An O-quinone form of estrogen produces free radicals in human breast-cancer cells—correlation with DNA-damage

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Earthquake sequence in and around Bhavnagar, Saurashtra, western India during August–December 2000 and associated tectonic features

S. N. Bhattacharya[1,*], R. V. Karanth[2], R. S. Dattatrayam[3] and P. S. Sohoni[2]

[1]Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur 721 302, India
[2]Department of Geology, Faculty of Science, M.S. University of Baroda, Vadodara 390 019, India
[3]India Meteorological Department, Mausam Bhavan, Lodi Road, New Delhi 110 003, India

An earthquake sequence started in Bhavnagar in eastern Saurashtra on 9 August 2000. Temporary field observatories were established immediately and 132 earthquakes of M (magnitude) 0.5–3.8 were recorded from 9 August 2000 to 15 December 2000. Among these, five earthquakes were of $M \geq 3$, with maximum magnitude of 3.8. The damages were disproportionately high considering the magnitudes of the events. This may be partly explained as due to presence of loose alluvium/poorly consolidated alluvium. Locations of 43 events were obtained from the data collected by the field observatories. The events were confined to an area of 6 km × 4 km, which is located in and around the southeastern part of Bhavnagar town and had focal depths ranging between 1 and 4 km. This earthquake sequence exhibits a doublet pattern (a pair of mainshock–aftershock sequences) with two mainshocks occurring on 10 August 2000 (M : 3.6) and 12 September 2000 (M : 3.8). Successive occurrence of mainshock–aftershock sequences is also known as earthquake swarm of the second kind. Past seismicity of the region shows that the eastern part of Saurashtra is more active than the western part. According to historical records, an earthquake of magnitude 7 occurred near Bhavnagar in February 1705. Earthquake swarm activity also occurred in and around Paliyad (60 km north of Bhavnagar) during July–August 1938 for about two months, with four earthquakes of $M \geq 5$ and maximum magnitude of 6.0. The north-south trending western margin Cambay basin fault passes close to the Bhavnagar area. Further, the east-west trending Shihor fault has offset the western margin Cambay fault near Bhavnagar. The earthquake activity in this area appears to be associated with these two fault systems.

SAURASHTRA region forms a vital geodynamic part of the western continental margin of India, and falls in the seismic zone-III of the Zoning Map of Bureau of Indian Standards. The region as a whole and the area around Bhavnagar in particular has been tectonically unstable, as revealed by the earthquakes that have taken place in the

*For correspondence. (e-mail: snb@gg.iitkgp.ernet.in)

region in the recent and historic past. Some of these earthquakes have been large enough to cause concern as far as damage to life and property is concerned. Although the region is identified as relatively low-risk seismic zone compared to Kachchh (zone-V) and the Himalayan region (zone-IV and zone-V), it poses a question as to whether it has a potential to produce earthquakes of large magnitudes.

Several places in Saurashtra region, for example, Junagadh, Dwarka, Rajkot, Paliyad, Ghogha and Bhavnagar have the history of recurring earthquake activity. This communication presents the type and nature of earthquake activity around Bhavnagar during August–December 2000 and its probable relationship with the existing structural/tectonic trends.

Understanding the tectono-structural aspects of a region not only furnishes a proper way to study the present-day deformational movements/seismotectonic status, but also plays a vital role in planning and decision making in the event of a major earthquake such as the 26 January 2001 Bhuj (Kachchh) earthquake.

Saurashtra region is bound by N–S trending Cambay basin in the east, the extension of Narmada geofracture in the south, Kachchh rift to the north and the major WNW–ESE fault which is an extension of the west coast fault system in the Arabian Sea in the west. According to Biswas[1,2] and Merh[3], the Aravalli trend in the SW portion of the region splays out into three components. The main NE–SW trend continues across the Cambay graben into Saurashtra as a southwesterly plunging arch. From the DSS study along Navibunder–Amreli profile, Kaila *et al.*[4] delineated basement fault near Mahiary with down throw towards west. Biswas and Deshpande[5] consider the Saurashtra region as a horst surrounded by rift grabens and demonstrate that central, southern and northern Saurashtra exhibit distinct volcano-tectonic characteristics. On the eastern side of Saurashtra, a sharp contact of alluvium with basalt is observed in the N–S direction, extending from the west of Nal Sarovar to Bhavnagar. This appears to be a faulted contact[6]. The E–W trending fault just south of Bhavnagar marks the boundary between considerably thick alluvium in the north and Deccan traps to the south. Basalts to the south of this fault dip northward at an angle between 25 and 40°.

