Bull Volcanol (2011) 73:737–752
DOI 10.1007/s00445-011-0450-7

RESEARCH ARTICLE

´A´ā lava flows in the Deccan Volcanic Province, India, and their significance for the nature of continental flood basalt eruptions

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Received: 19 February 2010 / Accepted: 6 January 2011 / Published online: 10 February 2011

Abstract Newly identified ´a´ā lava flows outcrop intermittently over an area of ~110 km^2 in the western Deccan Volcanic Province (DVP), India. They occur in the upper Thakurvadi Formation in the region south of Sangamner. The flows, one of which is compound, are 15–25 m thick, and exhibit well-developed basal and flow-top breccias. The lavas have microcrystalline groundmasses and are porphyritic or glomerocrystic and contain phenocrysts of olivine, clinopyroxene or plagioclase feldspar. They are chemically similar to compound pāhoehoe flows at a similar stratigraphic horizon along the Western Ghats. Petrographic and geochemical differences between ´a´ā flows at widely spaced outcrops at the same stratigraphic horizon suggest that they are the product of several eruptions, potentially from different sources. Their presence in the DVP could suggest relative proximity to vents. This discovery is significant because ´a´ā lavas are generally scarce in large continental flood basalt provinces, which typically consist of numerous inflated compound pāhoehoe lobes and sheet lobes. Their scarcity is intriguing, and may relate to either their occurrence only in poorly preserved or exposed proximal areas or to the flat plateau-like topography of flood basalt provinces that may inhibit channelization and ´a´ā formation, or both. In this context, the ´a´ā flow fields described here are inferred to be the products of eruptions that produced unusually high-effusion-rate lavas compared to typical flood basalt eruptions. Whether these phases were transitional to lower intensity, sustained eruptions that fed extensive low effusion rate pāhoehoe flow fields remains unclear.

Keywords ´A´ā lava · Flood basalt · Deccan Volcanic Province · Pāhoehoe

Editorial responsibility: A. Harris

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Introduction

A renewed interest in the morphology and physical characteristics of lavas in continental flood basalt provinces (CFBPs) has resulted in an increased understanding of the nature and dynamics of these exceptional eruptions on Earth and other rocky extraterrestrial bodies, such as Mars and Io (e.g. Reidel and Tolan 1992; Thordarson and Self 1998; Keszthelyi et al. 2006; Jay and Widdowson 2008; Self et al. 2008a). Such studies have also provided information on province evolution and architecture (Bondre et al. 2004; Jerram 2002; Single and Jerram 2004) and helped to understand volatile releases into the atmosphere (Self et al. 2008b). Several studies have indicated that extensive flood basalt flow fields are emplaced in a manner somewhat similar to that of small-volume Hawaiian pāhoehoe lava flows (i.e. by endogenous growth or inflation, Hon et al. 1994; see Self et al. 1997, 1998; Kent et al. 1998; Bondre et al. 2004; Sheth 2006; Waichel et al.

2006). The exact way in which individual provinces grow differs in detail. There are contrasts in the types of lava flows, and the relative abundances of the different types, and the style of emplacement can vary with time and space within a province (see Bondre et al. 2004). For example, lava flow fields within the Columbia River Basalt Group (CRBG) typically comprise one or more columnar-jointed sheet lobes each several metres or several tens-of-metres thick and each up to several kilometres in width (e.g. Reidel and Tolan 1992; Self et al. 1997; Thordarson and Self 1998). In the Deccan Volcanic Province (DVP), India, younger formations are typically extensive, thick, sheet lobes with highly vesicular, and in some cases rubbly, tops. In contrast, older formations are dominated by compound pāhoehoe flows (in which each lobe rarely exceeds a few metres in thickness, e.g. Duraiswami et al. 2003; Bondre et al. 2004; Jay 2005). Transitions between compound lava flows and more extensive tabular sheet flows (or sheet lobes) occur in the North Atlantic Igneous Province (Single and Jerram 2004; Passey and Bell 2007). Although the emplacement of individual lava types is relatively well understood, the reasons for the heterogeneity within and between provinces remain incompletely understood.

Walker (1971, 1999) spear-headed modern volcanological investigations of lavas in the DVP, describing the physical features and identifying flows he termed simple and compound. Kamarkar (1978), Rajarao et al. (1978) and Marathe et al. (1981) documented the characteristics of flows in the western DVP, noting variations in vesicularity, the presence of pāhoehoe flows, and what they termed ′a′ā lavas, but which lacked basal breccias. Recent studies have identified numerous pāhoehoe inflation features, including tumuli and squeeze-ups, as well as pāhoehoe lava types that may be transitional into ′a′ā lava (rubbly and slabby pāhoehoe, Duraiswami et al. 2001, 2003, 2008; Bondre et al. 2004).

In this paper we provide a detailed description of newly identified ′a′ā lava flows in the DVP. Their recognition is significant because, despite being a common product of basaltic volcanism on ocean island volcanoes and of basaltic volcanoes in continental settings, ′a′ā lavas are rare in many large flood basalt provinces (e.g. North Atlantic Igneous Province, Passey and Bell 2007; CRBG, USA, Self et al. 1998; Etendeka Province, Namibia, Jerram et al. 1999). They have, though, been documented in the Steens Basalt lava flows of south-eastern Oregon, USA (Bondre and Hart 2008), now considered part of the CRBG (Camp and Ross 2004), in the Kerguelen Plateau (Keszthelyi 2002) and in the Parana Volcanic Province of Brazil and Uruguay (Hartmann et al. 2010). The significance of this observation in the context of the dynamics of flood basalt eruptions and province morphology is discussed. Additionally, because ′a′ā lavas are thermally limited in how far they can travel from source (typically <<10's km; see Walker 1973; Harris and Rowland 2001, 2009) they are potential indicators of proximity to vents, which have remained elusive in the DVP.

Throughout we follow Walker (1971) and use the terms *flow-unit* to refer to a single ′a′ā lava flow (comprising a flow-base breccia, a core and a flow-top breccia); *compound* to refer to stacked flow-units that may relate to the same eruptive event (i.e., evidence for a time break is lacking) and *flow-field* to describe a large area covered by numerous outpourings (and multiple units) of lava that relate to the same eruptive event. In practice the latter is hard to distinguish in the geological record.

Emplacement of ′a′ā and pāhoehoe lava

Most basaltic lava flows can be classified according to their surface morphology as either ′a′ā or pāhoehoe (Macdonald 1953). These morphologies reflect fundamentally different emplacement conditions. It has been suggested that pāhoehoe flow fields usually develop under low effusion rate conditions (<5–10 $m^3\ s^{-1}$, based on observations on Hawai'i, Rowland and Walker 1990). They typically advance slowly, forming insulating crusts that create a thermally efficient transport system for the lava (Hon et al. 1994; Keszthelyi 1995; Keszthelyi and Denlinger 1996) all the way from the vent to the flow margins.

′A′ā development is a result of an exceeded threshold in viscosity-strain rate space (Peterson and Tilling 1980), and a comprehensive review of the evolution of ideas on ′a′ā formation is provided by Cashman et al. (1999). ′A′ā flows on Hawai′i are thought to develop when effusion rates are higher (>5–10 $m^3\ s^{-1}$; Rowland and Walker 1990) or when changes in slope, for example, lead to high strain rates (Hon et al. 2003). ′A′ā lavas tend to flow within open-channels that are typically 0.1–2.5 km wide (Rowland and Walker 1990) and that commonly widen downslope to form thick (up to 20 m-high) unconstrained flow fronts that advance steadily (Macdonald 1953). High flow velocities in channelized portions of ′a′ā flows result in continual turnover of the flow core and enhanced radiative cooling (e.g. Booth and Self 1973; Crisp and Baloga 1994; Harris and Rowland 2001). This promotes the crystallisation of microlites and results in increases in viscosity with distance from source. Rapid groundmass crystallisation is critical in the formation of ′a′ā lavas (Kilburn 1990; Cashman et al. 1999; Soule and Cashman 2005). Under these conditions the flow crust in channels can be continually disrupted into ′a′ā clinker if the shear stresses imposed by the flow exceed the tensile strength of the crust. This clinker is transported to the flow front and is incorporated into a layer of clinker at the flow base by a caterpillar track motion (Macdonald 1953). Solidified ′a′ā flows can be recognised in the geological record by basal and flow-top breccias and massive cores that are commonly texturally uniform, aphanitic and contain sparse, highly-deformed vesicles (Macdonald 1953).

Geological background: the Deccan Volcanic Province

The 65 Ma Deccan Volcanic Province, covering 5×10^5 km^2 of central and western India, ranks as one of the largest flood basalt provinces on Earth (Fig. 1a). Taking into account down-faulted regions on India's west coast, the total volume of erupted material may well have exceeded 1×10^6 km^3 (Widdowson 1997). The lava pile consists of hundreds of flows, is more than 2–3 km thick in the west (Kaila 1988), and thins to individual flows of ~10 m in thickness at the province margins. The DVP consists almost entirely of sub-horizontal tholeiitic basaltic lavas, which are locally intruded by dyke swarms (Auden 1949; Deshmukh and Sehgal 1988; Bondre et al. 2006; Ray et al. 2007).

