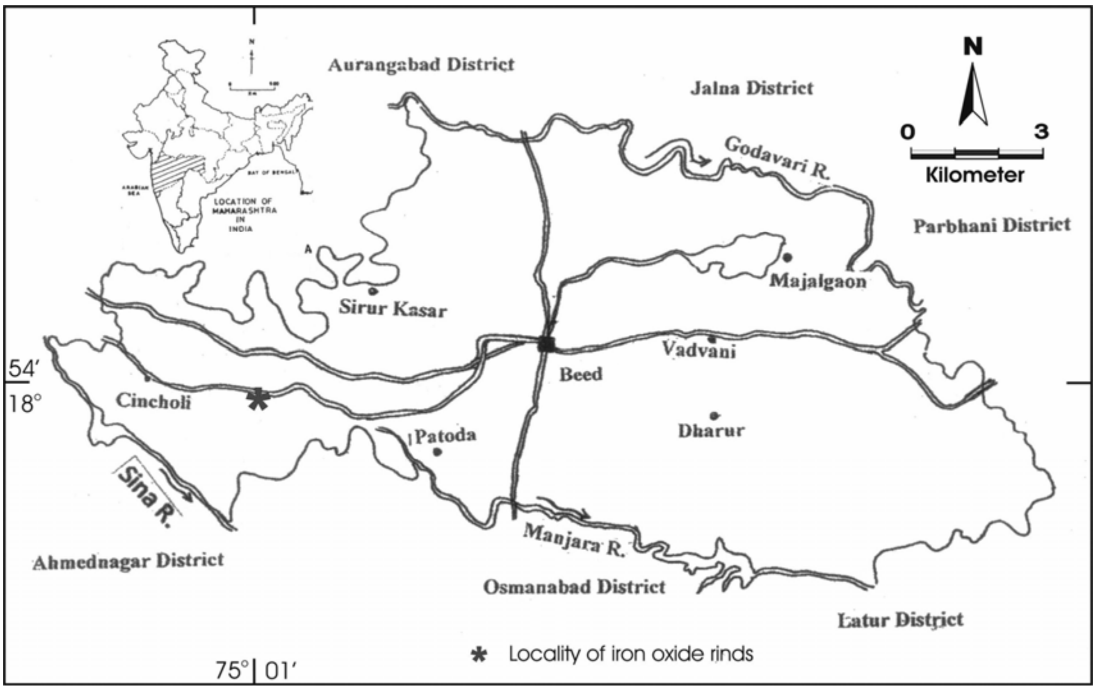

Figure 1. Map of Beed District, Maharashtra showing the location of enigmatic basaltic rinds near Chincholi.

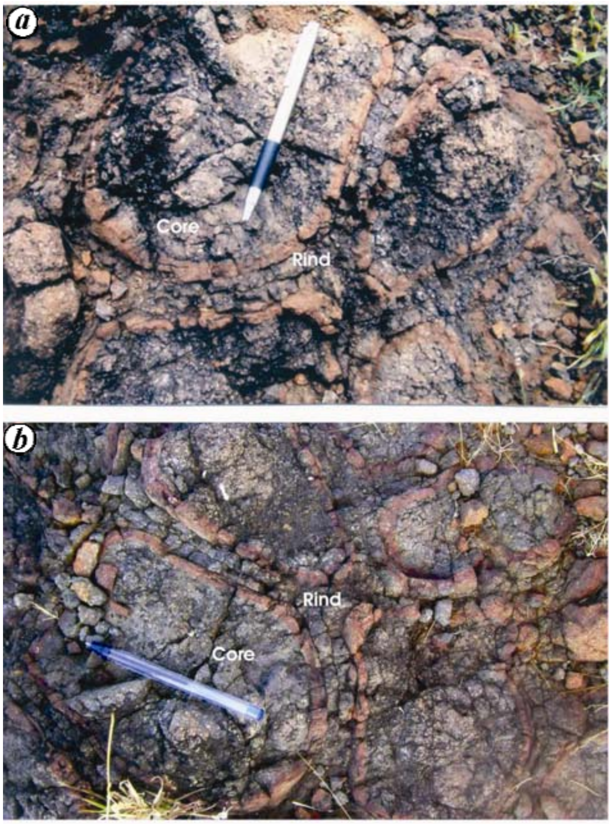

Figure 2. Field photographs of the enigmatic basaltic rinds.

