Geology of the Elephanta Island fault zone, western Indian rifted margin, and its significance for understanding the Panvel flexure

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The Panvel flexure is a 150-km long tectonic structure, comprising prominently seaward-dipping Deccan flood basalts, on the western Indian rifted margin. Given the active tectonic faulting beneath the Panvel flexure zone inferred from microseismicity, better structural understanding of the region is needed. The geology of Elephanta Island in the Mumbai harbour, famous for the ca. mid-6th century A.D. Hindu rock-cut caves in Deccan basalt (a UNESCO World Heritage site) is poorly known. We describe a previously unreported but well-exposed fault zone on Elephanta Island, consisting of two large faults dipping steeply east–southeast and producing easterly downthrows. Well-developed slickensides and structural measurements indicate oblique slip on both faults. The Elephanta Island fault zone may be the northern extension of the Alibag–Uran fault zone previously described. This and two other known regional faults (Nhava–Sheva and Belpada faults) indicate a progressively eastward step-faulted structure of the Panvel flexure, with the important result that the individual movements were not simply down-dip but also oblique-slip and locally even rotational (as at Uran). An interesting problem is the normal faulting, block tectonics and rifting of this region of the crust for which seismological data indicate a normal thickness (up to 41.3 km). A model of asymmetric rifting by simple shear may explain this observation and the consistently landward dips of the rifted margin faults.

1. Introduction

Many continental flood basalt (CFB) provinces, located on rifted continental margins, display monoclinical flexures with prominent dips towards the newly formed ocean basin. Well-known examples are in the CFB provinces of the Karoo (Lebombo monocline), the Parana (Torres flexure), East Greenland, and the Deccan (Panvel flexure) (e.g., Nielsen and Brooks 1981; Sheth 1998; Klausen 2009). These flexures have been ascribed to folding or monoclinical bending (e.g., Blanford 1867; Wynne 1886; Wager and Deer 1938; Auden 1949; Faller

and Soper 1979; Myers 1980), extensional faulting with block rotations (e.g., Nielsen and Brooks 1981; Dessai and Bertrand 1995), and reverse drag on off-shore listric master faults, with attendant faulting (Sheth 1998).

The western Indian rifted continental margin (figure 1) evolved during two major episodes of continental break-up and CFB volcanism, at ~85 Ma between India and Madagascar (Storey *et al.* 1995; Pande *et al.* 2001) and at ~63 Ma between India and Seychelles (Collier *et al.* 2008; Bhattacharya and Yatheesh 2015). The Panvel flexure in the ~65 Ma Deccan flood basalts runs along the

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Figure 1. Map of India and the Deccan Traps (grey), showing the Western Ghats escarpment and the locations of Mumbai and Ratnagiri areas, discussed in the text. Bold line indicated by PF is the Panvel flexure, exposed on the Konkan Plain west of the escarpment.

NNW–SSE-trending western Indian rifted margin for >150 km, and has a width of ~30 km (figure 1). Here we describe the geology of a fault zone in the Deccan basalts of Elephanta Island near Mumbai, in the Panvel flexure zone (figure 2). Unambiguous identification of faults in the Deccan flood basalts has been difficult because of the monotonous appearance of many basaltic sequences and the lack of marker horizons within them. The Elephanta Island fault zone is unreported in the existing literature, but it is well exposed, and provides valuable insights into the structure and tectonics of the Panvel flexure zone.

2. Regional and local geology

Mumbai, originally a group of several islands, is unusual in the Deccan CFB province due to its Danian-age (post-Cretaceous/Palaeogene boundary)

Figure 2. Map of Mumbai and the surrounding region, showing the major geographic, geological and structural features, and localities mentioned in the text (based on Dessai and Bertrand 1995; Sheth 1998). Hilly areas are shown by grey outlines, and elevations (in meters above sea level) by black triangles.