Extensive chemostratigraphic work has been completed for the DVP, particularly in the western parts where regional-scale formations and subgroups have been established on the basis of field relations and geochemistry (e.g. Cox and Hawkesworth 1985; Beane et al. 1986; Subbarao and Hooper 1988). Recent studies have focussed on other areas, such as the northeastern Deccan Traps (Peng et al. 1998) and the Satpura Range in the north (Sheth et al. 2004; Jay and Widdowson 2008). Construction of the DVP stratigraphy has been greatly aided by the presence of several distinctive giant plagioclase-bearing basalt flows, which contain plagioclase phenocrysts of up to several cm in length (Kamarkar et al. 1972; Beane et al. 1986). Successive chemostratigraphic units overstep towards the south and east with a regional dip of ~1° (Beane et al. 1986; Mitchell and Widdowson 1991). The vents for the DVP lavas still need to be identified and there is much debate over whether the lavas flowed from a central location, or whether they were erupted from numerous, geographically separate, sources (Beane et al. 1986; Kale et al. 1992; Battarcharjee et al. 1996).

All of our observations come from the Thakurvadi Formation of the Kalsubai sub-group, which is the most extensive of the lower chemostratigraphic units of the DVP and outcrops widely in the Western Ghats to the east and southeast of Mumbai (Fig. 2a; Beane et al. 1986; Khadri et al. 1988). The sub-group has a minimum thickness of 2,000 m and consists predominantly of compound pāhoehoe flows. The Thakurvadi Formation varies from <210 m thick to >400 m thick NW of Sangamner (Fig. 1). Most lavas in the Thakurvadi Formation have MgO=7.0–8.0 wt% and TiO_2=1.8–2.0 wt%, but more primitive picritic lavas are present,

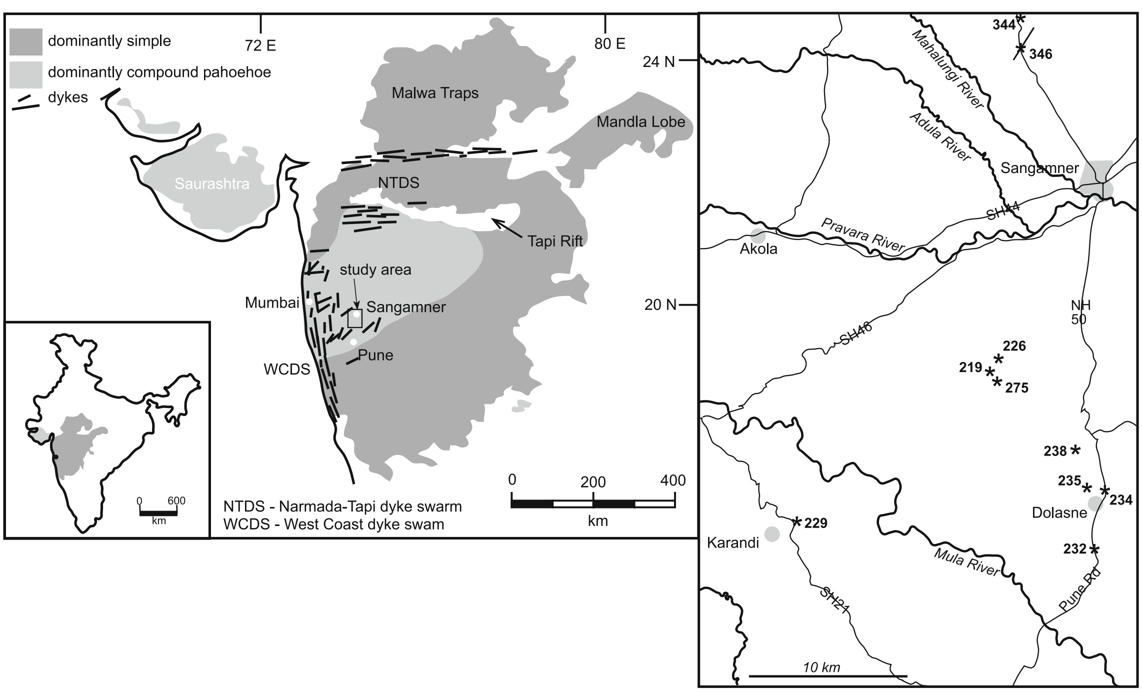


Fig. 1 **a** Map showing the limits of the Deccan Volcanic Province in western India (modified from Bondre et al. 2006). Inset shows position of province within India. **b** Localities for ´a´ā lavas in the Deccan and the dyke (top right) considered to be of similar age to upper Thakurvadi lavas (from Bondre et al. 2006)

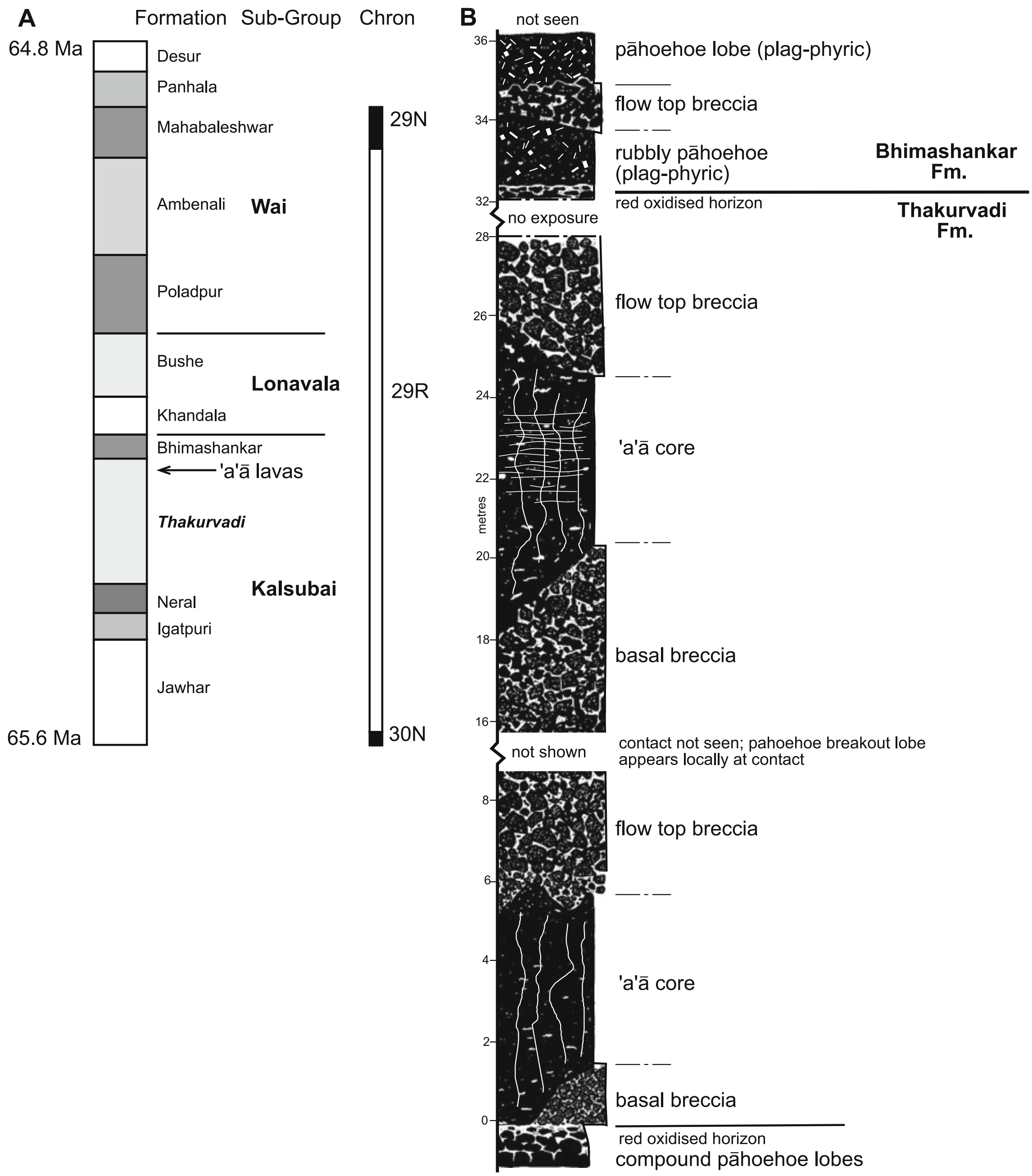


Fig. 2 **a** Stratigraphic column of the Deccan Volcanic Province showing Formations and sub-groups, along with chrons and radiometric ages for the start and end of volcanism (data from Chenet et al. 2008, 2009). Summary log through the ´a´ā lava flow field at the type locality (see Fig. 1) is also given

as well as some more-evolved lavas (Beane et al. 1986). While phenocrysts of olivine and glomerocrysts of clinopyroxene are common, plagioclase feldspar phenocrysts are rare and generally small. The formation contains several geochemically distinct flows that act as local chemostratigraphic markers (such as the Water Pipe Flow and the Jammu Patti Member) and its base and top are marked by the presence of giant plagioclase basalt lavas (Beane et al. 1986).