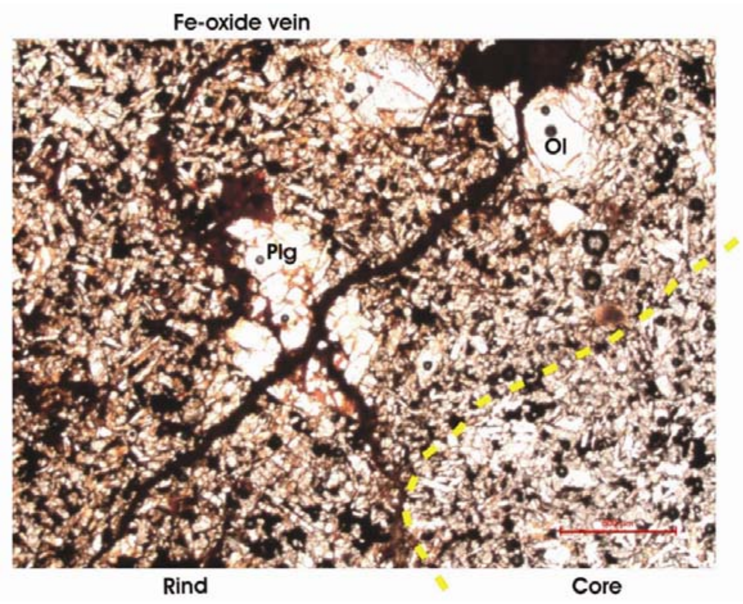

Figure 3. Photomicrograph of the basaltic rind–core contact. Note the distinct alteration in the rind compared to the clear core.

reddish-brown iron-oxide minerals in the rind basalt. The individual veins of iron oxide appear to be closely associated with large phenocrysts of opaques and pseudomorphically replaced olivine.

Two sets of sample were collected from the core and the rind of two columnar blocks for geochemical analysis. They were analysed using XRF method at the Department of Geology, University of Pune. Table 1 represents the major oxide (wt%) and selected trace elements (ppm) of the sample pairs. All samples are olivine normative. The Mg# for the core samples varies from 44.94 to 45.26, indicating that the basalt is fairly differentiated. Almost all major oxides (e.g. SiO_2, TiO_2, Al_2O_3, MgO, CaO and Na_2O), except iron, show a decrease from core to rind in the analysed samples. The FeO/MgO ratio increases from core to margin – from 2.58 to 5.19 in one pair and 2.54 to 4.15 in the second pair. The crystallization index (CI) of the first core–rind pair decreases from 60.30 to 41.36 and the second pair from 62.09 to 47.98. Most trace elements like Co, Cu, Sr, etc. tend to decrease from core to rind. In contrast, elements like Ni, Zn, Zr, Nb, Ba, etc. show variable behaviour. The systematic increase of Fe, V, Cr and to lesser extent Ni indicates that the opaques and olivines are involved in deuteric alteration of the basalt.

The rind structure in basalt under study bears some resemblance to the pillow lavas or hybrid columnar pillows[6], or to a cross-section of pahoehoe toes. At first glance it appears that the structures resemble stacks of pillow structures. Close observation, however, reveals that the bright oxide rinds are not distinctly more glassy as in the rinds of pillows or the outer layer of pahoehoe toes. The rind contains massive basalt similar to that in the core. The oval structure is also devoid of any zonal arrangement of gas vesicles or radiating joint patterns as in the pahoehoe toes and pillow lavas. The basalt with these structures does not show any quench textures, fretted plagioclase, etc. indicative of direct interaction of basaltic lavas with stagnant water. The absence of typical morphological and internal structure seen in pillows or pahoehoe toes negates the possibility of the present structures as having been inherited from either of the above structures after alteration.