A major portion of Saurashtra region is covered by the Deccan volcanics (Figure 1 *a*). The traps overlie the gently warped Mesozoic sequence in the NW parts[7]. Along the coast from Dwarka to Bhavnagar, the volcanics are seen overlain by Cenozoic sediments at many places. All these rocks are covered either by alluvium or by Quaternary miliolite limestone[3].

Apart from various studies on a regional scale, quite a few workers have attempted to look into the local structure and tectonics[8–10]. The lineament map (Figure 1 *b*) of the region shows several structural trends, i.e. E–W, NNE–SSW, N–S and NW–SE. However, the E–W trending structural trend seems to be more prominent. Karanth and Sant[9] gave a detailed account of post-trappean intrusives of plugs and dykes swarms as well as faults and other lineaments in the region (Figure 2). Just north of Bhavnagar, they have identified an E–W trending Shihor fault, which offsets N–S trending western Cambay rift fault.

There have been a number of earthquakes in the recent and historic past in the Saurashtra region (Table 1 and Figure 2). The most interesting being an event of February 1705, with an intensity nearly as high as XI (MMI) near Ghogha[11]. However, no records of damage to life and property are available. This event in a way brings out an important question as to whether the area around Bhavnagar is capable of producing an earthquake of magnitude 7. In addition, Figure 2 shows that there are three earthquakes of different magnitudes in and around Bhavnagar. In July 1938, the area around Paliyad (60 km north of Bhavnagar) witnessed an earthquake swarm, which is considered significant due to its continuation for about two months[12,13]. The swarm includes four shocks of magnitude 5 or more, with the largest event being of magnitude 6.0. Figure 2 shows that this earthquake sequence is related to west Cambay rift fault. Another event that solicits

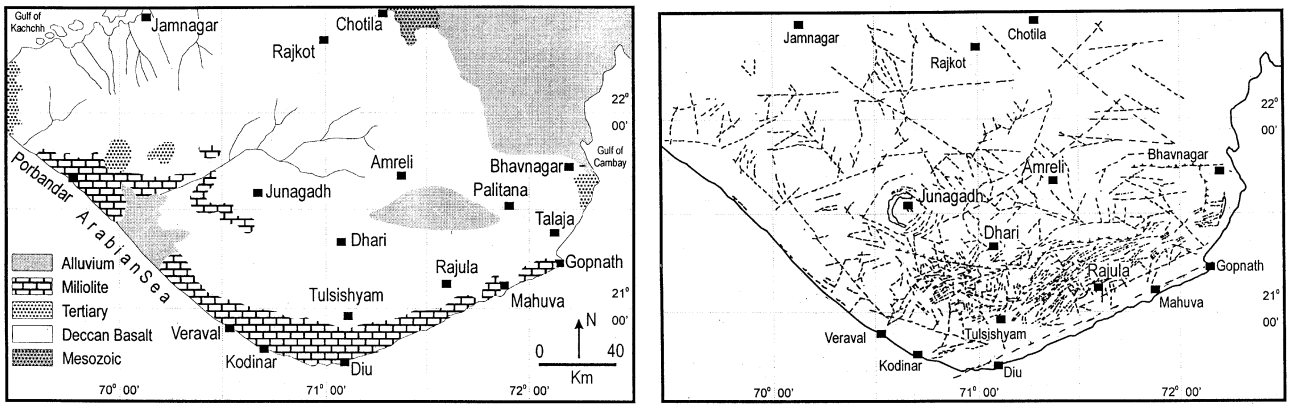

Figure 1. Geology (***a***) map lineaments and (***b***) of Saurashtra.

