Archaeological findings have indicated the existence of several ports, jetties and anchoring points along the west coast of India from the protohistoric period[17]. The discovery of a large number of stone structures and anchors at Dwarka suggests that it was a busy port during the historical and the medieval times[11]. Large limestone blocks have been profusely used for its construction. A later period jetty at Rupen Bandar was made of stone blocks as well as of wooden logs. As some comparison, a similar type of jetty remains has also been reported from Australia dating back to the late 19th century CE. There are also comparative instances, especially in northwest Australia, where the tidal range is often in excess of 10 m. In the 19th century, at places where there are no jetties, even large sailing ships were run aground at high tide in NW Australia. As the tide receded leaving bare sand beneath the ship, passengers and cargo were moved to and fro using large carts drawn by bullocks[18]. This is a direct reflection of the practices referred to above. Though there are no remains of an ancient jetty at Bet Dwarka, the presence of stone anchors in the inter-tidal zone indicates that the high tide was effectively used for anchoring the boats. Conversely, the northwest coast of India has jetties in creeks which are made of limestone blocks, while in the southern side traditional wooden jetties continued to be in use.

Tidal variation and seabed topography played a significant role in the construction of jetties. As stated earlier, the higher tidal variation in Gujarat has been used by navigators to anchor boats in the inter-tidal zone; thus loading and unloading become easier. This has also been confirmed with the discovery of stone anchors from the inter-tidal zone areas of Dwarka, Bet Dwarka and Armada. Stone anchors are the indicators of ancient anchoring points and underwater findings have indicated that the preferred anchoring points on the Saurashtra coast fall between 5 and 7 m water depth.

1. Kramer, S. N., The Indus Civilization and Dilmun: The Sumerian Paradise Land. *Expedition*, 1964, **6.3**, 44–52.
2. Kangle, R. P., *The Kautilya Arthasastra, Part II, An English Translation with Critical and Explanatory Notes*, University of Bombay, 1963 (later edition, 1972).
3. Schoff, V. (ed.), *The Periplus of the Erythrean Sea*, London, 1912 (reprinted in 1974, New Delhi).
4. Roy, U. N., Dronimukha and Lothal. *The Role of Universities and Research Institutes in Marine Archaeology* (ed. Rao, S. R.), NIO, Goa, 1994, pp. 33–36.
5. De Kerchove, R., *International Maritime Dictionary*, Van Nostrand, New Jersey, 1948 (2nd edn, 1961).
6. Muckelroy, K., *Maritime Archaeology*, Cambridge University Press, UK, 1977.
7. Raban, A., Sabastos: The royal harbour at caesarea Maritima – A short-lived giant. *Int. J. Nautical Archaeol.*, 1992, **21**, 111–124.
8. Woolley, L., *Excavations VI: Buildings of the Third Dynasty*, British Museum, London, 1974.
9. Rao, S. R., *Lothal – A Harappan Port Town*, Memoir of Archaeological Survey of India, No. 78, New Delhi, 1979.
10. Dhavalikar, M. K., Raval, M. R. and Chitalwala, Y. M., *Kuntasi, A Harappan Emporium on the West Coast*, Post Graduate Research Institute of Deccan College, Pune, 1996.
11. Gaur, A. S., Sundaresh and Sila Tripati, Ancient Dwarka: Study based on recent underwater archaeological investigations. *Migration Diffus.*, 2005, **6**, 56–77.
12. Gaur, A. S., Sundaresh and Sila Tripati, Dwarka: An ancient harbour. *Curr. Sci.*, 2004, **86**, 1256–1260.
13. Gaur, A. S., Sundaresh and Odedra, A. D., New light on the maritime archaeology of Porbandar, Saurashtra coast, Gujarat. *Man Environ.*, 2004, **XXIX**, 103–107.
14. Anon., *Indian Tide Table 2006: Indian and Selected Foreign Ports*, Surveyor General of India, Government of India, New Delhi, 2006.
15. Anon., *West Coast of India Pilot*, The Hydrographic Department, Admiralty, London, 1961.
16. Rao, S. R., *Dawn and Devolution of the Indus Civilization*, Aditya Prakashan, New Delhi, 1991.
17. Ray, H. P., *The Archaeology of Seafaring in Ancient South Asia*, Cambridge University Press, UK, 2003.
18. McCarthy, M., Archaeology of the jetty. *Bull. Australas. Inst. Marit. Archaeol.*, 2002, **26**, 7–18.

