Nat Hazards (2013) 65:1027–1044
DOI 10.1007/s11069-011-0077-1

ORIGINAL PAPER

Seismicity of Gujarat

B. K. Rastogi · Santosh Kumar · Sandeep Kumar Aggrawal

Received: 1 October 2011 / Accepted: 26 December 2011 / Published online: 13 January 2012

Abstract Paper describes tectonics, earthquake monitoring, past and present seismicity, catalogue of earthquakes and estimated return periods of large earthquakes in Gujarat state, western India. The Gujarat region has three failed Mesozoic rifts of Kachchh, Cambay, and Narmada, with several active faults. Kachchh district of Gujarat is the only region outside Himalaya-Andaman belt that has high seismic hazard of magnitude 8 corresponding to zone V in the seismic zoning map of India. The other parts of Gujarat have seismic hazard of magnitude 6 or less. Kachchh region is considered seismically one of the most active intraplate regions of the World. It is known to have low seismicity but high hazard in view of occurrence of fewer smaller earthquakes of $M \leq 6$ in a region having three devastating earthquakes that occurred during 1819 (M_w7.8), 1956 (M_w6.0) and 2001 (M_w7.7). The second in order of seismic status is Narmada rift zone that experienced a severely damaging 1970 Bharuch earthquake of M5.4 at its western end and $M \geq 6$ earthquakes further east in 1927 (Son earthquake), 1938 (Satpura earthquake) and 1997 (Jabalpur earthquake). The Saurashtra Peninsula south of Kachchh has experienced seismicity of magnitude less than 6.

Keywords Seismicity of Gujarat · Earthquake catalogue · Tectonics of Gujarat · Rift valleys

1 Introduction

Seismicity and seismotectonics are studied for the assessment of earthquake hazard of Gujarat region, where even moderate earthquakes seem to have higher hazard potential in larger areas due to dense population, non-engineered structures and efficient transmission of wave energy. The study is important as large-scale development of the region is planned. Moreover, the knowledge gained here will go a long way in understanding earthquakes in other SCR regions, where they are less frequent.

B. K. Rastogi · S. Kumar (✉) · S. K. Aggrawal
Institute of Seismological Research, Gandhinagar 382 009, India
e-mail: sundriyal007@gmail.com

Geographically the region is divided into three parts: The Kachchh Peninsula which is westernmost, the Saurashtra Peninsula south of it and the Mainland which is east of both these regions. The Kachchh region is seismically one of the most active intraplate regions of the World. It falls in zone V of the seismic zoning map of India with potential of $M8$. The other two regions mostly fall in zone III with $M \leq 6$ potential. The Kachchh region was known to have low seismicity but high hazard in view of the occurrence of several large earthquakes but fewer moderate or smaller shocks. Besides the aftershocks, seismicity in Kachchh and Saurashtra has increased multifold in the first decade of the twenty-first century but not increased along Narmada zone or in other parts of the Mainland. Paper describes seismotectonics, earthquake monitoring and estimated return periods of large earthquakes in Gujarat state, western India as well as gives a catalogue of earthquakes of the region.

2 Tectonics

The Gujarat region is at the tri-junction of three failed rifts: Kachchh, Cambay and Narmada, with several active faults (Biswas 1987). These rifts were formed by rifting along major Precambrian trends. The rifting occurred at successive stages during the northward movement of the Indian plate after the breakup from Gondwanaland in the Late Triassic or Early Jurassic (Mesozoic era at about 184 Ma). The Kachchh rifting took place in the Late Triassic-Early Jurassic, Cambay rifting in Early Cretaceous and Narmada rifting in the Late Cretaceous. The rifting ceased in the Late Cretaceous era during the pre-collision stage of Indian plate. Post-collision, the Kachchh and Narmada rifts became zones of compression giving strike-slip and thrusting. The Kachchh and Narmada rifts have E–W trending major faults that are active, while the Cambay basin has N to NNW trending marginal faults that are less active. There are some smaller transverse strike-slip faults in Kachchh. South of Kachchh, in the Deccan volcanics of Saurashtra, the NW and NE trending smaller strike-slip faults are also activated in the form of moderate earthquakes in response to the plate-tectonics stress.

3 Seismic monitoring

Starting 1970s, seismicity was monitored in Gujarat with several analog seismographs in the mainland and at Bhuj (Fig. 1; Table 1). It is believed that this network has not missed any earthquake of $M > 3$ in Gujarat in last four decades. Bhuj was upgraded to digital broadband seismograph in 1999 by India Meteorological Department, and Dharoi broadband seismograph station was started since 2000. From 2001, a network of up to ten broadband seismograph stations was operated in Kachchh. From mid-2006, a dense network has been installed by ISR, which currently has 60 broadband seismographs and 49 accelerographs in and around Gujarat (Fig. 2; Tables 2, 3, Chopra et al. 2008a). Thirty-six stations are connected via VSAT to ISR data center, which works round the clock. The autolocation program enables the estimation of earthquake epicenter and magnitude within minutes of the arrival of seismic waves. The detectability is $M2.0$ in Kachchh active area and $M2.5$ in other areas.

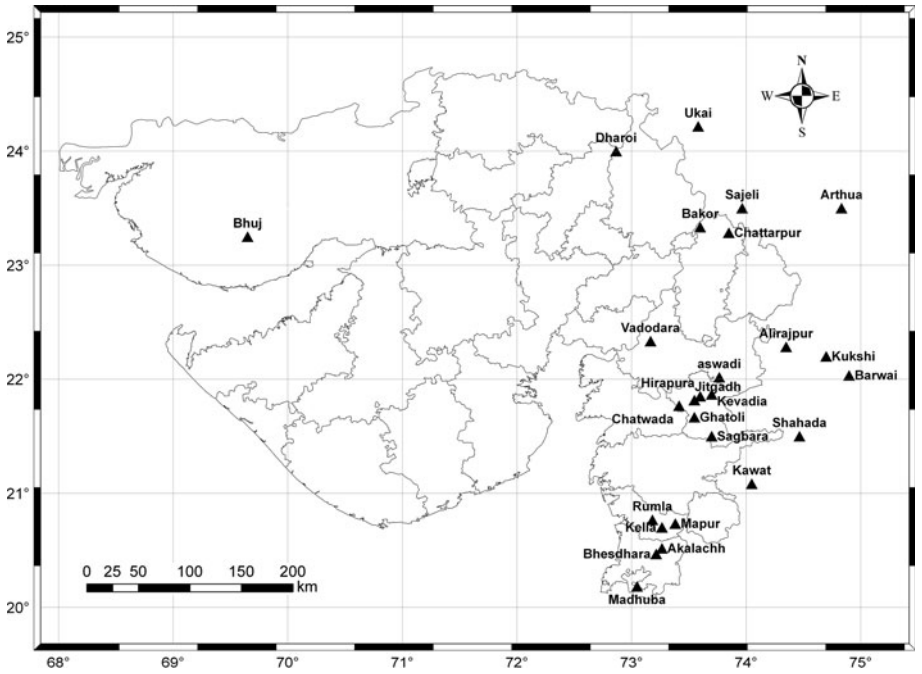

Fig. 1 Seismograph stations in and around Gujarat from 1977 to 2000

4 Earthquake catalogue

The earthquake catalogue of Gujarat and the adjoining region bound by 20°–25.5°N and 68°–75°E (Table 4; Fig. 3) has been prepared from the earliest times to 2010 with the help of all available earthquake catalogues (historical and recent) pertaining to the region. Historical earthquakes of this region before 1900 were taken from the catalogue prepared by Oldham (1883). The catalogues prepared by Tandon and Srivastava (1974), Chandra (1977), Srivastava and Ramachandran (1985), Ramachandran and Srivastava (1991), Srivastava and Rao (1997) and Malik et al. (1999) for this region and the Indian subcontinent have also been taken into consideration for some other historical and modern earthquakes. The intensity values given for historical earthquakes have been converted to magnitude using relation between magnitude and intensity. The sources of modern seismicity database are India Meteorological Department (IMD), Geological Survey of India (GSI), NEIC-USGS, International Seismological Centre (ISC), Gujarat Engineering Research Institute (GERI), National Geophysical Research Institute (NGRI) and Institute of Seismological Research (ISR). Aftershocks have been removed from the whole catalogue.