Morphology and stratigraphy of the newly identified a´ā flows

The ´a´ā flows outcrop discontinuously over an area of ~110 km^2 to the southwest of Sangamner (Fig. 1b) and have been recognised on the basis of brecciated bases and tops (or only brecciated bases when flow tops are not exposed). They also have dense lava cores with irregular stretched vesicles and show partially ingested clinker within the upper parts of the core, these being features characteristic of ´a´ā (e.g., Macdonald 1953; Crisp and Baloga 1994). They occur towards the top of the Thakurvadi Formation (Fig. 2a), beneath the Manchar giant plagioclase basalt flow that marks the base of the Bhimashankar Formation (Fig. 2; Kamarkar et al. 1972; Beane et al. 1986). The type locality for the ´a´ā flows is the mountain pass at Pimpalgaon Matha (above the village of Sāwargaon), 13 km SSW of Sangamner. Here ´a´ā flow units are exposed discontinuously for ~2 km along hillsides at an altitude of ~870 m (Locality 219; Fig. 1 and Table 1). The flows here are cut by several younger Deccan-age dykes trending NE-SW and E-W (*see* Bondre et al. 2006). The flow is compound and comprises at least two ´a´ā flow units, which cumulatively exceed 40 m in thickness (Figs. 2b and 3a).

The lower ´a´ā flow unit overlies the weathered, oxidised top of a compound pāhoehoe flow (Fig. 3b). Its base comprises a well-developed breccia locally forming lenses up to 70 cm thick and 2–3 m wide (Fig. 3c). Clasts in the breccia comprise sub-angular to sub-rounded clinker and their longest dimension is <8 cm (Fig. 3e). The vesicularity of the clasts varies from non- or poorly-vesicular to moderately-vesicular. Pore space within the breccia reaches 20–30 vol.% and is filled with secondary minerals (Fig. 3e). The flow-base breccia grades upwards into a dense, ~4.5 m thick, poorly vesicular aphanitic lava core. Vesicles in the lava core are spherical to sub-spherical or elongate, reach 2–5 vol.% and are up to 1 cm in diameter. Vesicularity in the lava core does not change significantly upwards. At some outcrops, centimetre to decimetre-sized angular patches with elevated vesicularity become common towards the top of the core; these are interpreted as entrained and partially resorbed vesicular clinker. At the flow top, the core grades upwards into the flow-top breccia at some locations. At other outcrops, the contact is sharp. The flow-top breccia is massive and homogeneous and is locally >12 m thick (Fig. 2b). Clasts rarely exceed 50 cm in diameter and are typically <10 cm. They are rounded, angular to sub-angular, and equant to weakly tabular. Most clasts are weakly to moderately vesicular, but both dense, non-vesicular clasts and highly vesicular clasts are also present at most localities. Vesicles in clasts exhibit a range of shapes and size distributions, from sub-millimetre and spherical to ~1 cm irregular-shaped vesicles. The total thicknesses for the flow unit (flow-top breccia, core + flow-base breccia) vary substantially, and in places the core pinches out within breccia zones (Fig. 3c).

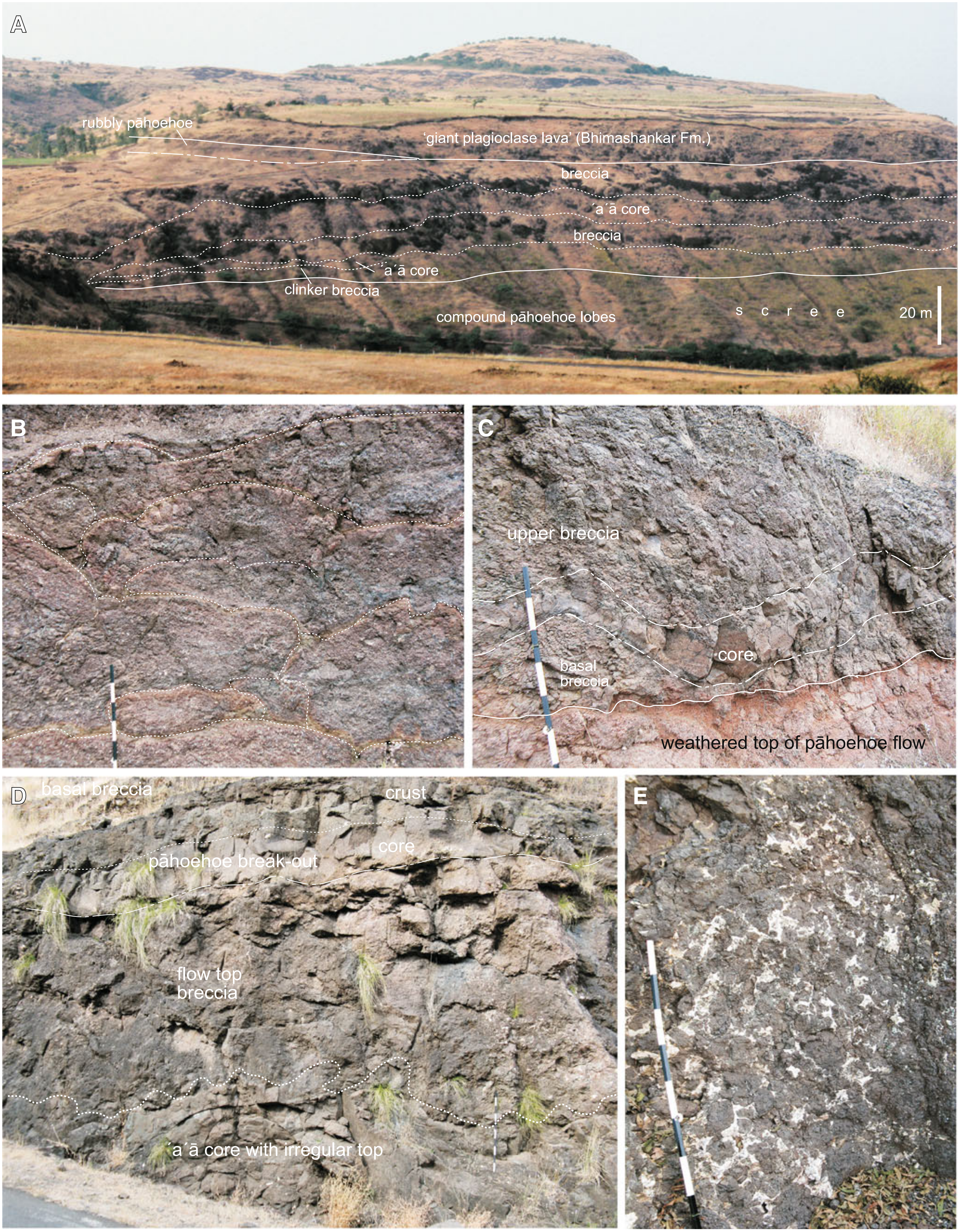
The flow-top breccia of the lower ´a´ā flow unit is overlain by the flow-base breccia of the upper ´a´ā flow

Table 1 Locations and descriptions of key outcrops of ´a´ā lava

Locality No.	Coordinates *Lat/lon hddd°mm'ss.s'*	Altitude	Description	Sample No.
219	N19 27 32.5 E74 08 17.2	876 m	Type locality: excellent roadcuts through compound ´a´ā flow field at top of pass above village of Sāwargaon; well exposed in hillsides north and south of pass, where it overlies compound pāhoehoe lobes; lava cut by dykes.	08-03 08-05 Ch4b[a]
226	N19 27 47.3 E74 08 27.6	871 m	Top of logged section NE of type locality; excellent exposure of ´a´ā lavas; >30 m thick.	
238	N19 25 07.0 E74 11 28.7	825 m	Basal breccia and core exposed between Warudi Pathar and Gunjālwādi.	
234	N19 23 44.3 E74 12 31.5	794 m	600 m NW of Dolasne, breccia exposed on ground.	
235	N19 23 47.0 E74 12 01.3	779 m	Good sections through basal breccia in roadcuts along dirt track south of gully.	08-14
232	N19 21 46.6 E74 12 16.6	762 m	Basal breccia and core exposed in roadcuts on NH50 3.3 km south of Dolasne.	08-13
229	N19 22 38.1 E74 01 26.2	889 m	Basal breccia and ´a´ā core exposed for about 100 m in roadcut on SH21, near Karandi village, above prominent red weathered horizon.	08-12
275	N19 27 32.2 E74 08 17.0	874 m	Rubbly pāhoehoe overlying ´a´ā lava in small roadside quarry south of Loc. 219.	08-15
344	N19 40 10.9 E74 09 29.7	713 m	Rubbly pāhoehoe exposed on ridge to east of NH50 road.	08-17 08-19 08-20
346	N19 38 50.3 E74 09 42.2	648 m	Pāhoehoe lava and dyke exposed in outcrops near NH50 road	08-22 08-23[b] Ch20[ab]