ACKNOWLEDGEMENTS. We thank the Director, NIO, Goa for permission to publish the paper. We are grateful to an anonymous reviewer for thoroughly reviewing the manuscript and suggesting various points for the improvement. Thanks also due to Mr Sundaresh and Dr Sila Tripati for help during field work. We thank S. N. Bandodker for photography, Mr S. B. Chitari and Mr R. Uchil for the drawings. This is NIO contribution No. 4278.

Received 14 November 2006; revised accepted 1 August 2007

Seismic evidences of faulting beneath the Panvel flexure

G. Mohan*, G. Surve and Pankaj Kr. Tiwari

Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India

Microseismic studies in the Konkan plains encompassing the Panvel flexure, adjoining Mumbai, reveal low seismicity associated with the 150 km long flexure. About 158 earthquakes (*Mc* 1.0–3.6), including 41 events of magnitude (*Mc* ≥ 2.5) occurred along the flexure and its flanks during the period 1998–2005. Historical seismicity indicates the occurrence of about 24 moderate earthquakes of intensity ≥IV in this region. Hypocentres estimated for 20 events reveal that the earthquakes occur at three depth levels – near surface (<2 km), shallow (2–15 km) and deep (>15 km). The near-surface earthquakes occur within the Deccan traps possibly due to failure of the faults flanking the flexure, while the shallow and deep crustal earthquakes

*For correspondence. (e-mail: gmohan@iitb.ac.in)

suggest reactivation of the basement faults. The 2 km contrast in crustal thickness across the flexure all along its axis coupled with geological evidences of block tectonics suggest isostatic adjustments leading to normal faulting to be the preferred mechanism for the observed seismicity. This study brings out the existence of an active fault system beneath the Panvel flexure, possibly linked to west-coast tectonics.

Keywords: Crust, fault, Panvel flexure, seismicity.

THE Global Seismic Hazard Map (GSHAP)[1] depicts Mumbai, which falls in zone III of the seismic zone map of India, as a region with a probabilistic hazard of 0.1*g*. A more recent study[2] quantifies the seismic hazard for Mumbai, considering the probability of ground motion that can be induced by several known faults around the city. Although there are several faults lineaments in and around Mumbai, the most conspicuous lineament is the coast-parallel Panvel flexure (Figure 1). It is along this 150 km long flexure that the predominantly horizontally lying basalts dip to the west, with increasing amounts of dip. The Panvel flexure was explained in terms of simple monoclinal bending of the lava flows[3], but later workers[4,5] linked the origin of the flexure to the west-coast rifting, subsidence and uplift of the Western Ghats. The flexure was interpreted variously to be an extensional fault structure comprising en-echelon east-dipping faults[6], and a reverse drag flexure[7] developed over an east-dipping listric fault lying offshore the west coast of India. Landsat imageries[6] coupled with field observations revealed the presence of three major lineament trends: N–S, NE–SW and NW–SE representing fracture zones, faults and dykes (Figure 1). Numerous dykes are seen in the Panvel flexure region cutting across the older basalts of the Cretaceous–Tertiary period. Evidences of post-Deccan trap normal faulting which have dissected and displaced the traps with varying throw amounts have also been reported in this region[8]. However, seismic evidences correlating the Panvel flexure with faulting at depth are scant. The age constraints on the formation of the flexure subsequent to 60 Ma is arrived at through $^{40}Ar–^{39}Ar$ dating of the trachytes of Mumbai[9]. In the present study, the nature of the Panvel flexure has been examined through a seismological approach to search for clues leading to seismic evidences of reactivation of faults possibly associated with the Panvel flexure.

