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ORIGINAL ARTICLE

The Volcanic Geoheritage of the Elephanta Caves, Deccan Traps, Western India

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Abstract Geoheritage, geoconservation, and geotourism studies are of increasing interest worldwide because of their scientific, societal, cultural, and aesthetic value. Volcanic areas (whether active, dormant, or extinct) are exciting targets for such studies. Mid-sixth century rock-cut caves in Deccan basalt on the island of Elephanta, in the Mumbai harbour, are the finest in western India. The Elephanta Caves contain exquisite religious sculptures related to the Hindu god Shiva. They are a protected monument of the Archaeological Survey of India and a UNESCO World Heritage Site, but no geological-volcanological account of them exists. Here, we illustrate typical and well-exposed hummocky pahoehoe lava flows with three-tiered flow lobes and toes, upper crustal vesicular banding and pipe vesicles along lobe bases, and tumuli with inflation clefts and squeeze-ups, from the Elephanta Caves monument. The field observations and simple calculations indicate formation by endogenous growth (inflation), as for pahoehoe flows in Hawaii and Iceland. Interestingly, despite differences in flow volumes of orders of magnitude between Hawaiian, Icelandic, and Deccan flows, their morphologies, internal structures, and even the scale of these structures are identical. We interpret this as indicating similarly low effusion-rate but much longer-lasting eruptions for the Deccan compared to the other two. We show that the Elephanta Caves, a world-renowned historical, artistic, and religious monument, are also a monument for geology and volcanology, and therefore, the need for their conservation is even greater.

Keywords Volcanism · Volcanic geoheritage · Lava flow · Elephanta · Deccan basalt · India

Introduction

The past few years have seen a significant surge in interest in geoheritage, geoconservation, and geotourism studies worldwide. *Geoheritage*, as defined by Brocx and Semeniuk (2007), includes geological features, of global to regional scale, which offer information or insights into Earth evolution or the history of science, or can be used for research, teaching, or reference. Geoheritage is linked to the historical, cultural, aesthetic, and religious values of humanity (Brocx and Semeniuk 2007). *Geoconservation* involves the environmental management of places with geoheritage, and an appraisal of their sustainability, hazard aspects, and geodiversity (the combined geological, geomorphological, pedological, and hydrological features). *Geotourism* is defined by Dowling and Newsome (2006, 2010) as sustainable tourism with a primary focus on experiencing the Earth's geological features in a way that fosters environmental and cultural understanding, appreciation and conservation, and is locally beneficial. It is a synergistic form of tourism in which the elements of the landscape and landforms together create a tourist experience that is richer than the sum of its parts, appealing to visitors with diverse interests (Dowling and Newsome 2010). A hierarchical system established for geoconservation, geoeducation, and geotourism consists of a geosite (or geomorphosite) at the smallest spatial scale, geotopes and precincts at larger scales, and a geopark at the largest scale (e.g., Eder 2008; Ieleniz

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2009; Joyce 2010; Moufti and Németh 2013, 2016). A geopark is a nationally protected area containing a number of geological heritage sites of particular importance, rarity, or aesthetic appeal, and achieves its goals through geoconservation, geoeducation, and sustainable development through geotourism (Dowling and Newsome 2010). Geoparks can play a significant role in the economic development of local or rural areas through geotourism.

Active volcanic and geothermal areas are exciting and widely popular geotourist attractions (e.g., Sigurdsson and Lopes-Gautier 2000; Lopes 2005; Erfurt-Cooper 2010, 2014). Increasing numbers of volcanic geoparks and geoheritage sites are becoming established worldwide. Designated national parks in countries like the U.S.A. include volcanoes (Decker and Decker 2001; see review thereof by Sheth 2003). Many of the UNESCO Global Geoparks (www. globalgeopark.org) include important volcanic geoheritage features, as do parks in Germany, Hungary, Slovakia, Spain, Iceland, and other countries in the European Geopark Network (www.europeangeoparks.org). An Asian example with important volcanic geoheritage is the Jeju Island Geopark and UNESCO World Heritage site in South Korea, with volcanoes <1 million years old (Woo et al. 2013).

India is another Asian country, of subcontinent size, and the seventh largest in the world by area. India has a very rich geological record dating from the Early Archaean, including a large, well-known, Late Cretaceous flood basalt province (the Deccan Traps). The Deccan has ancient rock monuments which are being managed and conserved by the Archaeological Survey of India, and several of these are UNESCO World Heritage sites. India has huge geotourism potential. However, whereas the Geological Survey of India, the country's premier geological mapping agency, has designated a few fossil parks and National Geological Monuments in the country, very little authentic, accurate, or practical information on them is available to the interested geotourist. Geological syntheses of the magnificent rock monuments of India, such as those abundant in the Deccan, are practically nonexistent. A decade ago, Ahluwalia (2006) and Mazumdar (2007) lamented incidents such as the destruction of well-preserved Late Cretaceous dinosaur eggs by a cement plant in central India, and the fact that India was nowhere on the world stage as far as geotourism and geoparks were concerned. The same is true today, though the rest of the world in the past decade has seen a significant surge in interest and activity in geoheritage and geotourism (e.g., Eder 2008; Dowling and Newsome 2010). This is reflected, for example, in the publication (since 2009) of the present Springer journal, *Geoheritage*, as well as Springer's *Geoheritage, Geoparks and Geotourism* book series under which five titles have been published as of this writing (e.g., Erfurt-Cooper 2014; Moufti and Németh 2016; see also a review of the latter volume by Sheth 2016).

The present paper has the objective to establish the Elephanta Caves near Mumbai, western India (a world-famous, mid-sixth century historical, artistic and religious monument in Deccan basalt), as a monument for geology and volcanology as well. We do this by illustrating the spectacular primary lava flow structures exposed in the Elephanta Caves, and discussing their scientific value.

The Deccan Traps and Elephanta Island

The ~65-million-year-old Deccan Traps flood basalt province (Fig. 1a) covers more than 500,000 km^2 in western and central India. The flood basalts are overwhelmingly pahoehoe, and contain both small-scale compound flows and thick, laterally extensive "simple" flows, many of which are recognized as rubbly pahoehoe (Walker 1971; Bondre et al. 2004; Sheth 2006; Duraiswami et al. 2008, 2014; Sheth et al. 2011). There are well over a thousand rock-cut caves known in the Deccan Traps. Deshmukh (1994) noted that out of some 1545 Hindu, Buddhist, and Jain religious rock-cut caves in India, 1200 are in the Deccan basalt in Maharashtra State in western India, overwhelmingly in the highly amygdaloidal compound flows (Fig. 1a), because of their ease of carving. Of all these rock-cut caves, the UNESCO World Heritage monuments of Ajanta and Ellora in the central Deccan Traps (Fig. 1a) are the largest, grandest, and most famous. The Ajanta Caves (ca. second century B.C. onwards) are renowned for their Buddhist sculptures and paintings, whereas the Ellora Caves (ca. seventh century A.D. onwards) are renowned for Buddhist, Hindu, and Jain sculptures.

