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Inflated pahoehoe lavas from the Sangamner area of the western Deccan Volcanic Province

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Notwithstanding the recent advances in petrology, geochemistry and determining the age of the Deccan Traps, there is no unanimity regarding the mechanism of their emplacement. Some of the basic questions regarding the source of the Deccan lavas, their actual eruption, and their post-eruptive behaviour have not been answered. In this paper, we describe the structure, physical characters and emplacement of some lava flows in the Sangamner area of the Deccan Volcanic Province (DVP). Our observations suggest that inflation (thickening by endogenous growth) was an important mechanism in the emplacement of flows in this area; and probably also in other parts of the DVP.

THE Deccan Volcanic Province (DVP) is one of the largest continental flood basalt provinces in the world. Considerable attention has been focused on this province in the last 10–15 years particularly because of its age, which corresponds closely with the Cretaceous–Tertiary boundary. Voluminous data regarding petrology, geochemistry, palaeomagnetism and age have emerged in the past two decades[1,2], but the physical volcanology of the lavas remains only sparsely recorded[3–6]. There is therefore considerable scope for physical volcanological studies that focus on the flow structures and thereby on the quantification of variables such as viscosity, temperature, volumetric flow rate, etc. This will help in the understanding of how the DVP lava flows and other flood basalt lavas were emplaced.

Studies in recent years on active lava flows in Hawaii[7], as well as those on the Columbia River Basalts[8,9] have shed considerable light on the emplacement of flood basalt lavas. These observations indicate that thick sheets of lava (about 4 m in Hawaii, 10–50 m in the Columbia Basalts) build up by the inflation and coalescence of thin (10–50 cm) pahoehoe lobes. Flows formed by this mechanism display certain diagnostic characters that are pointers to their mode of emplacement. Subsequently, such flows have been reported from the Mull area of Scotland, belonging to the North Atlantic Tertiary Province[10].

In this paper we discuss the structure, physical characters and emplacement of some lava flows in the area around Sangamner. Our observations[11] suggest that the mechanism of inflation played an important role in the emplacement of these lavas. Although compound pahoehoe flows have been recorded from several parts of the Deccan Traps[5,6], the mechanism of inflation has not been demonstrated before. This paper gives a detailed documentation of field evidences of inflation in the DVP, barring passing comments on their possible existence[2,12].

The area of investigation is bounded by the latitudes 19°25'N and 19°45'N and the longitudes 74°00'E and 74°15'E (Figure 1), and is close to the proposed eruptive centre for the Deccan basalts around the Igatpuri–Nasik region[13,14]. The basaltic flows exposed in this area belong to the lower and middle divisions of the Thakurwadi Formation of the Kalsubai Subgroup[1]. The