Table 1. Past earthquakes of magnitude 4 and above in Saurashtra and its neighbourhood (between lat 20.5° and 22.5°N, long 69.5° and 72.5°E)

Year	Month	Date	Lat (°N)	Long (°E)	Intensity (MM)	Magnitude	Source	Nearby place
1705	February	–	22.7	72.3	XI	7.0	KP	Ghogha
1872	April	14	21.76	72.23	VI	5.0	UMC, GB	Bhavnagar
1919	April	21	22.0	72.0	VIII	6.2	UMC, GB, TAN	Bhabnagar
1922	March	13	22.0	71.0	V	4.3	UMC, GB, TAN	Patdi, Jhalawad, Rajkot
1938	July	12	22.4	71.8	VI+	5.5	SR	Paliyad
1938	July	14	22.4	71.8	VI	5.0	GB	Paliyad
1938	July	19	22.4	71.8	VI+	5.3	TAN, UMC, GB	Paliyad
1938	July	23	22.4	71.8	VII	6.0	TAN, UMC, GB	Paliyad
1940	October	31	22.5	70.4	VII	6.0	TAN, UMC, GB	Saurashtra
1985	September	03	21.63	70.88		4.3	GERI	Visavadar
1993	August	24	20.90	71.50		5.2	GERI	Off coast of Rajula
1993	December	31	20.53	71.17		4.0	GERI	Off coast of Rajula
1998	July	19	22.42	70.86		4.4	IMD	Rajkot
2000	August	13	21.03	70.94		4.5	IMD	Girnar Hills

KP, Kapoor[11]; UMC, Chandra[16]; GB, Guha and Basu[17]; TAN, Tandon[13]; SR, Srivastava and Rao[12]; IMD, India Meteorological Department; GERI, Gujarat Engineering Research Institute.

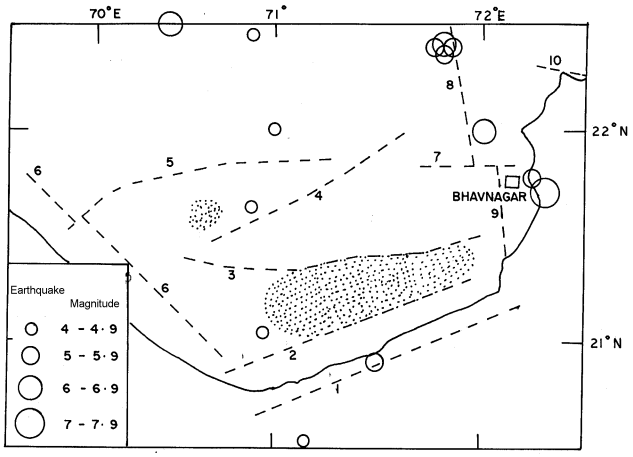

Figure 2. Location of past earthquakes of magnitude 4 and above. Dotted areas are dyke zones of swarms. Faults are shown by dashed lines. 1, South Saurashtra fault; 2, Rajula fault; 3, Saverkindala fault; 4, South Junagadh fault; 5, North Junagadh fault; 6, Umrethi fault; 7, Shihor fault; 8, West Cambay basin fault; 9, Eastward offsetted West Cambay basin fault, and 10, Camay–Dabhoi fault.

Table 2. Location of field observatories

Station	Code	Lat	Long
Bhavnagar	BHV	21°45.00′N	72°08.37′E
Sidsar	SDR	21°42.80′N	72°06.98′E
Malanka	ML1	21°43.67′N	72°10.48′E
	ML2	21°43.35′N	72°10.59′E

attention is the one that took place on 31 October 1940, which was felt in Dwarka. Along with this a few more events of magnitude 4 and above have been reported from Rajula and Rajkot.