The earthquake catalogue is homogenized with moment magnitudes as generally recommended (Johnston 1994). The moment magnitudes have been taken from different sources and estimated by us from isoseismals for past large earthquakes as well as digital data for smaller recent earthquakes. For other earthquakes, m_b or equivalent ML or the M estimated from intensity value is considered to be M_w as the following empirical relation derived by Jaiswal (2010) indicates only a minor average difference of <0.1:

Table 1 List of Seismograph stations in and around Gujarat since 1971 and their present status

Sr. No.	Seismograph station	River valley project	Lat.	Long.	Year of start	Year of closing	Details of seismic instruments
1	Ukai[b]	Ukai	24°13′N	73°35′E	1971	Continued upgraded	Benioff, EMS W.A.
2	Chattarpur[b]	Kadana	23°17′N	73°51′E	1976	Continued upgraded	Helicorder W.A. EMS
3	Sanjeli	Kadana	23°30′N	73°58′E	1976	1999	Helicorder EMS
4	Bakor	Kadana	23°20′N	73°36′E	1976	1999	Helicorder EMS
5	Arthuna	Kadana	23°30′N	74°50′E	1976	1999	Helicorder
6	Vadodara[b]	–	22°20′N	73°10′E	1982	Continued upgraded	EMS
7	Ankalachh	Kelia/Jhuj	20°31′N	73°16′E	1986	2000	Portacorder RV 320B
8	Manpur	Kelia/Jhuj	20°44′N	73°23′E	1992	2000	Portacorder RV 320B
9	Rumla	Kelia/Jhuj	20°46′N	73°11′E	1994	2000	Portacorder RV 320B
10	Bhesdhara	Kelia/Jhuj	20°28′N	73°13′E	1994	2000	
11	Kelia	Kelia/Jhuj	20°42′N	73°16′E	1986	2000	MEQ-800B
12	Madhuban[b]	Daman Ganga	20°11′N	73°3′E	1994	Continued upgraded	Portacorder RV 320B
13	Hirapura	Karjan	21°51′N	73°36′E	1992	2009	Portacorder RV 320B
14	Ghantoli	Karjan	21°40′N	73°33′E	1992	2002	Portacorder RV 320B
15	Chatwada	Karjan	21°46′N	73°25′E	1992	2002	Portacorder RV 320B
16	Dharoi	Dharoi	24°0′N	72°52′E	2000	Continued	BBS, Reftek
17	Kevadia[b]	SSNNL	21°52′N	73°42′E	1977	Continued upgraded	VR-60, DR-200
18	Naswadi[c]	SSNNL	22°01′N	73°46′E	1990	Continued upgraded	VR-60, DR-200
19	Jitgadh[c]	SSNNL	21°49′N	73°33′E	1990	Continued upgraded	VR-60, DR-200
20	Kawant[c]	SSNNL	21°05′N	74°03′E	1990	Continued upgraded	VR-60, DR-200
21	Sagbara[c]	SSNNL	21°30′N	73°42′E	1993	Continued upgraded	VR-60, DR-200
22	Alirajpur[c]	SSNNL	22°17′N	74°21′E	1990	Continued upgraded	VR-60, DR-200
23	Kukshi[c]	SSNNL	22°12′N	74°42′E	1990	Continued upgraded	VR-60, DR-200
24	Barwani[c]	SSNNL	22°02′N	74°54′E	1990	Continued upgraded	VR-60, DR-200
25	Shahada[c]	SSNNL	21°30′N	74°28′E	1990	Continued upgraded	VR-60, DR-200

Table 1 continued

Sr. No.	Seismograph station	River valley project	Lat.	Long.	Year of start	Year of closing	Details of seismic instruments
26	Bhuj[a] (IMD)	_	23°15′N	69°39′E	1979	Continued	Analog

Kevadia was upgraded in 1990 with DR-200 and DR-210

[a] Upgraded in 1999 with BBS

[b] Upgraded in 2006 with CMG 3T-BBS and DM24 Guralp Digitizer

[c] Upgraded in 2011 with 120P-BBS and Taurus Digitizer

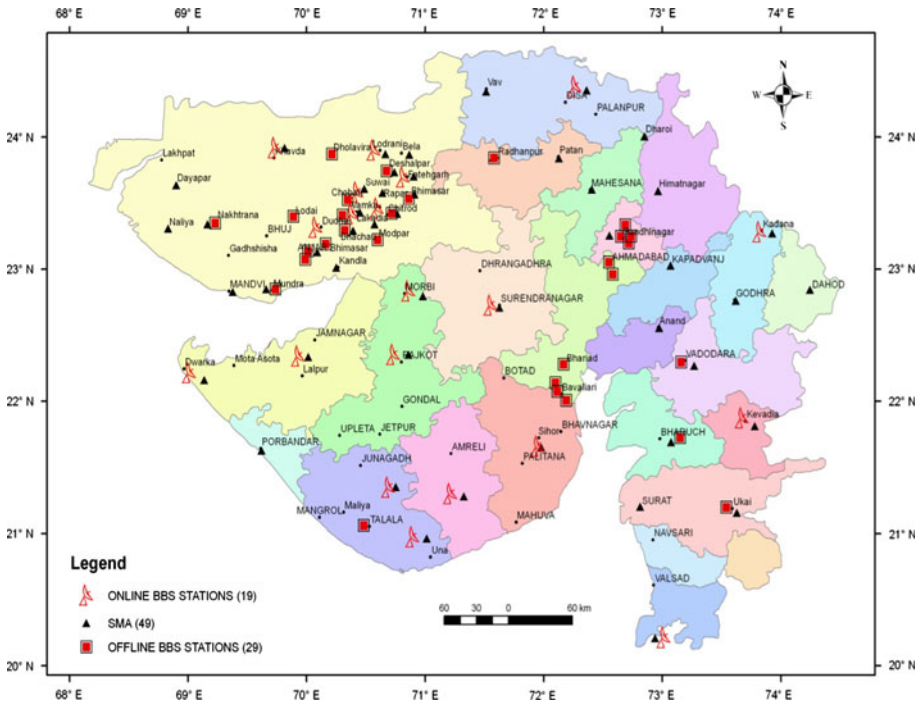

Fig. 2 Seismograph stations in Gujarat Net including 36 online broadband seismographs, 24 off-line broadband seismographs and 49 accelerographs

$$M_w = m_b + 0.07 \quad R^2 = 0.78 \quad \text{for } 4.8 \leq m_b \leq 7.0$$

For this study, data are taken from Harvard catalogue from 1976 onward and for earlier period (1411–2005) from some publications that includes 19 earthquakes of m_b 4.8–6.9 and M_w 5.0–7.6 for the period 1967–2005.