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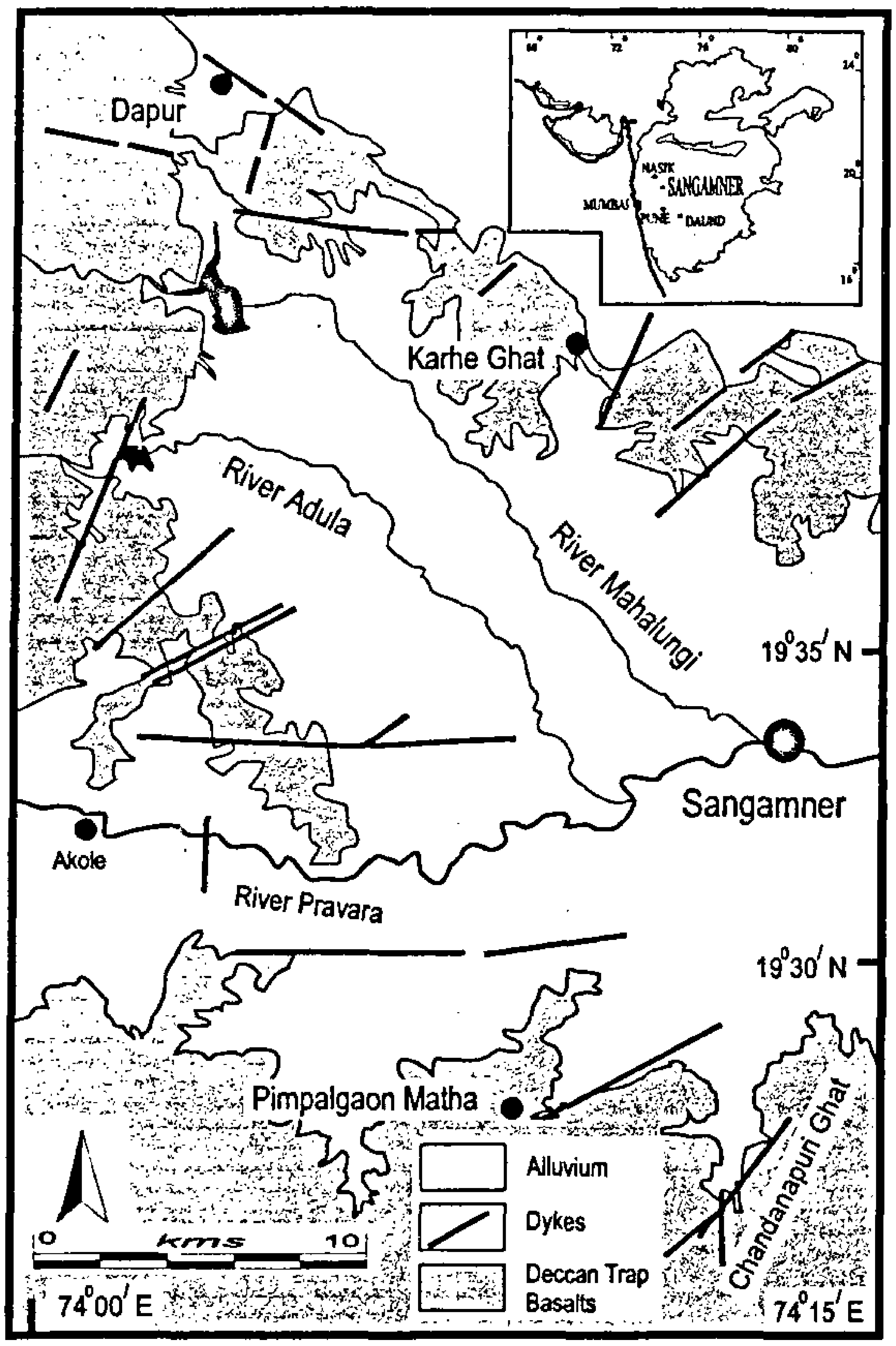

Figure 1. Geological map of the study area as interpreted from IRS *imagery and supplemented by field checks (modified after Bondre*[11]). (Inset) Extent of the Deccan Volcanic Province with the locations discussed in the text.

