

Triggered/migrated seismicity due to the 2001 M_w 7.7 Bhuj earthquake, Western India

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Abstract Paper describes triggered seismicity to 200 km distance and for a decade due to the 2001 M_w 7.7 Bhuj earthquake. The Kachchh region is seismically one of the most active intraplate regions of the World due to the occurrence of two large earthquakes 1819 (M_w 7.8) and 2001 (M_w 7.7). Though, it has high hazard but was known to have low seismicity in view of the occurrence of fewer smaller shocks. However, the status seems to have changed after 2001. Besides the strong aftershock activity for over a decade, seismicity has spread to nearby faults in Kachchh peninsula and at several places southward for 200 km distance in Saurashtra peninsula. Beyond the rupture zone of the 2001 Bhuj earthquake, more than 40 mainshocks of $M_w \sim 3-5$ have occurred at 20 different locations, which is unusual. The increased seismicity is inferred to be caused by stress perturbation due to the 2001 Bhuj earthquake by viscoelastic process. In Saurashtra, over and above the viscoelastic stress increase, the transient stress increase by water table rise in monsoons seems to be affecting the timing of mainshocks and associated sequences of earthquakes.

Keywords Triggered seismicity · Migrated seismicity · Bhuj earthquake

1 Introduction

Gujarat state in western India is geographically divided into three parts: the Kachchh peninsula, the Saurashtra peninsula situated south of it with an intervening gulf, and the mainland east of these peninsulas. Prior to 1999, seismicity was monitored in Gujarat with up to 25 analog seismographs. Though the Kachchh and Saurashtra regions were not well monitored until 2000, even then it is believed that the existing network has not missed any earthquake of $M_w > 3$ in Gujarat in last four decades. Bhuj station was upgraded with a digital broadband seismograph in 1999, and Dharoi broadband seismograph station was started in 2000. From 2001, a network of up to ten broadband seismograph stations was

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operated in Kachchh (Mandal et al. 2004a, b). Starting mid-2006 a dense network is operated by Institute of Seismological Research (ISR), Gandhinagar, which currently has 60 broadband seismographs and 50 accelerographs in and around Gujarat (Chopra et al. 2008a). The detectability is M_w 2.0 in Kachchh active area and M_w 2.5 in other areas.

Prior to 2001, Kachchh had experienced three large earthquakes: M_w 7.8 Allah Bund (24.00°N 69.00°E) earthquake in 1819, M_w 6.3 Lakhpat (23.80°N 68.90°E) earthquake of 1845, and M_w 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_w 3.5–4.9. In Saurashtra, the two significant earthquakes were 1919 M_w 5.7 Ghogha (22°N 72°E) and 1938 M_w 5.7 Paliyad (22.40°N 71.80°E).

During the first decade of the twenty-first century besides the aftershocks of 2001 earthquake, seismicity is substantially high compared to last twenty decades in Kachchh and also in Saurashtra. The sudden upsurge of seismicity appears to be influenced by stress perturbation due to the stress drop estimated to be 200 bars due to the 2001 Bhuj earthquake of M_w 7.7 (Bodin et al. 2001). Paper describes the details of the increase in seismicity and probable cause of it.

2 Seismicity of 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 the strain accumulation or fault weakening. Several studies (monitoring of seismicity through 25 or more local broadband seismographs, active fault investigations, geophysical surveys, 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 ($\sim 45^\circ$) hidden fault from 10 to 34 km depth. Three-dimensional velocity structure obtained from inversion of travel times of P and S waves of aftershocks indicates a high V_p magmatic body at regional scale and in 10–34 km depth range. This body is probably acting as a stress concentrator due to the density and rigidity contrast. A low velocity fluid-filled patch in 20–30 km depth range in the hypocentral zone might have acted as an asperity (Mandal et al. 2004a, b). In the epicentral region of the 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) due to rifting at around 184 Ma. Restructuring of this warm and thin lithosphere might have occurred due to the thermal plume at 65 Ma (Mandal and Pandey 2010).

3 Increased seismicity of Kachchh

Locations of seismograph stations operated since mid-2006 are shown in Fig. 1. Location accuracy since 2001 is better than 1 km from SEISAN program and better than 0.1 km from HYPO DD program in Kachchh seismic area. For Saurashtra, the location accuracy is 2 km from SEISAN and 0.1 km from HYPODD. For epicenter locations, velocity model of Mandal and Pujol (2006) for Kachchh region is being used and is given in Table 1 and Fig. 2. For Saurashtra region, velocity model of Kaila et al. (1981) is being used and is

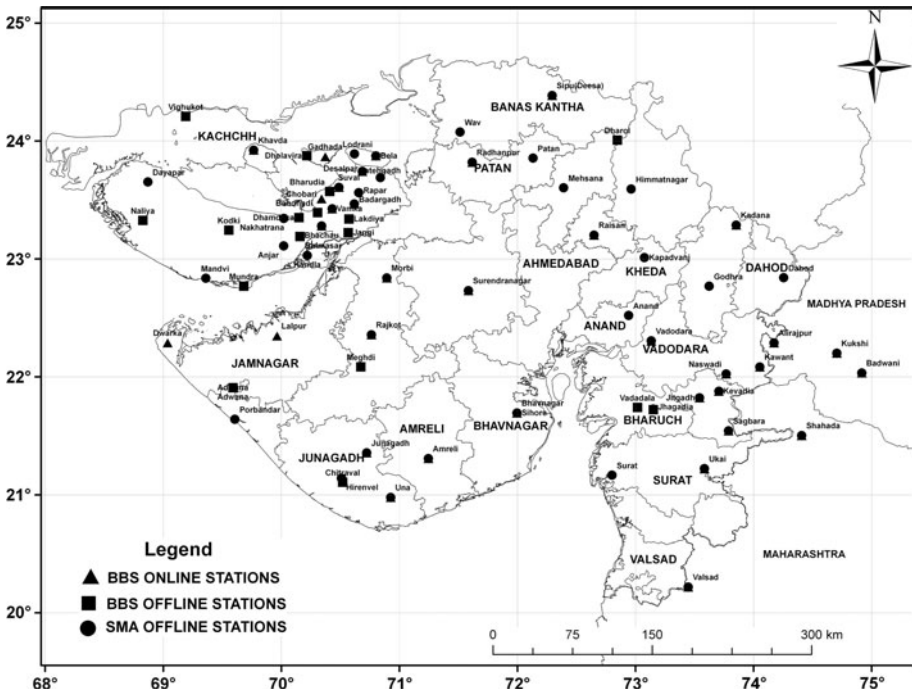


Fig. 1 Over 60 seismograph stations in Gujarat State Network (GSNet), out of which 36 are online broadband seismographs (including 2 very broadband seismographs), 25 are offline broadband seismographs, and 59 are accelerographs

Table 1 Velocity model being used for the location of earthquakes in Kachchh region

Depth to the top of layer (km)	Velocity of P wave (km/s)
0.0	3.0
3.0	5.43
6.0	6.00
10.0	6.45
15.0	6.48
20.0	6.72
25.0	7.15
30.0	7.49
35.0	7.88
42.0	8.20

given in Table 2 and Fig. 3. In the SEISAN program, V_p/V_s is taken as 1.73. In some parts of the Kachchh area, it is likely to be different. However, it is difficult to use different V_p/V_s values in the location program. Moment magnitude M_w is estimated and the catalog of Gujarat earthquakes (<http://isr.gujarat.gov.in>) has been homogenized to M_w values. M_L is given for $M < 2$.