[a] sample from Bondre et al. (2006)

[b] denotes a dyke sample


A
rubbly pāhoehoe
'giant plagioclase lava' (Bhimashankar Fm.)
breccia
´a´ā core
breccia
a´ā core
clinker breccia
compound pāhoehoe lobes
s c r e e
20 m
B
C
upper breccia
core
basal breccia
weathered top of pāhoehoe flow
D
basal breccia
crust
core
pāhoehoe break-out
flow top breccia
´a´ā core with irregular top
E

◀ **Fig. 3** ´A´ā lavas at the type locality (loc. 219). **a** Panorama of ´a´ā lavas northeast of the type locality looking north. **b** Compound pāhoehoe lavas immediately beneath the ´a´ā lavas. **c** Base of ´a´ā lava with thin core and thin basal breccia. **d** ´a´ā core with overlying breccia. Break-out pāhoehoe lobe occurs within the breccia (upper third of photograph). **e** Typical breccia with pore space filled with silica and zeolites. Scale is a rule with10 cm divisions

unit, although the contact is poorly exposed. The core of the upper flow unit is similar to that in the lower ´a´ā flow unit (Fig. 2b). It reaches 8 m in thickness and has a sharp irregular basal contact with the flow-base breccia. It is poorly vesicular, and vesicles in its lower parts are elongated sub-parallel to the basal contact and up to 1.5 cm long. In the upper parts of the core elongate vesicles reach 5 cm in length. Prominent centimetre-spaced sub-horizontal platy joints are present in the centre of the core at some outcrops, but mostly the joints form an irregular blocky pattern. On top of the core is a ~9 m-thick flow-top breccia. The contact between the core and the flow-top breccia is gradational, irregular and exhibits decimetre to metre-scale relief. In some cases the core forms sub-vertical projections or 'spines' that intrude several metres up into the breccia. At one location, at the inferred contact between the two ´a´ā flow units, we have found a 1.5 m thick inflated pāhoehoe flow lobe (Fig. 3d). This exhibits the typical tripartite pāhoehoe structure of a lower crust (with pipe vesicles), a poorly vesicular core and a banded vesicular upper crust (as defined by Walker (1971) for Hawaiian pāhoehoe). This lobe is at the contact between the two ´a´ā lavas, and is inferred to represent hot, volatile-rich lava that was squeezed out from the flow front of the lower flow unit. A similar process of forming squeeze-ups has been described recently by Applegarth et al. (2010) for Etnean ´a´ā flows.

The type locality appears to be close to a front or margin in the ´a´ā flows. NE of the type locality the contact between the flow-top breccia and core of the upper ´a´ā flow unit locally dips 40° S, giving the impression of scree covering the interior of the flow unit. Another flow margin is inferred to be present 500 m south of the type locality. Here, the ´a´ā flow unit(s) consist of only breccia and lack an exposed core. The ´a´ā flow pinches out to the south where is onlapped by younger rubbly pāhoehoe flows (Fig. 4), which are widely present at this horizon in the region. At the type locality, the ´a´ā lava flow is overlain by a plagioclase-phyric rubbly pāhoehoe flow belonging to the Bhimashankar Formation (for a detailed discussion of rubbly pāhoehoe morphology and emplacement, see Guilbaud et al. 2005 and Duraiswami et al. 2008).

Incomplete outcrops of ´a´ā flows also occur south and west of the type locality around Dolasne and near Karandi (Fig. 1,). Here only the flow-base breccias and lava cores are exposed (Fig. 5b). The flow-base breccias are up to 2.5 m thick and can occur as discontinuous lenses up to several 10's of metres wide. The cores are >5 m thick. The breccias resemble those seen at the type locality (Fig. 5a and b), except that large slabs of vesicular crust, ~1×0.3 m in dimension, are also present (Fig. 5c). Also present in the breccias are metre-sized accretionary lava balls with chilled, jointed exteriors and breccia cores (Fig. 5d).

Most of the ´a´ā flows in the study area appear to outcrop along the same stratigraphic horizon. The type locality is at an altitude of 870 m, whereas the most southeasterly outcrop (locality 232, Fig. 1), 11 km away, is at 760 m. The most south-westerly outcrop (locality 229, Fig. 1) is 16-20 km away and at an altitude of 889 m. This is consistent with the inferred regional apparent dip of 0.5° SE (Beane et al. 1986), and suggests that the lavas broadly lie on the same palaeosurface. We note, however, that they are not always present at this stratigraphic level across the region. In some locations pāhoehoe lavas are present instead.

Thick lava breccias were also observed topping lava flows lower in the Thakurvadi Formation north of Sangamner at locality 346 (Fig. 1). However a careful search did not reveal any basal breccias. Vesicular crust fragments were observed and suggest derivation from a broken pāhoehoe crust, and although texturally similar to the ´a´ā lavas at the type locality, we infer that this is a rubbly pāhoehoe flow. The units are cut by a dyke that Bondre et al. (2006) considered to be geochemically similar to ´a´ā lavas at our type locality.

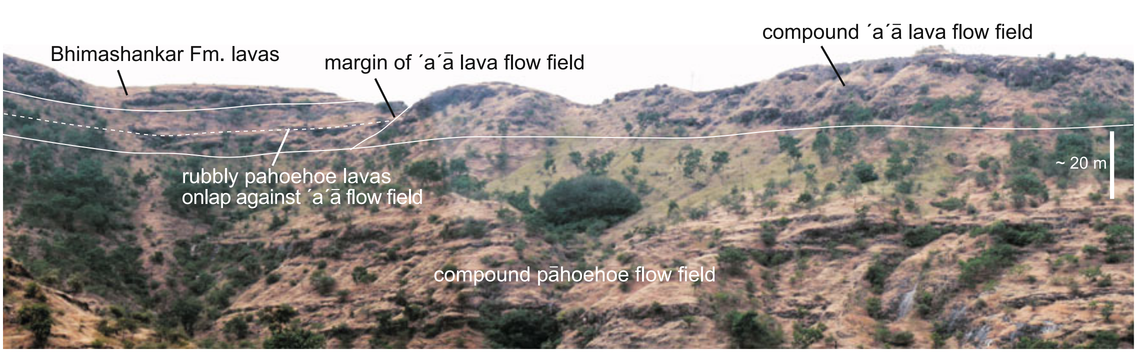


Fig. 4 Margin of ´a´ā flow field 500 m south of type locality. Younger rubbly pāhoehoe lavas onlap against the ´a´ā margins

