# Changes in stress pattern around epicentral region of Bhuj earthquake of 26 January 2001

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[1] The 26 January 2001 Bhuj earthquake (Mw 7.6) was one of the deadly Indian earthquakes that took about 20,000 lives. The region was seismically quite in the last 50 years. In the present paper, we have made efforts to understand the general nature of stress field and also spatial and temporal stress field around Bhuj prior and after the earthquake by analyzing lineaments extracted from remote sensing data. Our results demonstrate N to NE orientation of stress showing a high level of correlation between the $S_{Hmax}$ deduced from the lineament and earthquake focal mechanism. The present results show the use of lineaments derived from remote sensing data in the evaluation of seismic hazards of any region and will be useful in updating world stress map. **Citation:** Singh, V. P., and R. P. Singh (2005), Changes in stress pattern around epicentral region of Bhuj earthquake of 26 January 2001, *Geophys. Res. Lett.*, *32*, L24309, doi:10.1029/2005GL023912.

## 1. Introduction

[2] The 26 January 2001 Bhuj earthquake (Mw = 7.6) occurred in a tectonically active region (Figure 1), where already few large historical earthquakes namely the 1819 Allahbund (Dam of God) (Mw = 7.8) and 1956 Anjar earthquake (Mw = 6.0) have occurred. The Bhuj earthquake was shallow (depth = 18 km) and no prominent surface rupture was seen along any fault. The absence of primary surface rupture implies, movement along a blind fault that has been accompanied by wide spread liquefaction. Aerial and field surveys reported soil liquefaction and associated phenomena in the Great Rann, Little Rann, Banni Plains, Kandla River and Gulf of Kuchchh [*Hengesh and Lettis*, 2001]. Although the damage was extended up to 400 km from the epicenter, and liquefaction and cracks were observed in a very large region but all these efforts were concentrated around the epicenter.

[3] An effective understanding of seismicity requires good knowledge of the nature and distribution of contemporary stress field in the lithosphere. For evaluating the intense shaking damage and understanding of the regional tectonics, it is necessary to know the spatial variations of stress field and also the change of stress direction and magnitude after the earthquake. The static stress change was discussed by *Negishi et al.* [2002], here Efforts have been made to utilize remote sensing data to understand the change in stress field associated with the Bhuj earthquake. The present results demonstrate the nature of stress field and also spatial and temporal stress pattern around Bhuj prior and after the earthquake using remote sensing data.

## 2. Geology and Geomorphology of Bhuj

[4] The Bhuj earthquake occurred in the Kuchchh peninsula, the north and south boundary of the region is bordered by rift system [*Biswas*, 1987]. It is bounded by Nagar Parkar faults in north, Kathiwar Fault in south and north trending Cambay basin in east. Shallow seismic survey in Gulf of Kuchchh has revealed E–W trending offshore basin parallel to the southern boundary of the Kuchchh rift basin. Due to ongoing collision of the Indian and the Asian plate, the structures within these rift systems and on the Kuchchh mainland are subjected to compressional stress and reverse faulting [*Malik et al.*, 2001]. The landscape of Kuchchh shows a complex structural pattern marked by uplift on E–W trending faults namely Katrol Hill, Kuchchh Mainland, Banni, Island belt and Allah Bund, and low lying residual depression in great Rann-Banni plains [*Biswas*, 1987]. The coastal zone of Gulf of Kuchchh is alluvial covered, Kuchchh Mainland forming the central zone of rocky mainland, Banni-plains and Great Rann is also alluvial covered with saline-waste land.

## 3. Microseismicity and Fault Plane Solution of Bhuj Earthquake

[5] The earthquake of 26 January 2001 was thought to occur on one of the marked active faults, the focal mechanism show thrust faulting on E–W trending faults. Microseismic surveys were carried out by a joint Japanese - IIT Kanpur [*Negishi et al.*, 2002]. Aftershocks data have shown two major trends in NE and NW directions [*Kayal et al.*, 2002; *Bodin and Horton*, 2004] (Figure 2b). The fault plane solutions of observed NE aftershock trends show reverse faulting with a large left-lateral strike-slip motion which are also comparable to main shock. On the other hand, the fault plane solution of NW trending very shallow aftershocks (depth <10 km) shows reverse faulting with right-lateral strike-slip motion, whereas the mid–crustal earthquake shows pure reverse faulting [*Kayal et al.*, 2002]. The aftershock covers an area of about 40 * 40 $km^2$ which is very small for such a large magnitude earthquake and results in a high static stress drop of 13 to 25 MPa, this suggests possibility of another big earthquake in this region [*Negishi et al.*, 2001, 2002]. Tomographic study using microseismic data gives an evidence of fluids at the hypo-

