Enigmatic spiracle-like structures from a basaltic flow near Chekewadi, western Deccan Volcanic Province

Physical volcanology of flows from the Deccan Volcanic Province (DVP) has recently gained considerable attention[1–3]. The study of the morphology and internal structures of ancient flood basalt lavas can shed considerable light on the duration and emplacement history of these flows[4]. Pahoehoe flows in the DVP are strongly compounded and were emplaced at low (< 5–10 m^3/s) volumetric flow rate[3,5] by the mechanism of inflation[2,6]. ‘Spiracles’ are lava structures found in pahoehoe flows that are formed due to the injection of steam into the flow interior when lava flows over moist (wet) ground or very shallow water bodies[7,8]. The photograph of one such structure from the Pench River has been published earlier[9]. The structures described in this paper are unique because this is probably the first report of water/steam injection features within a flow from the western DVP.

The northwest–southeast trending Baleshwar ranges dominate the area south of Pathardi, District Ahmednagar (Figure 1 *a*). Six lava flows are exposed in the Pathardi–Manikdaundi ghat. Lava

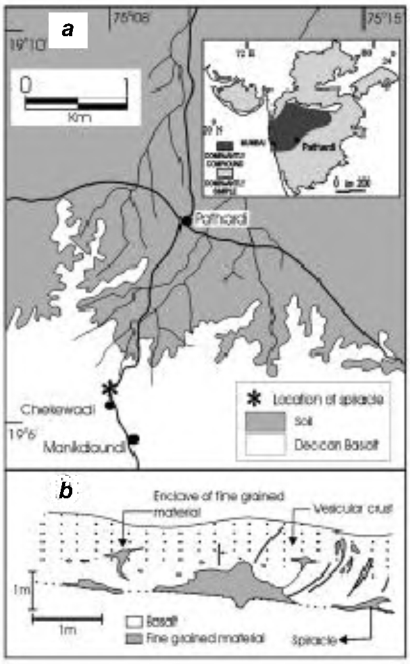

Figure 1. *a*, Map of the Pathardi area showing location of the spiracles. *b*, Schematic diagram of the outcrop near Chekewadi.

Figure 2. Field photographs of the fine-grained material and spiracle-like structures.

structures resembling spiracles are exposed near Chekewadi (19°06′19″N; 75°08′14″E) in a ~ 3 m thick sheet lobe at the base of the topmost flow (Figure 1 *b*). The lower vesicle zone of the sheet lobe is glassy and is devoid of pipe vesicles. A thick ~ 0.50 m layer of fine-grained material is exposed at the base (Figure 2 *a*). The fine-grained material is buff coloured and has a jointing pattern that resembles desiccated clay. A number of protrusions of the fine-grained layer rise into the lower surface of the flow. The structures are elongated, club-shaped and range in length from 0.50 to 0.80 m and are invariably filled with fine-grained material. On the basis of descriptions of such features from other provinces[7,8], we propose that these are spiracles. The longer spiracles tend to taper and bend in the down flow direction (Figure 2 *b*), implying that the flow was considerably mobile during their formation. Enclaves of fine-grained material related to curvilinear joints are seen in the crust (Figure 1 *b*). These have sharp contacts with the host basalt and are probably related to rise of steam and fine-grained material along distinct shear surfaces within the lava. Sporadic patches of the fine-grained material are also exposed in the crust as high as 2 m above the flow base (Figure 2 *c*). Close observation reveals that some of the fine-grained material has been injected into the vesicles. At places, larger vesicles in the crust appear to be preferentially stretched indicating mobility of the lava during flowage. Alternatively, since the vesicles are strongly deformed where spiracles are abundant, the deformation may be related to injection of the spiracles. Laterally, the spiracles appear to be exposed in a localized area and have formed from steam generated as the flow was emplaced over moist ground or a clogged water body (Figure 3).