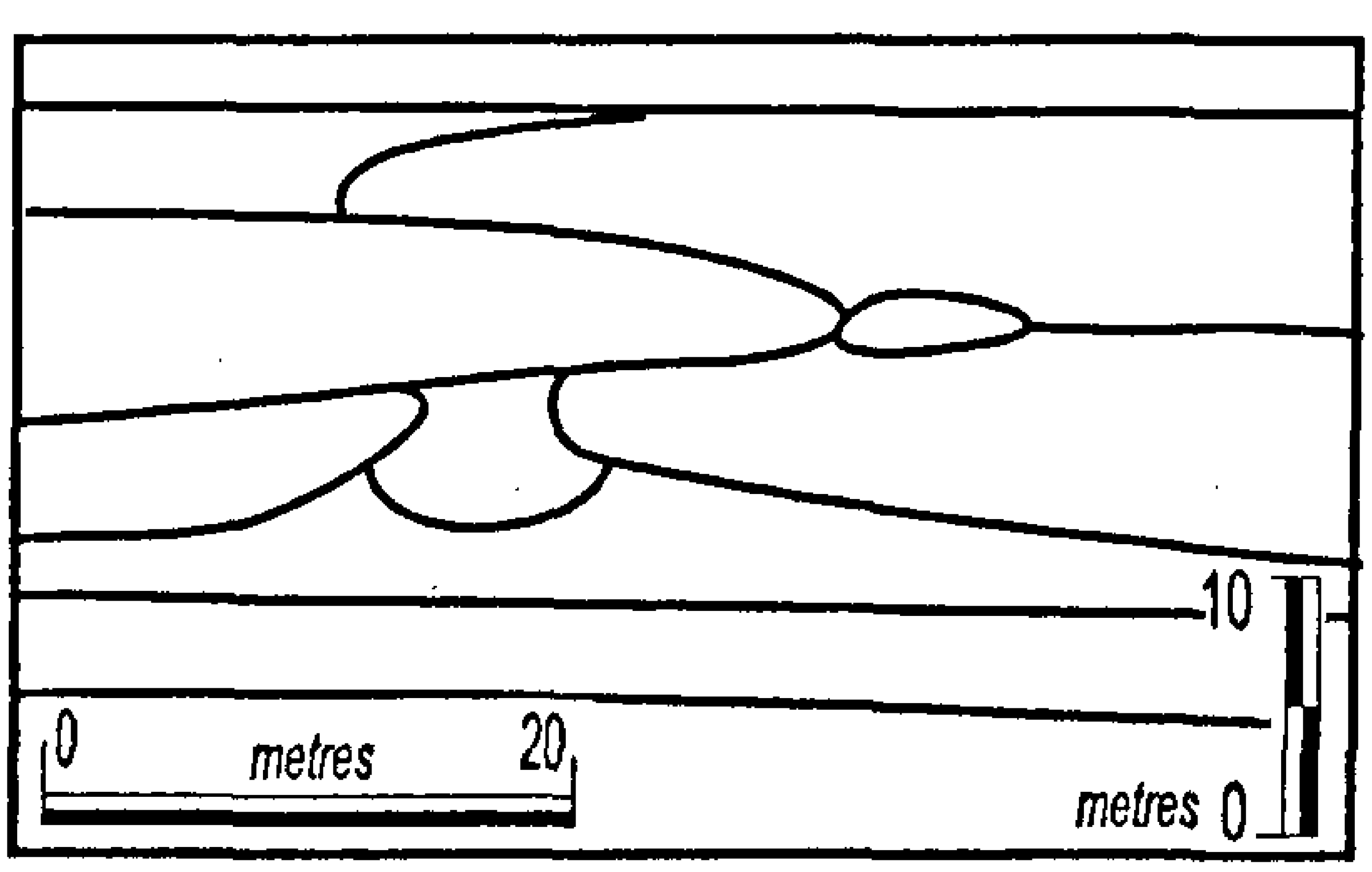

Figure 2. Generalized sketch of flow lobes observed in the cliffs in the vicinity of the Chandanapuri Ghat.

Deccan basalts are overlain at many places by Quaternary alluvial/colluvial deposits, which are as much as 15 m thick in the Chandanapuri valley.