Michell (2014) considers the Elephanta Caves, located on the island of Elephanta in the Mumbai harbour, as the best example of rock-cut caves in all of western India. Elephanta Island, made up entirely of Deccan basalt, has a 7-km coastline mostly covered by mangroves. The island consists of an eastern hill (rising 168 m above the sea) and a western hill (131 m) separated by a ~N-S-aligned median valley (Fig. 1b, c). Both hills are covered in jungle in large part (mostly palm, mango, and tamarind trees). Available rock exposures (such as on the western coast) show that the basalt flows forming the island dip west-northwest by ~10° and are part of the Panvel flexure, a large-scale tectonic structure on the western Indian rifted margin (Sheth 1998). Morphologically, the flows are small-scale compound pahoehoe flows, with the exception of a >40-m-thick flow of rubbly pahoehoe in the southeastern part of the island (Fig. 1b). The flow was quarried in the 1970's to provide construction material for the then upcoming major port of Nhava-Sheva only 1 km east of the island (Fig. 1b), but quarrying was found detrimental to the Elephanta Caves and therefore stopped. A fault zone consisting of two distinct, oblique-slip normal faults affects this rubbly pahoehoe flow (Samant et al. 2017).
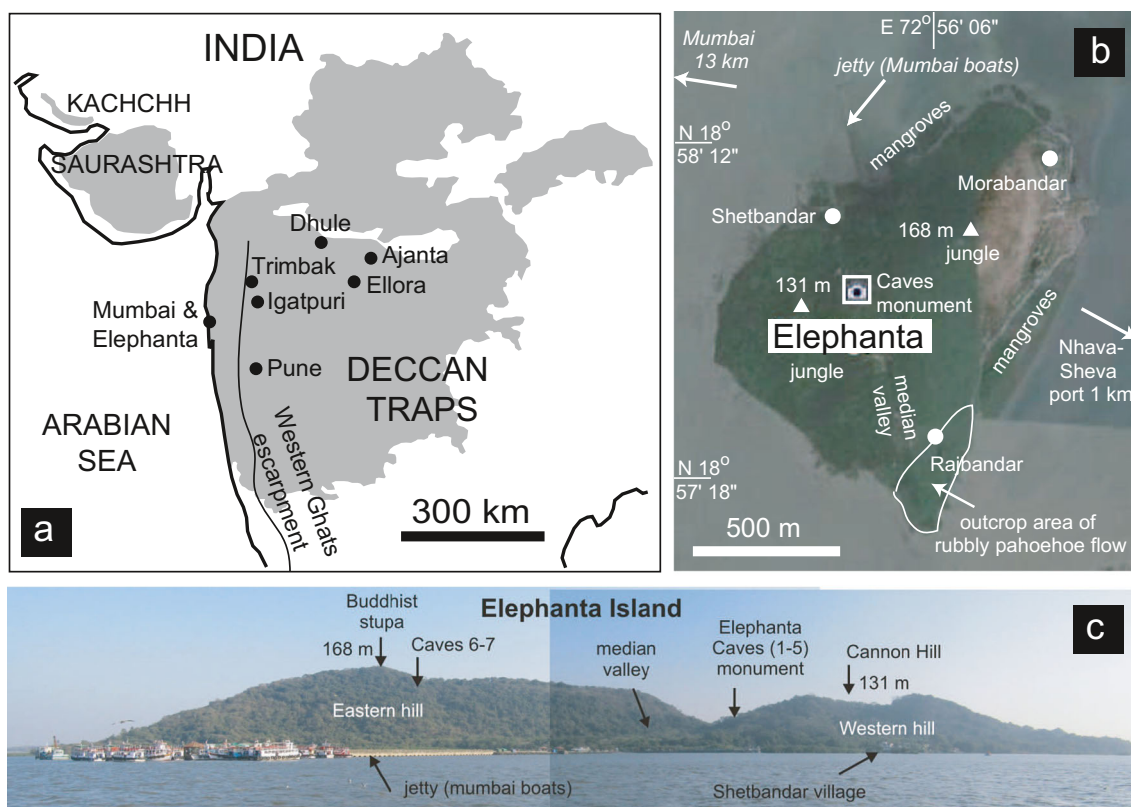
Fig. 1 **a** Map of the Deccan Traps (*shaded*), showing localities where compound pahoehoe flows are abundant, as well as Mumbai and Elephanta. **b** Google Earth image of Elephanta Island, showing the main physiographic features, three villages, and jetty, and the Elephanta Caves. **c** View of Elephanta Island, looking roughly southeast, from a boat arriving from Mumbai. The main features described in the text are indicated

The stratigraphic status of the lava flows of Elephanta Island relative to the thick Deccan lava flow sequences exposed on the Indian mainland is yet unknown, but they may represent the Poladpur or the Bushe Formations which outcrop to the south and the east (Subbarao and Hooper 1988). The Elephanta compound pahoehoe flows constitute a 120m exposed thickness of the eastern hill above the rubbly pahoehoe flow, up to the 168 m summit which is occupied by the ruins of a 10 m-high, second century B.C. Buddhist brick *stupa* (mound-like structure containing holy relics). The flows are mostly highly amygdaloidal and weathered, as seen in isolated outcrops in the jungle and in the rather simple and crude Caves 6 and 7 on this hill (Fig. 1c). Good exposures of compound flows are on the western coast of the island, but the best exposures are within the main group of Elephanta Caves, carved into the western hill at ~85 m elevation above sea level (Fig. 1b, c).

History of the Elephanta Caves

Michell (2014) provides a detailed and well-illustrated historical and artistic account of the Elephanta Caves and their sculptures which depict the scenes of life, moods, and relentless energy of the Hindu god Shiva (syn. Shankar, Mahadeva, and many other names). He considers the Caves to have been carved in the mid-sixth century A.D., possibly by Hindu kings of the Maurya dynasty; a subsequent 1000-year period is shrouded in mystery. The island and the nearby region were controlled by the Portuguese (from 1534 onwards) and by the British (from 1774 onwards), with a possible intervening and short-lived Maratha rule, and accounts of the Caves and the island by foreign travellers, from the sixteenth century onwards, can be found in Michell (2014). The island's original name is *Gharapuri*, and it was named Elephanta by the Portuguese in the eighteenth century after a 4.5 m long and 2.4 m high basalt stone elephant found on its southern shore near Rajbandar village (Fig. 1b), the old landing place (Michell 2014). The elephant began to disintegrate in the nineteenth century and was relocated to the city museum in Mumbai.

Michell (2014) also notes extensive vandalism of the monuments by Portuguese and British soldiers — the sculptures were the target of rifle-shooting and cannons were fired into the Caves for testing the echoes. In 1890, the Public Works Department of Bombay (now Mumbai) city began the task of preserving the Caves. The Caves were made a protected monument of national importance by the Archaeological

Survey of India in 1909 (note that India was under British rule until 1947) and were declared a UNESCO World Heritage Site in 1987. Despite the early vandalism, the sculptures still retain substantial glory, though only traces remain of the Caves' original paintings.

The Elephanta Island and Caves are visited by some 25,000 Indian and international tourists per month (Wikipedia). The tourists arrive by ferry boat from the Gateway of India in southernmost Mumbai (~13 km, 1 h) and must return there in the evening as night stay on the island is not permitted. There exists historical and archaeological technical literature on the Elephanta Caves (e.g., Chandra 1957; Kramrisch 1981; Spink 1983; Collins 1988; Khandalavala 1990; Michell 2014) as well as tourist guidebooks. However, with the exception of a study of a fault zone on the island by Samant et al. (2017), there are no published geological studies of the island or the Caves. The present paper on the volcanic geoheritage of the Elephanta Caves can also be considered a geologist's and volcanologist's guide to the Elephanta Caves.

Geology of the Elephanta Caves

The main group of Elephanta Caves comprises five caves, all at the same height (85 m) above sea level and aligned more or less on a N-S axis alongside the median valley of the island. The southernmost, Cave 5, is small and unfinished; work on it was apparently abandoned due to a collapsing roof. Cave 2 is similarly crude. Volcanological features of great interest (spectacular pahoehoe flow lobes, vesicle segregations, pipe vesicles, tumuli, and squeeze-ups) are found in Cave 3, Cave 4, and the northernmost cave, called Cave 1 or the main cave as it is the largest and grandest.