magmatism, of varied composition and style. It shows lava flows of tholeiites, pillow basalts and spilites, hyaloclastites and rhyolites, with inter-trappean sediments and pyroclastic deposits, trachyte intrusions, and many dykes of varied compositions (e.g., Sukheswala and Poldervaart 1958; Sethna 1981, 1999; Cripps *et al.* 2005; Zellmer *et al.* 2012; Sheth *et al.* 2014). The entire sequence is affected by the Panvel flexure and has acquired prominent (typically 17°) seaward dips (figure 2). Hooper *et al.* (2010) argued that the Panvel flexure was formed at 65–64 Ma, soon after the Deccan eruptions, whereas Sheth and Pande (2014) concluded that the Panvel flexure postdates the Dongri rhyolite flow in northwestern Mumbai, dated by them at 62.6 ± 0.6 Ma and 62.9 ± 0.2 Ma (2σ) ($^{40}\text{Ar}/^{39}\text{Ar}$ ages, relative to monitor MMhb-1 age of 523.1 ± 2.6 Ma). The Deccan lavas to the east of Mumbai, in the New Mumbai and Nhava–Sheva–Uran areas of the Indian mainland, are also affected by the Panvel flexure, though their westerly dips are more gentle (2 – 5°) (figure 2). The axis of the Panvel flexure passes through Panvel and Kalyan (figure 2), and further east the lavas are horizontal.

The island of Elephanta in the Mumbai harbour (rising 168 m above sea level and covered in large part in dense jungle, figure 3a) is little described in the geological literature. However, it is well known for the ca. mid-6th century AD Hindu rock-cut caves, a UNESCO World Heritage Site since 1987. The Deccan basalt lava flows of the island dip west-northwest by $\sim 10^\circ$ (Dessai and Bertrand 1995 and our field data). The southeastern part of the island (figure 3b) exposes a thick (>40 m) lava flow of rubbly pahoehoe (Duraiwami *et al.* 2008; Sheth *et al.* 2011, 2017) with thick flow-top breccia and fans of columnar joints. This flow was quarried during the early to mid-seventies to provide construction material for the then upcoming major port of Nhava–Sheva, 1 km east of the island (figure 3a), but quarrying was stopped in a few years as it was found detrimental to the historical monument. Observations on the fault zone that we describe here can be made in and around the abandoned quarry (figure 3b).

3. The Elephanta Island fault zone: Field observations

The Elephanta Island fault zone consists of two distinct faults ~ 70 m apart. The inner (western) fault (figure 4a, b) is best observed at the south-western top edge of the quarry. It has an overall N 25° E trend, and a steep dip of 65° due south-east (figure 4a). It is marked by a spectacular development of slickensides, filled by fine-grained white calcite and zeolites (slickenzones, Ragan

Figure 3. (a) Google Earth image of Elephanta Island in the Mumbai harbour, with parts of Nhava–Sheva port immediately to the east and on the Indian mainland. Box with black boundary shows the area of present study, enlarged in panel (b), where the locations of the faults studied in this paper and other features are marked.

2009). The slickensided surface is well exposed for a depth of ~ 10 m at the top of the quarry (figure 4b), below which it stands largely destroyed by the quarrying. The slickenlines are steeply inclined towards south-southwest on the fault surface (figures 4b, 5a). The slickenlines are smooth to the touch in the downward direction and rough in the upward direction. This implies that the missing block (the eastern block now removed by quarrying) moved down relative to the block west of the fault and forming the quarry face (Doblas 1998; Argles 2010). The amount of downthrow is not determinable, and probably only a few meters, as the quarry's eastern inner wall (seen in shadow in figure 4a) also exposes the same rubbly pahoehoe flow. Fractures striking N 20° E, subparallel to the fault, have formed in the basalt adjacent to the fault and are filled by thin veins of calcite and zeolites

Figure 4. (a, b) Two views of the inner (western) fault in the rubbly pahoehoe flow, in the southeastern part of Elephanta Island. Geologists provide a scale. Fault strikes $N25^{\circ}E$ and dips 65° due SE. White linear patches on the fault surface are due to secondary mineralization. Thick black arrows indicate the movement direction of the missing block. The quarry floor is ~ 35 m below the top edge with the geologists. The location of the red bole at the entrance of the quarry, and of the outer fault affecting it, are also shown in (a).

(figure 5b). A large vug, containing centimeter-size crystals of calcite and smaller crystals of stilbite (figure 5c), is also seen in the fault.