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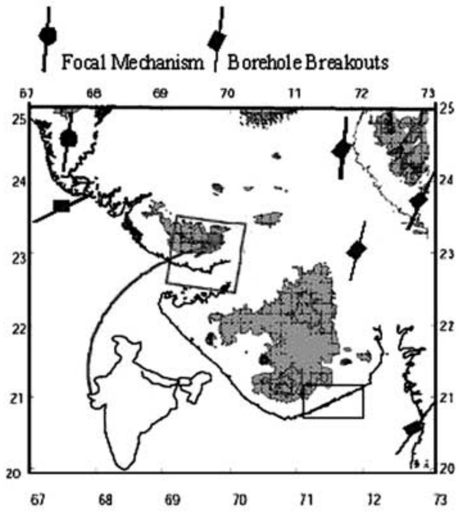


**Figure 1.** The regional stress direction (NE to NNE) determined by focal mechanism and borehole breakouts [*Gowd et al.*, 1992]. The study area shown by quadrangle. Rectangle shows a southeastern Saurashtra coastal region where neotectonic joint were analyzed for measuring stress orientation [*Khadkikar*, 2002]. The star shows epicenter of earthquake of 26 January 2001. See color version of this figure in the HTML.

center and its implications for rupture nucleation [*Kayal et al.*, 2002].

## 4. Lineament Study

[6] Lineaments represent a regional scale linear or curvilinear feature, pattern or change of pattern on the surface that represent tectonic structures that are identified in remote sensing images. The connection between joints and contemporary tectonic stress field has been established recently [*Khadkikar*, 2002]. Because of strong ground shaking, the Bhuj earthquake produces large surface deformations that can be easily mapped using remote sensing data. Recently, *Gahalaut and Burgmann* [2004] have used satellite images to map the changes in flooding pattern after the earthquake. Using optical and microwave remote sensing data, the surface manifestations, soil moisture, ocean and atmospheric parameters prior and after the Bhuj earthquake have been studied [*Singh et al.*, 2001, 2002; *Singh and Ouzounov*, 2003]. Here, we have analyzed Indian Remote Sensing (IRS-1D) LISS – III data and have studied the changes in stress direction after the main earthquake event. The date of pre earthquake image is 4 January 2001 and post earthquake image is 29 January 2001. The IRS – 1 D LISS – III data is available in four bands in the wavelength range visible to near infrared (0.52–0.59 $\mu$m, 0.62–0.68 $\mu$m, 0.77–0.86 $\mu$m) and in short wave infrared (1.55–1.7 $\mu$m). The spatial resolution in visible to near infrared (VNIR) is 23.6 meter and in short wave infrared (SWIR) is 70.8 meter. Due to high cost of the data, one scene which covers an area of 165 km $\times$ 140 km (covering epicentral region) is purchased from the National Remote Sensing Agency, Hyderabad, India. The whole scene was divided into 36 windows of size 25 $\times$ 25 km and a low pass filter of size 3 $\times$ 3 was applied for the image smoothing. The linear features were extracted using high pass filter (Sobel filter in all direction) of size 25 $\times$ 25. The tectonic lineaments were identified and extracted by using ground information, maps and toposheets.

[7] Major faults and lineaments have been identified by visual interpretation of standard FCC (False Color Composite) image. Visual interpretation has been carried out based on lithological dislocation, joint and fracture traces, truncation of outcrop, alignment of stream, sudden bending of stream etc. Usually the edge reflects the micro-lineament patterns of the area which were mapped by screen digitization of the edges with the help of toposheets of the area. During the digitization process, efforts were made to avoid the artificial linear features like road network, railway tracks, canal etc. The coordinate of each lineament extracted and slope of the lineaments were calculated. The mean values of rose diagrams were plotted for each window.