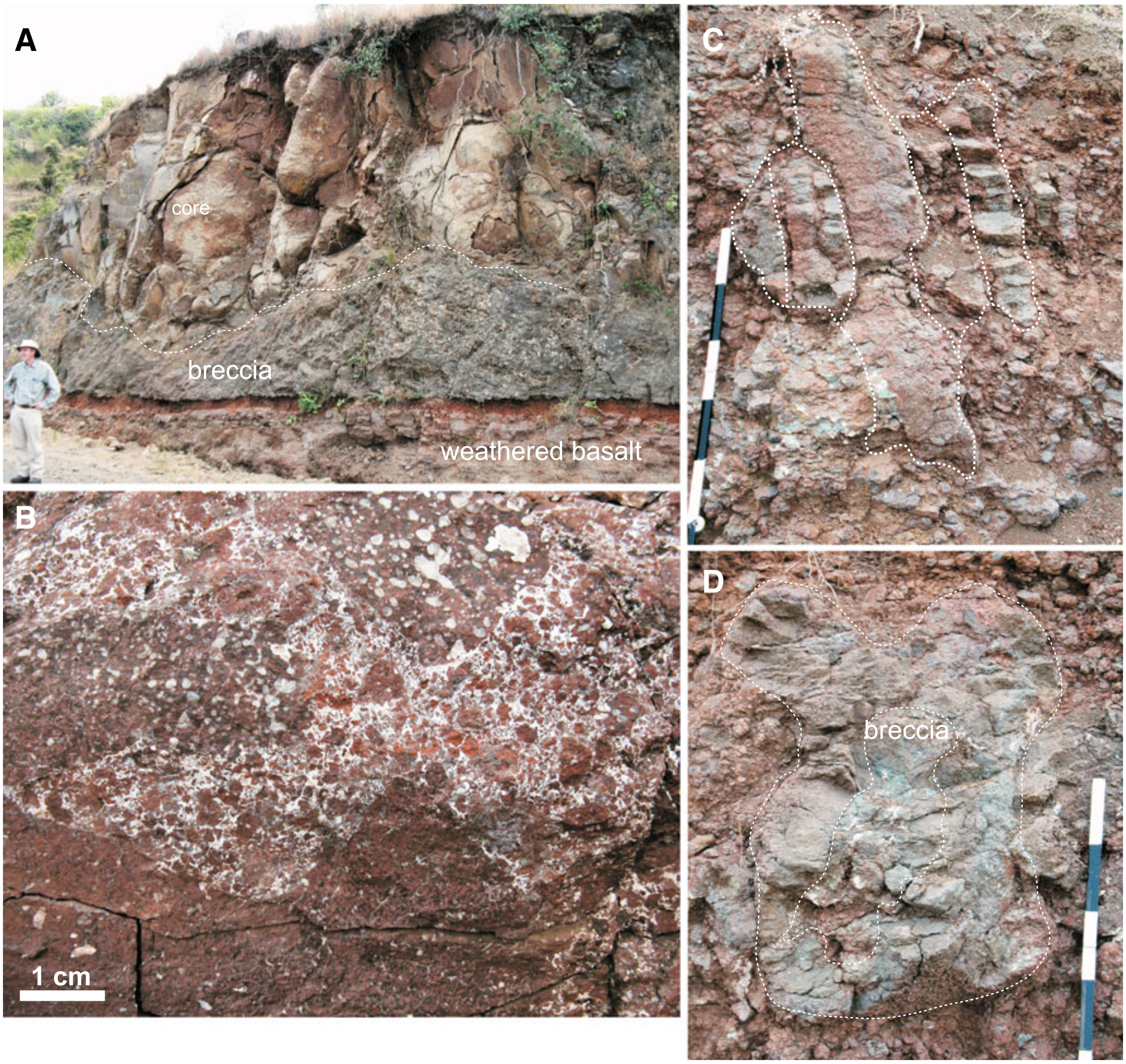


Fig. 5 ´A´ā features. **a** Variable thickness breccia at locality 229 (Fig. 1). **b** Detail of breccia with clasts of varying vesicularity. Pore space and vescicles are filled with zeolite minerals and silica cement. **c** Slab of columnar-jointed crust in basal breccia at locality 235 (Fig. 1). **d** Accretionary lava ball with clinker breccia core in basal breccia, also at locality 235. Scale is a rule with 10 cm divisions

Petrography and geochemistry

Analytical methods

Major and trace element analyses were run on (i) five samples of ´a´ā flow cores from the top of the Thakurvadi Formation (08-03, 08-05, 08-12, 08-13, 08-14; Table 1), (ii) one pāhoehoe core from the upper Thakurvadi Formation (sample 08-15), (iii) four samples from the cores of rubbly pāhoehoe flows from lower in the Thakurvadi Formation (08-17, 08-19. 08-20, 08-22) and (iv) the dyke (08-23) that was considered by Bondre et al. (2006) to be a geochemical match for the lavas at the type locality. The freshest samples possible were selected for analysis. Altered edges were removed and the remainders were carefully crushed to millimetre size. Any remaining altered parts were removed along with vesicle-filling zeolite minerals. Concentrations of major elements and trace elements were measured on pressed powder pellets and fused glass beads, respectively, by XRF at the Open University. Errors are less than 1.2% for most major elements (2.5% for K_2O) and 1% to 4.5% for most trace elements. Two geochemical standards were run (BHVO-1 and WS-E). All results are given in Table 2.

Petrography

The ´a´ā lavas are plagioclase, clinopyroxene, and olivine phyric, or glomeroporphyritic. All exhibit an intergranular or intersertal microcrystalline groundmass of plagioclase, clinopyroxene and opaque minerals 50–500 μm in diameter (Fig. 6). Sample 08-03 (from

Table 2 Major and trace element data for ´a´ā and rubbly pāhoehoe lavas in this study. 08-03 to 08-14 are cores of ´a´ā lava; 08-15 is from the core of a rubbly pāhoehoe flow

Location	219			229, 232, 235			275	344				346		Geochem. Standards	
No.	08-03	08-05	Ch4b[a]	08-12	08-13A	08-14	08-15	08-22	08-17	08-19	08-20	08-23	Ch20[a]	WS-E	WS-E[b]
Type	aa	aa	aa	aa	aa	aa	phh	phh	phh	phh	phh	dyke	dyke		
CPX	X	X		X	X	X	X	X	X	X	X	X			
OL	X	X						X				X			
PLAG		X		X		X	X			X	X	X			
Major elements (wt %)															
SiO_2	48.17	49.96	49.78	49.74	49.15	50.31	49.08	49.35	49.33	51.47	48.70	51.10	49.82	51.17	51.10
TiO_2	1.94	2.05	1.96	2.20	2.08	2.20	2.19	1.87	1.81	1.97	1.83	1.92	1.92	2.42	2.43
\\Al_2O_3	13.37	13.62	13.18	14.36	13.91	14.35	14.16	13.43	13.19	13.88	14.45	13.26	12.97	13.93	13.78
Fe_2O_3	12.33	12.38	12.08	13.34	13.19	13.16	13.43	12.53	12.47	12.35	12.27	12.04	11.76	13.27	13.25
MnO	0.16	0.17	0.18	0.18	0.18	0.18	0.19	0.17	0.17	0.17	0.17	0.18	0.18	0.17	0.17
MgO	8.06	7.53	7.83	6.24	6.79	6.32	6.88	8.06	8.10	6.77	7.16	7.34	8.97	5.58	5.55
CaO	11.68	11.50	11.12	11.33	11.19	10.60	11.28	10.88	10.83	10.38	10.72	10.88	11.16	9.04	8.95
Na_2O	1.88	2.05	1.98	2.19	2.10	2.18	2.13	2.16	2.10	2.43	2.34	2.11	1.93	2.41	2.47
K_2O	0.21	0.35	0.45	0.20	0.23	0.70	0.17	0.27	0.40	0.58	0.29	0.49	0.38	1.00	1.00
P_2O_5	0.18	0.18	0.17	0.21	0.20	0.20	0.21	0.21	0.20	0.25	0.23	0.20	0.16	0.30	0.30
L.O.I	1.06	0.72		0.17	0.23	0.17	0.18	0.92	0.17	0.32	1.2	0.15		0.85	0.85
Total	99.05	100.51	98.91	100.16	98.78	100.37	99.90	99.83	98.76	100.58	99.37	99.68	99.25	100.37	99.85
														BHVO1	BHVO1[b]
Trace elements (ppm)															
Rb	8	5	10	2	2	17	2	5	6	12	4	17	12	10	11
Sr	247	234	225	267	269	249	260	320	310	331	339	224	215	404	403
Y	26	27	25	30	28	29	30	26	26	29	27	28	24	28.5	27.6
Zr	116	119	116	139	136	135	140	128	123	136	127	142	112	175	179
Nb	9	8	8	10	9	10	10	10	11	7	7	8	8	18.2	19
Ba	83	90	68	99	108	114	90	156	158	177	136	134	81	137	139
Sc	35	34	37	33	36	35	34	32	32	33	32	36	31	32	32
V	334	336	338	344	356	358	361	303	301	301	306	313	302	316	317
Cr	474	362	381	148	317	145	319	451	472	363	389	348	466	290	289
Co	39	34	47	36	35	33	35	39	42	36	38	34	48	43	45
Ni	185	150	145	87	112	85	114	186	195	130	149	137	198	120	121
Cu	165	161	155	173	157	143	150	117	97	117	121	140	118	137	136
Zn	88	88	91	93	91	89	91	90	86	83	91	84	85	108	105
Ga	23	21	21	24	22	23	24	21	22	22	23	21	20	22	21

[a] Samples from Bondre et al. (2006); two right hand columns are measured and expected