The outer (eastern) fault is seen affecting the rubbly pahoehoe flow on a dirt path adjacent to the coastal road (figure 3b). The fault surface is again easily identifiable because of well-developed slickenlines (figure 6a–d). However, unlike the western fault which can be visually continuously traced for ~ 150 m, most of the eastern fault has been destroyed by quarrying and it is only exposed discontinuously. At one place, a large landslide has produced much bouldery rubble including boulders with slickensides (figure 7). Unlike the $N25^{\circ}E$

strike of the western fault, the eastern fault has an overall strike of $N36^{\circ}E$ (average of 32 readings ranging between $N10^{\circ}E$ and $N54^{\circ}E$, table 1), and it dips very steeply (average 73°) due southeast. The slickenlines have a rake of $\sim 68^{\circ}$ on the western fault, while the rake measured on the eastern fault is $\sim 55^{\circ}$, varying somewhat along the exposure but always due southwest (figure 6a–d). This means that the movement along the outer fault was also oblique-slip. Similar to the western fault, the slickensided faces are always smooth to the touch downwards and rough upwards, implying that the missing (eastern) block (on which we stood) has moved relatively down.

Figure 5. (a) View of the western fault looking roughly due south along the fault surface. White linear patches are secondary mineralization. (b) Secondary mineral veins adjacent to and parallel with the fault surface; view looking down along the fault from the cliff edge. (c) A large mineralized pocket with well-developed calcite and stilbite, on the fault surface shown in (a). Coin for scale is 2.5 cm in diameter.

A few tens of meters to the north of the outcrops shown in figure 6(a–d) is the wide entrance to the quarry. A small exposure of red bole occurs below the rubbly pahoehoe flow at the northern end of this entrance (figure 4a). This red bole may represent the chilled glassy base of the rubbly pahoehoe flow, subsequently heavily altered (see Duraiswami *et al.* 2008). Fragments of the red bole also show

the development of slickensides (figure 6e). The outer fault therefore passes through here (see figure 4a), and is untraceable further north along the coastal road owing to dense vegetation and lack of outcrops. The amount of easterly downthrow along the outer fault is again undeterminable, as the red bole (a potential marker horizon) is not exposed anywhere within or outside the quarry. Both faults may originally have been much longer than their current trace length of ~ 150 m, though they are now destroyed by quarrying or hidden by the jungle. A map of the two faults and a corresponding block diagram showing the topographic and structural features are shown in figure 8(a, b).

4. Structural measurements and data analysis

We carried out structural measurements in the fault zone with the objective to determine the net slip directions on both faults. Initially, the attitude of the western and the eastern faults was recorded at different locations. The rake of slickenlines was recorded at a 1 m grid interval on both faults (table 1) and the lineations were plotted and contoured with a 15% contour interval on Lambert's equal area projection. Contour diagrams of slickenlines for the western and eastern faults (figure 9a, b) show presence of maxima of $>45\%$ towards N158° and N195°, respectively.

The rake measurements were used to calculate the plunge of the slickenlines using the stereonet, and rose diagrams showing the plunge of these slickenlines on an equal-area projection were prepared for both faults (figure 9c, d). It is observed that the western fault has a dominant mode of 30% towards N157° and N162° and a mode of 24% towards N172°. The eastern fault has a dominant mode of 43% towards N192° with subordinate modes of 28% and 10% towards N197° and N152°, respectively.

Fossen (2010) has given a geometrical procedure to calculate orientations of the stress axes from fault slip data using the tangent lineation diagram. The plane containing the lineation on the fault plane and the pole to the fault plane is defined by him as the movement plane (M-plane). The M-plane contains the maximum and minimum principal stress axes. The tangent lineation for a known fault plane is found by plotting the M-plane and the fault plane on a stereonet, and the sense of movement is given by the orientation of the arrow tangential to the M-plane, at the pole to the fault plane. The principal stress directions were determined using this method, along with the movement of the footwall relative to the hanging

Figure 6. The outer fault striking N55°E and dipping 80° SE (locally) and with well-formed, mineralized or barren slicken-sides. Geologists (a, b), hammer (c) and hand (d) provide a scale. Panel (e) shows a hand-held red bole specimen with slickenlines. Small white arrows indicate two of the steps on the slickenlines. Thick black or white arrows in all panels indicate the direction of movement of the missing block.