[8] The orientations of lineaments are primarily controlled by the direction of the principle stress, the lineaments and the orientation of stress mapping is discussed in detail by *Sahoo et al.* [2000] and has been used by *Dash et al.* [2000]. Based on Mohr's theory of failure, the angle between the failure plane and $\sigma_1$ direction is given as $\Phi = 45^\circ - \phi/2$, where $\Phi$ is the angle between the failure plane and $\sigma_1$ direction, and angle $\phi$ is internal friction angle. The lineament and faults represent slip faces, which have been considered as a result of continued horizontal maximum compressive stress ($S_{Hmax}$) due to the Indian plate movement. The direction of stress acted on each elements of failure has been estimated using equation $\Phi = 45^\circ - \phi/2$. Stress direction has been estimated from lineament pattern using the standard value of $\phi$ of the rocks present in this area. The value of $\phi$ typically varies between 25°–35°. In the alluvial covered region like Southern coastal zone, Banni-plains and Rann of Kuchchh, the value of $\phi$ is taken as 35° and for Kuchchh Mainland forming the central zone of rocky mainland as 30°. The orientation of stress acting on each lineament with respect to north has been calculated and plotted on the image. The mean stress value of each rose diagram is shown on the respective image (Figures 2a and 2b).

## 5. Results and Discussion

[9] The record of earthquakes and the surface expression of rock structure suggest that a significant amount of horizontal shortening, accommodated by the formation of E–W trending folds and slip on east-west striking thrust faults, has occurred in the interior of the Indian plate [*Malik et al.*, 2001]. The absence of coseismic rupture in Bhuj 2001, earthquake suggests a movement along a blind fault. Therefore a detailed field survey of cracks, mud volcanoes, structural damages etc were carried out. The surface deformations were attributed to shaking effects. The major crack observed in the epicentral region were striking E–W are composed of normal faults down thrown to north, and associated with the rotated blocks result in series of half graben structure under extensional regime and E–W extending major cracks and linear bulge are almost parallel to each other and minor en-echelon cracks trending NW–SE oblique to the major ones are convex to down slope.