We will describe and illustrate the volcanological features of interest from Caves 3, 4, and 1, in that order. Before we do this, a brief summary of the emplacement of pahoehoe lava flows, understood largely from observations of active Hawaiian lava flows (e.g., Macdonald 1953; Rowland and Walker 1990; Hon et al. 1994; Self et al. 1996, Anderson et al. 1999, Hoblitt et al. 2012, and many others), is in order. Such flows grow mostly endogenously, i.e., lava is transported under a thick solidified crust (often in lava tubes), retains its heat, and travels long distances from the eruptive vent. Individual flows are typically compound (Walker 1971), made up of many smaller flow units (called flow lobes and toes). Each lobe develops an upper crust (solidifying downwards) and a lower crust (solidifying upwards) after emplacement. Escaping gas bubbles form pipe vesicles in the lower crust and get trapped beneath the upper crust, leaving a dense, vesicle-free core between the two crusts. A lobe swells (inflates) as lava that continues to be supplied lifts the upper crust. A viscoelastic upper crustal layer under the top brittle crustal layer undergoes ductile stretching and accommodates

the incoming lava. The lobe, inflating like a water-filled balloon, eventually bursts and a new lobe emerges and itself grows by inflation, this process repeating as long as lava continues to be supplied from the vent. On stagnation and after advanced solidification, residual differentiate can rise as vesicle cylinders that get deflected into horizontal vesicular sheets by the upper crust (Goff 1996). A key aspect of such inflated flows is that the final lobe thickness is many times the initial emplacement thickness.

The three-dimensional stacking of lobes in a compound pahoehoe flow can be very complex. Several types of such flows (such as hummocky and sheet flows, Self et al. 1996, 1998) and flow lobes (e.g., P-type lobes with pipe vesicles, Wilmoth and Walker 1993) are recognized. Primary volcanic structures of such flows which indicate inflation and endogenous growth include the classical three-tiered lobes with a core separating upper and lower crusts, pipe vesicles, horizontal vesicular zones (formed by trapping of bubbles at the downward-growing boundary of the upper crust), tumuli (domal uplifts containing extension clefts and lava squeeze-ups, e.g., Walker 1991), and many others. The same structures are known from similar-sized or larger compound flows on Iceland (Rossi and Gudmundsson 1996), and vastly larger continental flood basalt (CFB) lava flows such as those of the Columbia River and Deccan Traps provinces (Fig. 1a) (e.g., Self et al. 1996, 1997, 1998; Keszthelyi et al. 1999; Bondre et al. 2000, 2004; Duraiswami et al. 2001, 2002; Sheth 2006).

Elephanta Cave 3

The wall of Cave 3, behind the pillars (Fig. 2a, inset) exposes a number of stacked compound flow lobes with gently convex-up tops and convex-down bases (Fig. 2a). The central lobe is the best developed and exposed and shows the three-tiered structure typical of inflated flow lobes (Self et al. 1997, 1998). It shows a 40-cm-thick upper crust with spherical vesicles, an underlying dense, vesicle-free core, and a lower crust with pipe vesicles (Fig. 2b). Whereas many pipe vesicles are vertical, others pitch steeply either north or south, suggesting later local movement of highly viscous lava (Walker 1987; but see Philpotts and Lewis 1987 for an alternative interpretation). The top of the lobe is gently convex, whereas the base is also convex downward along the middle, and as a result the lobe is thicker along the middle than outwards. Another noteworthy aspect of this well-formed lobe is its bilateral symmetry. This lobe was emplaced in a depression between two older and adjacent lobes below, and then thickened by inflation. Hon et al. (1994) have observed the emplacement and growth of active pahoehoe lava lobes on Kilauea volcano and derived an expression for the time of growth of an active lobe based on its crustal thickness. Their equation is $t = 164.8\ C^2$, where t is the lobe formation time in hours and C the upper crustal thickness

Fig. 2 The main interesting features of Elephanta Cave 3. **a** A succession of pahoehoe lobes. Photo by N. Youbi. *Inset figure* shows the outer façade of Cave 3 with tourists for scale. **b** Close-up of the central lobe in **a**, showing its internal features. The *hand* provides an approximate scale. **c** Vesicle segregation features (indicated by *white arrows*) passing through the idols of the flying celestials, high up on the same wall
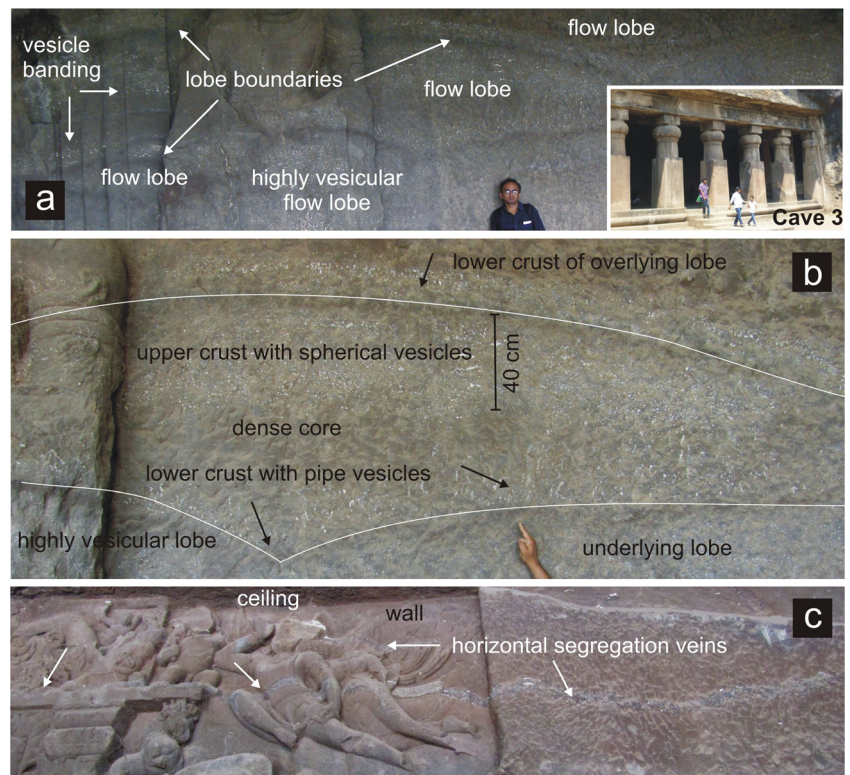
in meters. For the well-formed central flow lobe in Cave 3 (Fig. 2b), with a 40-cm-thick upper crust, we calculate a formation time of 26.3 h, i.e., this lobe could have been emplaced and grown over approximately 1 day. Bondre et al. (2004) have reported similar crustal thicknesses in other Deccan small-scale pahoehoe lobes, implying comparable emplacement times.

The upper part of the same wall in Cave 3 shows human-size sculptures of *gandharvas* (flying celestial beings) that are traversed by vesicle segregation features (Fig. 2c). One of these segregation veins runs nearly across the entire length of the cave, and another one, somewhat higher, is shorter. These segregation features represent late-stage residual differentiate after advanced solidification (e.g., Goff 1996; Costa et al. 2006).

Elephanta Cave 4

Flow lobes much thicker than those exposed inside the Caves are exposed on the roof of Cave 4 (Fig. 3a). Unfortunately, a close look is not possible as one is not permitted to climb to the roof from the Cave premises, but large loose boulders (up to a few meters in size) beside the path to Cannon Hill (the 131 m summit of the western hill) show no constituent small lobes. The thicker lobes forming the roof may indicate a locally or temporarily increased effusion rate, or longer formation times. A small outcrop between two British-era cannons kept on the summit shows small-scale lobes. We believe that

the precise location of the Elephanta Caves was chosen because of the suitability of the small-scale lobes for carving and the suitability of the overlying thicker lobes for a stable roof.

The outer wall of Cave 4 exposes a well-formed tumulus (Fig. 3b). Tumuli are positive topographic features in lava flow fields that form by pressurized injection of lava under the surface crust, causing the crust to undergo domal uplift. They indicate localized inflation, such as can occur when a lava tube under a solidified crust is blocked downstream, or when a considerably cooled lava front, still being supplied with lava, ceases to advance (e.g., Walker 1991; Rossi and Gudmundsson 1996). Though much of the lower part of the Cave 4 wall is covered with plaster, the tumulus can be unambiguously identified based on its steeply convex top, its higher aspect ratio (thickness/width) than typical for a lobe (compare Fig. 2b), tilted vesicle banding of the upper crust, and even an axial cleft at the centre of its top surface.