For the earthquakes prior to 1960, instrumental determinations of magnitude are not generally available. In such cases, magnitude, M, has been estimated from maximum intensity and Io by using the relation,

$$M = (2/3)\ \text{Io} + 1.$$

Table 2 List of present online seismographic stations in and around Gujarat

Sr no.	Seismograph station	Latitude	Longitude	Year of start	Detail of seismic instruments
1	Bela	23.874	70.801	April 2008	CMG 3T, DM-24
2	Desalpar	23.742	70.687	April 2008	CMG 3T, DM-24
3	Badargadh	23.466	70.619	April 2008	CMG 3T, EAM
4	Vamka	23.425	70.431	April 2008	CMG 3T, S3 DM-DCM
5	Gadhada	23.867	70.372	Sep 2010	CMG 3T, DM-24
6	Suvai	23.606	70.488	2006–07	CMG 3T, DM-24
7	Bhachau	23.280	70.342	June 2011	CMG 3T, DM-24
8	Chobari	23.509	70.34	June 2011	CMG 3T, DM-24
9	Khavda	23.922	69.766	2006–07	CMG 3T, EAM
10	Surendranagar	22.731	71.585	2006–07	CMG 3T, DM-24
11	Morbi	22.839	70.894	2006–07	CMG 3T, DM-24
12	Rajkot	22.357	70.764	2006–07	CMG 3T, DM-24
13	Lalpur	22.347	69.963	2006–07	CMG 3T, DM-24
14	Dwarka	22.289	69.037	Aug-2008	CMG 3T, S3-DM-DCM
15	Junagadh	21.355	70.724	2006–07	CMG 3T, EAM
16	Una	20.978	70.926	2006–07	CMG 3T, DM-24
17	Amreli	21.306	71.246	2006–07	CMG 3T, DM-24
18	Bhavnagar	21.694	71.997	Jan-2010	CMG 3T, EAM
19	Sipu	24.386	72.294	2006–07	CMG 3T, DM-24
20	Kadana	23.287	73.853	2006–07	CMG 3T, DM-24
21	Kevadia	21.878	73.707	2006–07	CMG 3T, EAM
22	Vadodara	22.306	73.134	July-2011	CMG 3T, DM-24
23	Ukai	21.222	73.584	July-2011	CMG 3T, DM-24
24	Valsad	20.217	73.447	2006–07	CMG 3T, DM-24
25	Gabana	21.878	73.707	Feb-2011	Trillium 120P Taurus
26	Jitgadh	21.822	73.542	Feb-2011	Trillium 120P Taurus
27	Naswadi	22.024	73.768	Feb-2011	Trillium 120P Taurus
28	Kwant	22.083	74.053	Feb-2011	Trillium 120P Taurus
29	Alirajpur	22.288	74.173	Feb-2011	Trillium 120P Taurus
30	Kukshi	22.200	74.705	Feb-2011	Trillium 120P Taurus
31	Badwani	22.033	74.917	Feb-2011	Trillium 120P Taurus
32	Shahada	21.502	74.408	Feb-2011	Trillium 120P Taurus
33	Sagbara	21.542	73.788	Feb-2011	Trillium 120P Taurus
34	Radhanpur	23.820	71.617	2006–07	CMG 3T, PFC 130
35	Raisan	23.202	72.649	2009–10	CMG 3T, PFC 130
36	Dhamkada	23.350	70.150	2011	CMG 3T, PFC 130

This formula gives a magnitude of 5 for intensity VI and a magnitude of 5.7 for intensity VII. The intensity data are taken from several Indian publications as well as from Martin and Szeliga (2010) and Szeliga et al. (2010).

As most of the regions have been populated for centuries, it is expected that for the last 200 years, no earthquake of magnitude ≥ 4 is missed as, such earthquakes are found to be

Table 3 List of presently off-line seismograph stations in Gujarat

Sr. no.	Seismograph station	Latitude	Longitude	Status	Detail of seismic instruments
1	Vighukot	24.209	69.191	Running	Reftek BBS
2	Dholavira	23.875	70.217	Running	Reftek BBS
3	Dhamkada	23.350	70.150	Running	Reftek BBS
4	Nakhatrana	23.344	70.021	Running	Reftek BBS
5	Dharoi	24.007	72.847	Running	Reftek BBS
6	Lakdiya	23.339	70.573	Running	Reftek BBS
7	Chitraval	21.106	70.520	Running	Reftek BBS
8	Meghdi	22.085	70.674	Running	Reftek BBS
9	Mundra	22.769	69.683	Running	Reftek BBS
10	Vadadala	21.740	73.018	Running	Reftek BBS
11	Bharudia	23.572	70.410	Running	Reftek BBS
12	Bandhadi	23.393	70.307	Running	Reftek BBS
13	Bhimasar	23.190	70.159	Running	Reftek BBS
14	Jangi	23.223	70.567	Running	Reftek BBS
15	Fatehgadh	23.690	70.839	Running	Reftek BBS
16	Adwana	21.908	69.591	Running	Reftek BBS
17	Naliya	23.327	68.828	Running	Reftek BBS
18	Jagdiya	21.726	73.151	Running	Reftek BBS

felt strongly in wide areas. However, the catalogue completeness has been also assessed with respect to time, and it is observed that for the earthquake of magnitudes *M*4.0–4.5, it is complete for the period 1918–2009; for *M*4.6–5.0, it is complete for 1908–2009; for *M*5.1–5.5, it is complete for 1890–2009; and for $M \geq 5.5$, it is complete for 1802–2009.

Earthquake catalogue of Gujarat and the adjoining region bound by 20°–25.5°N and 68°–75°E prepared for the period 1684 through 2010 contains a total of 242 earthquakes (Table 4) including 2 of *M*7.7 and 7.8, 2 earthquakes of *M*6 and 6.3, 27 earthquakes of *M*5–5.9, 68 earthquakes between *M*4.0 and 4.9, 89 earthquakes between 3.0 and 3.9, and 18 earthquakes of *M*2–2.9 (Table 5). The catalogue completeness has been assessed with respect to time, and it is observed that for the earthquake of magnitudes $M \geq 5.5$, it is complete from 1802; for *M*5.1–5.5, it is complete from 1890; for *M*4.6–5.0, it is complete for 1908–2009; and for *M*4.0–4.5, it is complete from 1918. However, most of the regions being populated for centuries, it is expected that for the last 200 years, no earthquake of magnitude ≥4 is missed as such earthquakes are found to be felt strongly in wide areas. Out of these, five shocks of $M \geq 5.0$ and about 25 strongly felt ($M < 5$) occurred in the decade after 2000.

5 Recurrence rates

Stochastic analysis of earthquakes of Gujarat region using Weibull, Gamma and Log-normal models indicated recurrence intervals of earthquake of $M \geq 5.0$ in Saurashtra, Mainland Gujarat and Kachchh as 40, 20 and 13 years, respectively (Yadav et al. 2008).