[b] standards used in study

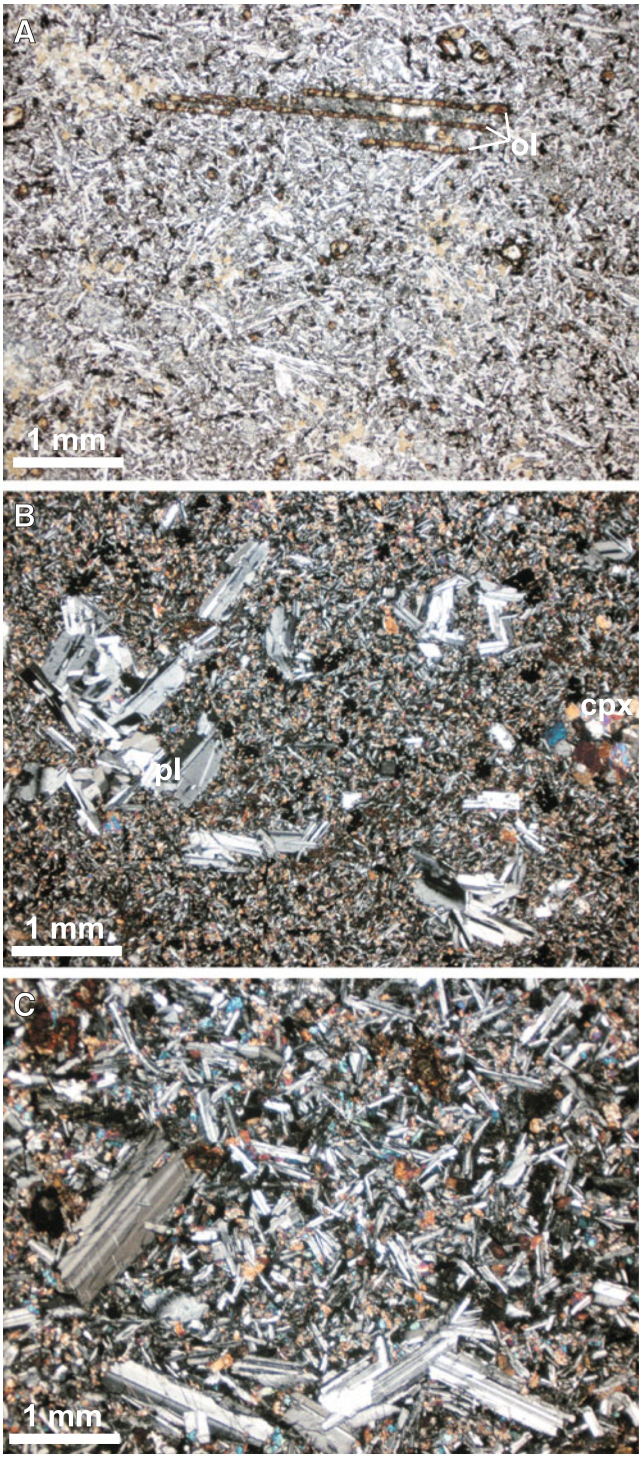


Fig. 6 Thin-sections of the sampled lavas in cross-polarised light. **a** Porphyritic basalt from an ´a´ā lava core (08-03) with parallel-growth olivine phenocrysts (ol) in a fine-grained intergranular- and intersertal-textured microcrystalline groundmass of plagioclase, clinopyroxene and opaque minerals. Olivine phenocrysts reach 4 mm in length. **b** Glomeroporphyritic basalt from an ´a´ā lava (08-12) with glomerocrysts of plagioclase and clinopyroxene and large skeletal oxide minerals. **c** Microcrystalline basalt from a pāhoehoe lobe with plagioclase phenocrysts (08-19). Note coarser groundmass grain size when compared to ´a´ā lavas in **a** and **b**

locality 219, Fig. 1) contains embayed and parallel-growth olivine phenocrysts, <4 mm in diameter, and sparse clinopyroxene (Fig. 6a). Sample 08-05 contains sparse plagioclase and clinopyroxene glomerocrysts as well as sparse olivine phenocrysts. Samples 08-12 and 08-14 (from locality 229, Fig. 1) contain abundant glomerocrysts of plagioclase and clinopyroxene, up to 5 mm in diameter (Fig. 6b). Sample 08-14 contains conspicuous coarser-grained opaque minerals up to 300 μm in diameter and with skeletal textures (Fig. 6b). Sample 08-13 (from locality 232, Fig. 1) is almost aphyric and contains very sparse clinopyroxene microphenocrysts.

The rubbly pāhoehoe lavas differ from the ´a´ā lavas in that they have a coarser-grained micro-crystalline groundmass, with an average crystal diameter of 200–700 μm (compare Fig. 6a with c) of plagioclase, clinopyroxene and opaque minerals, indicative of a slower cooling rate. Samples 08-15, 08-19 and 08-20 contain plagioclase-clinopyroxene glomerocrysts and sample 08-17 is clinopyroxene phyric, with crystal diameters of up to 1 mm. It also contains sparse plagioclase and plagioclase-clinopyroxene glomerocrysts of up to 5 mm in diameter. Sample 08-22 is olivine-clinopyroxene phyric and contains small plagioclase glomerocrysts (<1 mm in diameter). The dyke sample (08-23) contains plagioclase glomerocrysts, up to 3 mm in diameter, and sparse clinopyroxene and olivine phenocrysts in an intergranular microcrystalline groundmass of plagioclase, clinopyroxene and skeletal opaque minerals.

Geochemical characteristics

All of the sampled lavas are tholeiitic basalts (Table 2). SiO_2 contents for the ´a´ā lavas at the top of the Thakurvadi Formation range from 48.17 to 50.31 wt% (average of 49.46 wt%); TiO_2 varies from 1.94 to 2.20 wt% (average 2.09 wt%), Fe_2O_3 from 12.33 to 13.34 wt% (average 12.88 wt%), P_2O_5 from 0.18 to 0.21 wt% (average 0.19 wt %) and MgO from 6.24 to 8.06 wt% (average 6.98 wt%). Trace element concentrations are characterised by low Ba (83–114 ppm), moderate Sr (234–269 ppm), low Zr (116–139 ppm) and Cu concentrations of 143–173 ppm. The rubbly pāhoehoe (sample 08-15) from above the ´a´ā lavas at the type locality is geochemically similar to the ´a´ā lavas (Table 2). A distinction is seen between those lavas with olivine microphenocrysts (MgO>7 wt%) and those with clinopyroxene and plagioclase microphenocrysts, or just plagioclase microphenocrysts (MgO<7 wt%). Also reported in Table 2 is an analysis (Ch4b) of a'ā lava at the type locality by Bondre et al. (2006). This compares well with the analysis of our sample 08-05 from the same locality.

The rubbly pāhoehoe lavas sampled lower in the Thakurvadi Formation differ slightly from the upper Thakurvadi Formation lavas. SiO_2 contents are 48.7 to

51.47 wt%, with an average of 49.7 wt%. This is within analytical error of the upper Thakurvadi Formation lavas. TiO_2 is lower and varies from 1.81 to 1.97 wt% (average 1.87 wt%). Fe_2O_3 also spans a more restricted range and varies from 12.27 to 12.53 wt%, with a lower average value of 12.4 wt%. P_2O_5 is higher at 0.2 to 0.25 wt% (average 0.22 wt%), as is MgO which spans a range of 6.77 to 8.10 wt%, with an average of 7.52 wt% (Table 2). The difference between the two lava groups is also marked differences in trace element contents, with lavas lower in the Thakurvadi Formation having higher Ba (136–177 ppm), higher Sr (310–339 ppm), slightly higher Zr (123–136 ppm) and lower Cu concentrations (97–117 ppm).

The dyke sample (08-23) that cuts the rubbly pāhoehoe flow has a Thakurvadi Formation affinity but does not exactly match any of the ´a´ā flows. It has the highest SiO_2 content of any sample, at 51.1 wt%. While TiO_2, MgO and P_2O_5 contents are comparable to the ´a´ā flows, Fe_2O_3 contents are slightly lower. Also, although Zr, Sr, and Cu concentrations are broadly comparable with the ´a´ā flows, Ba is higher at 134 ppm. The mismatch between the analysis presented here and that taken from Bondre et al. (2006) may result from multiple injections within the dyke. Bondre (1999) reports evidence for multiple margins from an outcrop close to the road at this locality. Unfortunately this outcrop is no longer well exposed because of extensive quarrying along the dyke's softer margins. During the our study, the dyke was sampled further to the east, higher up on the hillside where it pinches and swirls but does not show any evidence of being multiply intrusive. This discrepancy in geochemical data awaits a more satisfactory explanation.