Microseismic studies were carried out in the Konkan plains encompassing the Panvel flexure, adjoining Mumbai, in western Deccan Volcanic Province (DVP) of India. A seismic network comprising one broadband (CMG-3T) and six short-period (L-4C-3D) three-component digital stations was established in phases during 1998–2005 (Table 1) in a 50 km × 100 km region encompassing the Panvel flexure (Figure 2). Initially, two short-period stations were deployed at MUL and SHN during 1998, and gradually a network was established over the next two years with the addition of one broadband and four short period stations which were operated in shift mode at different locations (Figure 2) till 2003. Subsequently, a single station has continued to be in operation at MUL till date. About 158

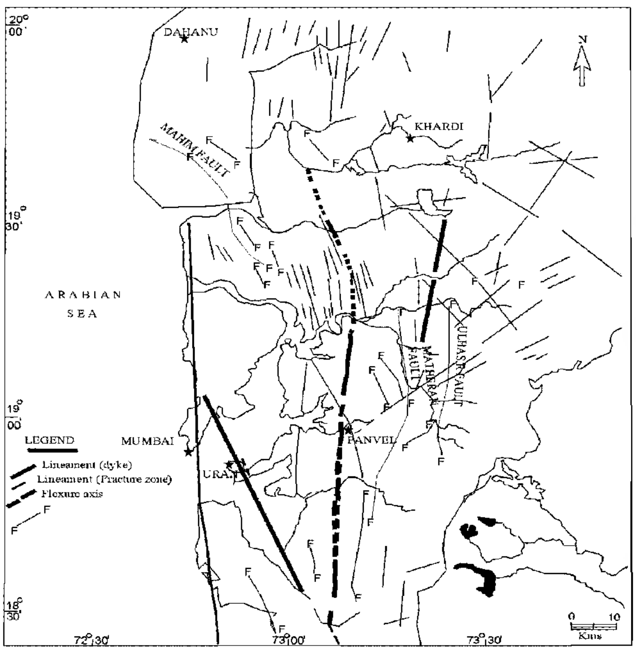

Figure 1. Lineament map of the study region (modified after Dessai and Bertrand[6], and Srinivasan[8]).

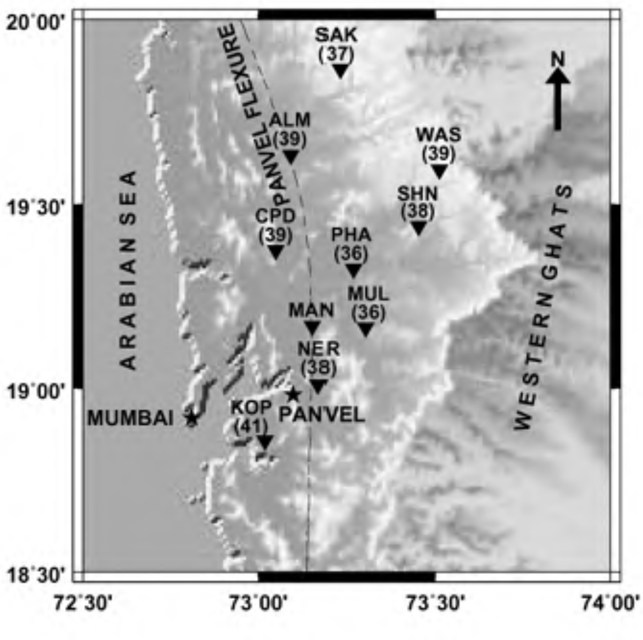

Figure 2. Map of the seismic network marked by inverted triangles. Abbreviations represent stations given in Table 1. Crustal thickness (km) beneath each station estimated from receiver function analysis (Mohan and Kumar[11]) is shown in brackets.