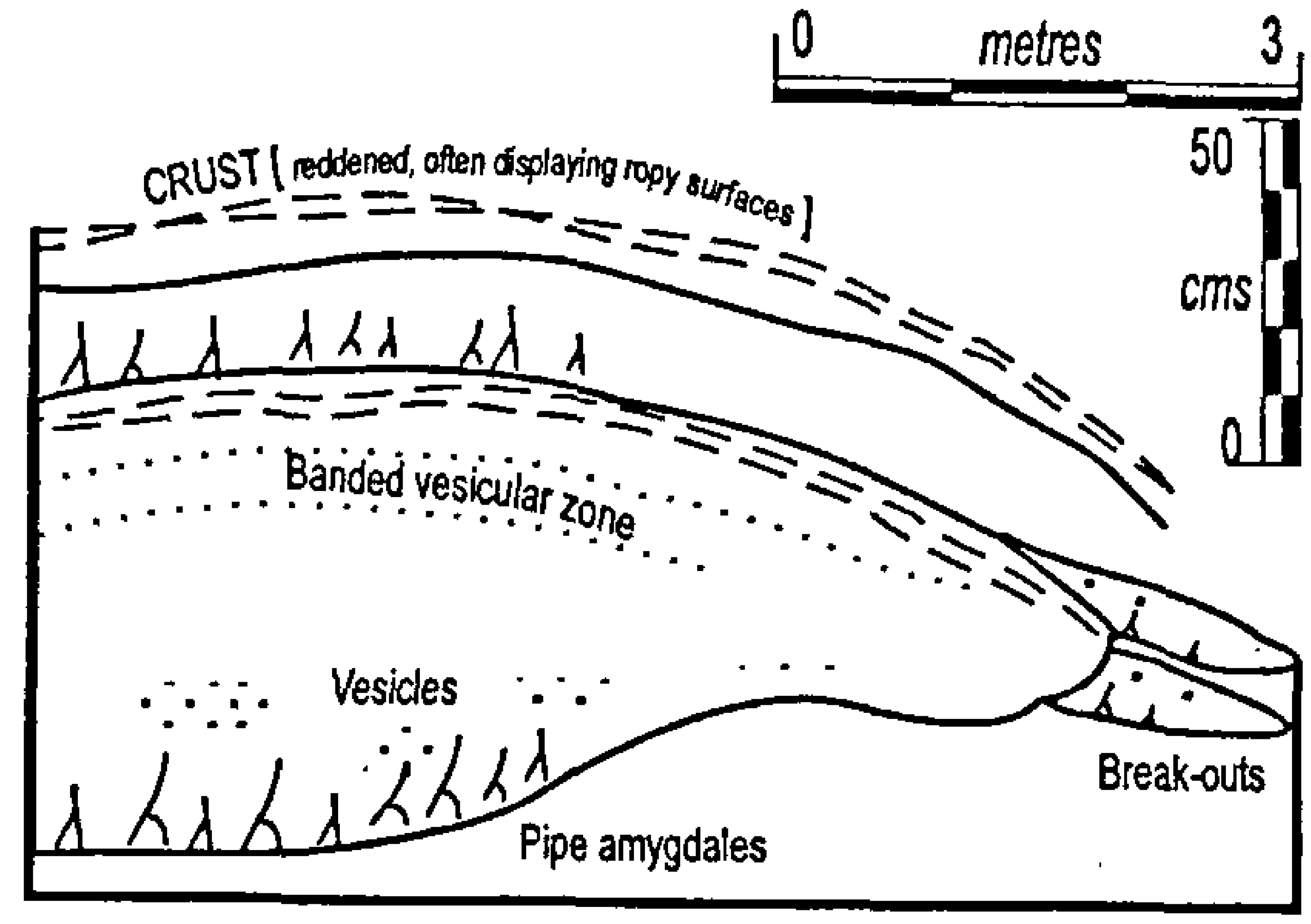

Figure 3. Field sketch of a lobate flow unit of a compound pahoehoe flow near Pimpalgaon Matha. Note the smaller 'toes' occurring as break-outs near the front of the lobe. The convex-up geometry seen on the left is indicative of the part proximal to the immediate source of the lava, while the distal end displays lesser 'inflation'. Such a geometry can be produced only by endogenous growth.

Most of the flows have a consistent, uniform thickness of more than 40 m in some cases, and display a tendency to form vertical cliff faces. Natural caves can be observed at various levels in the cliffs. This geomorphic expression can be best observed in the Chandanapuri Ghat and adjoining areas. The flows are divisible into multiple flow units[15] of varying dimensions, each unit having its own chill crust. The units are lobate in character, with a vesicular–amygdaloidal top and pipe amygdales at the base. The tops of these units often display ropy structure. It is evident that these flows are compound pahoehoe in character[5]. It should, however, be noted that the dimensions of some of the lobes constituting the cliff-forming flows in this area are much greater than small metre-scale 'toes' normally associated with compound pahoehoe flows (Figure 2).

The thickness of individual units is around 2–3 m and their sheet-like character is evident in many sections. Smaller flow units (toes) are associated with the larger lobes at many localities and some of them represent break-outs from the larger lobes (Figure 3). Their thickness remains constant over several tens of metres in a single section, indicating a sheet-like character. Observations along some of the cliffs in the area indicate that some flow units have a much greater thickness, probably in the range of 10 m. Most units display a distinct banding due to the presence of parallel horizons of vesicles and amygdales (Figure 4), similar to the horizontal vesicular zones described by Keszthelyi, Self and Thordarson[12]. Vesicle cylinders and segregation veins are also observed in the cores of some units (Figure 5).