The rind structures from Chincholi also resemble outwardly the columnar spheroidal structures seen in basalts of New Mexico[7]. In the New Mexico basalts, the spheroidal structures are developed by the interaction of meteoric water on water-laid volcaniclastic dykes. The olivines from the core and the rim of the spheroidal structures show distinct alteration pattern. In the core the olivines have altered to serpentine, whereas in the rim they have altered to iddingsite. There

Table 1. Major oxide (wt%) and selected trace elements (ppm) of basalt sample at Chincholi, Beed District, Maharashtra

	CCL1		CCL2	
Sample no.	Core	Margin	Core	Margin
SiO_2 (wt%)	48.69	46.29	48.26	46.94
TiO_2	2.89	2.75	2.83	2.68
Al_2O_3	13.98	13.48	13.26	12.71
Fe_2O_3	2.08	2.97	2.20	2.87
FeO	10.39	14.84	10.98	14.36
MnO	0.19	0.20	0.21	0.19
MgO	4.76	3.38	5.09	4.08
CaO	12.67	12.01	13.04	12.03
Na_2O	3.80	3.48	3.68	3.61
K_2O	0.29	0.37	0.24	0.32
P_2O_5	0.28	0.24	0.22	0.22
Total	100.02	100.00	100.01	100.01
Mg#	44.94	28.86	45.26	33.63
FeO^T/MgO	2.58	5.19	2.54	4.15
$Fe_2O_3/(Fe_2O_3 + FeO)$	0.17	0.17	0.17	0.17
Salic	47.61	43.96	43.64	42.19
Femic	31.73	29.26	33.51	31.42
DI	30.88	28.09	28.98	28.79
SI	22.32	13.49	22.95	16.18
AR	1.36	1.36	1.35	1.38
CI	60.30	44.86	62.09	47.98
Co (ppm)	49	41	50	48
V				
Ni	99	103	99	98
Cu	160	131	174	147
Zn	87	94	112	109
Sr	237	230	226	223
Zr	146	141	140	141
Nb	8.7	8.6	8.7	8.9
Ba	61	40	1	51

B. subal., Subalkali basalt; Salic, Sum of salic normative minerals; Femic, Sum of femic normative minerals; CI, Crystallization index; DI, Differentiation index; AR, Alkalinity ratio; FeO_3T, Total iron expressed as Fe_2O_3; Mg#, 100 $Mg^{2+}/(Mg^{2+} + Fe^{2+})$; Atomic FeO^T, Total iron expressed as FeO. CIPW norms are on an anhydrous 100% adjusted basis and using Fe_2O_3/FeO ratio after Middlemost[12] and the SINCLAS computer program[13].

is a decrease in the ferric–ferrous iron ratio from the rim to the core. These foregoing features are not recorded in the basaltic rind structures of Chincholi area, which suggests that the iron oxide rind here did not develop due to interaction with meteoric water as in the case of the New Mexico basalt.

The probable mechanism for the development of the enigmatic rind structure in the basalts at Chincholi is depicted in Figure 4. In the present study, the red-rimmed basalt has a textural and mineralogical similarity to the basalt in the core. However, the minerals in the rim are stained by a reddish-orange tinge, which can be attributed to an intricate network or fine meshwork of reddish-brown iron oxide. The veins of iron oxide appear to be closely associated with large phenocrysts of opaques and iddingsite pseudomorphs after olivine. On the basis of these observations we conclude that the veins were probably formed due to the high-temperature deuteric alteration of olivine and/or opaques, as suggested by Stephen *et al.*[8] According to them, high-temperature oxidation of basaltic olivine results in exsolution of iron from olivine lattice. The released iron oxide that was mobilized as criss-cross veins penetrated the groundmass and plagioclase phenocrysts (Figure 3). The fine mesh of highly oxidized iron gave the outer margins the typical reddish-brown appearance.