The contact of the tumulus with the overlying lava lobe is not traceable throughout and has to be imagined through the large idols on the southern side (dashed black line in Fig. 3b) and much of the northern side. The radius and height of the tumulus are ~4.83 and ~2.67 m, respectively (Fig. 3b). These are approximate and minimum values because the entire tumulus is not exposed, requiring extrapolations of the observed features, and because the tumulus floor may be below the level of the cave floor. Nevertheless, making the reasonable assumption of a typical, regular tumulus shape, the aspect ratio (height/width) of the Cave 4 tumulus (Fig. 3b) is 0.28 which, considering
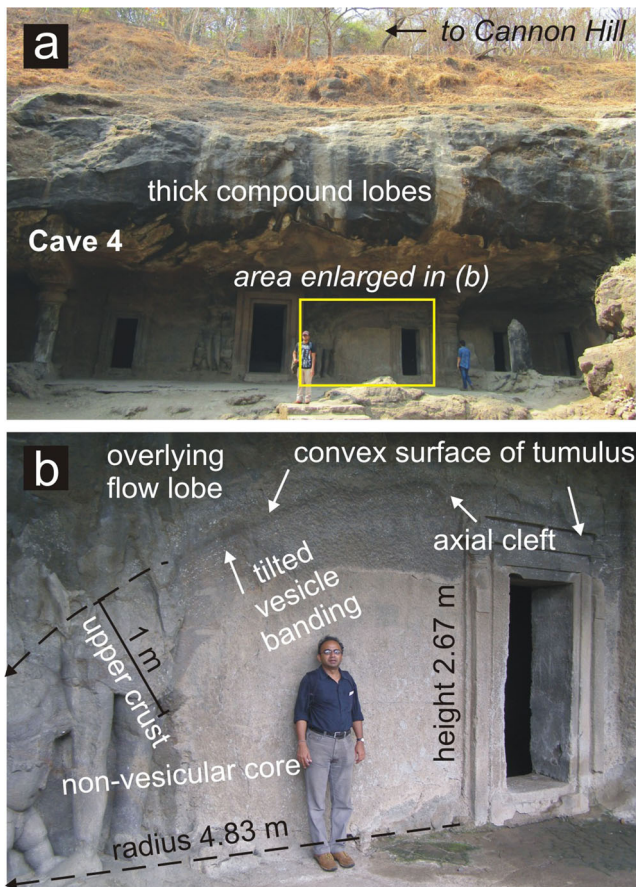
Fig. 3 a The outer facade of Elephanta Cave 4. People for scale. Note thick lobes forming the roof. b Tumulus in the wall of Cave 4. The planform of the tumulus is indicated, where not clear, by *dashed black lines*, and the approximate dimensions indicated. Photo by N. Youbi

the uncertainties, is nearly the same as the range for Icelandic tumuli (0.30–0.35, Rossi and Gudmundsson 1996). In comparison, size measurements of tumuli around Pune and Dhule in the Deccan (Duraiswami et al. 2002) yield median and mean values of 0.18 and 0.20, respectively.

Rossi and Gudmundsson (1996) modelled Icelandic flow-lobe tumuli (single lava lobes that were domed up, like the Cave 4 tumulus) as uplifted circular elastic plates subjected to a uniform magmatic overpressure in the flow interior. Using their methodology and equations, we compute the magmatic overpressure that produced the Cave 4 tumulus. The height of a tumulus is a function of the internal magmatic overpressure and the surface crust's flexural rigidity (a measure of resistance to deformation, controlled by its thickness). The general convex shapes of tumuli worldwide and their V-shaped axial clefts suggest that bending and extensional stresses are involved with domal uplift. For a tumulus of radius a, with lava crust of thickness h and Poisson's ratio υ, subject to a uniform magmatic overpressure P_m on its bottom (Fig. 4), and with E the Young's modulus of the lava crust and υ its Poisson's ratio (with values of 5 GPa and 0.28 respectively, appropriate for fresh basaltic lava flows, Gudmundsson 1983; Ray et al.
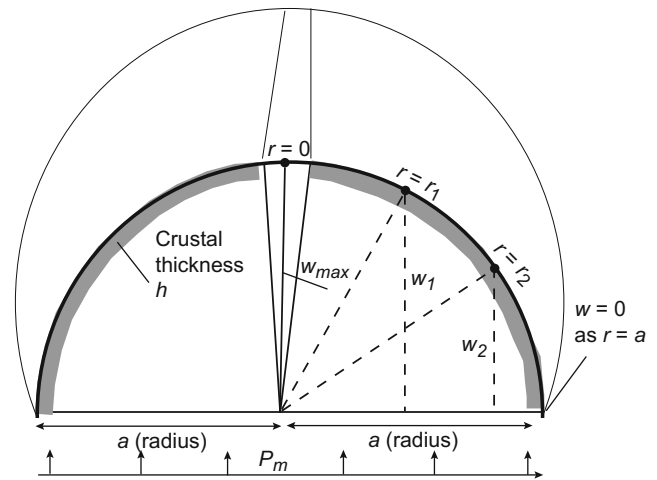

Fig. 4 Sketch showing the general features of tumuli, and explaining the terms used in the mathematical model

2007), flexural rigidity (D) of the rigid crust is obtained by:

$$D = \frac{Eh^3}{12(1-\upsilon^2)} \tag{1}$$

The parameter h represents *viscoelastic* crust thickness, because it is the viscoelastic crust that is subject to compression during bending and offers the main resistance to it. The uppermost, brittle crust is jointed and fractured, with very low tensile strength and low resistance to uplift and bending. Hon et al. (1994) reported that viscoelastic crust initially represents 100% of the total crust thickness, and 70% of the crustal thickness after 1 h, 60% after 2 h, and 50% after 10 h of lobe emplacement. Viscoelastic crust thickness stabilizes to 40% after about 4 days. Taking a value of 40 cm (see Fig. 3b) for viscoelastic crust in Eq. 1, we get flexural rigidity $D = 28.9 \times 10^6$ Pa m^3.

The vertical displacement or deflection w of the lava crust varies along its arcuate length (as measured in cross section), with a maximum at the centre, and is zero at the two ends. The vertical deflection (w) at any point along this length varies with r, the radial distance from the centre (Fig. 4). When $r = a$, $w = 0$. When $r = 0$, at the centre of the tumulus, w has its maximum value w_{max}. This is obtained by

$$w_{max} = \frac{(P_m a^4)(5 + \upsilon)}{64D(1 + \upsilon)} \tag{2}$$

w_{max} is measured in the field (maximum height of a tumulus), and the equation can be rewritten to calculate the magma overpressure P_m. For the Cave 4 tumulus, using $a = 4.83$ m, $w_{max} = H = 2.67$ m, $h = 0.4$ m, $D = 28.9 \times 10^6$ Pa.m^3, $E = 5$ GPa, and $\upsilon = 0.28$, we get $P_m = 2.2$ MPa. Rossi and Gudmundsson (1996) calculated a P_m of about 1 MPa for Icelandic flow-lobe tumuli.

To form the axial crack in the tumulus, the static overpressure must exceed the tensile strength of the upper part of lava crust. If σ_{max} is the maximum radial and circumferential tensile stress at the centre of an uplifted tumulus ($r = 0$), it is given by

$$\frac{\sigma_{max}}{P_m} = \frac{3(3 + \upsilon)a^2}{8h^2} \qquad (3)$$

Using $a = 4.83$ m, and the same values for the other terms as above, the potential tensile stress σ_{max} in the central part of the surface of the Cave 4 tumulus is 395 MPa, or 179 times the magma overpressure P_m. In Iceland, the in situ tensile strength in the uppermost part of the basaltic lava pile is from 1 to 6 MPa (Gudmundsson 1983). Thus, the potential tensile stress in the centre of a tumulus greatly exceeds the tensile strength of the lava crust.