During 2001, the aftershocks in Kachchh were confined to 20 km radius of the main-shock epicenter. During 2006, an earthquake of M_w 5.7 and associated sequence was

Fig. 2 Velocity model being used for Kachchh shocks

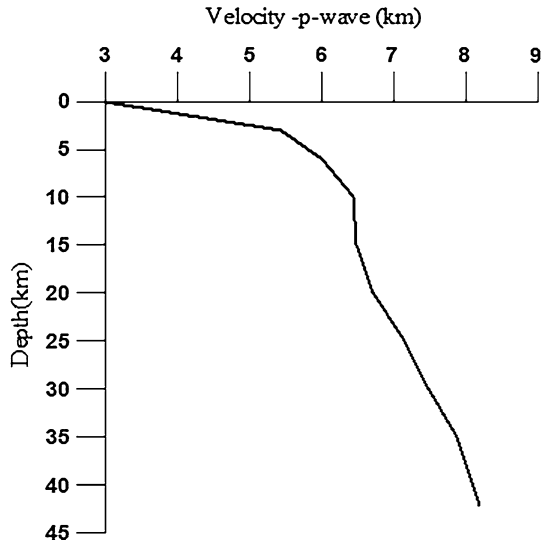


Table 2 Velocity model being used for the location of earthquakes in Saurashtra region

Depth to the top of layer (km)	Velocity of <i>P</i> wave (km/s)
0.0	4.95
1.0	6.2
20.0	6.6
30.0	6.9
37.0	8.26

Fig. 3 Velocity model being used for Saurashtra shocks

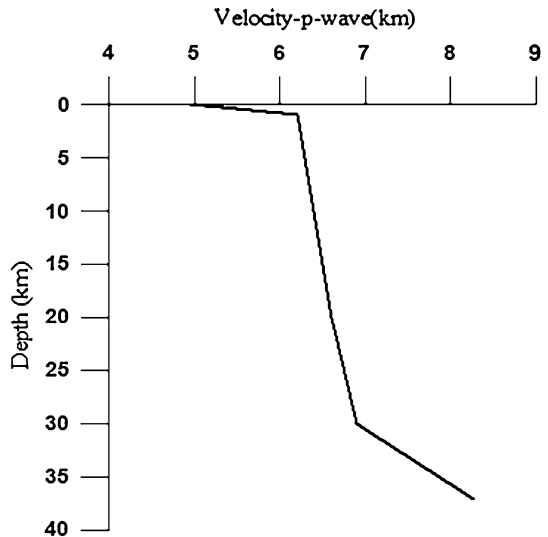
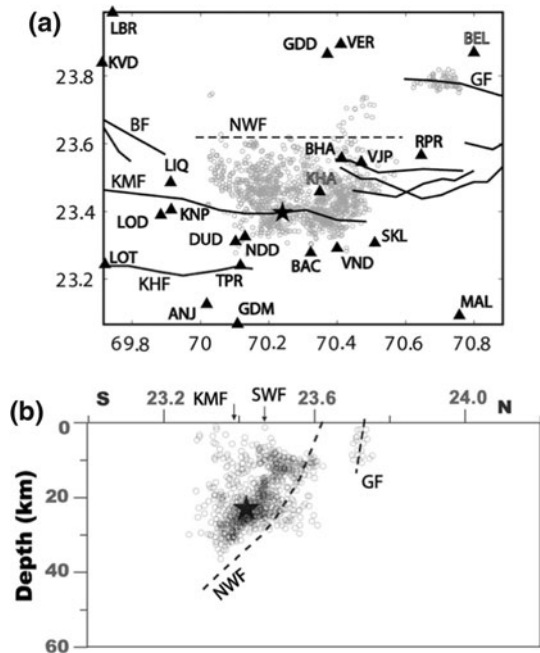


Fig. 4 HYPODD Relocated epicenters (a) and depth section (b) of 1402 Kachchh shocks during 2001–2006 (Mandal 2010). During 2001, the shocks were within 20 km radius of the mainshock (star) but migrated to South Wagad and Gedi faults during 2006. Inferred depth with depth is shown. Triangles show seismograph locations



triggered along the Gedi Fault about 60 km NE and M_w 5.6 along the South Wagad Fault in the east direction (Fig. 4). During the first decade of the twenty-first century due to the aftershocks of 2001 earthquake, seismicity is substantially high in Kachchh (Fig. 5, Tables 3, 4, 5, 6) compared to last twenty decades. The aftershock activity includes over 10,000 shocks of 1–2.9, 2,401 shocks of M_w 3–3.9, 357 shocks of M_w 4–4.9, and 20 shocks of $M_w \geq 5.0$, which have occurred during 2001–2010. In this region, M_w 5.7 level seismicity continued until mid-2006. From mid-2006, there is no shock of $M_w \geq 5.0$; however, shocks of $M_w < 5.0$ are continuously occurring with earthquakes of $M_w > 4$ once every 2 months and five or so of $M_w > 3$ every month.

Nevertheless, the mainshock number away from aftershock zone is double of the decadal frequency in previous two decades (Table 3). During 2006–2008, several nearby faults in Kachchh up to 100 km distance from Bhachau are activated with M_w 4–5.7 earthquakes along South Wagad, Gedi, Allah Bund, Island Belt, Gora Dungar, Banni, and Karol Hill Faults (Fig. 5). Locations of mainshocks in Kachchh and Saurashtra since 2000 are shown in Fig. 6. The trends of shocks and their associated faults in Kachchh are better seen in Figs. 7 and 8. All these faults experience sporadic earthquakes since then. Other than the aftershock activity of the 2001 Bhuj earthquake, 20 mainshocks (of M_w 3–5) occurred at 16 different locations in Kachchh. Focal depths are about 10–35 km in the aftershock zone of the 2001 Bhuj earthquake. Similar focal depths may be along the Island Belt Fault but shallower along some other faults like Gedi and Gora Dungar Fault. Only the Gedi earthquake of March 7, 2006, of M_w 5.7, the Gora Dungar October 28, 2009, earthquake of M_w 4.6, and the two earthquakes of January 8 and August 13, 2011, of M_w 4 and 4.5, respectively, had associated sequences of up to about 50 shocks of magnitude ≥ 1 . More details of these few clusters and other significant activities are as follows:

Table 4 Earthquakes in Kachchh for three decades during 1980–2000

SN	Y-M-D	<i>H</i>	<i>M</i>	Sec	Lat°N	Lon°E	<i>D</i>	<i>M</i>	Location
1	1981-04-26	04	26	18 12	24.12	69.51	33	4.3	ABF
2	1982-01-31	01	31	16 48	24.21	69.84	33	4.8	NPF
3	1982-07-18	07	18	15 46	23.40	70.66	33	4.8	Bhuj, KMF
4	1985-04-07	04	07	21 10	24.36	69.74	33	5.0	NPF
5	1987-02-10	02	10	22 02	24.10	70.39	10	3.9	IBF
6	1987-04-10	04	10		24.55	70.12	10	2.0	NPF
7	1988-07-17	07	17		25.16	70.00	33	2.0	Kachchh
8	1989-03-21	03	21	00 57	24.27	68.96	33	4.0	NPF
9	1989-12-10	12	10	11 58	24.81	70.88	33	4.7	Kachchh
10	1991-01-20	01	20		23.13	69.83	35	2.0	Bhuj, KHF
11	1991-01-20	01	20	19 44	23.40	69.71	33	4.9	Bhuj, KMF
12	1991-09-10	09	10	06 54	24.16	68.68	35	4.7	ABF
13	1991-09-10	09	10	07 20	24.28	68.80	26	4.7	NPF
14	1996-02-17	02	17		23.33	69.67	33	4.5	Bhuj, KMF
15	1996-08-05	08	05	22 15	22.83	68.43	23	3.8	Mandvi
16	1998-10-08	10	08	15 01	24.45	69.80	33	3.7	NPF
17	2000-12-24	12	24	11 22	24.01	70.09	43	4.7	Khavda

2009: Gora Dungar Fault (23.71N 69.91E) M_{\max} 4.6 on October 28, 2009, the cluster of earthquakes in the Gora Dungar had 38 earthquakes, and the duration of the cluster was 2008-04-14 to 2011-01-05.

2011: Rapar (23.46N 70.36E) M_{\max} 4.0 on January 8. The sequence included 48 shocks in 10 km radius for 10 days.