Table 1. Seismic stations

Station code	Latitude (°N)	Longitude (°E)	Elevation (m)	Sensor type	Period of operation	
					From	To
MUL	19:09:55.30	73:18:03.65	79	SP	01/07/1998	05/10/1999
				BB	05/10/1999	01/03/2003
				SP	01/04/2003	Till Date
SHN	19:26:26.04	73:27:09.50	120	SP	21/07/1998	29/05/2000
SAK	19:51:56.30	73:13:46.16	313	SP	30/01/1999	25/05/2000
ALM	19:37:59.61	73:05:35.99	215	SP	16/04/1999	20/10/2000
				BB	08/04/2003	04/12/2003
CPD	19:22:30.00	73:03:00	20	SP	23/11/1999	26/02/2001
KOP	18:51:30.06	73:01:10.40	58	SP	07/06/2000	10/09/2000
WAS	19:35:36.98	73:30:41.21	261	SP	02/06/2000	18/10/2000
NER	19:00:35.45	73:10:12.71	27	SP	08/07/2000	26/02/2001
PHA	19:19:27.39	73:16:00.96	20	SP	14/02/2000	15/10/2000
MAN	19:10:11.15	73:09:14.70	22	SP	30/10/2001	05/11/2003

SP, Short period (L-4C-3D); BB, Broadband (CMG-3T).

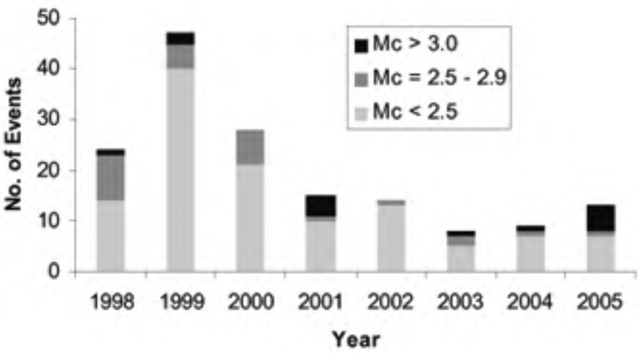

Figure 3. Time distribution of the recorded seismicity.

earthquakes (*Mc* 1.0–3.6) were recorded during the period 1998–2005, of which 36 events were recorded by three or more stations, 19 by two stations and the rest by a single station at MUL, which is about 30 km NE of Panvel and is the only station to be in operation continuously since 1998. The events were located with HYPO71 using the *P*-velocity model obtained from the DSS profiles at Koyna[10] and the Poisson's ratio of 0.26 obtained through receiver function studies[11] in the station at MUL. The hypocentres were determined only for events recorded by three or more stations using the option of fixed depth wherever required to constrain the solution. The single and two-station recordings were analysed using the approach of predictive coherence method[12] to calculate azimuths, and the time differences between *S* and *P* phases were used to determine epicentral distances. The hypocentral parameters were determined with small rms errors of ≤0.05 and 0.06–0.17 for 9 and 11 events respectively (Table 2). Hypocentral errors in the latitude, longitude and depth were on an average within 4 km. The accuracy of the single station method was cross-checked with several events recorded by multiple stations (at least four) for consistency and the errors in epicentres were found to be around 3–7 km for events occurring within a radius of 50 km from MUL.

A majority of the events recorded were microseisms of coda magnitude (*Mc* < 2.5), with about 27 events of *Mc* between 2.5 and 2.9, and 14 events of *Mc* ≥ 3.0 (Tables 2 and 3). The largest recorded[13] earthquake in recent years was of *Mc* 3.6, which reportedly occurred at a depth of 5 km close to Panvel. The time distribution of events indicates that on an average 20 events per annum occurred during 1998–2000, while about ten events per annum were recorded during 2001–05 (Figure 3). About 80% of the recorded events, including four events of *Mc* > 3.0 occurred in the region around Panvel. Seismicity was confined to the Panvel flexure and its flanks, with a cluster of events at the northern end of the flexure near Dahanu (Figure 4). Based on a limited number (20), but reasonably well-constrained hypocentres (Table 2), it was observed that the earthquakes occurred at three depth levels, which we classify as near-surface (<2 km), shallow (2–15 km) and deep (>15 km). Independent evidence for the occurrence of shallow and deep earthquakes along the flexure is seen from other sources[13,14] (Table 2), which corroborate the present findings. Majority of the microearthquakes (*Mc* 1–2) coinciding with the fracture zones in the basaltic rock may be categorized as near-surface events, while several events in the magnitude range 2.5–3.3 (Table 3), for which depths could not be estimated, may have deeper origin. Six best-located events with the smallest rms errors (⩽0.03) clearly indicate shallow and deep basement faulting all along the flexure axis from south to north. It is observed that the events (*Mc* > 3.0) in the northern, central and southern segments of the flexure are also the sites of earlier historical earthquakes. Historical records[15,16] (Table 4) indicate that several earthquakes (about 24) of intensity IV and greater occurred parallel to the axis of the Panvel flexure from 18.5°N to 20°N latitudes (Figure 4). The Bombay earthquake of 1618 with intensity IX, whose