Table 4 Catalogue of earthquakes in Gujarat region from earliest time to December 2010

Year	MM	DD	O.T.	Lat (N)	Long (E)	Dep.	Mag.	MMI	Location
1668	05	06		25.00	68.00		7.8	X	Samaji, Indus
1684				21.20	72.90		3.7		Surat
1819	06	16		24.00	69.00		M_w 7.8	X	Kachchh
1820	01	27		23.20	69.90		3.7		Kachchh
1820	11	13		23.20	69.90		3.7		Kachchh
1821	08	13		22.70	72.70		4.6		Kaira
1828	07	20		23.24	69.66		4.4		Kachchh
1840	11	10		23.05	72.67		4.6		Ahmedabad
1842	10	09		22.30	73.20		4.3	V	Baroda
1843	02	08		23.00	72.70		3.7	IV	Ahmedabad
1844				24.33	69.50		4.3		Lakhpat
1845	04	19		23.80	68.90		6.3	VIII	Lakhpat
1845	06	19		23.80	68.90		5.7	VII	Lakhpat
1848	04	26		24.40	72.70		5.7	VII	Mount Abu
1856	11	02		23.20	69.90		4.6		Anjar
1856	12	25		20.00	73.00		5.7	VII	Surat
1858	12	31		21.00	75.00		4.3	V	Khandeish
1863	11	18		22.00	75.00		5.0	VI	Barwani
1864	04	29		22.30	72.80		5.7	VII	Ahmedabad
1869	07	04		20.20	74.20		4.3	V	Nasik
1869	07	12		20.90	74.80		4.3	V	Dhulia
1871	01	03		21.20	72.90		4.3	V	Surat
1871	01	31		21.20	72.90		5.0		Surat
1872	04	14		21.75	72.15		5.0	VI	Bhavnagar
1882	06	10		23.20	71.38		3.5		Bhachau
1882	06	28		23.35	70.58		5.0		Lakadia
1882	06	29		23.35	70.58		5.0		Bhachau
1883	10	20		21.70	71.97		4.4		Bhavnagar
1886	04	14		22.47	70.10		4.4		Jamnagar
1887	11	11		22.30	70.88		4.4		Rajkot
1888	08	20		23.83	70.00		3.5		Khavda
1890	06	01		23.83	68.83		4.0		Lakhpat
1891	07	27		21.33	71.37		4.4		Amreli
1892	01	11		23.83	70.00		3.5		Lakhpat
1892	07	09		23.50	70.72		3.5		Rapar
1893	11	04		23.83	68.83		3.5		Lakhpat
1896	02	26		23.83	69.67		3.5		Lakhpat
1897	10	00		23.00	72.70		3.7		Ahmedabad
1898	01	30		23.16	70.08		3.5		Anjar
1898	04	01		23.25	69.67		4.0		Bhuj
1898	09	13		23.30	69.75		4.0		Bhuj
1898	10			23.05	72.67		4.3		Kheda
1898	10	15		23.33	69.67		4.0		Bhuj

Table 4 continued

Year	MM	DD	O.T.	Lat (N)	Long (E)	Dep.	Mag.	MMI	Location
1900	12	21		23.50	70.67		3.5		Rapar
1903	01	14		24.00	70.00		5.6		Kachchh
1904	04	09		23.33	68.67		4.0		Bhuj
1904	04	28		23.50	70.16		4.0		Anjar
1904	07	30		23.83	70.33		3.5		Khadir
1904	11	30		24.33	69.58		3.5		Lakhpat
1905	07	10		23.33	69.67		3.5		Bhuj
1906	01	11		23.83	70.33		3.5		Khadir
1906	06	30		23.83	69.75		3.5		Khavda
1906	08	15		24.40	72.70		4.3	V	Mount Abu
1907	03	12		23.83	69.75		3.5		Khavda
1907	07	12		22.91	69.83		3.5		Mundra
1907	10	09		23.83	69.75		3.5		Khavda
1907	10	21		23.25	70.33		3.5		Bhachau
1908	09	29		23.83	69.75		3.5		Khavda
1908	10	21		23.83	69.75		3.5		Khavda
1909	02	07		23.83	69.75		3.5		Khavda
1909	04	09		23.25	70.33		3.5		Bhachau
1910	03	24		23.25	69.75		3.5		Bhuj
1910	08	01		23.83	69.67		3.5		Khavda
1910	12	13		23.41	70.58		4.0		Lakadia
1910	12	16		23.25	70.33		3.5		Bhachau
1911	01	23		23.41	70.58		3.5		Lakadia
1911	10	11		24.33	69.50		3.5		Lakhpat
1912	10	01		23.83	69.75		3.5		Khavda
1912	11	07		23.83	70.33		3.5		Khadir
1913	06	26		23.75	69.75		3.5		Khavda
1918	06	10		23.50	70.41		3.5		Bhachau
1919	04	21		21.70	72.25		5.7	VII	Ghogha (Bhavnagar)
1920	10	18		23.50	70.75		3.5		Rapar
1920	11	13		23.33	69.58		3.5		Bhuj
1921	02	11		25.00	70.70		4.2		Thar, Pakistan
1921	10	26		25.00	68.00		5.5		Indus, Kachchh
1921	10	27		23.83	69.67		4.0		Narayan, Sarovar
1922	02	09		23.41	70.67		3.5		Chitrod
1922	03	13		23.41	69.37		3.5		Mandvi
1922	03	13		22.00	71.00		4.3	V	Jhalavad
1923	08	07		22.91	69.45		4.0		Bhuj
1924	03	05		23.91	69.83		3.5		Khavda
1924	10	25		23.67	68.91		3.5		Khavda
1925	10	01		23.83	69.67		3.5		Khavda
1925	10	13		23.33	70.28		3.5		Shikra
1926	12	26		23.91	69.70		3.5		Khavda