Flow units observed in the area are remarkably similar in morphology to 'inflated' lava flows reported from Hawaii and the Columbia River Province[7–9], which sug-

Figure 4. Field photograph of an inflated pahoehoe flow unit displaying prominent banding of vesicles and amygdales exposed near Dapur.

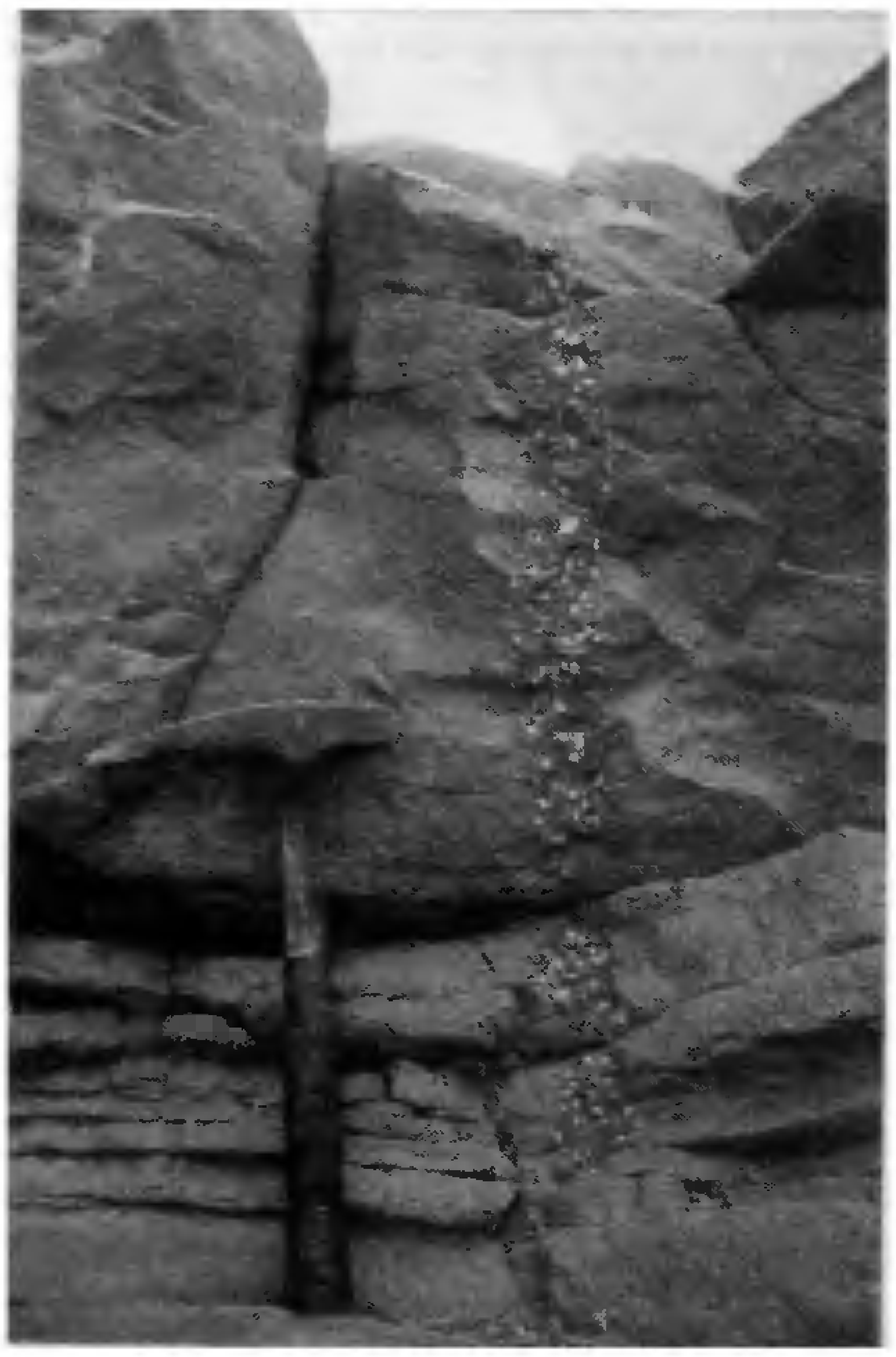

Figure 5. Field photograph of an ideal vesicle cylinder observed in a flow unit near Karhe Ghat.