wall (figure 10a, b). Due to the frictional resistance offered by the internal properties of various solids, the angle of internal friction (φ) is a major factor determining the angle at which failure takes place in the rock relative to the orientations of the stress axes (Ragan 2009). In extensional stress regimes, where the maximum principal stress (σ_1) is vertical, a set of two fractures may develop at an angle θ from σ_1 . As explained by Coulomb's theory of faulting, and with an angle of internal friction of 30° for most rocks, the angle $\theta = \pm 45 - (\varphi/2)$, i.e., 30° on either side of σ_1 (Fossen 2010). Therefore, σ_1 is plotted on the M-plane at an angle of 30° from the lineation. The minimum principal stress σ_3 is plotted on the M-plane at an angle of 90° from σ_1 . The intermediate principal stress σ_2 can therefore be plotted as the pole to the M-plane and it will always lie on the fault plane itself. This method is used for rocks without structural fabric or pre-faulting deformation. Since the rubbly pahoehoe flow hosting the faults does not show

signatures of any prior deformational events, we used Fossen's (2010) method to estimate the palaeostress conditions that generated these faults. The western fault indicates a steeply plunging σ_1 (70°/226°), a gently plunging σ_2 (20°/035°), and a nearly horizontal σ_3 (03°/126°) (figure 10a). The eastern fault indicates moderately plunging σ_1 (55°/245°) and σ_2 (32°/047°) and a gently plunging σ_3 (08°/142°) (figure 10b). The orientations of the stress axes for both the faults are thus similar.

The palaeostress method mentioned above relates fault slip and stress through the Wallace–Bott assumption which states that the slip directions are not affected by pore fluid pressures (Yamaji 2007), and thus oversimplifies the crustal condition (Fossen 2010). A kinematic analysis of the fault slip data, which relies on palaeostrain analysis rather than stress, was therefore carried out (Fossen 2010). In this method, the P- and T-axes are symmetry axes for contractional and extensional quadrants, which are separated

Figure 7. Landslide rubble and cliff face in the rubbly pahoehoe flow over the eastern fault. Large block in lower left corner shows a slickenside, and a boulder of flow-top breccia is seen near the lower right edge of the photo. A columnar rosette is seen near the top of the cliff.

by the fault planes and their complementary shear planes (at 90° to the former). The P- and T-axes are plotted in the middle of these quadrants at an angle of 45° on either side of the lineations (figure 10c, d). The orientations of the palaeostrain axes were measured by plotting the maximum and minimum directions of extension, X and Z, in the middle of the T- and P-fields, respectively. The intermediate strain axis, Y, was plotted at the intersection of the fault- and complementary planes (Fossen 2010) (figure 10e, f). The magnitude of the palaeostrain is not determined since the displacement along the faults could not be measured. The strain axes were determined using Bingham Analysis (Cheeney 1983) which gives objective directional maxima for the compression and extension axes for a fault array (Marrett and Allmendinger 1990). The obtained orientations of the principal strain axes for the western fault are X ($08^\circ/131^\circ$), Y ($31^\circ/036^\circ$) and Z ($58^\circ/234^\circ$) (figure 10e), while those for the eastern fault are X ($20^\circ/152^\circ$), Y ($34^\circ/048^\circ$) and Z ($49^\circ/267^\circ$) (figure 10f). According to Fossen (2010), Z must lie in the P-field while X should lie in the T-field. Since the rubbly pahoehoe flow lacks structural fabric, layering or rheological variations, it

can be considered homogeneous and mechanically isotropic. Hence the obtained orientations of the stress axes (figure 10a, b) and the strain axes (figure 10e, f) are consistent with each other for each fault, and the strain axes are indicative of instantaneous stretching directions.

5. Discussion

5.1 Net slip directions on the Elephanta Island faults

As noted, the slickenlines on the two faults are not oriented downdip, but are steeply to moderately inclined towards south-southwest or southwest (40° – 75°), suggesting oblique slip on both faults. The western fault strikes $N25^\circ E$, and the net slip direction on this fault determined from the structural measurements is towards $N157^\circ$ (figure 9c). This confirms the oblique nature of the slip on the western fault. The eastern fault strikes $N36^\circ E$, and the net slip direction on the fault, from the structural measurements, is towards $N192^\circ$ (figure 9d). This confirms that neither of the faults has purely downdip movement, and both had significantly oblique-slip movements. The directions of maximum shear stress on the fault planes are indicated by the slickenlines developed, and movement along fault planes is only possible when the shear stress is greater than the frictional resistance offered by the fault planes.