Table 2. Hypocentral parameters and associated errors from the present study along with hypocentres from other sources

	Hypocentre				Error (in km)					
Origin time	Latitude (°N)	Longitude (°E)	Depth (km)	Fixed depth	Latitude	Longitude	Depth	RMS	NST	*Mc*
1999 519 18:30:09.94	19.290	73.089	1.7	F	0.9	1.4	–	0.05	4	2.1
2000 329 01:10:53.98	19.034	73.181	7.5	F	1.6	1.8	–	0.07	5	2.6
2000 329 01:46:38.26	19.026	73.190	7.5	F	2.6	3.1	–	0.12	5	2.6
2000 329 01:58:31.68	19.031	73.186	7.4	F	1.1	1.3	–	0.03	4	2.5
2000 425 13:50:07.39	19.525	73.701	1.7	F	1.4	2.4	–	0.09	5	2.3
2000 10 6 09:16:12.24	18.789	73.747	0.6		4.4	4.2	4.7	0.15	4	2.5
2000 1114 20:30:21.54	19.033	73.150	8.9		1.8	2.6	3.5	0.08	4	1.8
2001 11 3 05:12:12.35	19.262	73.142	0.5	F	2.8	2.1	–	0.03	4	1.6
2001 1115 20:08:39.18	19.225	72.955	7.3		0.7	0.9	2.2	0.04	5	3.1
2002 4 19 12:26:50.19	18.917	73.236	13.1	F	5.7	3.5	–	0.12	3	1.8
2002 10 1 21:51:24.20	19.496	73.024	8.3	F	1.3	2.4	–	0.09	5	2.7
2003 3 7 10:37:55.62	18.834	73.132	7.9		1.8	2.2	3.3	0.02	4	2.8
2005 3 2 11:36:25.46	18.977	73.240	0.1	F	3.2	1.8	–	0.16	3	2.3
Hypocentres with depth >15 km										
1999 630 12:39:25.75	19.981	72.767	25.8		4.5	5.5	3.2	0.03	3	3.0
2000 2 5 07:46:51.09	18.757	73.195	18	F	2.7	3.5	–	0.05	3	2.6
2000 7 4 09:26:3.61	19.947	73.062	16	F	3.8	3.1	–	0.08	3	2.4
2002 517 06:07:59.75	19.817	72.843	22.5	F	1	0.7	–	0.02	3	2.2
2003 116 14:24:13.83	19.487	73.229	23.0		2.6	0.8	5.3	0.17	4	2.3
2003 512 19:59:21.69	18.469	73.035	20.1		3.3	8.5	2.8	0.08	5	3.3
2003 10 1 20:32:39.56	19.526	73.315	23.2		0.5	0.5	1.0	0.02	4	2.4
Hypocentral parameters from other sources										
1998 531 18:58:42	19.083	73.118	5	Gupta *et al.*[13]						3.6
2001 3 25 08:53:19.75	18.577	73.067	5	IRIS[14]						1.8
2001 9 13 13:40:59.80	18.538	73.516	12.8	IRIS[14]						2.5
2001 11 15 20:8:39.70	19.155	73.007	5	IRIS[14]						2.8
2003 5 12 19:59:20.47	18.402	73.0414	19.4	IRIS[14]						3.5