2011: 8 km SW of Rapar (23.552N 70.574E) May 23

2011: 10 km NE of Vamka (23.462 70.411) M_{\max} 4.6 on August 13

4 Seismicity of Saurashtra

Locations of shocks in Saurashtra and their trends are shown in Figs. 9, 10, and 11. 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 and has experienced earthquakes of magnitude up to 5.7. Off coast southeastern part of Saurashtra near Rajula (20.6N 71.4E) M_5 earthquake occurred on August 24, 1993, along with two other shocks of M_w 3–4. The interior part of Saurashtra is either covered by volcanic Deccan Traps or covered by 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 Proterozoic Aravali trends in NW direction or Mesozoic Narmada trend in ENE direction. The focal depths are up to 15 km, indicating that most of the stresses are concentrated in the upper 15 km. Faults in Kachchh (Chandrasekhar et al. 2005; Mishra et al. 2005) and Saurashtra (Mishra et al. 2001; Chandrasekhar et al. 2002) could be extending to crustal depths and are

Table 5 Mainshocks in Kachchh after 2001 Bhuj earthquake of M_w 7.7

SN	Date 2001	Lat°N, Lon°E 23.44, 70.31	D (km) 16	M_w 7.7	Location Bhachau
1	2004-01-08	23.91, 70.90	20.0	4.2	IBF
2	2005-03-08	23.85, 69.74	11.6	4.3	GDF
3	2005-10-09	23.74, 69.93	06.6	4.3	GDF
4	2006-02-03	23.92, 70.44	28.7	5.0, m_b 4.5*	IBF
5	2006-03-07	23.79, 70.73	03.0	5.7, m_b 5.5*	GF
6	2006-04-06	23.34, 70.39	29.3	5.6, m_b 5.5*	SWF, Lakadiya
7	2006-04-10	23.51, 70.05	35.0	4.9, m_b 4.9*	NWF
8	2007-05-13	23.44, 70.42	20.4	4.7	SWF
9	2007-10-08	23.30, 70.07	09.6	4.7	KMF
10	2008-03-09	23.39, 70.33	30	4.9, m_b 4.5*	Chobari
11	2008-04-04	23.00, 70.36	11.1	2.6	Kandla**
12	2008-07-05	23.53, 69.80	08.9	3.3	BF
13	2009-10-28	23.71, 69.91	08.5	4.5	GDF
14	2010-10-21	24.32, 69.37	06.0	3.0	NPF
15	2010-12-31	24.31, 69.87	10.4	3.2	NPF
16	2011-02-04	24.28, 69.13	12.5	3.0	NPF
17	2011-05-17	23.54, 70.54	20.4	4.2	NWF
18	2011-09-27	23.12, 70.31	38.0	3.0	Kandla**

Many of these are associated with their own foreshock–aftershock sequences. The mainshocks marked by double stars are single events

NWF North Wagad fault, *SWF* South Wagad Fault, *IBF* Island Belt Fault, *GDF* Gora Dungar Fault, *GF* Gedi Fault, *BF* Banni Fault, *KMF* Kachchh Mainland Fault, *KHF* Katrol Hill Fault, *ABF* Allah Bund Fault, *NPF* Nagar Parkar Fault

* USGS magnitude

** No foreshocks/aftershocks and similar to regional seismicity in the past

associated with block movements and high-density mafic intrusive as indicated by gravity anomalies.

5 Increased seismicity of Saurashtra

The Saurashtra region has been experiencing stray tremors once in a while in the last two centuries. In the last three decades of 1970s to 1990s, there were 3–5 shocks per decade (Tables 7 and 8) and had two damaging earthquakes of M_w 5.7 in 1919 and 1938. During 2000, the Bhavnagar (21.7N, 72.3E) M_{max} 4.2 earthquake on September 12 caused wide cracks in tens of houses. A foreshock of M 3.6 on August 9 was also damaging. It caused subsidence of several houses. Some 50 shocks were felt during August to October 2000. During the 1st decade of twenty-first century, Saurashtra peninsula experienced damaging earthquakes accompanied by long sequences. The three most significant are as follows: (1) 2006 M_w 4.0 Khankotda area in Jamnagar district (2) 2007 M_w 5.0 Talala, Junagadh, and (3) 2007 M_w 3.7 Sayala, Surendranagar (Chopra et al. 2008b). There were thirteen other sequences and some 12 tremors of $M_w \sim 3$ to 4 (without sequences) at different locations in Saurashtra (Fig. 4; Table 6 and the list below).

Table 6 Decennial number of earthquakes in Saurashtra indicates unusually large number of mainshocks during the decade starting 2000 inferred to be due to triggering caused by stress pulse generated by $M_w7.7$ earthquake in 2001 at distances of 100–200 km away

Decade	No. of earthquakes	Magnitudes
1870–1879	1	5.0
1889–1889	4	4.4 × 4
1890–1899	1	4.4
1900–1909	–	
1910–1919	1	5.7
1920–1929	1	4.3
1930–1939	8	4.3, 4.1, 5.5, 5.7
1940–1949	1	5.0
1950–1959	–	
1960–1969	2	4.3, 4.3
1970–1979	5	4.3, 3.3, 3.1, 3.6, 3.3
1980–1989	7	3.2, 2.9, 3.2, 3.1, 3.5, 4.3, 3.8
1990–1999	5	3.1, 4.4, 3.0, 3.2, 2.5
2000	3	3.6, 4.6, 4.2,
2001–2010	+30	Thirty mainshocks at twenty different locations

Significant earthquakes occurred during 1919 and 1938

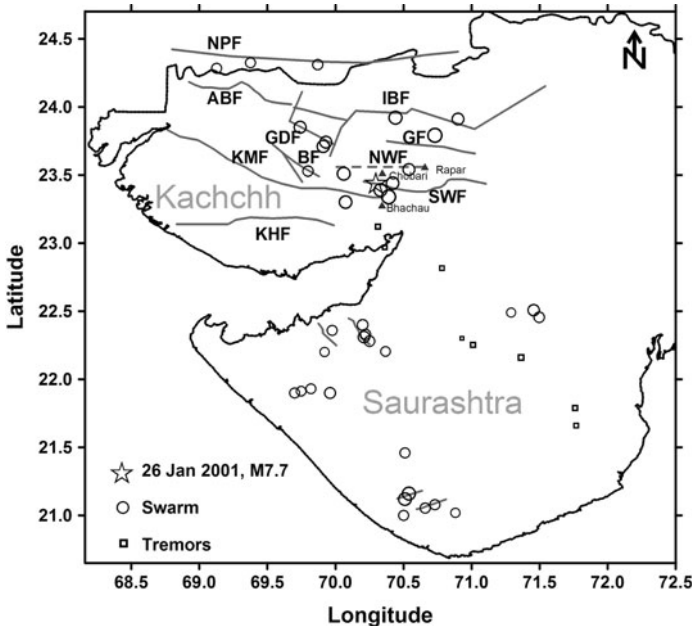


Fig. 6 Triggered seismicity (Tremors with or without swarms) in Kachchh and Saurashtra regions of Gujarat after the 2001 Bhuj earthquake $M_w7.7$

Examples of Swarm-type earthquake sequences in Saurashtra:

1938: Paliyad (22.4N 71.8E), July–August, Swarm had four shocks of magnitude more than 5.0, $M_{max}5.7$. More than 190 shocks felt with rumbling sound.

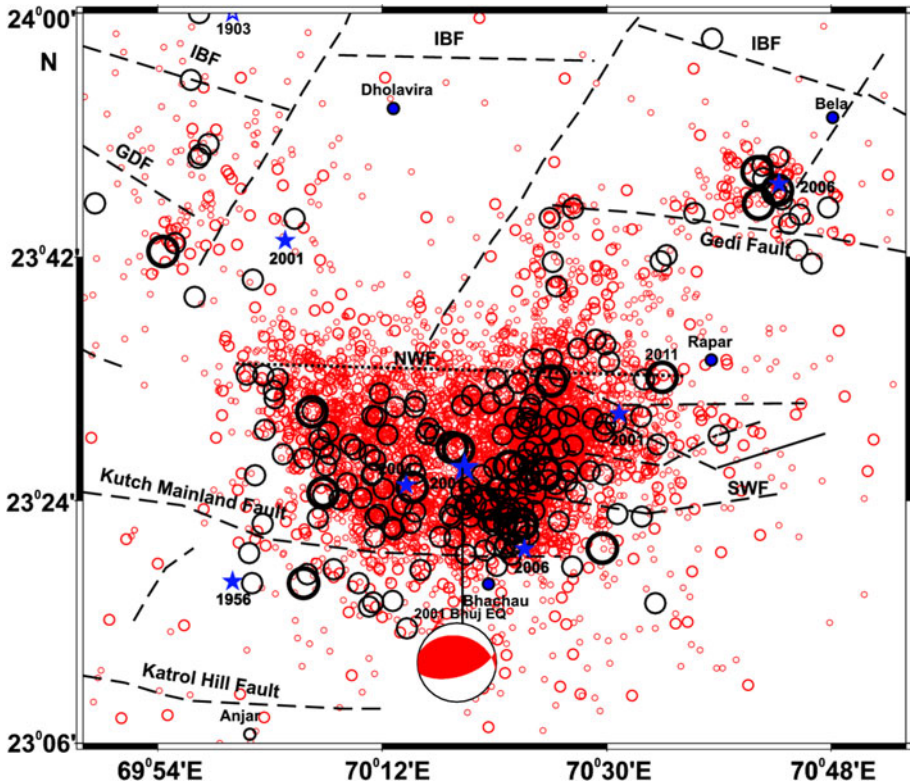


Fig. 7 HYPO71 locations in Kutch during January 2007 to May 2011 of M_{2-5} by different sizes of circles. The dashed lines represent the major tectonic faults in this region: SWF South Wagad Fault, NWF North Wagad Fault, GDF Gora Dungar Fault, IBF Island Belt Fault. The stars represent historical $M \geq 5$ earthquakes. The Focal mechanism is for the 2001 Bhuj earthquake

2000: Bhavnagar (21.78N 72.31E) August 9–25, M_{\max} 3.6 on August 10, 43 aftershocks. Cracks in tens of houses.