Some flow-lobe tumuli are supplied with magma from tubes that originate from small crusted-over channels (Holcomb 1981). If the tube is closed with no leakage of lava through cracks, the maximum magmatic overpressure in a tumulus that the tube feeds is given by:

$$P_m = \Delta z g \rho_m \qquad (4)$$

where Δz is the elevation difference between the surface of the lava lake (the ultimate source of the tubes) and the flow-lobe tumuli, g is the acceleration due to gravity, and ρ_m is the density of the lava in the tubes. The magmatic overpressure that forms the tumuli is thus proportional to this elevation difference between the tumuli and the surface of the source lava lake. Using a value of 2700 kg/m^3 for the density of liquid

basalt (Ray et al. 2007), and the computed maximum magmatic overpressure of 2.2 MPa for the Cave 4 tumulus, the maximum elevation difference required between the surface of the source lava lake and the tumulus fed by it, via a continuous lava transport network, is 83 m. Rossi and Gudmundsson (1996) computed required elevation differences of 40 m for Icelandic pahoehoe flow-lobe tumuli, and observed actual elevation differences of 100 m between the tumuli and the vents. The 83-m figure computed for the difference in level between the Elephanta Cave 4 tumulus and its source vent is therefore reasonable.

Elephanta Cave 1

The main cave is a great columned hall with entrances on three sides and was carved in a well-planned geometrical pattern following the cardinal directions (Fig. 5; see Michell 2014 for details). It displays exquisite historical-sculptural *and* volcanological treasures. The cave is currently entered from its northern entrance, and the immediately adjacent panel and pillar on the right (western) side expose small flow lobes and toes as well as the topmost part of an underlying tumulus with a summit inflation cleft (Fig. 6a). The next lava lobe has filled this inflation cleft, and there is a succession of several lobes and small toes well displayed in the pillar (Fig. 6a). The adjacent recessed panel (Fig. 6b) contains a 2.7 m tall figure of dancing Shiva in which flow lobe contacts and horizontal vesicular banding of the upper crust can be perceived. Some of the upper lobe parts show vesicular banding, and there are distinct thin red zones along the boundaries of most of these

Fig. 5 Layout of the Elephanta Cave 1 (simplified from Michell 2014), with the locations of the various features and panels photographed for the present paper added. *Open squares* are pillars
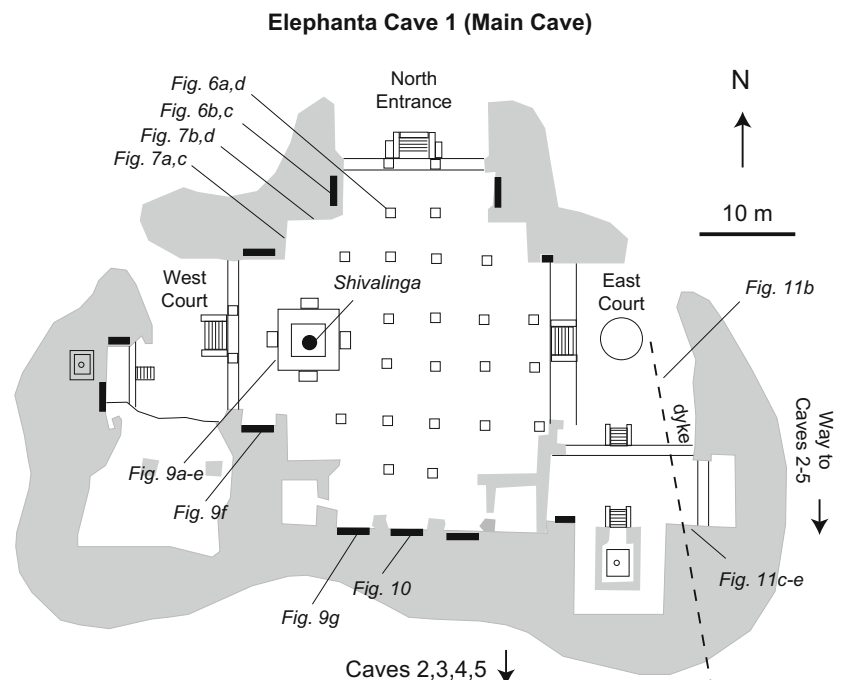

Elephanta Cave 1 (Main Cave)

Fig. 6 Panel and pillar near the northern entrance of Cave 1. **a** Pillar showing top of tumulus with inflation cleft and overlying lobes with reddening of most contacts. **b** Larger view of the pillar in **a** and adjacent panel, depicting Shiva performing the violent and dangerous *tandava* dance associated with the destruction of the world. His wife Parvati, sons Kartikeya and Ganesh, as well as other personalities are also seen. Interlobe contacts and horizontal vesicle banding (upper crust of a lobe) are indicated by arrows. Photo by N. Youbi. **c** Close-up of a part of **b**, with a small lava toe and vesicle banding. **d** Close-up of the inflation cleft in **a**. Note the millimeter-thin tip of the cleft
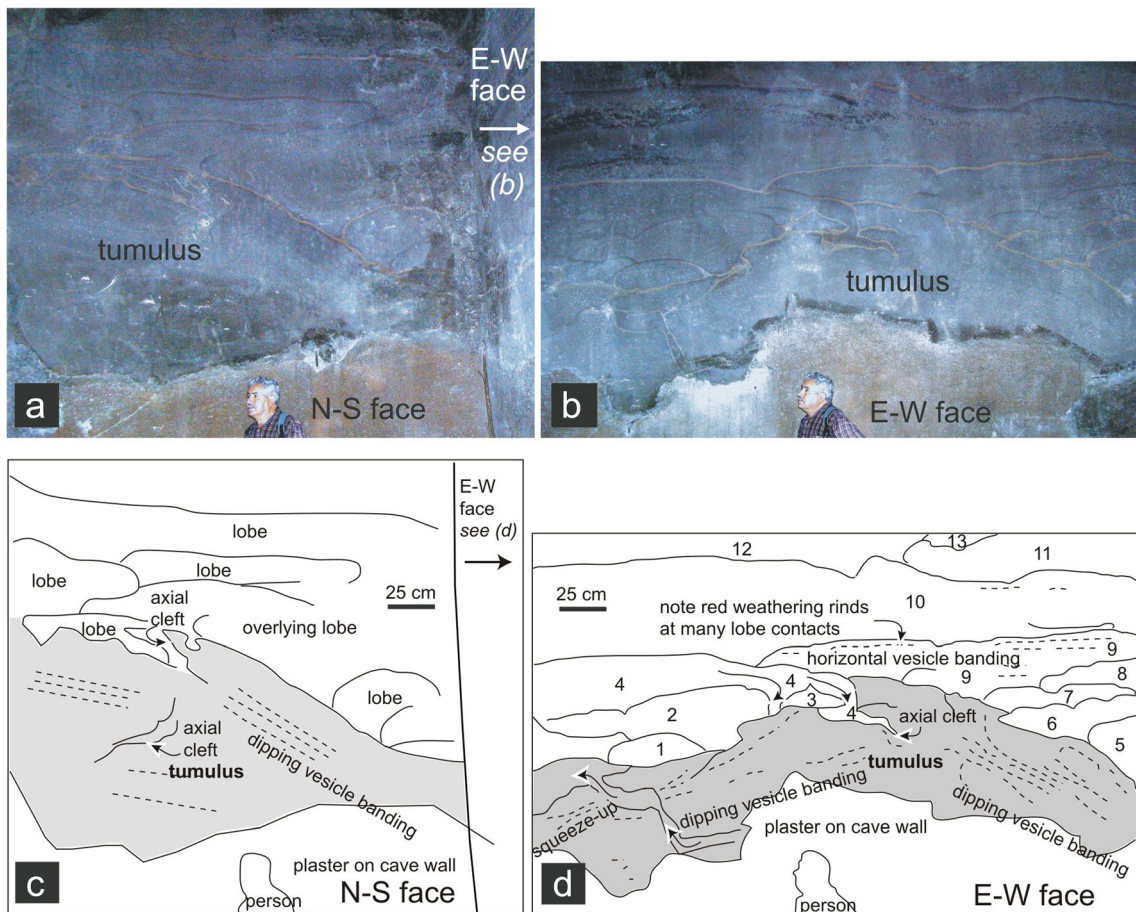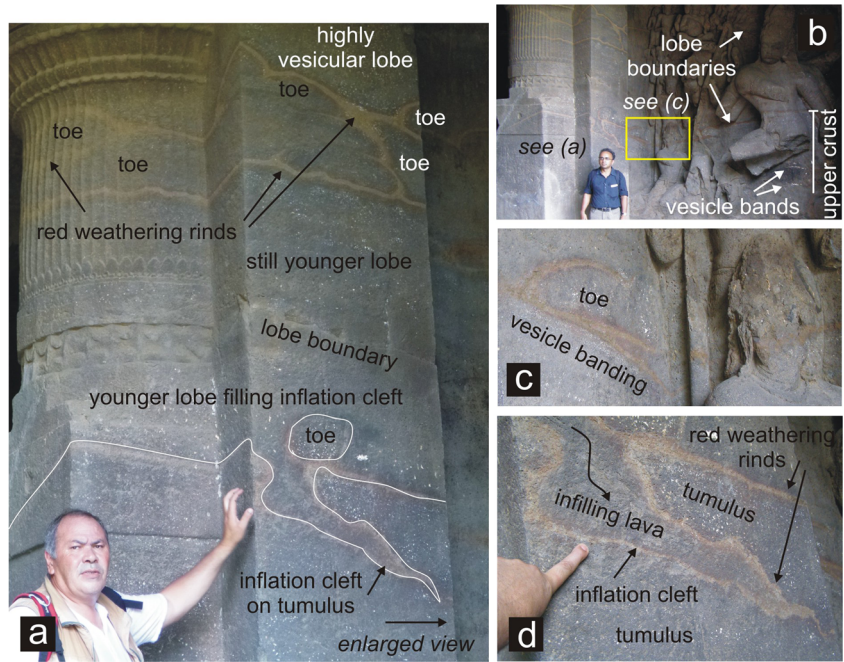