Table 4 continued

Year	MM	DD	O.T.	Lat (N)	Long (E)	Dep.	Mag.	MMI	Location
1927	11	18		23.45	69.67		3.5		Bhuj
1930				22.40	71.80		4.3	V	Paliyad
1930	12	30		23.91	69.45		3.5		Khavda
1932	03	06		23.83	70.33		3.5		Khadir
1935	01	25		23.75	70.67		3.5		Rapar
1935	07	20		21.00	72.40		5.7		Surat
1935	07	23		23.25	69.50		3.5		Bhuj
1938	06			22.30	71.60		5.0		Botad
1938	07	19		22.40	71.80		5.0		Paliyad
1938	07	23		22.40	71.80		5.7	VII	Paliyad
1940	10	31	10:03	22.50	70.40		5.0	VI	Jamuanathali, Jamnagar
1940	11	13		23.57	70.33		4.0		Anjar
1941	01	30		23.83	70.25		3.0		Khadir
1950	06	14	04:24	24.00	71.20		5.3		Kachchh
1956	07	21	15:32	23.30	70.00	35	M_w 6.0	VIII	Kachchh
1956	07	22		23.16	70.00		3.0		Anjar
1962	03	12		24.10	70.90		3.0		Kachchh
1962	09	01	22:01	24.00	73.00		4.6		Palanpur
1963	07	13	19:08	24.90	70.30	35	5.3		Thar, Pakistan
1965	03	26	10:04	24.40	70.00	33	5.1		Kachchh
1966	05	27	22:14	24.46	68.69	5.0	5.0		Thar, Pakistan
1966	11	12	12:16	25.12	68.04	33.	4.8		Kachchh
1967	01	06	11:41	21.97	74.27		4.5		Tankhala
1968				21.60	71.25		4.3	V	Amreli
1968				21.73	70.45		4.3	V	Dhoraji
1969	03	23	04:21	24.54	68.79	19	4.4		Kachchh
1969	10	24	11:45	24.76	72.54	31	5.5		Mount Abu
1970	02	13	15:05	24.60	68.61	33	5.2		Kachchh
1970	03	23	01:53	21.60	72.96	8	5.4		Bharuch
1970	08	09		21.70	73.00		3.5		Bharuch
1970	08	30		21.70	73.00		4.1		Bharuch
1970	09	10		21.60	72.70		3.4		Bharuch
1971	05	14	17:14	25.12	68.11	57	4.5		Thar, Pakistan
1971	06	18		21.70	73.00		3.4		Bharuch
1973	06	05	01:19	25.09	68.07	33	4.8		Thar, Pakistan
1974	10	20		21.70	74.20		4.6		Narmada
1975				22.10	71.20		4.3	V	Jasdan
1975	09	19	16:49	24.69	71.03	33	3.7		Kachchh
1975	09	25		20.80	74.20		4.2		Gujarat
1976	06	04	00:43	24.51	68.45	18	5.1		Allah Band, Pakistan
1977	09	26	19:48	25.38	68.24	33	4.5		Kachchh
1978	04	10	09:10	21.84	72.90		3.0		Amod
1978	11	25	10:09	21.97	72.91		2.8		Amod

Table 4 continued

Year	MM	DD	O.T.	Lat (N)	Long (E)	Dep.	Mag.	MMI	Location
1979	02	22	22:11	21.33	72.15		3.3		Bhavnagar
1979	06	09	22:43	21.83	73.85		2.6		Rajpipla
1979	08	24	01:13	22.11	72.43		3.1		Khambhat
1979	09	05	10:08	21.33	72.12		3.6		Bhavnagar
1979	09	22	22:48	21.75	72.15		3.3		Bhavnagar
1979	12	10	22:19	21.90	72.90		3.2		Amod
1980	01	06	00:42	22.23	71.78		3.2		Botad
1980	03	18	18:22	21.81	73.03		2.9		Nabipur
1980	06	04	11:16	21.68	73.21		2.6		Nartrang
1980	06	04	11:17	21.68	73.21		3.1		Nartrang
1980	07	21	04:08	22.87	72.14		3.1		Nartrang
1980	08	27	06:20	22.82	72.82		2.7		Chandraga
1980	10	20	11:40	21.96	72.95		2.6		Kevadia
1981	04	26	18:12	24.12	69.51	33	4.3		Bhuj
1982	01	31	16:48	24.21	69.84	33	4.8		Kachchh
1982	03	10	03:45	21.38	73.00		3.1		Bharuch
1982	04	09	09:00	22.07	72.19		2.9		Khadi
1982	05	10	01:00	21.90	72.27		3.2		Bhavnagar
1982	06	24	01:27	22.00	72.88		3.6		Amod
1982	06	26	18:48	22.25	71.82		3.1		Dhandhuka
1982	07	02	16:30	21.86	72.04		3.5		Bhavnagar
1982	07	18	15:46	23.40	70.66	33	4.8		Bhuj
1984	09	13	04:48	24.95	70.46	33	4.2		Allah Band, Pakistan
1985	04	07	21:10	24.36	69.74	33	5.0		Kachchh
1985	04	27	04:59	20.66	73.21		4.6		Dharampur
1985	09	03		21.03	70.88		4.3		Visavadar, Junagadh
1986	02	26	12:47	20.48	73.72	33	4.3		Gujarat
1986	09	16		20.60	71.40		3.8		Rajula
1986	11	15	00:25	24.45	73.57	22	4.1		Near Mount Abu
1987	02	10	22:02	24.10	70.39	10	3.9		Kachchh
1987	04	10		24.55	70.12	10	2.0		Kachchh
1987	12	31		21.71	74.38		3.5		Narmada
1988	07	17		25.16	70.00	33	2.0		Kachchh
1989	03	21	00:57	24.27	68.96	33	4.0		Bhuj
1989	06	21	15:35	20.09	72.91	33	4.1		Valsad
1989	12	10	11:58	24.81	70.88	33	4.7		Kachchh
1991	01	20		23.13	69.83	35	2.0		Kachchh
1991	01	20	19:44	23.40	69.71	33	4.9		Bhuj
1991	01	30	10:44	20.55	73.15		4.6		Anklach
1991	09	10	06:54	24.16	68.68	35	4.7		Kachchh
1991	09	10	07:20	24.28	68.80	26	4.7		Kachchh
1992	05	04	11:20	24.52	70.13	33	3.4		Allah Band, Pakistan
1993	02	09	20:51	24.62	68.93	36	4.3		Allah Band, Pakistan

Table 4 continued

Year	MM	DD	O.T.	Lat (N)	Long (E)	Dep.	Mag.	MMI	Location
1993	08	09		20.60	71.40		3.1		Rajula
1993	08	24	23:18	20.60	71.40	29	5.0		Rajula
1993	12	31	13:32	21.12	72.72	35	4.1		Rajula
1996	02	17		23.33	69.67	33	4.5		Bhuj
1996	08	05	22:15	22.83	68.43	23	3.8		Bhuj
1996	11	17	18:12	21.40	73.06	10	4.0		Gujarat
1998	07	19		22.42	70.86		4.4		Rajkot
1998	09	21	06:23	21.81	71.93		3.0		Bhavnagar
1998	10	08	15:01	24.45	69.80	33	3.7		Bhuj
1998	11	28	16:59	21.94	71.06		3.2		Gondal
1999	09	21	11:00	21.70	72.10		2.5		Bhavnagar
2000	08	10	13:30	21.78	72.31		3.6		Bhavnagar
2000	08	13	13:28	21.02	70.99	7	4.6		Tulsi Shyam, Junagadh
2000	09	12	00:53	21.72	72.16	10	4.2		Bhavnagar
2000	12	24	11:22	24.01	70.09	43	4.7		Bhuj
2001	01	26	03:16	23.44	70.31	16	M_w 7.7	X	Kachchh
2001				21.02	70.88		2.5		Tulsi Shyam, Junagadh
2003	01	13		22.30	70.93		2.0		Rajkot
2003	01	29		21.46	70.51		3.1		Haripur, Junagadh
2003	08			22.20	69.92		2.5		LalpurTq, Jamnagar
2004				21.00	70.50		3.0		Talala Tq, Junagadh
2006	02	03	00:54	23.92	70.44	28	M_w 5.0 m_b 4.5[a]		Gedi, Rapar
2006	03	07	18:20	23.79	70.73	3	M_w 5.7 M_w 5.5[a]		Gedi, Rapar
2006	04	06	12:02	23.78	70.74	3	M_w 4.8 m_b 4.9[a]		Gedi, Rapar
2006	04	06	17:59	23.34	70.39	29	M_w 5.6 m_b 5.5[a]		Lakadia
2006	04	10	22:05	23.51	70.06	4.9	M_w 4.9 m_b 4.9[a]		Kachchh
2006	09	30	00:16	22.31	70.21	10	M_w 4.0	V	Khankotda, Jamnagar
2007	07	16	21:21	22.49	71.29	18	M_w 3.9		Paliyad
2007	09	02	16:38	22.33	70.22	10	M_w 3.2		Khankotda, Jamnagar
2007	10	09	03:49	21.08	70.73	11	M_w 3.1		Ankolwadi, Junagadh
2007	11	06	00:27	21.12	70.51	8.5	M_w 4.8 m_b 4.9[a]		Hirenvel, Junagadh
2007	11	06	09:38	21.16	70.54	4.5	M_w 5.0 m_b 5.0[a]		Haripur, Junagadh
2007	11	11	13:03	21.93	69.82	10	M_w 2.9		Verad, Bhanwad
2008	01	25	23:36	21.79	71.76	35	M_w 2.8		Bhavnagar
2008	03	09	11:03	23.39	70.33	30	M_w 4.9 m_b 4.5[a]		Chobari, Kachchh
2008	05	20	08:57	21.16	73.05	7.4	M_w 3.2		Surat
2008	11	5	03:53	21.95	73.89	8.5	M_w 2.9		Kevadiya