2000: Bhavnagar (21.7N 72.3E) August–October: M_{\max} 4.2. Some 132 foreshocks and aftershocks in the magnitude range of 0.5–3.8 were located (Bhattacharya et al. 2004). Eleven shocks of $M \geq 3$. Most shocks were felt with subterranean sounds. Cracks in a number of houses and low-rise buildings.

2000: Una-Tulsi Shyam, Girnar Hills (21.02N 70.99E) M_w 4.6 on August 13, a few aftershocks. Wall cracks and collapses in 75 houses in Gir Gadhada and in several houses in Una.

2001: Sasan Gir area (Haripur village, Talala, Junagadh, 21.16N 70.54E), October–December (2 months), M_{\max} 3.2 on November 11, 1689, shocks recorded, 9 shocks of $M_w \geq 3$. Many accompanied by blast sounds with occasional shaking.

2003–2004: Sasan Gir area (Haripur, 21.16N 70.54E), September 03–January 04, M_{\max} 3.1 on January 29, shocks felt with rumbling sound.

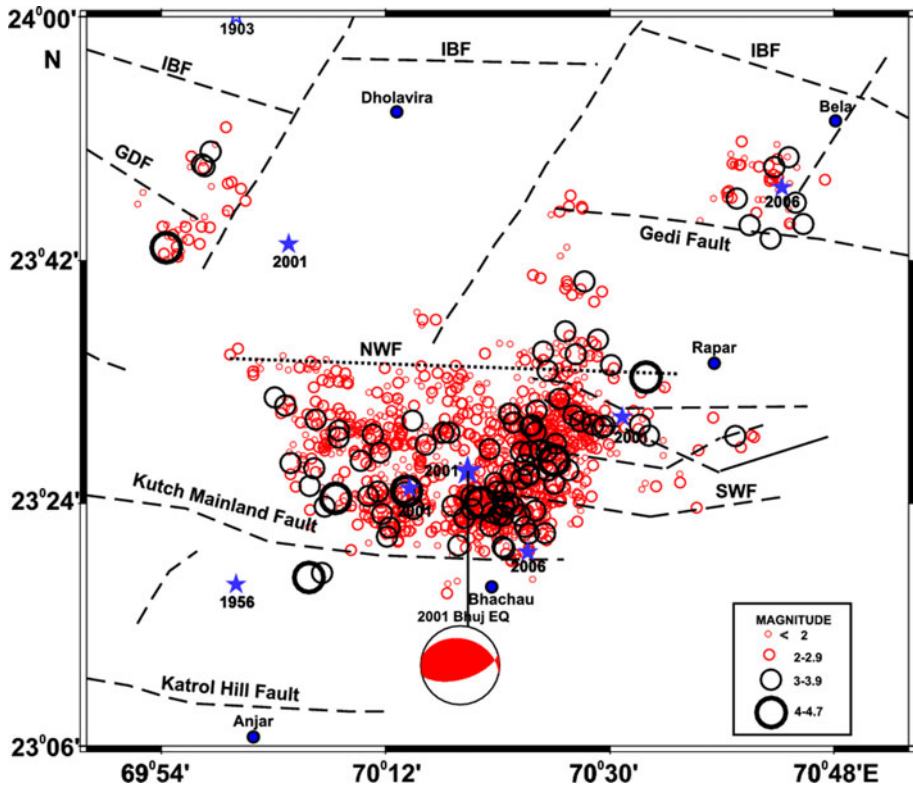


Fig. 8 Results of HYPODD clustering analysis of the HYPO71 locations during January 2007 to May 2011 in Kutch (other details as in the previous figure. The North Wagad, Gedi, and Gora Dungar faults show clear concentration. Some shocks are along Pachchham, Khadir, and Bela Transverse Faults

- 2003: Sasoi Dam near Lalpur magnitude 3.0 and numerous small shocks felt with blast-like sounds.
- 2006: Lalpur (22.2N 69.9E) September–October 2006, M_{max} 4.0, 200 shocks felt with blast sound.
- 2006: Kalavad, Khankotda (22.3N 70.22E) September–October 2006, M_{max} 4.0, September 30, 200 shocks felt with blast sound. Slight damage reported to some adobe-type houses. Some 50 hypocenters of $M_w \sim 2$ –3.3 were located by local network.
- 2007: Khankotda (22.33N 70.22E) M_{max} 3.2 on September 2.
- 2007: Vijrakhi (22.4N 70.2E) August–October 2007 M_{max} 3.5 on September 9, over 200 shocks felt with blast sound. Slight damage reported to some adobe-type houses.
- 2007: Ankolwadi, about 15 km SE of Sasan Gir, Talala (21.08N 70.73E) M_{max} 3.1 on December 10. Swarm of 50 foreshocks and aftershocks of M 0.5–2.9 during October 4–10 and December 10–20 indicating about 50 km long ENE trend (ISR Annual Report 2008).
- 2007: Verad, Bhanvad (21.93N 69.82E) M_{max} 2.9 November 11, 12 foreshocks and aftershocks of magnitude 0.5 to 2.9 during August to December 2007.

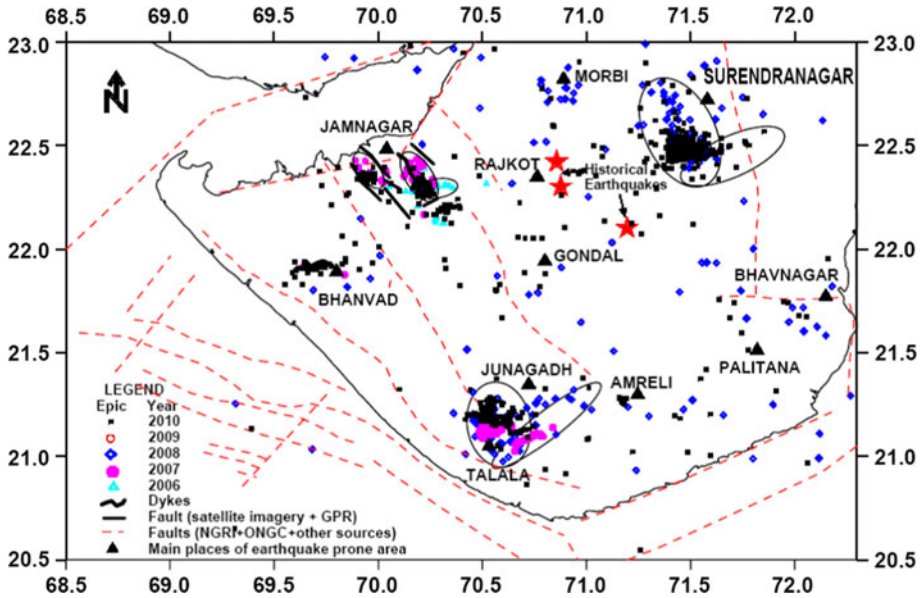


Fig. 9 Epicenters in Saurashtra during 2006–2009 of $M1$ – 5.0 . Some shocks of $M < 1$ were also located by local networks at Talal and Surendranagar. Faults inferred by NGRI and ONGC are marked by *broken lines*