Slickenstructures (Fleuty 1974, 1987; Ragan 2009) are produced by abrasional or depositional processes acting during slip and have been used to deduce the sense of shear on fault surfaces (Angelier 1994; Doblas 1998; Fossen 2010). According to Groshong (2006), the orientation of slickenlines indicates the slip direction of fault. Doblas (1998) has divided slickensides into eleven major groups based on their morphology, namely 'V' or crescentic markings, steps, fractures, trains of inclined planar structures, trailed minerals, asymmetric elevations, deformed elements, mineralogical and crystallographic orientations, asymmetric cavities, asymmetric folds and asymmetric plan view features. The slickensides on the Elephanta Island faults show the presence of steps facing towards SSE and SSW respectively, i.e., in the direction of net slip vector. Such steps represent extension fractures, which are commonly mineralized (Petit and Laville 1987; Doblas *et al.* 1995; Doblas 1998; Fossen 2010). On the slickensided surfaces of both the faults, thin fibrous coatings showing stretched slickenfibers were seen. This type of coating was termed slickenzones by Ragan (2009), who considered it deposited from aqueous solutions during sliding. The orientation of

Table 1. *Structural measurements of slickenlines on the western and eastern fault planes, Elephanta Island.*

Sl. no.	Strike, dip (°)	Attitude of slickenlines		
		Bearing (°)	Plunge (°)	Rake (°)
Western fault				
1	N029, 59	N167	52	68
2	N010, 66	N155	58	68
3	N021, 61	N148	58	76
4	N013, 71	N165	61	68
5	N016, 64	N158	57	69
6	N015, 65	N157	58	69
7	N016, 59	N153	52	68
8	N015, 65	N157	53	69
9	N020, 56	N159	49	66
10	N019, 55	N142	51	76
11	N010, 60	N153	51	65
12	N010, 59	N146	52	69
13	N029, 58	N159	54	73
14	N013, 59	N156	50	64
15	N011, 64	N141	51	72
16	N020, 55	N156	52	68
17	N011, 56	N152	55	68
18	N025, 62	N172	30	62
19	N022, 60	N160	37	65
20	N018, 54	N183	47	52
21	N010, 68	N178	42	55
22	N008, 67	N169	42	50
23	N022, 62	N183	50	56
24	N013, 68	N164	44	55
25	N025, 57	N175	46	58
26	N016, 58	N175	48	54
27	N008, 67	N167	52	58
28	N025, 68	N164	42	52
29	N014, 58	N174	44	52
30	N016, 62	N176	40	48
31	N015, 58	N169	42	53
32	N020, 57	N175	45	55
33	N019, 60	N171	47	58
34	N011, 60	N166	41	52
35	N018, 56	N172	40	52
36	N010, 55	N169	41	50
37	N012, 59	N162	44	57
38	N006, 57	N139	56	68
39	N006, 58	N151	42	53
40	N015, 54	N163	43	57
Eastern fault				
1	N021, 82	N192	50	50
2	N022, 89	N201	53	53
3	N023, 82	N191	55	56
4	N010, 78	N178	44	45
5	N029, 79	N185	51	52
6	N043, 62	N182	50	61
7	N039, 74	N194	56	60
8	N046, 74	N200	56	60
9	N037, 80	N205	49	50
10	N042, 76	N192	49	50

Table 1. (Continued.)

Sl. no.	Strike, dip (°)	Attitude of slickenlines		
		Bearing (°)	Plunge (°)	Rake (°)
11	N034, 75	N194	52	55
12	N041, 76	N200	54	56
13	N039, 69	N195	46	50
14	N030, 78	N199	42	43
15	N032, 69	N191	41	45
16	N048, 69	N196	54	60
17	N042, 68	N200	42	46
18	N030, 77	N195	48	50
19	N029, 83	N202	50	50
20	N026, 74	N186	48	50
21	N031, 84	N200	59	60
22	N046, 74	N213	39	40
23	N040, 80	N208	48	49
24	N054, 60	N187	52	65
25	N038, 69	N180	58	60
26	N036, 74	N191	56	60
27	N049, 65	N168	61	75
28	N043, 63	N194	43	50
29	N049, 64	N193	50	58
30	N043, 64	N169	59	72
31	N030, 64	N175	46	55
32	N043, 64	N190	48	55