Table 4 continued

Year	MM	DD	O.T.	Lat (N)	Long (E)	Dep.	Mag.	MMI	Location
2008	10	4	05:29	21.90	69.96	3.7	M_w 3.6		Bhanvad
2009	3	28	05:57	22.17	70.75	6.2	M_w 3.0		Rajkot
2010	1	26	01:22	23.29	72.98	15	M_w 2.3		Gandhinagar
2010	3	30	19:57	23.61	72.57	11	M_w 3.2		Mehsana
2010	9	2	08:39	23.88	71.87	6.1	M_w 4.4		Patan
2010	6	23	16:54	22.16	71.36	21	M_w 3.3		Botad
2010	9	23	23:44	21.90	69.7	3.1	M_w 3.0		Advana
2010	11	28	07:04	22.28	70.25	6.6	M_w 3.4		Sanala
2010	12	6	23:35	22.35	74.03	12	M_w 3.2		Chota, Udaipur

[a] USGS

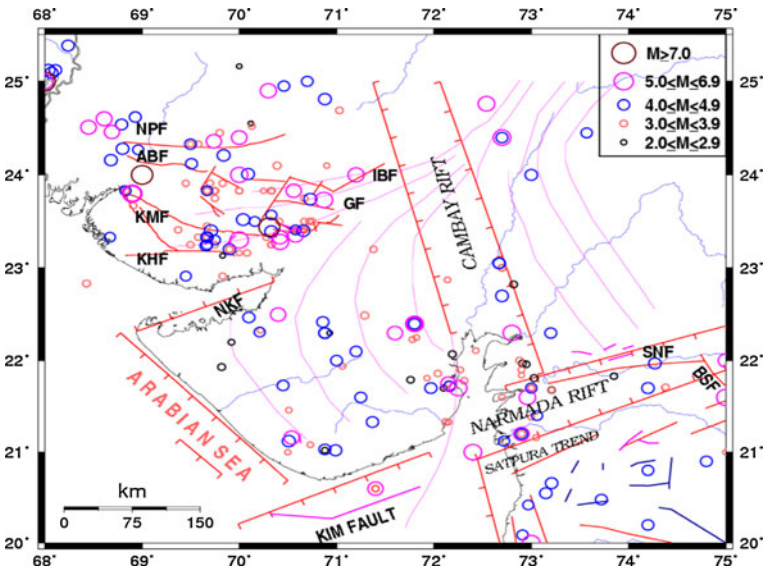

Fig. 3 Epicenters of earthquakes of *M*2 or greater from 1684 to 2010 excluding aftershocks

Table 5 Magnitudewise no. of earthquakes in Gujarat from 1686 to 2010 excluding aftershocks

Magnitude	No. of earthquakes
7–7.9	2
6–6.9	2
5–5.9	27
4–4.9	68
3–3.9	89
2–2.9	18
Total	242

6 Seismicity patterns and seismotectonics

The Kachchh region is considered seismically one of the most active intraplate regions of the World. It was known to have high hazard but low seismicity in view of the occurrence of several large earthquakes but fewer moderate or smaller shocks. Normally, the number of earthquakes increases ten times for every unit of lower magnitude. In Kachchh for two earthquakes of *M*7.8 and 7.7, earthquakes of $M < 7$ are fewer. In Saurashtra as part of regional seismicity, earthquakes of $M < 6$ have occurred on the eastern part and around West Cambay Fault near Bhavnagar. Narmada rift zone has experienced shocks of magnitude *M*5.4 at Bharuch in 1970, but *M*6 or more at east of Gujarat. The Cambay rift has shown less seismicity, which is confined more to its southern part and to *M*5.7 level.

Prior to 2001, Kachchh had experienced three large earthquakes: *M*7.8 Allah Bund (24.00°N 69.00°E) earthquake in 1819, *M*6.3 Lakhpat (23.80°N 68.90°E) earthquake in 1845 and *M*6 Anjar (23.30°N 70.00°E) earthquake in 1956. Smaller shocks include seven earthquakes of magnitude 5–5.6, and only 71 of *M*3.5–4.9. Other areas of Gujarat have experienced a few damaging earthquakes of magnitude <6, for example, the 1970 *M*5.4 earthquake in Bharuch (21.625°N 72.96°E) along the South Narmada fault. In Saurashtra, the two significant earthquakes were 1919 *M*5.7 Ghogha (22°N 72°E) and 1938 *M*5.7 Paliyad (22.40°N 71.80°E).

6.1 Seismotectonics of the Kachchh rift

Earthquakes (up to M_w 7.8 level) occur in about 250 km × 150 km size Kachchh rift along E–W faults. The entire crust is brittle as evidenced by focal depths of earthquakes from near surface to 36 km. Sometimes hidden faults are active. As most parts of the basin experience seismicity, it is critically stressed. The pre-existing faults get reactivated due to strain accumulation or fault weakening. Several studies (monitoring of seismicity through 25 or more local broadband seismographs, active fault investigations, geophysical surveys and GPS network) for the 2001 Bhuj earthquake and aftershocks have given insights into seismogenesis of earthquakes in intraplate regions. The main shock and most of the aftershocks occurred along a south dipping ($\sim 45°$) hidden fault from 10 to 40 km depth. Three-dimensional velocity structure obtained from inversion of travel times of P and S waves of aftershocks indicates a high Vp magmatic body at regional scale and in 10–40 km depth range (Singh et al. 2011). This body is probably acting as a stress concentrator due to density and rigidity contrast. A low-velocity fluid-filled patch in 20–30 km depth range in the hypocentral zone might have acted as barrier. In the epicentral region of 2001 earthquake, lithosphere is inferred to be hot and thin (only 70 km as compared to normal 100 km) and crustal thickness is also thin (34 km as compared to 40 km in the surrounding region) caused due to rifting at around 184 Ma. Restructuring of this warm and thin lithosphere might have occurred due to thermal plume at 65 Ma (Mandal and Pandey 2010).