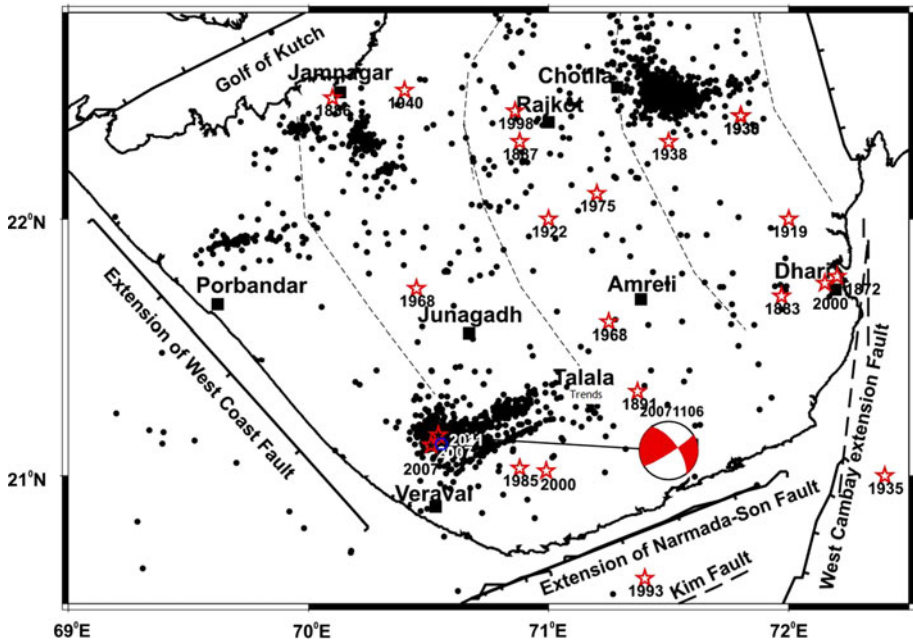


Fig. 10 HYP071 locations of earthquakes of $M \geq 1$ in Saurashtra region during January 2007 to May 2011. The stars represent historical as well as recent earthquakes of $M \geq 4$ in the region. The dotted lines represent the Aravalli trends. The boundary faults are also shown. Location accuracy is 0.5 km for relocated epicenters from HYP071 and 0.1 km in HYP0DD

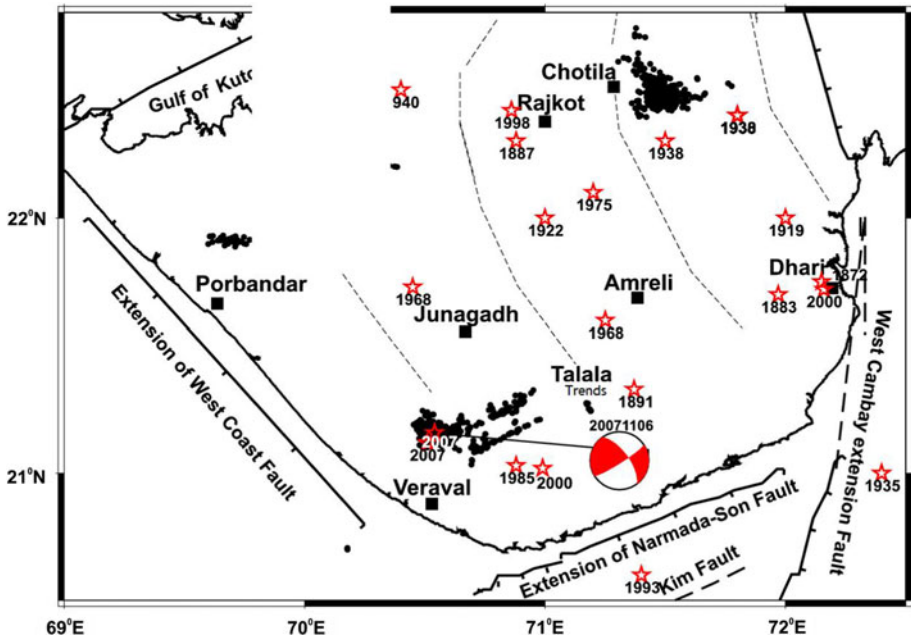


Fig. 11 Cluster analysis through HYPODD of HYPO71 locations shown in Fig. 8. Location accuracy is 0.1 km for relocated epicenters from HYPODD. The MTS focal mechanism is for the 2007 Talala earthquake of M_w 5.0 which indicates *right*-lateral movement along a NW-trending fault or *left*-lateral movement along the ENE-trending fault. A similar mechanism is obtained for the 2011 Talala earthquake of M_w 5.1 whose epicenter was a little SW

Table 7 Earthquakes in Saurashtra during 1980–2000

SN	Date	Hr	Mn	Sec	Lat	Lon	D (km)	Mag	Location
1	1980-01-06	01	06	00 42	22.23	71.78		3.2	Botad, Rajkot
2	1982-05-10	05	10	01 00	21.90	72.27		3.2	Bhavnagar
3	1982-06-26	06	26	18 48	22.25	71.82		3.1	Dhandhuka
4	1982-07-02	07	02	16 30	21.86	72.04		3.5	Bhavnagar
5	1985-09-03	09	03		21.03	70.88		4.3	Visavadar
10	1998-07-19	07	19		22.42	70.86		4.4	Rajkot
11	1998-09-21	09	21	06 23	21.81	71.93		3.0	Bhavnagar
12	1998-11-28	11	28	16 59	21.94	71.06		3.2	Gondal, Rajkot
13	1999-09-21	09	21	11 00	21.70	72.10		2.5	Bhavnagar
14	2000-08-10	08	10	13 30	21.78	72.31		3.6	Bhavnagar
15	2000-08-13	08	13	13 28	21.02	70.99	7	4.6	Tulsi Shyam
16	2000-09-12	09	12	00 53	21.72	72.16	10	4.2	Bhavnagar

2008: Chotila, Surendranagar rm of hundreds of shocks from 2007 and continued through 2011.

2008: Bhanvad, Jamnagar (21.90N 69.96E) M_{max} 3.6 on October 4, 6 foreshocks and aftershocks of magnitude 0.5 to 2.9 during October to December 2008.

Table 8 Mains shocks in Saurashtra after 2001 Bhuj earthquake of $M_w 7.7$

SN	Date	Lat°N, Long°E	D (km)	M_w	Location
1	2001	21.02, 70.88		2.5	Tulsi Shyam, Junagadh
2	2003-01-13	22.30, 70.93		2.0	Rajkot**
3	2003-01-29	21.46, 70.51		3.1	Haripur, Junagadh
4	2003-08-	22.20, 69.92		2.5	Lalpur Tq, Jamnagar
5	2004	21.00, 70.50		3.0	Talala Tq, Junagadh
6	2006-09-30	22.31, 70.21	05.2	4.0	Khankotda, Jamnagar
7	2007-07-16	22.49, 71.29	18.0	2.4	Paliyad**, Rajkot
8	2007-09-02	22.33, 70.22	10.0	3.2	Khankotda, Jamnagar
9	2007-09-09	22.40, 70.20	14.0	3.5	Vijrakhi, Jamnagar
10	2007-10-09	21.08, 70.73	11.0	3.1	Ankolwadi, Junagadh
11	2007-11-06	21.12, 70.51	08.5	4.8, m_b 4.9*	Hirenvel, Junagadh
12	2007-11-06	21.16, 70.54	04.5	5.0, m_b 5.0*	Haripur, Junagadh
13	2007-11-11	21.93, 69.82	10.0	M_w 2.9	Verad, Bhanvad
14	2007-12-10	21.05, 70.66	07.4	M_w 3.1	Ankolwadi, Junagadh
15	2008-01-25	21.79, 71.76	35.0	M_w 2.8	Bhavnagar**
16	2008-02-15	21.66, 71.77	03.1	M_w 2.7	Bhavnagar**
17	2008-02-24	22.25, 71.01	06.1	M_w 2.9	Kotda, Rajkot**
18	2008-03-03	22.45, 71.50	12.8	M_w 3.4	Paliyad, Bhavnagar
19	2008-03-15	22.51, 71.45	10.6	M_w 3.9	Chotila, Surendranagar
20	2008-04-02	22.82, 70.78	18.6	M_w 2.7	Morbi**
21	2008-10-04	21.90, 69.92	03.7	M_w 3.6	Verad, Bhanvad
22	2009-03-28	22.17, 70.75	06.2	M_w 3.0	Rajkot
23	2010-06-23	22.16, 71.36	21.0	M_w 3.3	Botad**, Rajkot
24	2010-09-06	22.20, 70.37	15.0	M_w 2.8	Kalavad, Jamnagar
25	2010-09-23	21.90, 69.70	03.0	M_w 3.0	Advana, Porbandar
26	2010-09-25	21.91, 69.75	03.2	M_w 2.8	Bhanvad, Jamnagar
27	2010-11-25	22.29, 70.24	06.9	M_w 3.4	Khankotda, Jamnagar
28	2010-11-28	22.28, 70.25	06.6	M_w 3.4	Khankotda, Jamnagar
29	2010-09-29	22.36, 69.98	3.1	M_w 3.0	Motikhavadi, Jamnagar

Many of these are associated with their own foreshock–aftershock sequences. The mains shocks shown by rectangles in Fig. and marked by double stars are single events

2010: Kalavad, Jamnagar (22.20N 70.37E) M_{\max} 2.8 on September 6, 55 foreshocks and aftershocks of magnitude 0.5 to 2.9.