In thin sections, the fine-grained material appears as a colloidal mass, too fine for any meaningful identification of individual minerals. In contrast, the basalt displays intersertal texture and is characterized by an assemblage of plagioclase, clinopyroxene and glass. The fine-grained material was subjected to XRD studies at the Department of Geology, Miami University, Ohio. Pack mounts of the samples were run in their original state at a scan rate of 1 degree/minute with a 2θ of 5–60°. The major peaks obtained were at 26.660° (2θ), 3.341 Å (d) and 9.876° (2θ), 8.949 Å (d) and were identified as quartz and montmorillonite respectively. Samples of the fine-grained material, host basalt and two established 'bole' samples from Pune were geochemically analysed by the Direct Current Plasma Atomic Emission Spectrometry (DCP-AES). The fine-grained material from the spiracles is characterized by 77.62 wt% SiO_2, 5.60 wt% Al_2O_3, 0.44 wt% TiO_2, 4.24 wt% Fe_2O_3 and 1.35 wt% MgO and is distinctly different from the basalt (Table 1). Similarly, the fine-grained material is geochemically different when compared to the boles from the Deccan and British Tertiary Province[10]. The chemistry of the fine-grained material contains more than 77% silica, which agrees with the interpreted high quartz content from the XRD studies. It is therefore speculated that such a material may be derived from volcanic ash or has undergone sufficient cation exchange[11] to produce the distinct chemistry.

Spiracles are good palaeotopographic indicators, their presence especially in ancient flows has important bearings in deciphering their emplacement history. The absence of pipe vesicles *vis-à-vis* presence of spiracles at the base of the sheet lobe opens up an interesting debate on the genesis of the former structures. The absence of pipe vesicles is in contrast to the established fact that even small lava toes exhibit well-developed pipe vesicle in the DVP. The view that pipe vesicles form where lava flows over damp or marshy ground is obsolete. Thus availability of water is not essential for the formation of pipe vesicles[12]. If this is true, then absence of pipe vesicles at the base of the sheet lobe in the present case may be because moist ground or surface water at the base of the flow may enhance cooling and retard coalescence of vesicles to pipes. This is supported by the fact that the entire lower vesicular zone appears glassy in comparison to the usual 2–4 cm thick glassy rind commonly seen in sheet lobes. Thus, surface water may not be essential for the formation of pipe vesicles but it probably affects their formation in a different way. Spiracles like pipe vesicles have an additional utility as palaeoslope and flow direction indicators[12]. The spiracles from Chekewadi are bent towards the northeast, indicating that the sheet lobe advanced from southwest to northeast. This interpretation, however, may be local and on the contrary the flow may have advanced in a totally different direction in response to the regional palaeoslope.

Reports of aqueous lava forms such as lava pillows[13,14] and hyaloclastites[15] are