The present activity commenced with the occurrence of an earthquake of magnitude 2.5 on 9 August 2000. This was followed by a main earthquake of magnitude 3.6 on 10 August 2000 and its aftershocks. These events created a lot of panic amongst the local population. The India Meteorological Department (IMD) immediately established a network of three observatories with high-gain short-period portable seismographs on 14 August 2000, to closely monitor the activity. The observatories were located at (i) Circuit House, Bhavnagar town (BHV), (ii) Sidsar village (SDR) and (iii) Malanka village (ML1, ML2). At Malanka, the initial location (ML1) was shifted to a better place (ML2) on 16 September 2000. Locations of the observatories are given in Table 2 and shown in Figure 3. A few important locations and observatories operated by the National Geophysical Research Institute (NGRI) are also shown in Figure 3.

The number of earthquakes on each day from 9 August to 15 December 2000 is shown in Figure 4. The maximum magnitude on each day, if it is 3 or more, is also shown. This episode of earthquake activity, reduced by the end of August, appears to follow a foreshock–mainshock–aftershock pattern with maximum magnitude of aftershock as 3.1, which is only 0.5 units less in magnitude relative to the mainshock. There was only one foreshock which occurred a day earlier to the mainshock of 10 August. The activity resurfaced with the occurrence of another mainshock of magnitude 3.8 on 12 September 2000. Significant aftershock activity continued till the end of September. However, a low level activity continued till 12 December. The maximum magnitude of this group of aftershocks is also 3.1.

Locations of many of these earthquakes were obtained using the data from local field observatories. Epicentres of 43 earthquakes occurring between 13 September 2000 and 23 November 2000 are shown in Figure 3. It may be seen that the activity is confined to an area of 6 km × 4 km from Bhavnagar Circuit House to Kalia Beet (21°44.36′N, 72°08.62′E) and further to southeast of

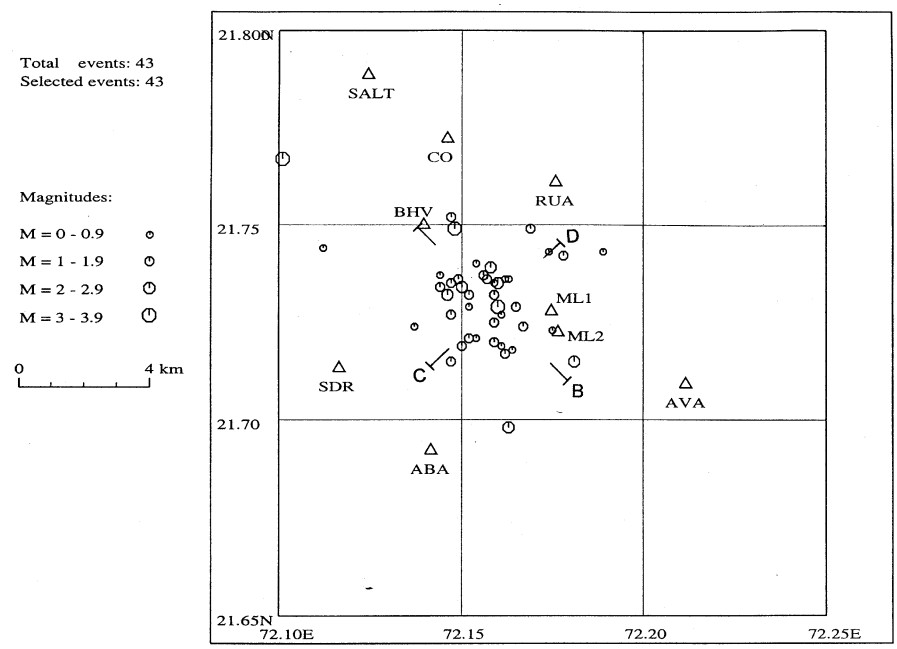

Figure 3. Location of field observatories. IMD observatories are BHV, SDR and ML1 and ML2 (Table 2). NGRI observatories are SALT, AVA, RUA, ABA. CO, Collector's Office. Epicentres occurring between 13 September 2000 and 23 November 2000 have also been shown. Vertical cross-sections of hypocentres along BHV to B and along C to D are shown in Figure 5 *a* and *b* respectively.