slickenfibers in such coatings identifies the latest slip direction, or shear direction (Blekinsop 2002). According to Hobbs *et al.* (1976), the steps on slickensides normally face the direction of movement on the fault, but inverses have also been produced experimentally. Argles (2010) has stated that slickenfibers grow during the fault creep and in the direction of slip, while steps on the slickenfibers indicate the sense of motion of the fault, which is down the steps. In the Elephanta Island faults, clusters of undeformed zeolites and calcite across slickenlines were also seen. These are definitely post-slip and thus indicate at least two phases of mineralization along the fault planes.

To summarize, slickenstructures observed on the Elephanta Island faults are kinematic indicators signifying oblique-slip nature of the faults, with net slip vectors oriented towards SSE (for the western fault) and SSW (for the eastern fault). The oblique-slip nature of these faults is further supported by the southwesterly plunging maximum principal stress for both of them (figure 10a, b).

5.2 Structural framework and age of the Elephanta Island and associated fault zones

We have reported here, from the Deccan basalts of Elephanta Island, two well-exposed normal faults, with oblique slip and southeasterly downthrows.

Figure 8. (a) Google Earth image of the area, including the abandoned quarry, where the faults described in the paper are best exposed. (b) Block diagram explaining the topographic and structural features of this area. The top of the western fault scarp stands 45 m above sea level and ~35 m above the quarry floor.

These faults have not been reported in the previous literature. That they are indeed faults, and not merely fractures or joints, is indicated by well-developed slickensides.

A question is whether these faults are of Deccan age or formed much later. If the former, the faults would provide clues to the structure and tectonics of the Panvel flexure. Otherwise, they have no relationship with the Panvel flexure, and may be related to neotectonic activity along the

western Indian rifted margin. There is geophysical and geological evidence for neotectonics along the margin and in the Panvel flexure zone in particular, covering the region shown in figure 2. Mohan *et al.* (2007) carried out microseismic studies in the Panvel flexure zone and reported that 158 earthquakes (with coda magnitude M_c 1.0–3.6) including 41 events of magnitude $M_c \geq 2.5$ occurred along the flexure and adjacent areas during 1998–2005. Historical seismicity records from the year 1594 to

Figure 9. (a, b) Contour diagrams for slickenlines on Elephanta Island faults. (c, d) Rose diagrams of bearings of slickenlines for the Elephanta Island faults.

1967 (see their table 4) indicate about 24 moderate earthquakes of intensity $\geq IV$ in this region. Several such earthquakes have occurred near Uran, including possibly the 1618 Bombay earthquake of intensity IX (and equivalent magnitude 7). Mohan *et al.* (2007) grouped the microearthquake depths into near-surface (<2 km and within the Deccan lava pile), shallow (2–15 km) and deep (>15 km), and considered the latter two as due to reactivation of basement faults. They also inferred block faulting of the region and *active* subsurface faulting under the Panvel flexure zone.

Kundu and Matam (2000) described geological evidences for neotectonic activity in the Deccan basalts of Ratnagiri area (figure 1), including very straight streams, rock fractures, and shearing and boudinage of quartz veins. They reported NNW–SSE-trending dip-slip faults with slickensides, and considered them possibly neotectonic. Widdowson and Mitchell (1999) argued for denudational isostasy in the Deccan Traps, meaning that erosional unroofing of the Deccan Traps leads to the upward propagation of basement fractures into the basaltic pile. Notably, the fabric of the Precambrian Dharwar basement south of the Deccan province

is NNW–SSE to NW–SE, and the NNW–SSE-trending neotectonic faulting reported by Kundu and Matam (2000) may have this cause. The same mechanism, however, is unlikely for the Elephanta faults we have described, as these trend N25°E and N36°E.