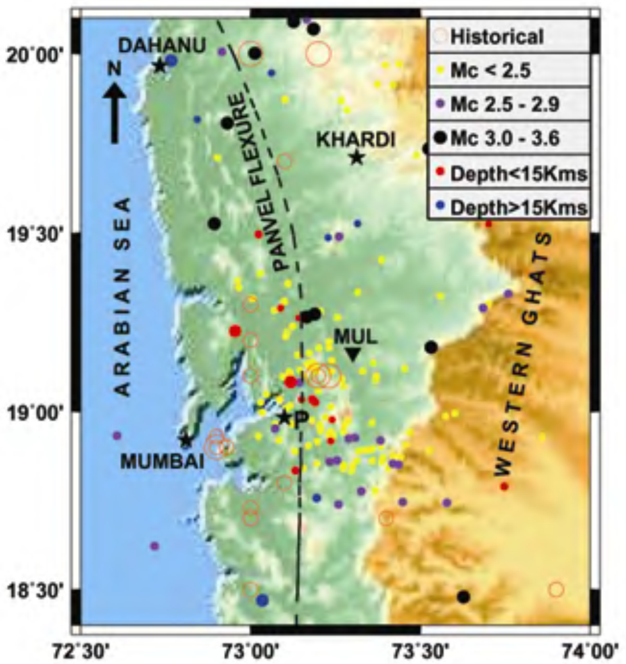

Figure 4. Seismicity map of the study region (P, Panvel). Locations of historical earthquakes are taken from Chandra[15] and Bansal and Gupta[16].

location and intensity are nevertheless doubtful[16], is the largest event mentioned in historical records. The observed and historical seismicities show similar trend (N–S), which correlates well with the flexure axis (Figure 4). In view of scant subsurface evidences of faulting along the flexure, the presence of seismicity at depth provides a reliable indication of active subsurface faulting along the flexure axis.

The zone of observed seismicity coincides with a tectonically disturbed zone of weakness which developed as a consequence of west-coast rifting, volcanic eruptions and subsequent effects. Evidences for block tectonic activity along the west coast are found in the western Indian continental shelf which is rifted and features north-south trending grabens/half-grabens and horsts exhibiting block faulting[17]. In the absence of DSS profiles across the flexure, subsurface evidences of faulting are remarkably brought out by the 2 km contrast in the crustal thickness across the flexure through receiver function studies[11], suggesting faulting at the Moho (Figure 2). The RF studies[11] thus indicate step faulting, with the western block downthrown relative to the eastern block, consistent with the regional tectonic settings of the western margin of India[17]. Geological evidence[18] for subsidence of the block

Table 3. Epicentres of earthquakes of magnitude ($Mc > 2.5$)

Origin time								
YYYY	MM	DD	H	M	S	Latitude (°N)	Longitude (°E)	*Mc*
1998	09	30	02	44	32.95	18.919	73.383	2.5
1998	10	09	12	41	08.90	18.854	73.419	2.5
1998	10	18	08	08	05.00	18.739	73.259	2.6
1998	11	05	12	11	57.06	18.924	73.289	2.7
1998	11	11	07	43	21.53	18.926	73.308	2.5
1998	11	17	14	44	20.93	19.490	73.261	2.9
1998	12	02	10	09	51.37	19.290	73.685	2.5
1998	12	05	08	20	18.45	18.776	73.326	2.5
1998	12	09	07	40	15.26	19.330	73.759	2.5
1999	01	21	22	12	25.51	19.735	73.525	3.5
1999	02	16	07	58	09.15	18.863	73.255	2.7
1999	03	01	11	52	22.25	18.851	73.436	2.7
1999	08	21	17	58	42.88	18.622	72.718	2.5
1999	10	19	13	49	23.83	18.746	73.448	2.5
1999	11	09	23	32	20.09	20.096	73.165	2.6
2000	01	01	16	21	27.50	20.006	72.916	2.8
2000	07	09	05	38	00.24	18.744	73.578	2.5
2001	03	14	14	10	09.56	19.526	72.894	3.0
2001	03	25	08	53	18.84	18.859	73.233	2.5
2001	09	13	13	41	04.78	18.479	73.627	3.0
2001	12	22	12	55	24.93	19.807	72.932	3.3
2003	02	12	05	08	57.50	19.081	73.144	2.5
2004	01	17	20	25	27.29	18.932	72.607	2.7
2004	07	05	20	29	35.83	19.180	73.532	3.0
2005	06	14	12	16	13.38	19.273	73.189	3.3
2005	06	18	03	08	48.23	19.265	73.165	3.1
2005	10	15	23	07	41.97	20.090	73.127	3.3
2005	10	28	08	05	8.68	20.002	73.013	3.3
2005	10	28	08	54	21.87	20.069	73.185	3.3
2005	10	28	10	48	36.60	18.952	73.072	2.8