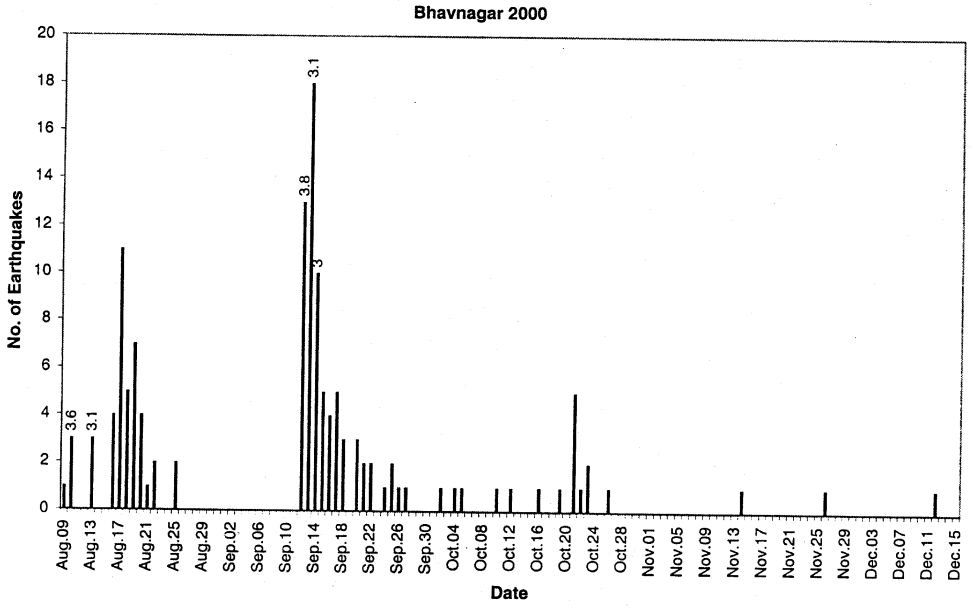

Figure 4. Number of earthquakes on each day from 9 August 2000 to 15 December 2000. Maximum magnitude (above 3) on each day is also shown at the top of the bar.

Bhavnagar town. Vertical cross-sections of hypocentres are drawn for those 36 earthquakes whose focal depths could be obtained precisely. Figure 5 *a* is the vertical cross-section of events from Bhavnagar Circuit House (BHV) towards SE direction, while Figure 5 *b* is the cross-section in the direction perpendicular to it along NE–SW direction. The focal depths of these events are seen to be lying between 1 and 4 km.

The recent activity in Bhavnagar not only caused a lot of panic amongst the people, but also caused appreciable damage in and around Bhavnagar. At quite a few locations, ground cracks were also reported. Most of the affected