6.2 Seismicity of Saurashtra

Saurashtra region is bounded on all the sides by boundary faults. However, no seismicity has been noticed along these faults except the West Cambay Fault that borders the eastern side that has experienced earthquakes of magnitude up to 5.7. Interior part of Saurashtra is either covered by volcanic Deccan Traps or Quaternary deposits due to which no clear fault has been identified and neither any significant earthquake has occurred. The earthquakes in this region are likely to be associated with small faults corresponding to Aravali trends in

NW direction or Narmada trend in ENE direction. The focal depths are determined to 15 km.

6.3 Seismicity of mainland Gujarat

The two important tectonic features in the mainland region of Gujarat are the Narmada and Cambay rifts. The third tectonic feature, south of Narmada rift and considered part of it, is the Tapi rift zone that has low seismicity. Seismicity of magnitude about 6 has been associated with the ENE trending Narmada rift zone while of magnitude up to 5 along the NW trending Cambay and ENE trending Tapi rifts. The significant earthquake in this region was Bharuch *M*5.4 earthquake in 1970. It was followed by some aftershocks (Gupta et al. 1972). During 1986 in Valsad, south Gujarat, a sequence of foreshocks-aftershocks was experienced for about a year associated with *M*4.6 earthquake on April 30 (Rao et al. 1991). There is no other long sequence known to have occurred in Mainland Gujarat.

6.4 Enhanced seismicity during the 1st decade of the twenty-first century in Kachchh and Saurashtra

$M_w = m_b + 0.07$ $R^2 = 0.78$ for $4.8 \leq m_b \leq 7.0_w7.7$ great Bhuj earthquake of 2001 is followed by damaging aftershocks over a decade. The aftershock activity includes over 10,000 shocks of *M*1–2.9, 2401 shocks of *M*3–3.9, 357 shocks of *M*4–4.9 and 20 shocks of $M \geq 5.0$. In this region, *M*5.5 level seismicity continued until mid-2006. From mid-2006, there is no shock of $M \geq 5.0$; however, shocks of $M < 5.0$ are continuously occurring once every 2 months or so. Until 2003, the activity concentrated along the 2001 rupture zone of 40 km × 40 km (Fig. 4) but migrated subsequently (Fig. 5). During 2006–2009, several nearby faults in Kachchh up to 100 km distance from Bhachau are activated with more than ten mainshocks of *M*4–5.7 occurred along different faults like South Wagad Fault, Gedi Fault, Gora Dungar Fault and Island Belt Fault. Most of these mainshocks are associated with their own foreshock-aftershock sequences. There is no such report that so many faults were active simultaneously in the known 200-year history. Hence, it can be said that during the first decade of the twenty-first century besides the aftershocks of 2001 earthquake, the seismicity (in terms of mainshocks alone along different faults) is substantially high in Kachchh compared to last twenty decades. No doubt that the detectability of earthquakes has improved with time, the space–time changes inferred here are gross and not much influenced by it.

In 2000, Bhavnagar, Saurashtra, experienced damaging earthquake of *M*4.2 and several earthquakes associated with a months-long sequence (Bhattacharya et al. 2004). After 2006, more than twenty mainshocks of *M*3.0–5.0 with long sequences of foreshocks and aftershocks have occurred in the Saurashtra region along small faults (Fig. 3, Chopra et al. 2008b) at (1) Khankotda, Kalavad, Sanala, Moti Khavdi and Bhanvad areas in Jamnagar district, (2) Talala in Junagadh district, and (3) Sayala-Chotilla in Surendernagar district. The activity of these areas was monitored by local broadband seismograph (BBS) networks. The areal extent of the epicenters is 2–30 km. The shocks are shallower than 10 km and are associated with subterranean sounds.

The unusually high seismicity in Kachchh and Saurashtra since 2006 is suggested to be due to stress increase by stress perturbation due to 2001 Bhuj *M*7.7 earthquake up to 200 km distance in the south (ISR annual reports, isr.gujarat.gov.in). The sudden rise in water table by 30 m from pre- to post-monsoon in Saurashtra is inferred to cause 3 bars stress change that triggers small to moderate earthquakes.

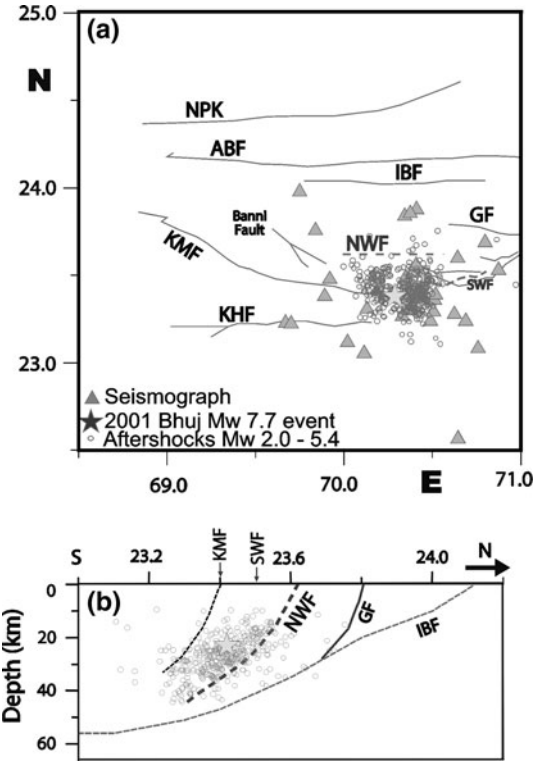

Fig. 4 Epicenters and focal depths of Kachchh mainshock and aftershocks during 2001 show that they were confined to NWF and 40 km × 40 km area. Nearly the same pattern continued for the next 2 years of 2002–2003 (NGRI data)

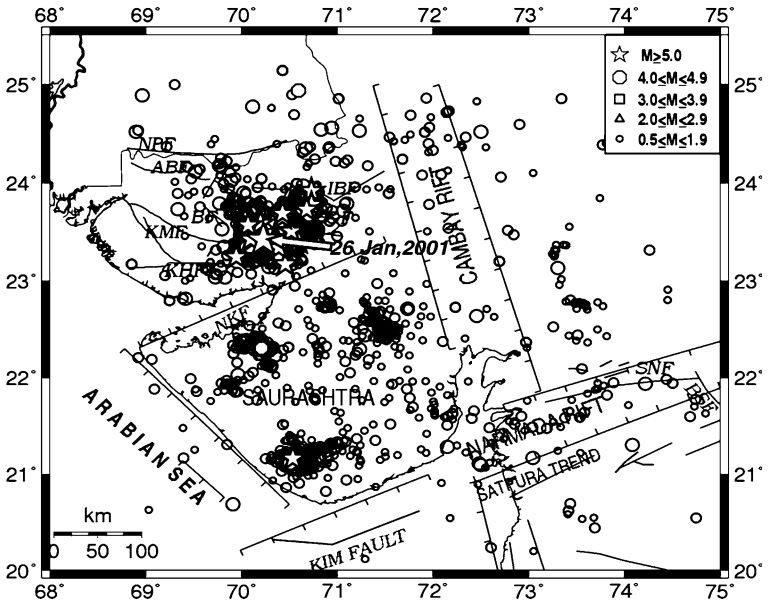

Fig. 5 Epicenters of earthquakes of $M \sim 1$ or greater in Gujarat during 2001–2010 including aftershocks

7 Discussion

Seismicity in Gujarat is monitored from 1970s, with several analog seismographs. It is believed that this network has not missed any earthquake of $M > 3$ in Gujarat in last four decades. Digital broadband seismographs were deployed at Bhuj in 1999 and subsequently at 60 locations. Thirty-six stations are connected online and the autolocation program installed during 2011 gives information of earthquake epicenter and magnitude within seconds of the arrival of seismic waves.