2010: Advana, Porbandar (21.90N 69.70E) M_{\max} 3.0 on September 23, 50 foreshocks and aftershocks of magnitude 0.5 to 2.9.

2010: Bhanvad, Jamnagar (21.91N 69.75E) M_{\max} 2.8 on September 25, 20 foreshocks and aftershocks of importance 0.5 to 2.7.

2010: Khankotda, Jamnagar (22.29N 70.24E) M_{\max} 3.4 on November 25.

2010: Khankotda, Jamnagar (22.28N 70.25E) M_{\max} 3.4 on November 28, 65 foreshocks and aftershocks of magnitude 0.5 to 2.9.

2010: Motikhavadi, Jamnagar (22.36N 69.98E) M_{\max} 3.0 on September 29, 56 foreshocks and aftershocks of magnitude 0.5 to 2.9.

2011: Sasan Gir area (21.09N 70.45E), October–December 2011, M_w 5.1 on October 20 at about 8 km SW of 2007 epicenter. Walls collapsed in about 30 houses and wide cracks in about hundred houses. Over 300 shocks of magnitude ≥ 1 located including nine shocks of M_w 3–3.9 and two shocks M_w 4.0 and M_w 4.1. The mainshock indicated left-lateral strike-slip along an ENE trend. Shocks have occurred along a 40-km-long ENE trend. (ISR Tech. Report, 2011).

In contrast, the earlier twenty decades experienced only a sequence during 1938 for M_w 5.7 Paliyad earthquake and the other for earthquake of M_w 4.2 Bhavnagar (21.72°N 72.16°E) in 2000 as listed above. Soon after the 2001 Bhuj earthquake, two sequences occurred during 2001 and 2003–2004. However after 2006, earthquakes of M_w 3.0–5.0 with long sequences of foreshocks and aftershocks started occurring at a number of places along small faults (Chopra et al. 2008b). The sequences that have continued for several years are at (1) Khankotda, Kalavad, Sanala, Motikhavadi, and Bhanvad areas in Jamnagar district, (2) Talala in Junagadh district, and (3) Sayla-Chotila in Surendranagar district. Shocks have recurred every year since 2006 in Jamnagar district, since 2007 in Talala, Junagadh district and Surendranagar district. At these three sites, several hundred magnitude ≥ 0.5 shocks were recorded on local networks of broadband seismographs. Earthquakes of M_w 4.8 and M 5.0 that occurred in November 2007 in Talala and M_w 4.0 in Kalavad in September 2006 caused damage to numerous houses. The areal extent of the epicenters is up to 30 km. The shocks are shallower than 10 km and are associated with subterranean sounds. A number of short sequences localized in small areas occurred during 2010 at Khankotda, Kalavad, and Motikhavadi in Jamnagar district.

Khankotda and adjoining villages in Jamnagar district of Gujarat experienced over 200 shocks during September–October 2006, out of which about 50 shocks of magnitude ~ 2 –3.3 were located. The shocks were felt with blast-like subterranean sounds. The largest tremor of magnitude 4.0 occurred on September 30, 2006 (22.31°N 70.22°E, at focal depth of 5 km). The sequence was monitored with local seismic stations. The activity recurred from August 11, 2007, after heavy rainfall in Khankotda, but this time spreading northward to Vijrakhi area 15 km short of Jamnagar, which is major city and petro-hub. The maximum magnitude was 3.4 on September 9, 2007, located close to Khankotda. The tremor caused cracks in a few houses in Khankotda. Over 200 shocks were felt and over 50 of magnitude ~ 2 to 3.4 were located during August–September 2007 in 50 days from regional network (and with local network since September 8, 2007). A shock of M_w 2.9 on September 7, 2007, caused minor cracks in a few houses at Vijrakhi village. Seismicity in Khankotda area continued to recur for further 3 years from 2008 to 2010. Most of the epicenters are located in a 15-km-long NW trend between Vijrakhi and Khankotda villages (Fig. 9). Some shocks have occurred about 15 km west of this trend along a NNW–SSE lineament. These lineaments are along dolerite dykes.

During August–September 2003, numerous events followed by blast-like subterranean sounds were felt by local people in and around Sasoi dam (filled in 1954) in Lalpur area of Jamnagar. The maximum intensity observed was around IV, which corresponds to magnitude 3.0. The swarm-type earthquake sequence was highly localized and subsided in a month's time. This activity was associated with a major N–S-trending dyke with two offsets in E–W and NW–SE directions (Srivastava and Rao 1997).

Sasan Gir Asiatic Lion Sanctuary area (Haripur village closest to the epicenter) in Talala taluka (120 km south of Khankotda) of Junagadh district experienced earthquake

swarms in 2001, 2004, and 2007 with maximum magnitude 3.2, 3.4, and 5.0, respectively. Earthquakes of $M_{4.8}$ and $M_{5.0}$ that occurred in November 2007 in Talala caused damage to a number of houses. Geological investigations and satellite investigations in the Sasan Gir area revealed existence of a N–S trending and about 20-km-long strike-slip fault. The moment-tensor fault mechanism indicated a right-lateral slip along a NNW trend.

The shocks in Advana of Porbandar district to Bhanvad, Sanala, and Jam Jodhpur areas of Jamnagar district form a E–W trend of about 40 km length.

The shocks near Chotila-Sayla area in Surendranagar district have recurred every year since 2006 after the monsoons. The shocks define a 40-km-long NW trend. The $M_{\max}3.1$ (22.51, 71.45) occurred on March 15, 2008.

All these sequences in Saurashtra occurred mostly during September to November after heavy rains. The unusual seismicity in Saurashtra since 2001 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. However, the sudden rise of water table by 30 M from pre- to post-monsoon is inferred to cause 3 bars stress change which triggers small to moderate earthquakes at particular period of the year.

In Khankotda, the ground water-level fluctuation from summer to monsoon season is reported to be quite high. Ground water in summer is usually encountered at a depth of around 25 m, but after rains it is available near surface. During 2006 and 2007, water table is reported to have risen by about 24 m. Ground water table measurements are done quarterly in several observation wells of Gujarat. The values of four wells in nearby areas are depicted in Fig. 12. The well at Motimatli is in earthquake zone at a distance of 6 km NE of Khankotda. It indicates 18-, 6-, and 18-m change during 2005, 2006, and 2007, respectively. During 2006, the seismicity started a fortnight after 57-mm rainfall on August 3 and largest shock of M_w4 of September 30 occurred 12 days after 59-mm rainfall on August 18. Rise in water table may be following the rainfall in a couple of days only as water table would be close to surface.

6 Modes of post-seismic deformation and possible ways of stress increase

The possible modes of post-seismic deformation and stress perturbation currently invoked are: short-time triggering of earthquakes due to passage of seismic waves (not noticed in Gujarat), the shear deformation as adjustment process (became negligible in the 2001 Bhuj earthquake zone since 2005 (Fig. 13) as deduced from only 2–3 mm/year movements of GPS stations), co-seismic Coulomb stress increase (the NE migration of seismicity to Gedi area which is in the zone of decreased stress (Mandal et al. 2007) and seismicity up to 200 km distance can't be explained by this mechanism). Hence, stress transfer by viscous flow of lower crust and upper mantle both upwards and outwards across a broader region (Freed et al. 2007) which may explain the stress increase and triggering of earthquakes even after some years has been modeled.

6.1 Temporal variation of Coulomb stress

The calculation of Coulomb stress changes is based on the concept of a critical Coulomb failure stress, σ_c , in which