gests that they must have been emplaced by an analogous mechanism. We propose that a continued influx of lava into slow-moving toes or lobes of lava, led to their balloon-like inflation (Figure 6) and coalescence. A visco-elastic skin (1070–800°C) underlying the cooled brittle crust provided the necessary tensile strength to retain the incoming lava[5], and the significance of this crust cannot be overemphasized[8,9]. Continuous inflation led to the increase in vertical thickness as well as the advance of the lobes by continued break-outs. The thin initial thickness of the lava flows in Hawaii is attributed[7] to the low viscosity of the tholeiitic Hawaiian basaltic lava. The physical characters of pahoehoe lavas in the DVP are closely comparable to that of the Hawaiian pahoehoe lavas, which suggests that these lavas were also highly fluid and were initially emplaced as thin, rather than thick sheets of lava.

Many of the characters that we observed in the basaltic flow units in this area can be explained by the above mechanism. The horizontal vesicular zones probably form when bubbles rising from the fluid core accumulate at the base of the solidifying upper crust and are trapped in the visco-elastic crystal mush[12]. Alternatively, Hon *et al.*[7] observed that the sheet-like variations in vesicle size and distribution in flow interiors are indicative of internal pressure fluctuations during inflation. Continued injection of lava in the core is implied by the several parallel zones of vesicles and amygdales that we have recorded in many of the flow units. Banding of vesicles often occurs due to the growth of the lava by continued injection under a surface crust, i.e. by an endogenous growth mechanism[16]. We have observed units that show more than one zone of pipe vesicles, which is also an evidence of multiple lava injections under a cooled outer crust[17]. The vesicle cylinders form after stagnation of the lava and initiation of crystallization, when a vesicular residuum rises in cylindrical conduits towards the upper crust[12,18].

Variations in the rate of inflation give rise to a wide range of features[19]. Hummocky pahoehoe flows are fed by a well-developed distributary tube system[7,20] and inflation in such flows is localized, leading to the formation of tumuli, localized lava rises, etc. Lava in actively inflating sheet lobes is initially distributed evenly throughout the liquid core[7] and is not fed to the flow front by a definite tube system. Preferred pathways or tubes may eventually develop in these flows (after stagnation) due to edge effects and result in an efficient lava transfer to the flow front[20]. We have observed hummocky pahoehoe and tumuli near Pune and Daund (Figure 1: inset map) and are in the process of documenting their morphology. Such features indicate that inflation was an important mechanism in the emplacement of basaltic flows in some parts of the DVP. We have not observed any lava tubes in the area of investigation.

The mechanism of inflation satisfactorily explains the behaviour of the Deccan Trap lavas in the area of investigation, and allows at least qualitative estimates to be made of some of the variables involved in emplacement. It is a well-known fact that compound pahoehoe lavas form at low volumetric rates of eruption[21,22]. In this context, the mechanism of inflation may allow an initially thin lava flow unit to attain a considerable thickness with a moderate rate of effusion, during a sustained eruption. The compound pahoehoe flows formed in this manner would then be constituted of larger flow units.