Table 4. Historical events in the Panvel region

Event date	Latitude	Longitude	Intensity (I)	$M = (2/3) * I + 1$
1594	19.1	73.2	IV	3.7
26 May 1618	18.9	72.9	IX	7.0
May 1678	19.1	73.2	VI	5.0
9 December 1751	19.1	73.2	VI	5.0
5 February 1752	18.7	73.4	V	4.3
1760	18.5	73.9	IV	3.7
29 May 1792	18.5	73.0	V	4.3
23 February 1812	18.5	73.9	IV	3.7
26 December 1849	18.9	72.9	IV	3.7
1 November 1854	18.9	72.9	IV	3.7
4 July 1869	20.0	73.8	IV	3.7
20 July 1935	20.0	73.0	VI	5.0
13 December 1965	19.2	73.0	IV	3.7
4 May 1966	18.7	73.0	V	4.3
17 February 1967	19.3	73.0	–	–
20 June 1967	18.7	73.0	V	4.3
1702	19.7	73.1		3.7
28 December 1854	18.9	72.9		3.7
25 December 1856	20.0	73.0		5.7
December 1877	18.9	72.9		3.7
16 September 1935	19.1	73.0		3.0
28 May 1941	18.0	73.1		4.3
19 November 1965	18.8	73.1	–	–
1 February 1967	19.3	73.0	–	–

Source: Chandra[15] and Bansal and Gupta[16].

west of Panvel is also seen from the intratrappeans and sub-aqueous volcanic eruptions in Mumbai compared to the sub-aerial eruptions on the east.

Presence of several normal faults with the western blocks downthrown, exhibiting a step-like configuration between the coast and the Western Ghats have also been reported[8]. It is postulated[19] that owing to denudational isostacy, fractures/faults from the weaker zones in the basement propagate upwards into the overlying Deccan traps. The study region is also found to be underlain by a sub-Moho low-velocity zone[20], which provides the buoyancy for the rift flank uplift of the Western Ghats. Thus, regional tectonics involving isostatic adjustments along the west coast of India, plays an important role in the observed seismicity. The near-surface earthquakes occurring within the 2 km thick basalts are possibly due to failure of the faults flanking the flexure, while the shallow and deep crustal earthquakes occurring along the major axis of the Panvel flexure suggest reactivation of the basement faults. Although the observed activity is predominantly microseismic, historical records suggest that several moderate earthquakes have occurred in the past, trending parallel to the flexure. Further, the zone of seismicity near Panvel adjoins a major pluton within the crust, a source for stress amplification[21], as indicated by the anomalous gravity high observed over Mumbai[22]. Although the preferred mechanism is isostatic, other models developed to explain moderate to large earthquakes in continental interiors[21] may also be applicable here. A review[21] of models for intraplate seismicity revealed that the ambient stress grows to exceed the strength of pre-existing zones of weakness due to stress amplification near the plutons, localized strain in the mid-lower crust and stress accumulation near intersecting faults. Thus, the interplay between several factors responsible for stress build-up in the weak zones/faults which developed during rifting of the western margin of India explains the observed seismicity, which is possibly a manifestation of the deeper faulting beneath the flexure. Occurrence of shallow and deep earthquakes along the flexure, historical seismicity, crustal structure, geological evidences and the regional tectonic setting suggest that the Panvel flexure is a potential seismogenic zone underlain by an active fault system.