Misra *et al.* (2014) have identified $\sim$ N–S-trending brittle shear zones and faults with slickensides in the Deccan basalts of the western Indian rifted margin. Samant (1997) previously showed centimeter-scale faults with slickensides, of the kind illustrated by Misra *et al.* (2014) and related by them to regional-scale, Deccan-age strike-slip tectonics. The Elephanta faults described here are much larger (figures 4, 6) than these centimeter-scale faults and are unlikely to be neotectonic. More importantly, the Elephanta Island fault zone is not an isolated one but part of a *system* of regional subparallel fault zones. Dessai and Bertrand (1995) have shown three parallel faults in the area south and east of Elephanta Island (figure 2). The westernmost is a N35°E-trending, 25 m wide fault zone to the north of Alibag which becomes N–S and 200 m wide at Uran, and shows close-spaced fracturing, slickensides and iron oxide

Figure 10. (a, b) Stereographic projection of lineations present on the western and eastern fault planes along with the tangent-lineations (arrows) marked tangential to each M-plane, at the poles to the respective fault planes. The maximum and minimum principal stresses σ_1 and σ_3 are plotted on the M-planes while the intermediate principal stresses σ_2 lie on the fault planes. 'l' indicates the lineations on the fault planes. The plots were prepared using the Stereonet 9 software of Richard Allmendinger (<http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html>). (c, d) Plots of the western and eastern fault planes, lineations and the complementary fault planes. Each P- and T-axis bisects these two planes and lies 45° on either side of each fault plane. The P- and T-axes have been contoured to represent the overall contractional and extensional fields. (e, f) Plots showing the orientation of the palaeostrain axes X, Y and Z for the western and eastern fault planes, respectively. The intermediate strain axis Y plots at the intersections of the fault planes and their respective complementary planes while the directions of maximum and minimum extension, X and Z, plot in the middle of the T- and P- fields respectively. The plots in panels (c-f) were prepared using the FaultKin 7 software of Richard Allmendinger (<http://www.geo.cornell.edu/geology/faculty/RWA/programs/faultkin.html>) (see Marrett and Allmendinger 1990; Allmendinger *et al.* 2012). Note how, for each fault, the maximum and minimum strain axes (X and Z in figure 10e, f) correspond to the minimum and maximum stress axes (σ_3 and σ_1 in figure 10a, b), respectively.

vein networks. At Alibag, the fault plane dips 40°E , though the relative displacement cannot be determined in the absence of marker horizons. Also, the basalts dip 10° west at Uran, but adjacent to the fault zone they dip 25° west or southwest, which led Dessai and Bertrand (1995) to infer block *rotations* (in an approximately E–W plane) adjacent to

faults (see their figure 5). The second fault depicted by them is the N–S-trending Nhava–Sheva Fault (figure 2), for which an easterly downthrow (of unspecified magnitude) was identified by Ghodke (1978). The easternmost of the three faults is the N–S-trending Belpada Fault (figure 2), also with fracturing and slickensides, for which

Ghodke (1978) inferred an easterly downthrow of 60 m.

Dessai and Bertrand (1995) therefore suggested a step-faulting configuration with downthrows systematically to the east for all three faults. The key sections affording these observations have either become destroyed in the massive urbanization the region has experienced, or become inaccessible due to strategic constructions. The faults we describe from Elephanta Island have survived due to lack of such development on the island, though large parts of these faults have been destroyed by quarrying. The Elephanta Island fault zone was not described by Dessai and Bertrand (1995), but it is very likely a northward extension of the Alibag–Uran fault zone they described. This fault zone thus changes in strike from south to north, from N35°E (and 25 m wide) at Alibag, to N–S (and 200 m wide) at Uran, and again splaying into two distinct faults striking N25°E and N36°E and 70 m apart, on Elephanta (figure 2). Even though we do not know the amount of downthrow on either of the two Elephanta faults, we know that both faults dip steeply east–southeast and the downthrows for both were towards the east, with net slip vector towards SSE (for the western fault) and SSW (for the eastern fault). Our observations are therefore consistent with the systematic easterly step-faulting envisaged by Ghodke (1978) and Dessai and Bertrand (1995), with the modifications that (1) the movements along the normal faults were not simply down-dip but also oblique-slip, and (2) there were even local block rotations (as at Uran) in planes approximately perpendicular to the faults. Such rotations, resulting in differential tilts between imbricate fault blocks, themselves require faults with listric geometry at depth (Wernicke and Burchfiel 1982; Jackson and McKenzie 1983). Listric faulting with roll-over of hangingwall strata (Hamblin 1965; Gibbs 1984) is a key element of Sheth’s (1998) model for the Panvel flexure. The colinearity of the Elephanta Island fault zone with the Alibag–Uran fault zone, and the systematic eastward step-faulting identified for the entire set of subparallel fault zones in this area, suggest that they are all Deccan-age faults and integral elements of the Panvel flexure. The Panvel flexure formed at 62.5 ± 0.5 Ma, during the late stages of Deccan flood basalt volcanism (Sheth and Pande 2014). Therefore, the Elephanta Island fault zone arguably formed at ~ 62.5 Ma and is not a neotectonic feature.