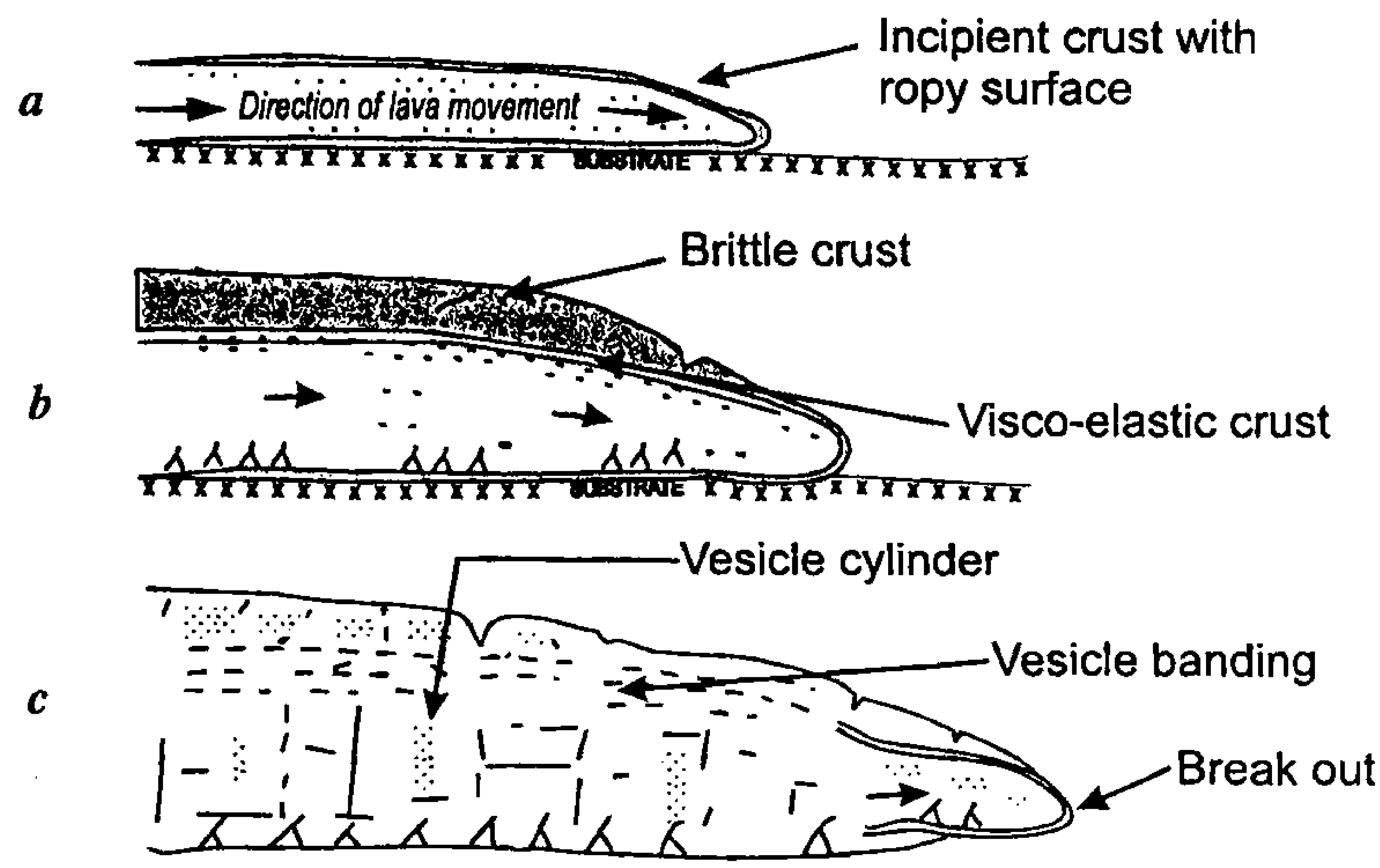

Figure 6. Schematic cross-section depicting the emplacement of a typical inflated lava[8]. Vertical scale varies from 1 to 4 m for flow units in the study area. ***a***, Initial pahoehoe lobe with a thin crust; ***b***, Continued injection of lava into the lobe results in the uplift of the upper crust, giving rise to the convex-up geometry as seen in Figure 3. During inflation, bubbles rising from the fluid core are trapped at the base of the upper crust, resulting in a banding of vesicles as seen in Figure 4. Typical pipe vesicles (including those with inverted-Y geometries) develop in the lower crust; ***c***, The flow front advances by continued break-outs. Stagnation in the core leads to the formation of vesicle cylinders (depicted in Figure 5) and segregation veins and a more regular jointing.

The thickness of flow units in this area is up to 4 m, which is comparable to that of Hawaiian inflated lavas[7].

It is interesting to note that the inflation of lava and the subsequent development of a feeder system have an important bearing on the lateral spread of lava. The crust formed over actively inflating flows and the feeder system developed subsequently could both effect a very efficient delivery of lava to the flow front without significant cooling of that lava[23].

There is a growing realization of the commonness of eruptive mechanisms of continental flood basalts all over the world[8,9]. In this context, the emplacement of the Deccan lavas merits a detailed study. Our observations suggest that inflation was an important emplacement mechanism in some parts of the DVP. However, the relative importance of inflation in the context of the entire province can only be gauged after ascertaining the exact proportion of inflated lava flows in the province.

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