Discussion as to whether the deuteric alterations took place on homogeneous basaltic prisms or on an already differentiated, non-homogeneous prism is pertinent. In the first case, the deuteric alteration of homogeneous prisms would lead to alteration (reddening) of the entire prism or where partial, the alteration would be restricted exclusively to the outermost parts of the prism margin. Such alterations could exist in basaltic prisms in lava flows from the Deccan, but we confess to having seen none at the present. However, the field disposition of the Chincholi rinds supports the contention that deuteric alteration took place along a pre-existing circular front well within (inside) the basalt prism, sup-

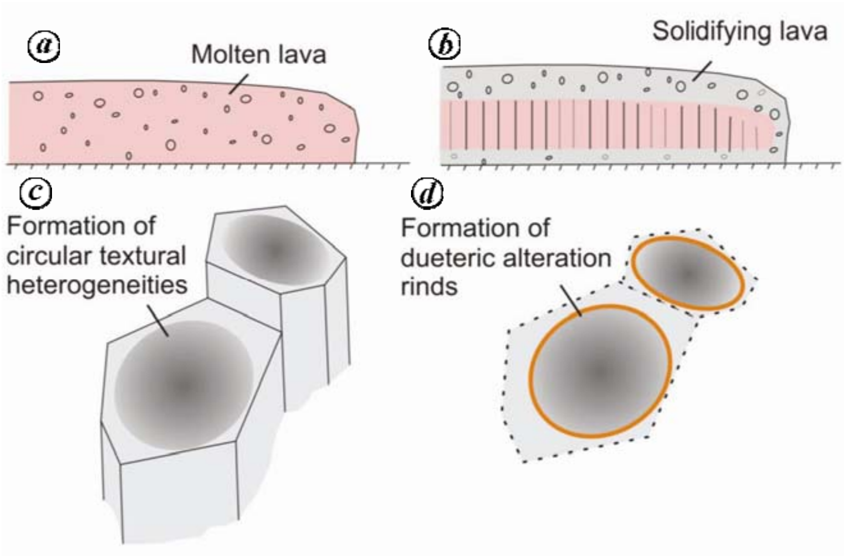

Figure 4. Cartoon depicting the stages in the emplacement of the Chincholi flow and the subsequent development of the enigmatic glassy rinds. ***a***, Eruption of lava and subsequent spread as lava flow. Note that almost all the lava is liquid and hence the vesicles are trapped within the liquid lava. ***b***, Solidification of lava flow into distinct vesicular crust, massive core and basal vesicular zone. Note that the flow solidified around the periphery, but is still molten within the core. ***c***, Compositional supercooling of lava flow with minor thermal contraction is responsible for the formation of prismatic columnar joints. Note that the liquid to solid or glass may have taken place during this phase. ***d***, Deuteric alteration occurs contemporaneous with prism formation in the presence of moisture/volatiles expelled from the solidifying liquid lava.

porting the non-homogeneous column hypothesis.

The deuterically altered basaltic columnar structures near Chincholi are a common feature in the simple flows in the Deccan Trap, as these structures are also seen at several localities in the Ahmednagar, Sholapur and Osmanabad districts. Similar structures have also been reported from basalts in Oregon, USA[9], Skaftafell Park, Iceland; Giant Causeway, Ireland; Saint Arcons d'Allier, Haute-Loire, France[10], etc. In columns or basalt prisms, circular or semicircular structures are ubiquitous features. Heterogeneities in columnar basalts are revealed by bubble circles or radiating structures within circular structures related to textural differences in size, shape, alignment of crystals, abundance of glass, etc. rather than compositional differences[10] that are attributed to melt migration driven by crystallization-induced pressure gradients[11].

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Causative fault of swarm activity in Nanded city, Maharashtra

Nanded city in Maharashtra is a part of the Godavari river basin and is located about 3 km north of the Godavari river. The Godavari river basin is bounded by the Manjira Tectonic Zone to the south and the Pranahita Godavari Graben to the north, both structures trending along the NW–SE direction. Further, the NW–SE trending Kadam fault lies to the north at a distance of 90 km and Latur lineament about 100 km south (Figure 1). The lineaments located within the study area are mostly oriented in the NW–SE, NE–SW, ENE–WSW and NNE–SSW directions[1]. A NW–SE trending minor linea-