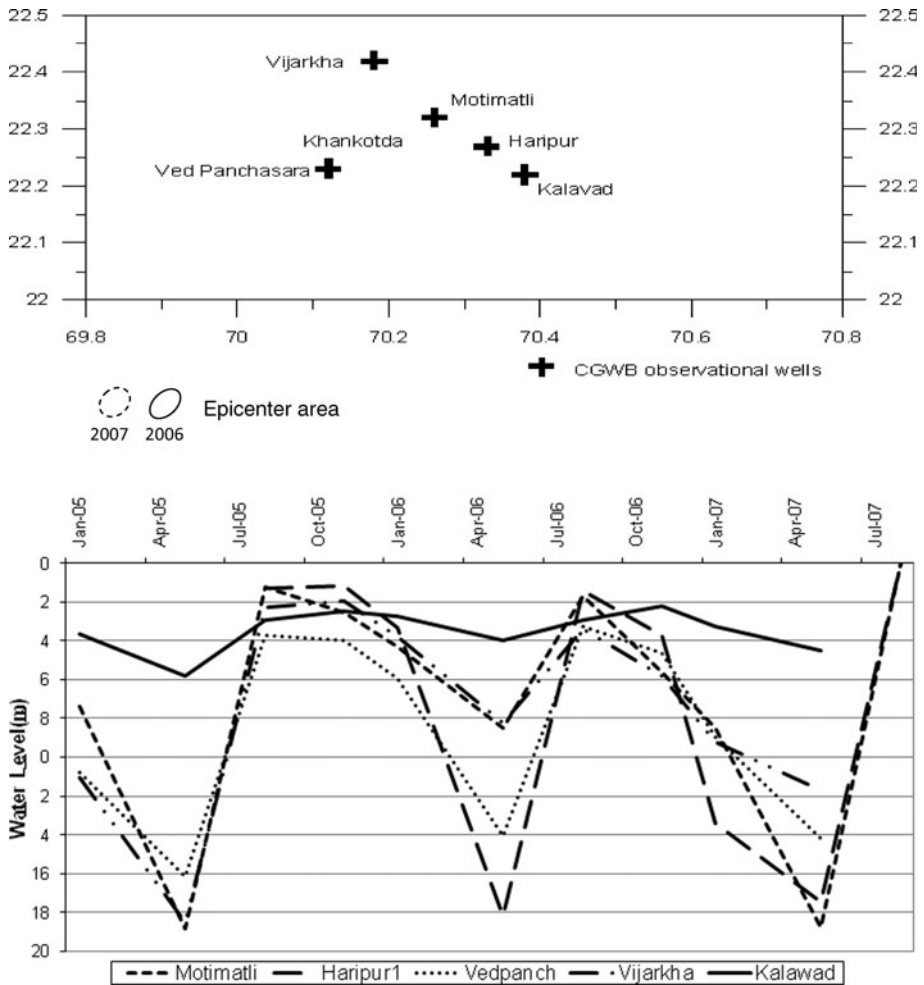


Fig. 12 Location of CGWB wells in and around Khankotda and ground water table levels for period of two and half years during January 2005 to July 2007

$$\sigma_c = \tau - \mu(\sigma_n - p) \tag{1}$$

where τ is shear stress, σ_n is normal stress, p is pore pressure, and μ is the coefficient of friction (Jaeger and Cook 1979; Scholz 2002). As the absolute stress field is difficult to determine, we calculate stress changes over a period of time using the relation

$$\Delta\sigma_c = \Delta\tau - \mu'\Delta\sigma_n \tag{2}$$

where $\Delta\sigma_c$ represents change in stress and μ' is the apparent friction, which takes into account reductions in friction due to the pore pressure changes. A positive Coulomb stress change implies that a fault is brought closer to failure, whereas a negative Coulomb stress change implies that a fault is brought farther away from failure.

Here, we calculate the amount of Coulomb stress present in Kachchh and Saurashtra regions even after some years by considering contribution from post-seismic deformation

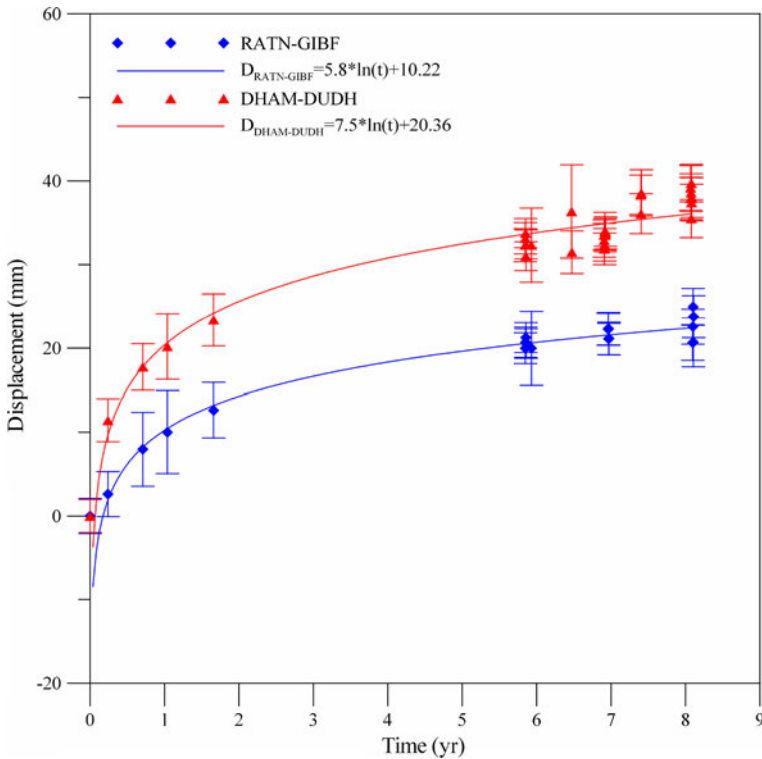


Fig. 13 Composite map of resultant displacement of 2 GPS sites [DHAM-DUDH (*upper curve*) and RATN-GIBF (*lower curve*)] plotted with respect to ISRG from 14 days to 8 years after the 2001 Bhuj earthquake. DHAM and RATN are two GPS stations of Reddy and Sunil 2008 co-located with DUDH and GIBF of ISR stations respectively

since the 2001 Bhuj earthquake. Our objectives were to determine the role of post-seismic mechanism in the evolution of stress since 2001 and to determine how stress at subsequent hypocentres was influenced.

We calculated the post-seismic stress change in the Gujarat region due to the 2001 Bhuj earthquake considering viscoelastic mechanism using EDGRN/EDCMP code developed by Wang et al. (2003), which is based on the representation of a layered spherical earth with elastic–viscoelastic coupling. We adopted the earthquake source parameterization of Yagi and Kikuchi (2001). Strike, dip, rake, and seismic moment are 78° , 58° , 81° , and 2.5×10^{20} Nm, respectively. The model rupture is 75 km long and 35 km deep. The variable slip distribution of Yagi and Kikuchi (2001) was taken to calculate the post-seismic stress transfer. The velocity model of Kachchh was adopted from Mandal and Pujol (2006). Viscosity of lower crust/upper mantle (at a depth ~ 34 km) was taken as 2×10^{19} Pa s (Chandrasekhar et al. 2009).

Figure 14 shows the stress transfer in bars after 6 years of the 2001 Bhuj earthquake. The calculated post-seismic stress changes (+1 bar) following the Bhuj earthquake seem to correlate with the migration of seismicity toward east along the SWF and toward NW in the Banni area. The Gedi area in this model also falls in a zone of stress decrease. Lobe of positive stress change (0.1 bars) is also observed in Jamnagar, Junagadh, and

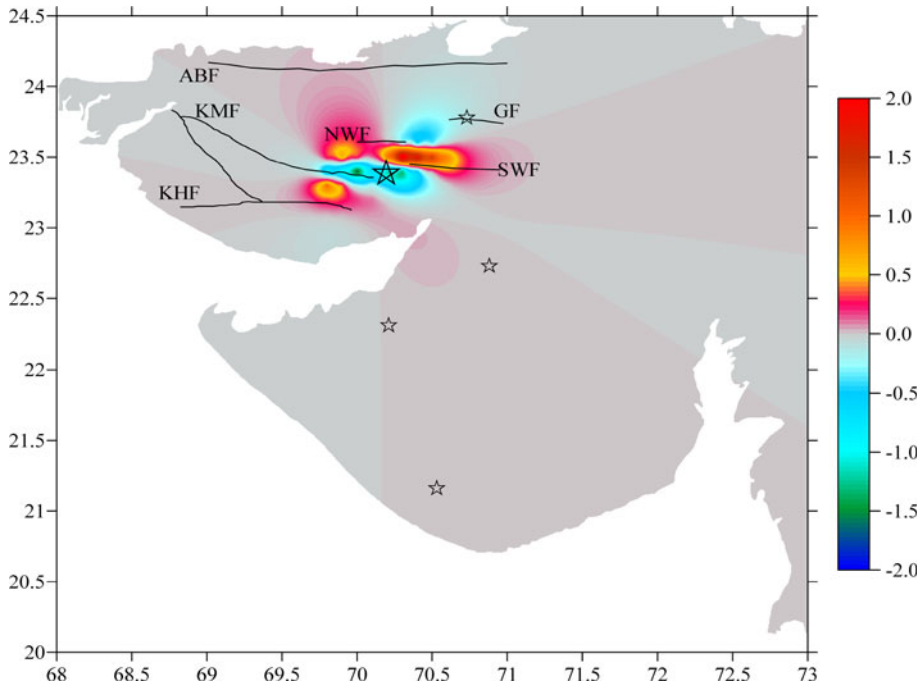


Fig. 14 Post-seismic stress changes (*bars*) after 6 years of the 2001 Bhuj earthquake. A good correlation is observed between the positive stress region (max 1 *bar*) and the migration of seismicity toward east along the SWF and toward NW in the Banni area. Positive stress changes of 0.1 *bar* are also observed in Jamnagar and Surendranagar, while 0.05 *bar* at Talala of Saurashtra. The stars represent the mainshocks of Bhuj M_w 7.7 in 2001, Gedi M_w 5.7 in 2006, Jamnagar M_w 4.0 in 2006, Talala M_w 5.0 in 2007 as well as M_w 5.1 in 2011 and Surendranagar M_w 3.2 in 2008