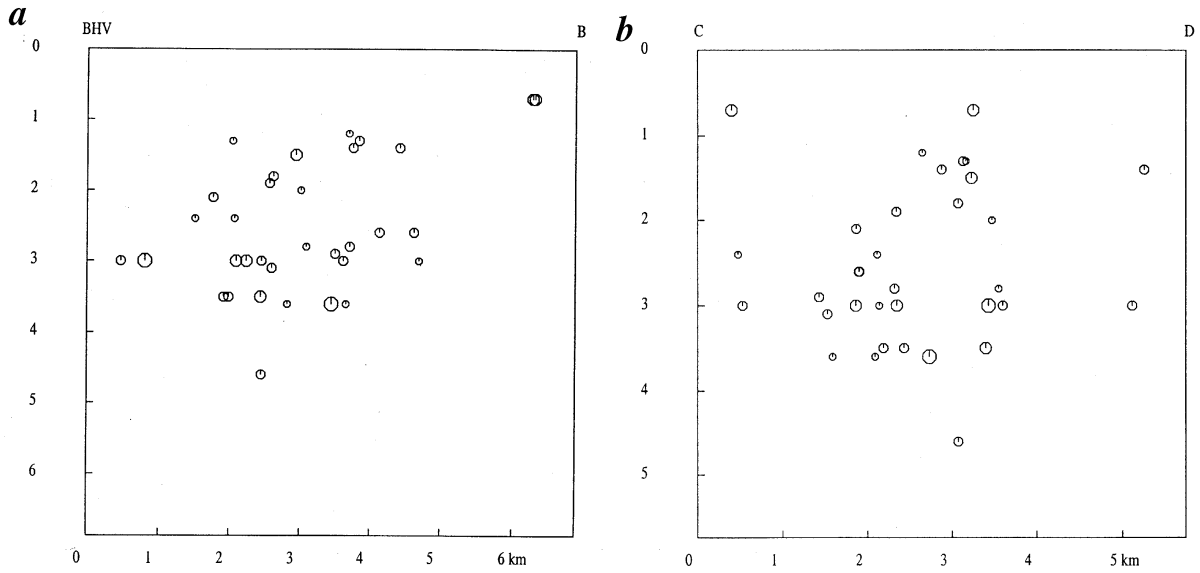

Figure 5. Vertical cross-sections (***a***) along NW–SE profile from Bhavnagar Circuit House (BHV) to B (Figure 3) and (***b***) along NE–SW profile from C to D (Figure 3).

places are located in the SE part of Bhavnagar town (e.g. Bharatnagar, Gayatrinagar). In Gayatrinagar area, E–W trending ground cracks were observed and houses lying along this line were damaged. Near Bharatnagar also, an E–W trending ground crack was noticed and considerable damage was caused to houses made by a local Housing Board. According to local residents, about 90 houses suffered damage. It was seen that most of the damage done in this area is because of the poor construction. The Circuit House at Bhavnagar town also developed several cracks in the walls.

Apart from these, some of the villages located in the southeastern part of Bhavnagar town (e.g. Tarshamia and Malanka) also experienced ground cracking and damage to houses. Malanka village sustained N–S trending ground cracks in at least two places. In one of these locations, the ground crack was seen to extend up to a distance of 150 m. Here, two parallel cracks were noticed with a spacing of about 70 cm. In some of these places, a hollow space was also created in the ground. Tarshamia village on the outskirts of the Bhavnagar town, sustained cracks in the kuchha houses. The damage caused by such low magnitude earthquakes ($M \leq 3.8$) appears to be disproportionately high considering the magnitudes of the events. This may partly be explained as due to the presence of loose alluvium/poorly consolidated alluvium.

The recent seismic activity in Saurashtra region, particularly in the area around Bhavnagar indicates that the region is under the influence of active tectonic processes. Some of the faults may be active and seismogenic in nature. The area around Bhavnagar is traversed by two major faults (Figure 2): (a) the western margin Cambay basin fault, (b) the E–W-oriented Shihor fault that has offset the western margin Cambay basin fault. As far as the present study is concerned, these two faults are important. Both N–S and E–W structural elements demarcate the contact between the basalts and the younger alluvium. Although not much data are available on these faults, Karanth and Sant[9] and Prasad *et al.*[6] suggest a down throw of block to the south of Bhavnagar, which has been gradually filled by the alluvium. The Shihor fault may have been activated during Quaternary and experienced a slip.

The present seismic activity consists of two episodes with the mainshocks on 10 August 2000 (M: 3.6) and on 12 September 2000 (M: 3.8). These two mainshocks may be considered as doublets. The first one was preceded by a foreshock only a day in advance. Similar doublets (with a gap of approximately one month between the two mainshocks) were seen in the case of Erratupetta (Kerala) earthquake sequence[14] during December 2000–January 2001. Successive occurrence of mainshock–aftershock sequences is also known as earthquake swarm of the second kind[15]. The hypocentre locations (Figures 3 and 5) show that the present activity is confined to a small area of 6 km × 4 km from Kalia Beet in Bhavnagar town towards southeast. The present activity lies in the vicinity of the contact between the trap and the alluvium. Two villages, i.e. Tarshamia and Malanka, which experienced most of the tremors, fall closely in line with E–W trending Shihor fault traversing from Damnagar in the west towards Ghogha in the east. In all probability, the epicentre of February 1705 Ghogha earthquake also falls in line with the Shihor fault. Detailed geological, geophysical and palaeoseismo-

logical studies on the Shihor fault and adjoining west Cambay rift fault are expected to throw more light on the ongoing tectonic processes in the region in particular and Saurashtra in general.

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