Fig. 7 **a**, **b** The tumulus near the northern entrance of the Elephanta Cave 1, dissected by N-S and E-W walls. Because of poor lighting conditions and insufficient contrast in the original photographs, they have been edited to emphasize the features and particularly the reddened interlobe contacts. **c**, **d** Interpretative sketches drawn from **a** and **b**, showing the features of the identified tumulus and the overlying lobes. Thirteen distinct lobes are identifiable on the E-W face (**d**), and the numbering 1–13 does not imply order of emplacement, except that lobes marked 1, 2, and 4 are progressively younger, lobes 5 to 9 are progressively younger, 10 is younger than 9 and 4, and 13 younger than 11

lobes and toes (Fig. 6a–d), which we ascribe to post-eruption tropical weathering of their once-glassy rinds.

A little further into the Cave, adjacent to the dancing Shiva panel, another well-formed tumulus is exposed as vertical sections on N-S and E-W-trending walls (Fig. 7a, b). Its aspect ratio is however rather difficult to estimate. The tumulus is overlain by many flow lobes. There is distinct reddening at most lobe contacts, due to weathering of their chilled glassy rinds. The poor lighting and state of preservation of the walls, as well as the plaster in the lower part, hide many features, but inflation clefts at the summit of the tumulus, filled by overlying lava, are distinct, as is a lava squeeze-up (Fig. 7a, b). Squeeze-ups are the lava extrusions that often occur from the axial and transverse clefts of tumuli (Walker 1991), and are good evidence for lava inflation. Bondre et al. (2004) and Duraiswami et al. (2001, 2002) have illustrated squeeze-ups in other Deccan pahoehoe flows. An interpretative sketch of the features in Fig. 7a, b is given in Fig. 7c, d. Note that though the lobes overlying the tumulus appear to be horizontal in the N-S face (Fig. 7a, c) and very gently west-dipping in the E-W face (Fig. 7b, d), the attitude of such small lobes of fluid lava strongly depends on the existing microtopography and has no relationship to the regional dip of the Elephanta Island lavas, which is 10°–12° west-northwest. We note here that good examples of squeeze-ups, centimeters to several meters in size, are also found in the small-scale compound flows forming a small coastal cliff and the associated wave-cut platform on the 200-m-long westernmost shore of Elephanta Island (Fig. 8a–e).

In Cave 1, the principal object of worship is a *shivalinga* (Shiva's phallic emblem) enclosed within a square shrine with four doors. Each door is guarded by two giants (*dvarpalas*, meaning guardians of the door), sometimes with idols of dwarfs representing *ganas*, Shiva's servants (Fig. 9a, b). Small-scale pahoehoe lobes with vesicular banding, pipe vesicles, and reddening along contacts are well seen on these guardian idols (Fig. 9c–e). The same interlobe contacts can be seen in large panels in the Cave, such as the one showing the marriage of Shiva and Parvati (Fig. 9f) and another showing Shiva (Gangadhar Shiva) bringing the holy river Ganga (Ganges) to Earth from the heavens via his hairlocks (Fig. 9g). Poor lighting hides some of these interlobe contacts, but professional photography with artificial lighting, such as that by Bharath Ramamrutham in Michell's (2014) book, shows them very distinctly.

The trademark sculpture of the Elephanta Caves is the famous bust of Shiva called the *Trimurti* (literally "three idols"). This 6-m-high idol carved in a deep recess at the south end of the N-S axis of the main cave (Fig. 10) is one of exquisite workmanship and great beauty and leaves an immensely powerful spiritual impression. It combines the three forms of Shiva, namely the creator (on the right of the viewer), the preserver (middle), and the destroyer (left of the viewer). Interlobe contacts can be seen in most sculptures in Cave 1, including the *Trimurti*. See for example the photograph on p. 19 of Michell (2014), or the wrist level of the central figure in Fig. 10.

The tumuli in the Elephanta Caves correspond to the flow-lobe tumuli in Iceland (Rossi and Gudmundsson 1996), i.e., these are originally single lobes that were domed up. The identification of several tumuli in the Elephanta Caves implies that their host lava flow should
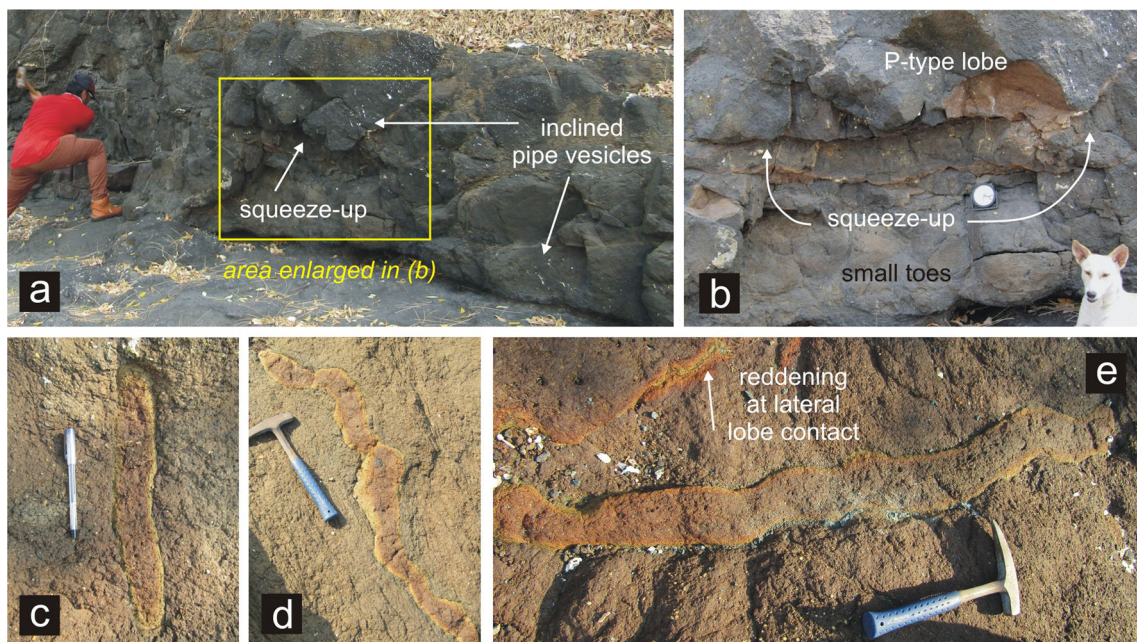