1. Ravi Kumar, M. and Bhatia, S. C., A new seismic hazard map for the Indian plate region under the global seismic hazard assessment programme. *Curr. Sci.*, 1999, **77**, 447–453.
2. Raghu Kanth, S. T. G. and Iyengar, R. N., Seismic hazard estimation for Mumbai city. *Curr. Sci.*, 2006, **91**, 1486–1494.
3. Auden, J. B., Dykes in western India. A discussion of their relationships with the Deccan traps. *Trans. Natl. Inst. Sci. India*, 1949, **3**, 123–157.
4. Devey, C. W. and Lightfoot, P. C., Volcanological and tectonic control of stratigraphy and structure in the western Deccan Traps. *Bull. Volcanol.*, 1986, **48**, 195–207.
5. Watts, A. B. and Cox, K. G., The Deccan Traps: An interpretation in terms of progressive lithospheric flexure in response to a migrating load. *Earth Planet. Sci. Lett.*, 1989, **93**, 85–97.
6. Dessai, A. G. and Bertrand, H., The Panvel flexure along the western Indian continental margin: An extensional fault structure related to Deccan magmatism. *Tectonophysics*, 1995, **241**, 165–178.
7. Sheth, H. C., A reapprisal of the coastal Panvel flexure, Deccan traps as a listric fault controlled reverse drag structure. *Tectonophysics*, 1998, **294**, 143–149.
8. Srinivasan, V., Post-Deccan trap faulting in Raigad and Thane districts of Maharashtra. *J. Geol. Soc. India*, 2002, **59**, 22–31.
9. Sheth, H. C., Pande, K. and Bhutani, R., ^{40}Ar–^{39}Ar ages of Bombay trachytes: Evidence for a Palaeocene phase of Deccan volcanism. *Geophys. Res. Lett.*, 2001, **28,** 3513–3516.
10. Kaila, K. L., Reddy, P. R., Dixit, M. M. and Lazarenko, M. A., Deep crustal structure at Koyna, Maharashtra indicated by deep seismic soundings. *Geol. Soc. India Mem.*, 1981, **3**, 218–232.
11. Mohan, G. and Kumar, M. R., Seismological constraints on the structure and composition of western Deccan volcanic province from converted phases. *Geophys. Res. Lett.*, 2004, **31**, L02601.
12. Roberts, R. J., Christofferson, A. and Cassidy, F., Real time events detection, phase identification and source location estimation using single station component seismic data and a small PC. *Geophys. J.*, 1989, **97**, 471–480.
13. Gupta, S., Mohandas, V. and Lakshmanna, S., Earthquake in Thane–Kharghar (Panvel) belt on 31 May 1998. In Proceedings of the 11th Symposium on Earthquake Engineering, Roorkee, 17–19 December 1998.
14. IRIS – Incorporated Research Institutes for Seismology, New York; http://www.iris.edu
15. Chandra, U., Earthquakes of peninsular India – A seismotectonic study. *Bull. Seismol. Soc. Am.*, 1977, **67**, 1387–1413.
16. Bansal, B. K. and Gupta, S., A glance through the seismicity of peninsular India. *J. Geol. Soc. India*, 1998, **52**, 67–80.
17. Biswas, S. K., Rift basins in western margin of India and their hydrocarbon prospects with special reference to Kutch basin. *Bull. Am. Assoc. Pet. Geol.*, 1982, **66**, 1497–1513.
18. Sethna, G. F., Geology of Mumbai and surrounding area and its position in the Deccan volcanic stratigraphy, India. *J. Geol. Soc. India*, 1999, **53**, 359–365.
19. Widdowson, M. and Mitchell, C., Large scale stratigraphical, structural and geomorphological constraints for earthquakes in the southern Deccan traps, India: The case of denudationally driven seismicity. In *Deccan Volcanic Province* (ed. K. V. Subbarao), Mem. Geol. Soc. India, 1999, vol. 43, pp. 425–452.
20. Pankaj Kr. Tiwari, Surve, G. and Mohan, G., Crustal constraints on the uplift mechanism of the Western Ghats of India. *Geophys. J. Int.*, 2006, **167**, 1309–1316.
21. Talwani, P., Fault geometry and earthquakes in continental interiors. *Tectonophysics*, 1999, **305**, 371–379.
22. Takin, M., An interpretation of positive gravity anomaly over Bombay and west coast of India. *Geophys. J. R Astron. Soc.*, 1966, **11**, 5.

ACKNOWLEDGEMENTS. This work was sponsored by the State Government of Maharashtra. We thank both the anonymous reviewers for their critical observations and useful comments.

Received 20 February 2006; revised accepted 9 July 2007