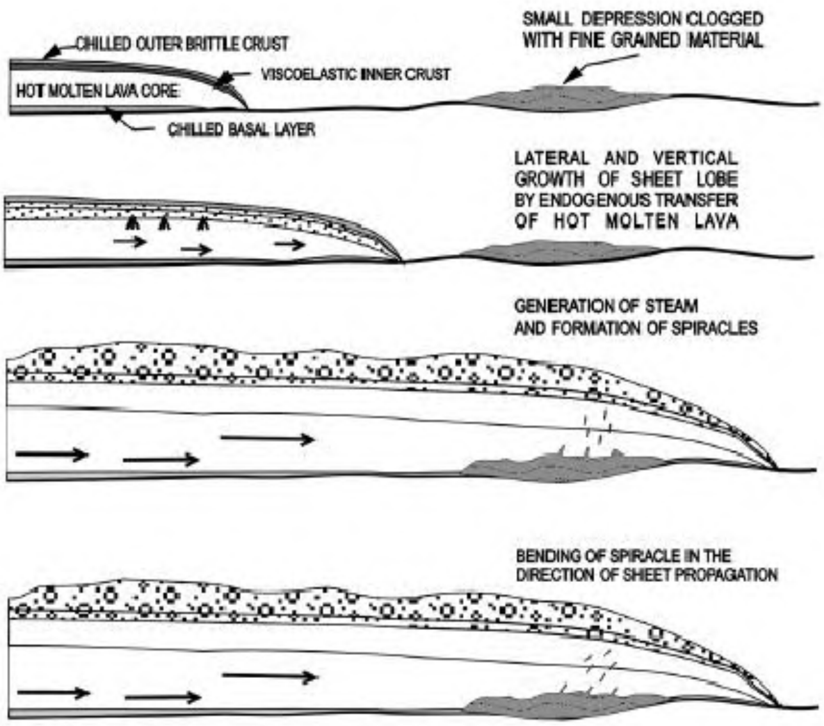

Figure 3. Cartoon depicting the stages in the formation of spiracles.

Table 1. Major oxide (wt%) and selected trace element concentrations (ppm) of basalt and fine grained material from Chekewadi

	Chekewadi Basalt	Chekewadi fine grained material	Pune Bole 1	Pune Bole 2	Sinhagad, Pune Bole[10]	Mull Bole[10]	Skye Bole[10]
SiO_2	45.49	77.62	54.16	53.84	43.86	31.32	32.19
Al_2O_3	14.10	5.60	12.49	14.20	12.70	22.82	17.82
TiO_2	2.37	0.44	1.53	1.94	1.97	2.88	3.41
Fe_2O_3	16.22	4.24	15.00	16.14	15.11	22.60	20.38
MnO	0.20	0.16	0.05	0.09	0.15	0.23	0.17
CaO	10.91	1.94	2.29	2.41	4.18	3.91	1.77
MgO	4.19	1.35	3.91	4.86	4.57	3.59	3.09
K_2O	1.12	0.90	2.19	0.12	0.45	0.38	0.33
Na_2O	2.55	0.11	0.19	0.04	0.33	1.39	0.44
P_2O_5	0.31	0.26	0.17	0.16	0.13	0.28	0.20
LOI	n.a.	6.53	7.12	6.41	16.55	10.60	20.20
Total	97.46	99.15	99.10	100.21	100.00	100.00	100.00
Ba	193.59	256.81	93.05	46.65	79	260	199
Cr	110.15	24.09	79.69	108.03	96	331	6
Cu	209.75	47.51	366.66	246.85	339	89	68
Ni	70.62	18.26	58.21	60.44	86	8	25
Rb	11.05	45.16	0.18	93.85	14	214	18
Sc	37.44	13.47	30.69	35.14	26	29	14
Sr	232.69	336.51	64.73	72.09	60	515	227
V	380.17	53.44	224.95	228.16	231	269	147
Y	35.46	15.57	28.21	25.79	41	31	82
Zn	124.86	39.97	39.12	89.96	81	185	117
Zr	157.64	40.09	125.87	136.80	191	204	304

rare and are restricted to the island of Bombay and Kutch, i.e. to the western margins of the province. In light of the above, the presence of spiracle-like structures from Chekewadi and the Pench River are significant as they provide evidence to show that moist ground and/or small shallow water puddles did exist in the central parts of the province at the time of the Deccan volcanism. It is envisaged that small, rain-fed puddles may have developed in shallow depressions on larger sheet lobes and between lobes in hummocky flow and got clogged due to the accumulated fine-grained material. Subsequent emplacement of sheet lobes over these puddles produced the slender, steam injection structures, now spectacularly preserved as spiracles within the flow.

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RAYMOND A. DURAISWAMI[†,*]
NINAD BONDRE[‡]
GAURI DOLE[†]

[†]*Department of Geology, University of Pune, Pune 411 007, India*
[‡]*Department of Geology, Miami University, Oxford, Ohio 45056, USA*
**A/6 Gurudut Housing Society, Kalewadi Phata, Srinagar, Pune 411 017, India*
**For correspondence.*
e-mail: raymond_d@rediffmail.com