Fig. 8 **a** Small-scale pahoehoe lobes in a small cliff on the western shore of Elephanta Island. **b** Close-up of a part of **a**, showing a squeeze-up between two lobes. **c–e** Some of the numerous squeeze-ups exposed on the wave-cut terrace on the western shore (plan views). *Pen* in **c** is 15 cm long

Fig. 9 **a**, **b** Giants and dwarfs guarding the doors of the square room with the Shivalinga inside. *Double-headed arrow* shows passage from one side to another, and the panel at the end of the path in **b** is enlarged in **f**. **c**, **d** Internal features of the small-scale pahoehoe lobes. Photos by N. Youbi. **e** Contacts between small lobes in one of the giant figures indicated by *white arrows*. **f**, **g** Other life-size or larger figures in other panels in Cave 1. Some of the interlobe contacts are indicated by *arrows*. The panels are 3.5 to 4 m wide and high
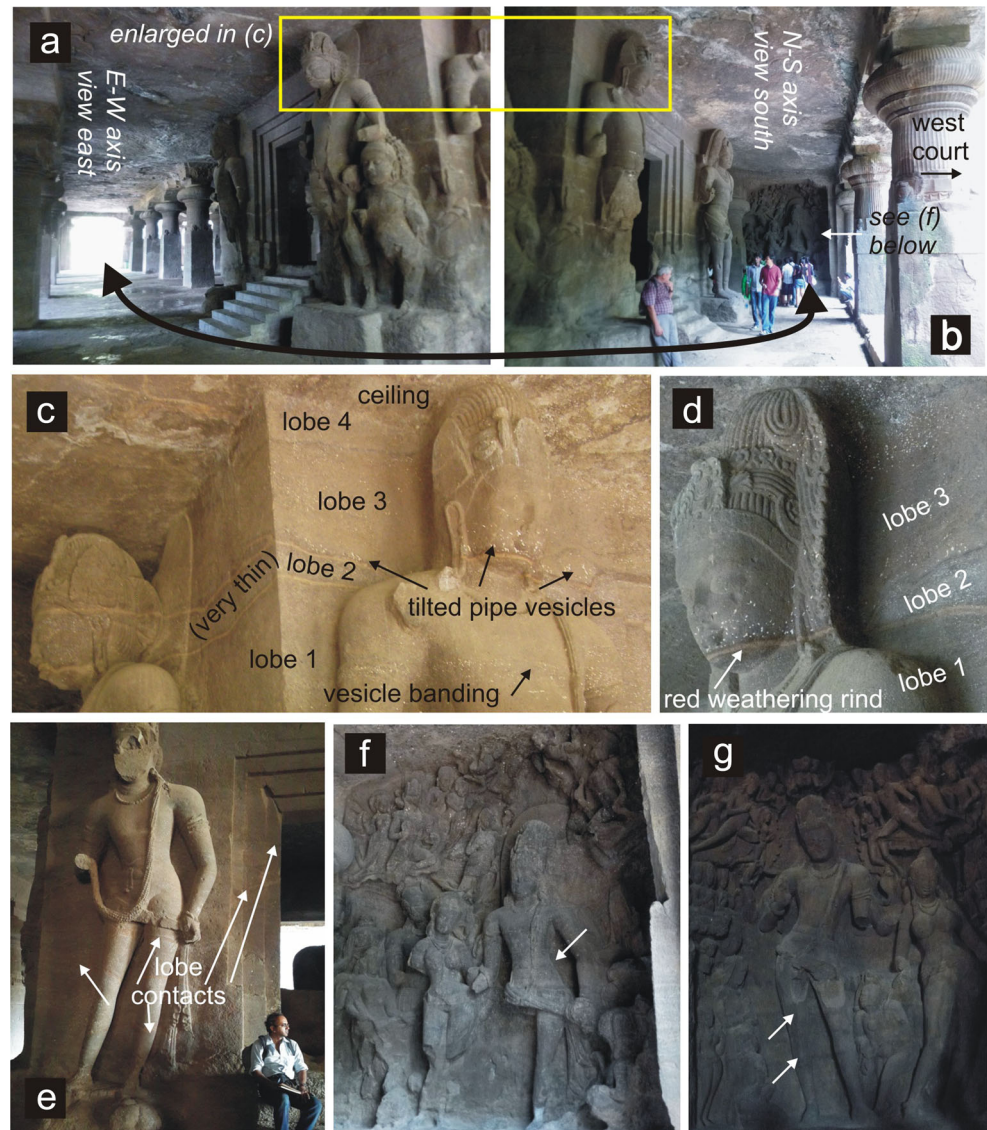
be considered a "hummocky" (Self et al. 1998) compound pahoehoe flow. Hummocky flows have been described from the Deccan Traps (Duraiswami et al. 2001, 2002). Internal features of Deccan compound pahoehoe flows that are remarkably similar to those of Hawaiian flows are described by Walker (1971), Keszthelyi et al. (1999), Duraiswami et al. (2001, 2002), Bondre et al. (2000, 2004), and Sheth (2006). The present study further supports these similarities. An interesting observation is that, though individual small-scale compound pahoehoe flows of the Deccan have volumes hundreds or thousands of times larger than those of Hawaiian flows, the Deccan and Hawaiian flows, as well as intermediate-sized Icelandic flows, display the same small (meter-scale) lobe and tumulus sizes, lobe morphology, and internal flow architecture. The emplacement and growth mechanisms of all these flows were therefore evidently the same, with