We briefly note that Srinivasan (2002) has proposed a structural scenario for the western Indian rifted margin, including the region shown in figure 2 and northeast of it, involving progressive *westward* step-faulting. One of the problems with this scenario is that a major fault proposed

by Srinivasan (2002) – the Mahim Fault north of Mumbai – runs southwards right through Uran and Nhava–Sheva, can be identified with the faults described above, and yet large-scale downthrow on this fault to the west is proposed by Srinivasan (2002). This is in direct conflict with the eastward step-faulting we observe and support, as described above.

Sheth *et al.* (2014) observed numerous subvertical, late-stage tholeiitic dykes with a strong preferred orientation in the Ghatkopar–Powai area of Mumbai, ~ 18 km NNW of Elephanta Island (figure 2). They found that 25% of the dykes had a N–S strike, 25% had a NNW–SSE strike, and 50% had a NNE–SSW strike. Because dykes are preferentially emplaced perpendicular to the σ_3 direction (e.g., Gudmundsson and Marinoni 2002), Sheth *et al.* (2014) inferred a strongly ESE–WNW (broadly E–W) extensional tectonic regime from the dyke trends. We note that their inferred ESE–WNW σ_3 direction is completely consistent with the ESE–WNW and gently plunging σ_3 directions determined in the present study for the Elephanta Island faults (03°/126° for the western fault and 08°/142° for the eastern fault). This is additional evidence for the late-Deccan age of the Elephanta Island faults.

Some interesting questions remain. For example, all authors (Chandrasekharam 1985; Dessai and Bertrand 1995; Sheth 1998; Srinivasan 2002) have described the western Indian rifted margin as a thinned and block-faulted rifted margin. Receiver function analysis of teleseismic data by Mohan and Ravi Kumar (2004) shows that the continental crust over much of this area has normal thickness. Mohan and Ravi Kumar (2004) computed a 41.3 km crustal thickness for Koproli near Uran, and a 38.2 km crustal thickness for Nere a little northeast of Panvel (figure 2). The next step is therefore to understand the structural and tectonic evolution of a piece of continental crust that has suffered significant normal faulting and block tectonics, and even rifting, all the while maintaining a crustal thickness typical of cratonic interiors. This may be possible to explain with the simple shear rifting model of Wernicke (1985), which would also explain the consistently landward dips of the rifted margin faults as observed.

6. Conclusions

Elephanta Island in the Mumbai harbour, famous for the ca. mid-6th century AD. Hindu rock-cut caves in Deccan basalt (a UNESCO World Heritage site), is poorly described in the geological literature. Here we report a previously unknown fault zone on the island, comprising two large normal

faults dipping steeply east-southeast. Both faults show well-developed slickensides, and structural measurements indicate oblique-slip movements on both faults. Three other fault zones have been previously described in the region, to the east and south of Elephanta. These are the Alibag–Uran, Nhava–Sheva and Belpada faults, and we suggest that the Elephanta Island fault zone and the Alibag–Uran fault zone constitute a single fault zone with a moderate fluctuation in strike direction along its length. Previously available data and our new data on these fault zones indicate a progressively easterly step-faulting configuration for the whole system, with the important realization that the individual movements were not simply downdip but also oblique-slip, and locally even rotational as at Uran. These combined results provide valuable insights into the internal architecture of the Panvel flexure, a 150 km long tectonic megastructure along the western Indian rifted margin. Though extensional block faulting of thinned continental crust is a key element of several models proposed for the Panvel flexure, teleseismic studies have indicated crust of normal thickness (as much as 41.3 km) under Uran and other areas. This means that attention should be now focussed on understanding how continental crust can undergo normal faulting, block tectonics and even rifting to form a new ocean basin, while maintaining a thickness typical of continental interiors. The simple shear rifting model of Wernicke (1985) may explain this observation and the consistently landward dips of the faults.

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