A catalogue prepared for Gujarat indicates four severely damaging earthquakes of magnitude 5.4–7.8 (Kachchh 1819, Anjar 1956, Bharuch 1970 and Bhuj 2001) and two lightly damaging earthquakes of magnitude about 5 (Valsad 1986 and Bhavnagar 2000). For two earthquakes of *M*7.7 and 7.8, one expects a large number of *M*6 and 5 earthquakes according to Gutenberg-Richter relation. Missing of such earthquakes defines the region of high hazard but low seismicity.

Aftershocks of 2001 earthquake are continuing for over a decade. Post-seismic deformation can be large and long lasting. For example, the post-seismic deformation for 1964 Alaska earthquake is 15–20 mm/year even 46 years after and for 1967 Koyna earthquake even after 42 years.

Seismicity has increased several fold in Kachchh after the Bhuj (23.44°N 70.31°E) earthquake of $M_w = m_b + 0.07$ $R^2 = 0.78$ for $4.8 \leq m_b \leq 7.0_w7.6$ in 2001 as some ten small to moderate mainshocks with associated foreshocks and aftershocks occurred along a number of faults besides the continuing damaging aftershocks of *M*4 and 5 for over a decade in the 2001 rupture zone. In Saurashtra, south of Kachchh and a region of relatively much low seismicity, and also the number of small to moderate earthquakes increased substantially (Chopra et al. 2008b) when over 20 felt/damaging shocks of *M*3–5 occurred at a dozen different locations. Long sequences of shocks for months/years were experienced at three locations. Even though the detectability has improved since 2006, the increase in seismicity is anomalous.

The seismicity in Kachchh was found to have been extended first eastward and northeastward and then in the north along newly activated faults from 2006 to 2008. Further, it extended to the Saurashtra region, in the south since 2006. The seismicity seems to be affected by the 2001 Great Bhuj Earthquake.

In Saurashtra, at unusually large number of places, swarm type of activity is associated with earthquakes of *M*3.5–5. This is unusual comparing the catalogue of last 200 years. Though the stress pulse may propagate horizontally through lower crust and upper mantle, it is transferred vertically to faults at near surface. The seismicity in Saurashtra is very shallow with 5–6 km focal depth. Seismicity in Kachchh too is shallower than 10 km.

The increase in seismicity in Gujarat after 2001 earthquake appears to have been triggered by critically stressed preexisting faults.

8 Conclusions

Gujarat has active tectonics along E–W faults in the Mesozoic rift zones of Kachchh and Narmada with earthquakes of *M*8 and *M*6, respectively. Cambay rift is less active and has experienced earthquakes in its southern part to *M*5.7 level. Seismicity is monitored for last four decades, and earthquakes of $M > 3$ are not likely to be missed during this period. Catalogue of earthquakes for last 325 years includes independent 242 mainshocks of magnitude 2–7.8. The three earthquakes of Allahbund 1819 (*M*7.8), Anjar 1956 (*M*6) and

Bharuch 1970 (M5.4) have been severely damaging, while 2001 Bhuj earthquake of M7.7 has been devastating. Twenty-seven other earthquakes were moderate with M5–6. In the first decade of the twenty-first century, several faults in Kachchh and Saurashtra have become active due to stress increase caused by 2001 Bhuj earthquake. In Saurashtra, 30 m rise in water table during monsoons adds additional 3 bars stress triggering earthquakes during September to November.

Acknowledgments The study was partly supported by Ministry of Earth Science, New Delhi. Authors are thankful to Dr. H.N. Srivastava for critically reviewing the manuscript.

References

Bhattacharya SN, Karanth RV, Dattatrayam RS, Sohoni PS (2004) Earthquake sequence in and around Bhavnagar, Saurashtra, Western India during August–December 2000 and associated tectonic features. Curr Sci 86:1165–1170

Biswas SK (1987) Regional framework, structure and evolution of the western marginal basins of India. Tectonophys 135:302–327

Chandra U (1977) Earthquakes of Peninsular India: a seismotectonic study. Bull Seism Soc Am 67(5): 1387–1413

Chopra S, Rao KM, Sairam B, Kumar S, Gupta AK, Patel H, Gadhavi MS, Rastogi BK (2008a) Earthquake swarm activities after rains in peninsular India and a case study from Jamnagar. J Geol Soc In 72:245–252

Chopra S, Yadav RBS, Patel H, Kumar S, Rao KM, Rastogi BK, Hameed A, Srivastava S (2008b) The Gujarat (India) seismic network. Seismol Res Lett 79(6):806–815

Gupta HK, Mohan I, Narain H (1972) The Broach earthquake of March 23, 1970. Bull Seismol Soc Am 62:47–61

Jaiswal RK (2010) Seismic characteristics of earthquakes in India and tsunami in the Indian Ocean. Ph. D. thesis, Osmania University

Johnston AC (1994) The stable continental region earthquake database, in the earthquakes of stable continental regions: assessment of large earthquakes potential. EPRI Report TR-102261, Chapter 3. Electric Power Research Institute, Palo Alto, p 75

Malik JN, Sohoni PS, Karanth RV, Merh SS (1999) Modern and historic seismicity of Kachchh Peninsula, western India. J Geol Soc In 54:545–550

Mandal P, Pandey OP (2010) Relocation of aftershocks of the 2001 Bhuj earthquake: a new insight into seismotectonics of the Kachchh seismic zone, Gujarat, India. J Geodynamics 49:254–260

Martin S, Szeliga W (2010) A catalogue of felt intensity data for 589 earthquakes in India 1636–2008. Bull Seism Soc Am 100(2):562–569

Oldham TA (1883) Catalogue of Indian earthquakes. Mem Geol Surv India 19:163–215

Ramachandran K, Srivastava HN (1991) New catalogue of felt earthquakes over India during 1901–1971. Mausam 42:171–187

Rao DT, Jambusaria BB, Srivastava S, Srivastava NP, Hamid A, Desai BN, Srivastva HN (1991) Earthquake swarm activity in south Gujarat. Mausam 42:89–98

Singh AP, Mishra OP, Rastogi BK, Kumar D (2011) 3-D seismic structure of the Kachchh, Gujarat and its implications for the earthquake hazard mitigation. Nat Hazards 57(1):83–105

Srivastava HN, Ramachandran K (1985) New catalogue of historical earthquakes for peninsular India during 1839–1900, Mausam 36:351–358

Srivastava S, Rao DT (1997) Present status of seismicity of Gujarat. Vayu Mandal 27(1–2):32–39

Szeliga WS, Hough S, Martin S, Bilham R (2010) Intensity magnitude location and attenuation in India for felt earthquakes since 1762. Bull Seism Soc Am 100(2):570–584

Tandon AN, and Srivastava HN (1974) Earthquake occurrence in India, In: Earthquake Engineering (Jai Krishna Vol.). Ind Soc Earthq Tech Roorkee 1–48

Yadav RBS, Tripathi JN, Rastogi BK, Chopra S (2008) Probabilistic assessment of earthquake hazard in Gujarat and adjoining region, India. Pure Appl Geophys 165:1813–1833