Correlations with Deccan chemostratigraphy

The ´a´ā flows at the top of the Thakurvadi Formation have not been sampled by previous chemostratigraphic studies (e.g. Beane et al. 1986; Khadri et al. 1988), but are compositionally similar to compound pāhoehoe flows that cap the Formation along the Western Ghats (Fig. 7a). Thakurvadi Formation lavas are distinguished from those of the overlying Bhimashankar Formation (Fig. 2) primarily by the former's elevated MgO contents (>6 wt%, Beane et al. 1986). Beane (1988) recognised a Thakurvadi Formation geochemical type along the Western Ghats that is characterised by the presence of olivine and clinopyroxene phenocrysts, an absence of plagioclase phenocrysts, MgO contents of <8.1 wt% and TiO_2 contents of 1.65 to 2.75 wt% (Fig. 7a). Beane (1988) subdivided this chemical type into several subtypes based on trace element abundances: high-Ni, low-Ni, high-Ti and high-Cr (Fig. 7b). Khadri et al. (1988) refined this chemostratigraphy further, but their trace element analyses by IC-PMS do not allow easy comparison with data presented here or with the data of Beane et al. (1986). As shown in Fig. 7b,

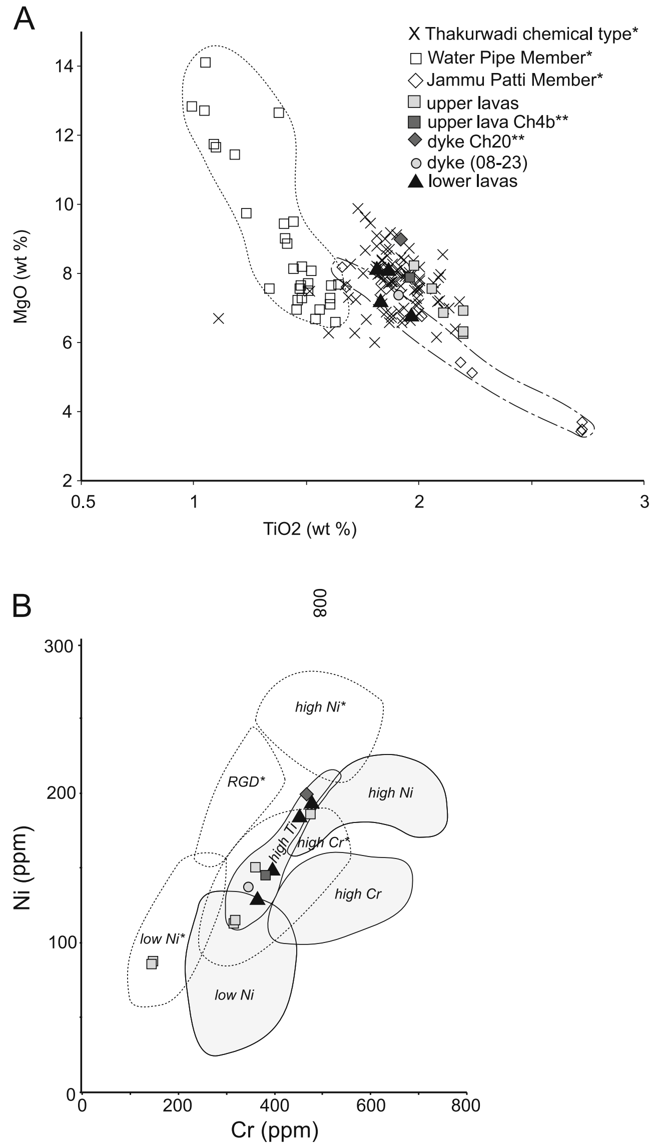


Fig. 7 **a** TiO_2 vs. MgO for the Thakurvadi Formation and lavas of this study (* denotes data from Beane et al. 1986 and Beane 1988). Water Pipe and Jammu Patti Members are chemically distinct lavas within the Thakurvadi Formation. ´A´ā and rubbly pāhoehoe lavas of this study overlap with the Thakurvadi Formation geochemical type. ** data from Bondre et al. (2006). **b** Subdivision of the Thakurvadi Formation geochemical type based on Ni and Cr concentrations (Beane et al. 1986; Beane 1988). ´A´ā and pāhoehoe lavas have affinities with the low-Ni and high-Ti subtypes of Beane et al. (1986). Upper lavas—´A´ā and pāhoehoe lavas at top of Thakurvadi Formation; Lower lavas—pāhoehoe lavas lower in Thakurvadi Formation at localities 344 and 346 (Fig. 1)

most lavas analysed in this study have affinities with the high-Ti group of Beane et al. (1986). Two samples of the ´a´ā flows (08-12 and 08-14), which contain abundant plagioclase microphenocrysts and glomerocrysts, have relatively low MgO (<6.35 wt%), Ni (85 ppm and 87 ppm), and Cr (145 ppm and 147 ppm; Fig. 5b) contents and could belong to the Bhimashankar Formation (Fig. 7a and b).

Discussion

The ´a´ā flows described in the DVP exhibit features typical of ´a´ā flows observed elsewhere. That is, they have basal and flow-top breccias comprising variably vesicular clinker that locally grade into a dense, finely crystalline core characterised by stretched vesicles. Accretionary lava balls, slabs of pāhoehoe crust and pāhoehoe break-outs (Figs 3 and 4) are also typical features of ´a´ā flow fields. We thus infer that our flows were emplaced in a similar manner to other ´a´ā flows observed during emplacement. That is, they were initially channelized flows that cooled rapidly, and were subject to extensive microlite crystallisation. This increased viscosity and yield strength resulted in the brecciation of the crust under the shear stresses imposed by the flow (e.g., Peterson and Tilling 1980; Kilburn 1990; Cashman et al. 1999; Soule and Cashman 2005). The following sections develop ideas on why and how these ´a´ā flows developed in the DVP.

Significance for the DVP and continental flood basalt volcanism

´A´ā flows are a common product of basaltic volcanism (e.g. Macdonald 1953; Holcomb 1980; Lockwood and Lipman 1987; Kilburn and Lopes 1988) and their discovery in the DVP poses the intriguing question of why they appear to be so rare and volumetrically minor in many large CFBPs? Most flood basalt lava flows studied to date are extensive inflated pāhoehoe sheet lobes or compound pāhoehoe flow fields (Walker 1971; Thordarson and Self 1998; Self et al. 1997, 1998; Passey and Bell 2007; Jerram et al. 1999; Duraiswami et al. 2001; Bondre et al. 2004). ´A´ā flows were reported in the CRBG (Swanson and Wright 1980; Reidel 1983), but these are presently considered to be rubbly pāhoehoe (Self et al. 1997). ´A´ā flows are present in the Steens Basalts (CRBP) of southeastern Oregon (Bondre and Hart 2008). Recently, basaltic andesitic ´a´ā flows have been reported from the Parana province (Hartmann et al. 2010) and elsewhere in the DVP (eastern Deccan Traps, Kumar et al. 2010). Duraiswami et al. (2003, 2008) also report the presence of rubbly and slabby types of pāhoehoe that are considered transitional to ´a´ā lavas (e.g. Lipman and Banks 1987; Rowland and Walker 1987).

The recognition of ´a´ā lavas adds to the spectrum of basaltic lava types recognised in the DVP. They exhibit petrographic and geochemical variations which, together with the wide area over which they outcrop, suggest that they are the products of several eruptions potentially from several sources. The presence of flow margins (e.g. Fig. 4) and the compound nature of the ´a´ā lavas at the type locality suggests a complex architecture. Rubbly pāhoehoe in younger chemostratigraphic Formations flows to the south of the study area are also reported by Duraiswami et al. (2008).

There are several reasons why ´a´ā flows are apparently rare in CFBPs. Firstly, large tracts of many CFBPs have not been mapped or logged in detail, so that it remains a possibility that other examples of a'ā lavas may be uncovered during future studies. However, ´a´ā lavas are not commonly reported in CFBPs that have been mapped and studied in reasonable detail, such as the CRBG (e.g., Swanson et al. 1980) or the Faroe Islands Basalt Group (Passey and Bell 2007; Passey and Jolley 2008). Secondly, their rarity may result from their being confined to proximal regions. ´A´ā lava flows are commonly channel-fed (e.g., Lipman and Banks 1987; Rowland and Walker 1990) and are short in comparison to pāhoehoe lava flows, which can reach 100 s to 1000 km from source (e.g. Self et al. 1998, 2008a; Stephenson et al. 1998): the longest ´a´ā lava flow seen forming extended 51 km during the 1859 eruption of Mauna Loa, Hawai'i (Rowland and Walker 1990). The comparatively short lengths of ´a´ā lava flows are primarily a result of the thermal inefficiencies of their transport system (cooling-limited flow) due to the lack of insulating crust and to continual stirring during channelized flow (cf. pāhoehoe flows; e.g. Kilburn 1990; Crisp and Baloga 1994). ´A´ā lava flowing in open-channel conditions with a stable carapace of clinker cools at rates of 5–20°C km^{-1} (Harris et al. 2005), which if flow stops after ~200°C of cooling (Harris and Rowland 2009), will give a maximum travel distance of ~40 km.