Surendranagar region of Saurashtra, which may be sufficient for triggering seismicity in those regions. Hence, the viscoelastic process appears to be the plausible mechanism for long distance and delayed triggering of earthquakes by migration of stress pulse generated by the 2001 earthquake with diffusion rates of 5–30 km/year or area growth of 4,000 sq km/year contributing stress vertically upwards from lower crust and upper mantle to distance of 200 km in 6 years. The increased stress in the lower crust or upper mantle appears to be transmitted upwards to near surface depths. It may cause more vertical deformation. Unusually high vertical deformation is detected by GPS to the tune of up to 13 mm/year and by InSAR measurements up to 40 mm/year at several places in Kachchh (ISR annual report 2009; Sreejith et al. 2011).

Post-seismic deformation results in three ways: after-slip of the fault zone, poroelastic rebound, and viscoelastic relaxation of the mantle and lower crust. The shallow afterslip itself (Smith and Wyss 1968) can lead to an increase in stress (Freed 2005). But afterslip may not be the contributor to post-seismic stress transfer in Gujarat region as very negligible (~2–5 mm/year), horizontal deformation is observed through GPS measurements. Poroelastic rebound, which is deformation driven by fluid flow that relieves pressure differences caused by the earthquakes, is generally considered close to the fault and near geometric complexities such as fault stepovers and bends (Freed 2005). However, it appears to act in Gujarat in the same fashion as stress transfer through pore pressure

diffusion invoked for reservoir-triggered seismicity (Talwani et al. 2007). The post-seismic models in which the mantle is linear and viscoelastic predict transient deformations that always extend to great distance, even a long time after earthquake (Savage and Prescott 1978). Hence, both poroelastic and viscoelastic mechanisms may be potentially important to post-seismic deformation in this area.

7 Discussions

Aftershocks of the 2001 earthquake are continuing for over a decade. Post-seismic deformation can be large and long lasting (Wang 2007). For example, the post-seismic deformation for 1964 Alaska earthquake is 15–20 mm/year even after 46 years (Suito and Freymueller 2009).

Besides the aftershocks, seismicity in Gujarat has substantially increased in the first decade of the twenty-first century. The seismicity in Kachchh was found to have been extended first eastward and north-eastward and then in the north along newly activated faults from 2006 to 2008. 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 catalog of last 200 years. The seismicity increased in Saurashtra region also with short or long sequences of earthquakes: during 2001–2007 and through 2011 in Sasan Gir of Talala area of Junagadh district, in 2003 near Sasoi dam area of Jamnagar district, from 2006 through 2010 at Khankotda area of Jamnagar district and several spots like Kalavad, Vijrakhi, and Motikhavadi area south of Jamnagar and Chotila-Sayla area of Surendranagar district, and in 2010 at Advana in Porbandar district to Bhanvad, Sanala, and Jam Jodhpur areas of Jamnagar district forming an E–W trend of about 40 km length. During the earlier 20 decades, only one strong sequence happened in 1938 at Paliyad and two small sequences in 2000 at Una and Bhavnagar. A large number of sequences and several other individual shocks suggest that the seismicity since 2001 in Saurashtra may be affected by the 2001 Bhuj earthquake and same in Kachchh region. The stress increase may be due to viscoelastic process or stress pulse migration due to some other process.

Worldwide, there are many examples to indicate that one earthquake can trigger another by stress transfer. Stress changes in the crust due to an earthquake can hasten the failure of nearby or far faults and induce earthquake sequences in some cases. It has been shown that viscous flow in the lower crust or upper mantle after a moderate or major earthquake can lead to significant increases in stress and strain in the seismogenic upper crust (Freed and Lin 2001; Stein 1999; Harris et al. 1995; Pollitz et al. 2003).

Long-distance and delayed triggering of earthquakes in space or time, or both, is less documented. Some cases are reported: (1) One example of long-distance, short-time triggering is due to 1992 Landers earthquake that triggered earthquakes at remote distances after a few minutes or hours (Hill et al. 1993), (2) example of intermediate-distance, long-time triggering is for inland earthquakes in northern Honshu (Rydelek and Sacks 1990), and (3) an example of short-distance, long-time triggering is of the 1999 Hector Mine $M_w7.1$ earthquake triggered by the 1992 Landers $M_w7.3$ earthquake 20 km away (Freed and Lin 2001; Zeng 2001; Pollitz 2002). Sometimes local process may also cause further increase in stress.

It appears that the stress pulse due to 20 MPa stress drop has migrated via viscoelastic process (rheology change) in lower crust and upper mantle. Unusually, all the surrounding faults of 2001 epicentral zone became activated by 2008. In Saurashtra also, at unusually high number of places swarm type of activity is associated with earthquakes of $M_w3.5-5$.

This is unusual comparing the catalog of last 200 years. Though the stress pulse may propagate horizontally through lower crust and upper mantle, it is transferred vertically to faults near the surface.

Gujarat region seems to be critically stressed as evidenced by the occurrence of earthquakes along several faults. It is well known that the critically stressed faults can be triggered by small stress perturbation. To et al. (2004) estimated that due to the 1819 earthquake, 0.1 bar Coulomb stress increase near the epicenter of the 2001 Bhuj earthquake has influenced the 2001 earthquake. Viscoelastic modeling indicates stress perturbation of up to 1 bar in Kachchh and 0.1 bar in Saurashtra seismic zones. Hence, the sudden appearance of earthquakes along several faults in Kachchh and Saurashtra to 200 km distance from the 2001 Bhuj earthquake epicenter might have been triggered by stress perturbation.

In Saurashtra region, less than 1 bar stress increase due to the 2001 Bhuj earthquake may not be enough and 2–3 bar stress increase due to the rapid rise in water table by 20–30 m then triggers the seismicity soon after monsoons. In the Kachchh region, the stress increase of 1 bar may be enough for the triggering effect.

It has been observed that the changes in Coulomb stress ranging between 0.1 and 1 bar and sometimes even smaller than 0.01 bars can trigger future seismicity (Reasenber and Simpson 1992; King and Cocco 2000; Rajput et al. 2005; Raju et al. 2008), even though these values are much lower than the stress drop in an earthquake (commonly several bars to hundred bars). Triggering does not mean that the coseismic stress changes associated with an earthquake are enough to generate another earthquake at originally stress-free location; it means that the stresses at the location of the ensuing shock are already close enough to failure that the first earthquake can trigger the second one by introducing a positive increase in changes in Coulomb stress such as to move it into the failure regime (Papadimitriou and Sykes 2001; Papadimitriou 2002; Papadimitriou and Karakostas 2003).

Hence, it can be said that the heightened seismicity in Kachchh and Saurashtra during the 1st decade of the twenty-first century is triggered by stress increase due to the 2001 Bhuj earthquake. In Saurashtra, the local stress increase due to water table rise after the monsoons influences the timing.

8 Conclusions

In the first decade of the twenty-first century, unusually several faults in Kachchh and Saurashtra have become active maybe because of stress increase of up to 1 bar due to the 2001 devastating Bhuj earthquake by viscoelastic process. In Saurashtra, 30 m rise in water table during monsoons added additional 3 bars stress probably causing triggering of earthquakes during September to November during several years. The faults in Kachchh are well recognized and have potential of up to $M7$ or more earthquakes. In Saurashtra, the seismicity trends indicate 20- to 40-km-long faults that have potential of $M6$ earthquakes. The activeness of 50- to 100-km-long faults in Kachchh may indicate higher probability of occurrence of $M6-7$ earthquakes along these faults, and activeness of 20- to 40-km-long faults in Saurashtra may indicate higher probability of $M6$ earthquakes along such faults. The faults in Saurashtra are masked due to Deccan Traps or Quaternary cover. However, gravity data indicate the presence of faults. The two prominent trends are NW Proterozoic Aravali trend and ENE Mesozoic Narmada trend.

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