the Deccan small-scale compound pahoehoe flows forming over greatly longer time spans than their Hawaiian and Icelandic analogues.
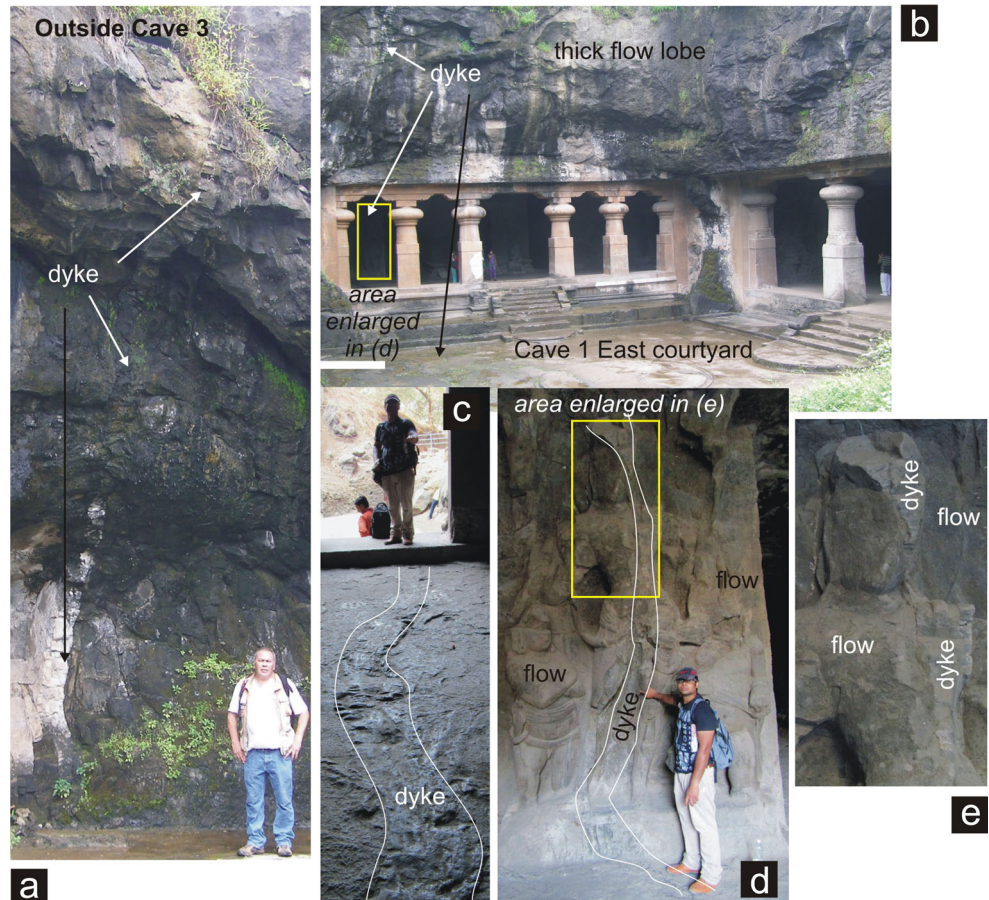
We have observed tens of basaltic and doleritic dykes on Elephanta Island that are a part of the coastal dyke swarm of the Deccan Traps (Vanderkluysen et al. 2011; Sheth et al. 2014). Most have strike directions between NNW-SSE and NNE-SSW and are well exposed in the intertidal zone on the southwestern, western, and northeastern coastal flats (Fig. 1b). A small number is found within the island's interior. One of these dykes, >2 m thick, striking N355° and dipping 75° E, outcrops beside the paved road following the median gulley to the back of the Elephanta Caves. Another dyke, striking N345°, subvertical, and ~35 cm wide, is exposed outside Cave 3 (Fig. 11a). The same dyke is observed cutting the thick flow lobe forming the roof of Cave 1 above the Cave's

Fig. 10 The *Trimurti*. Note horizontal lobe boundary at the wrist level of the middle figure

eastern courtyard, and on the floor of the same courtyard (Fig. 11b). This dyke can be traced from the courtyard

well into one of the large guardian figures (Fig. 11c, d), where it forms roughly one half of the idol itself (Fig. 11d, e).

We have described above the principal volcanological features of the Elephanta Caves monument that are well-exposed and have a high educational value.

Discussion and Conclusions

Sigurdsson and Lopes-Gautier (2000) have described volcano tourism in historical times (with Italy as the prime destination for volcanologists and naturalists) and in modern times, when travel to anywhere around the globe is possible and easier. The reasons why volcanoes or volcanic areas make appealing tourist destinations are as follows (Sigurdsson and Lopes-Gautier 2000): (i) volcanic eruptions (e.g., Kilauea); (ii) spectacular scenery (e.g., Cascade Range volcanoes, Haleakala); (iii) hot springs, geysers, and spas (e.g., Iceland, Japan); (iv) mountaineering, climbing, and skiing opportunities (e.g., Popocatépetl-Iztaccíhuatl, El Misti); (v) ecology, nature, and adventure travel (e.g., Arenal); (vi) black and green sand beaches (e.g., Hawaii); (vii) archaeological interest (e.g.,

Fig. 11 a Dyke exposed in the wall outside Cave 3. **b** Eastern courtyard of Cave 1, with the same dyke exposed in the roof and on the floor. **c–e** The dyke traced into one of the large idols in this eastern part of the Cave 1

Pompeii-Herculaneum, Santorini); and (ix) religious significance (e.g., Fuji, Bromo).

The Elephanta Caves monument in Deccan basalt is rather small in size compared to the examples above and also lacks most of the above attractions. However, it combines great archaeological, historical, and artistic delights with religious importance. In fact, having been carved in a high-intensity volcanic area that has long been extinct (65 million years), the monument is without many of the hazards that invariably accompany active and even dormant volcanic tourist attractions (e.g., eruptions, boiling mud pools). Moufti and Németh (2016) distinguish "time-dependent" volcanic geoheritage (e.g., a particular eruption that affected human society and culture) from "time-independent" volcanic geoheritage (which provides a valuable learning lesson in formative volcanic processes). The Elephanta Caves monument described in this paper is an example of the latter category. It is in fact timeless in its cultural, religious, artistic, and scientific value.

While the Elephanta Caves are already a protected monument of the Archaeological Survey of India, and a UNESCO World Heritage Site, they could also be additionally designated as a geosite. In fact, all of Elephanta Island could be developed as a geopark, though societal and infrastructural problems that stand in the way are daunting. Several major issues adversely affect Elephanta Island and the Elephanta Caves monument today. These include (i) severe pollution of the surrounding sea by activities in the busy Mumbai and Nhava-Sheva ports and by chemical industries that have been established all over the area; (ii) uncontrolled proliferation of restaurants, beer bars, and hawkers; (iii) a huge garbage disposal problem; and (iv) water seepage in the Caves (see article by Tasneem Mehta, Convenor of the Mumbai Chapter of the Indian National Trust for Art and Cultural Heritage, in the Michell 2014 book). Regarding (iii) in particular, matters are not being helped by the casual attitude of the local population (a few thousand people) as well as the large hordes of typical Indian tourists who throw plastic (empty water bottles, tea cups, candy wrappers, etc.) and other waste anywhere on the island and even from the ferry boats. The trash washes up on and permanently clogs the coastline, providing a repelling sight to any environmentally concerned visitor and constituting a major health hazard to shore birds, marine life, and the locals themselves.

Such problems notwithstanding, the abundant rock-cut caves and monuments of the Deccan, some world-famous from the archaeological, historical, artistic, and religious points of view (e.g., the Elephanta Caves described here, the Kanheri Caves near Mumbai which are carved into pyroclastics, and the Ajanta and Ellora Caves in the central Deccan), seem to be excellent potential geosites where invaluable geological and volcanological education can be acquired. In fact, Walker (1971), who commented on the prolific development of compound pahoehoe flows in the Deccan Traps, stated that the

Ajanta Caves (Fig. 1a), famous for their religious sculptures and monuments carved in basalt, ought also to be famous for the magnificent compound flows themselves. The same is true of the Elephanta Caves.

Some of the sculptures in the Elephanta Caves (particularly Cave 1), depicting the moods and scenes from life of the Hindu god Shiva, have suffered deformities (see Figs. 6b and 9b), partly from vandalism. However, they are still magnificent 15 centuries after they were carved out of basalt, and we have described here, for the first time, the well-preserved small-scale (Hawaiian-type) compound pahoehoe lava flows of the Elephanta Caves monument. This mid-sixth century monument has always been important for students of history and the arts, and we show that it is important for the geological and volcanological community as well. A large number of primary structures of inflated compound pahoehoe flows, such as flow lobes and toes with three-tiered structure, pipe vesicles, and tumuli with inflation clefts and squeeze-ups, are well-exposed here, and generations of students can be trained in flood basalt volcanology here and in the rest of the island. This famous monument combines great historical, artistic, and religious significance with high scientific and educational value, and the need to conserve this monument is therefore even greater.

We hope that the present contribution will motivate Indian and foreign geologists, volcanologists, geoheritage researchers, and geotourists traveling to western India to include the Elephanta Caves in their itinerary.

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