On Hawai'i, opening, high-intensity fountain phases of eruptions, which can feed lavas at high effusion rates (>5–10 m^3 s^{-1}; Rowland and Walker 1990) typically generate channel-fed ´a´ā flow fields (e.g. Lipman and Banks 1987; Lockwood and Lipman 1987; Wolfe et al. 1988; Harris et al. 2009), whereas long-lived, low-intensity eruptions often produce extensive, low effusion rate tube-fed pāhoehoe flow fields (e.g. Holcomb 1980; Hon et al. 1994). During a single eruption, a characteristic sequence can occur of early ´a´ā buried by pāhoehoe fields formed during the later, sustained lower-intensity phases (Lockwood and Lipman 1987). The dominance, over time, of pāhoehoe leads to the construction of broad shield volcanoes with shallow-dipping slopes. Bondre and Hart (2008) proposed that the compound pāhoehoe flows from the Steens Basalt may form parts of scutulum-type shields similar to those from the Snake River Plain (e.g., Greeley 1982). A similar argument was made for lavas in the Faroe Islands Basalt Group by Passey and Bell (2007). Flood basalt eruptions, with durations estimated at 10–10^2 years (Self et al. 1998), can be likened to persistent eruptions on Hawai'i, but presumably at much higher mean output rates. Thus the dominance of pāhoehoe flow fields in CFBPs is not unexpected. Mean output rates are inferred to be high during flood basalt eruptions (7.0×10^6–22×10^6 kg s^{-1}, Thordarson and Self 1996), but local effusion rates (in m^3 s^{-1}) for lavas supplying individual flows or lobes are not known, nor are effusion rates per unit length of fissure (in m^3 s^{-1} m^{-1}). There is no reason to suspect that the dynamics of rising magma in a flood basalt eruption differs significantly from those during a Hawaiian eruption, so that high-intensity opening phases driven by gas-rich magma, and capable of supplying lava at high effusion rates, should be expected. However, in the youngest and most well-exposed CFBP, the CRBG, a'ā lavas are not present even close to the vents (Swanson et al. 1975; RJ Brown, unpublished observations around the Roza fissure system). One possibility is that the high effusion rates needed to generate strongly channelized flow and ′a′ā lava were not reached.

Another possible reason for the scarcity of ′a′ā lava in CFBPs relates to the fundamental control exerted by topography on the transport of lava (e.g. Kilburn and Lopes 1988; Guilbaud et al. 2005). Experimental studies on lava analogue materials illustrate that steeper slopes promote stronger channelization, whereas low gradients produce wide channels (Hallworth et al. 1987; Gregg and Fink 2000; Kerr et al. 2006). Spreading of lava over horizontal surfaces results in initially axisymmetric flow, leading to rapid deceleration and increased initial cooling, both of which act to promote stable crust development and production of complex tube-fed pāhoehoe flow fields (Blake and Bruno 2000). Lava flowing beneath stable crusts cools very slowly (0.6–1°C km^{-1}, Cashman et al. 1994; Hon et al. 1994; Helz et al. 1995, 2003; Keszthelyi 1995; Keszthelyi and Denlinger 1996). By contrast, strong channelization focuses flow, results in elevated velocities and rapid cooling due to continual turnover (stirring) of the hot core and ingestion of cool crust (Booth and Self 1973; Crisp and Baloga 1994; Harris and Rowland 2001). This promotes groundmass crystallisation, which increases lava viscosity (Kilburn 1990; Polacci et al. 1999; Cashman et al. 2006). High shear rates imposed on the crust under this regime result in its continual disruption and ′a′ā Formation (Peterson and Tilling 1980).

The inferred long-lived nature of flood basalt eruptions, their enormous erupted volumes, and the dominance of extensive pāhoehoe flow fields favours the construction of plateau-type topography with average slopes of 0.1% (Keszthelyi et al. 2006). Even close to source, very little material accumulates near the vents relative to medial and distal locations (Self et al. 1998) so that edifices with steep slopes are not constructed. The effect of slope gradient on lava transport can be seen readily on Kilauea and Mauna Loa shields where the steeper (4–6°) slopes are covered predominantly in ′a′ā lavas and the lower gradient slopes are paved in pāhoehoe (e.g., Holcomb 1980; Greeley 1982; Lockwood and Lipman 1987). Kilburn (2004) found that Hawaiian basalts produced ′a′ā when the flows advanced at a speed (U) greater than a critical value which varied with $\sin^{-1}\alpha$, where α is the ground slope, (U>0.06 $\sin^{-1}\alpha$). The very low average slope gradients typical of flood basalt provinces may help inhibit high flow velocities, open-channel flow and ′a′ā formation and instead favour the construction of slowly advancing pāhoehoe flow fields.

If there are several reasons why a'ā flow fields are uncommon in continental flood basalt provinces, then what special conditions led to their formation in the DVP? Our limited survey data and field investigations indicate that the a'ā lavas capping the Thakurvadi Formation lie on a gently south- and eastward-dipping palaeo-surface with an apparent dip of ~0.5° and lacking significant relief. It is unclear whether this surface represents the original attitude of the palaeosurface, but it is consistent with the plateau-like morphologies of other large CFBPs (e.g. Keszthelyi et al. 2006). Detailed mapping and surveying over an area of several thousand square kilometres would be required to accurately assess palaeoslopes and the extent of the lavas. In the absence of slopes to drive high flow velocities, the mass eruption rate (at source), and its control on lava effusion rates, becomes important. The ′a′ā lavas could be the products of particularly high-intensity eruptions that generated high effusion rate channelized lavas. Flow must have occurred at these rates over timescales long enough to allow cooling, groundmass crystallisation and subsequent crust disruption to occur. Whether these were short-lived eruptions (similar to ′a′ā-forming eruptions on Hawai'i), or opening phases that merged into sustained, lower effusion rate eruptions (i.e. flood basalt eruptions *sensu stricto*) that produced extensive pāhoehoe flow fields remains unknown. Further work is needed and, without observations of an eruption of flood basalt proportions and output rates or without being able to trace a flow uninterrupted from source to distal margin in the DVP (or, in fact, in any flood basalt province), inferences about why the ′a′ā lavas formed remain somewhat limited.

A source for the ′a′ā lavas

Surface vents for Deccan lavas have not yet been recognised, despite an abundance of DVP-age dykes in the province (e.g. Auden 1949; Deshmukh and Sehgal 1988; Bondre et al. 2006; Ray et al. 2007; Sheth et al. 2009). Given that the number and thickness of lavas in the province decreases eastwards, many authors have proposed that the vents are located in the west and potentially offshore (see Mahoney 1988 and references therein). Beane et al. (1986) proposed that dykes in the Igatpuri area (in the western fringe of the Western Ghats) might be feeders, but geochemical matches between specific dykes and lava flows have proved elusive across the province (Bondre et al. 2006; Sheth et al. 2009). Khadri et al. (1988) documented the thickening of Thakurvadi Formation lavas into the Sangamner region, suggesting that this region might be more proximal to source. Numerous dykes intrude the Sangamner region, but only two of the dykes sampled by Bondre et al. (2006) had a similar composition to ′a′ā lavas sampled in this study. Unfortunately, as discussed earlier, one of the same dykes sampled during this study yielded a different composition to previous analyses, for reasons which remain unclear. Two dykes intrude the breccias associated with the ´a´ā flow at the type locality in this study (locality 219, Fig. 1). Bondre et al. (2006) suggested that this outcrop might be welded spatter associated with one of the dykes but further investigation has ruled out this possibility. If the maximum lengths of ´a´ā flows from Hawaii and Etna are any indication, their presence south of Sangamner suggests that this area is close to the source of some Thakurvadi Formation lava flows, perhaps within several kilometres to tens of kilometres. Our field studies have yet to reveal any pyroclastic rocks at this horizon but it is unlikely that dykes further away (e.g. in the Igatpuri area) served as feeders for the ´a´ā flows.

Conclusions

´A´ā flows occur in the western DVP within the Thakurvadi Formation of the lowermost Kalsubai sub-group of lavas (Fig. 2). They outcrop over an area of ~110 km^2 and are considered good indicators of proximity to source. The lavas exhibit micro- and macro-scale features typical of ´a´ā flows at other basaltic volcanoes (e.g. on Hawai'i and Mt. Etna). They are of interest due to the general absence of ´a´ā lava in CFBPs, which may result from a combination of exposure issues (e.g., their short length, confinement to proximal regions and thus limited exposure) and from physical conditions that inhibited their formation. The latter factors include low slope gradients due to plateau-like topography and moderate-to-low effusion rates from point sources, or from short-active-fissure segment sources that make it difficult to meet the conditions required for ´a´ā emplacement (high volumetric flow rates or high strain rates). The conditions that allowed the ´a´ā lavas to form in the DVP over an apparently very low-gradient palaeosurface could relate to unusually high effusion rates from high-intensity fire fountains. How the eruptions that formed the ´a´ā lavas compared to those that fed the more voluminous and extensive pāhoehoe flow fields in the DVP remains, however, unclear.

Acknowledgements This research was funded by a Natural Environment Research Council Standard Grant (NE/E019021/1) awarded to S. Self (Open University). XRF analyses were run by J. Watson at The Open University. Thanks to P. Hooper, C. Vye and M. Widdowson for discussion. Careful reviews by Simon Passey, Raymond Duraiswami, and Editor Andy Harris, are gratefully acknowledged.

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