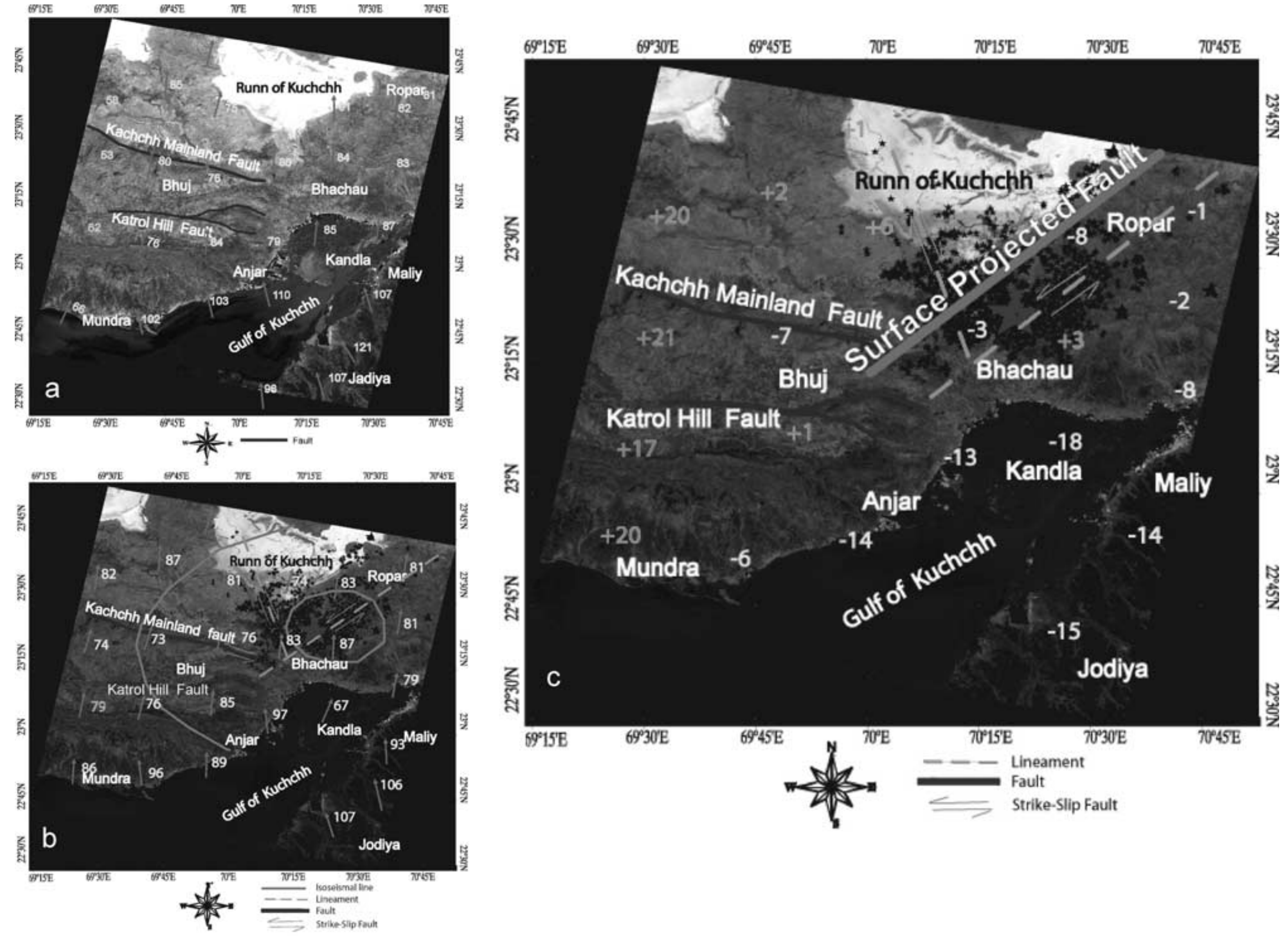


**Figure 2.** (a) Pre earthquake (4 January 2001) average stress field map. The pink arrows are the orientation of stress (NNE to NNW). The red star is epicenter of 2001 Bhuj earthquake. Along Mundra, Anjar and Bhachau stress direction is almost perpendicular to the continent boundary. (b) Post earthquake (29 January 2001) stress field map. The pink arrows are the orientation of stress. The black star is the epicenter of micro-earthquakes recorded in Bhuj earthquake during 2 February to 6 March 2001 [*Negishi et al.*, 2002]. The two active lineaments are shown by sky blue line. (c) The fault plane of main earthquake event dips toward the south about 50°. The fault strike is E to NE. If the fault is extended on the surface, it will intersect on the ground surface near the southern edge of Runn of Kuchchh (green line) [*Negishi et al.*, 2002]. The value shows the rotational anomaly (Post-Pre). See color version of this figure in the HTML.

[10] The lineaments measured on pre earthquake image give an impression about the average stress field that developed during the past and the change in the lineaments after the earthquake is attributed to the changes in surface features associated with the earthquake. The regional stress field direction is mostly N–S to NE–SW, determined by borehole breakouts and earthquake focal mechanisms (Figure 1) [*Gowd et al.*, 1992]. The stress direction established by lineament analysis (Figure 2a) are N–S to NE–SW, they are well correlated with the borehole breakout and focal mechanism solution (Figure 1).

[11] The pre earthquake image (Figure 2a) shows a systematic variation of stress field along the Gulf coast. The stress direction in Figure 2a (west to east, along the Gulf coast of Kuchchh) varies from NNE–SSW to NNW–SSE, almost normal to the coastal boundary. The stress directions along the Kuchchh coastal boundary always remains normal to the boundary, direction of boundary change near Mundra, and here the stress direction also changes its direction suddenly from NNW to NNE, and thus $S_{Hmax}$ always remains normal all along the boundary. The tectonic stress field in southeastern coastal Saurashtra (Figure 1) also demonstrate the stress direction normal to the coastal boundary [*Khadkikar*, 2002]. Similar results were also obtained by focal mechanism analysis of Vanuatu subducting slab where maximum compression always remains normal to the slab although the slab strike varies over 70° [*Christova and Scholz*, 2003]. These results suggest that stress guidance hypothesis [*Isacks and Molnar*, 1971] is not only valid in subduction zone but it also seems to be true for the Kuchchh shield region. The stress field is uniform along the boundary. The intercontinental thrusting and shearing along the northwestern boundary seems to play an important role.

[12] The lineaments observed from the post earthquake image predominantly reflects the changes in stress field after the Bhuj earthquake on 26 January 2001. The region lying on right side from the epicenter shows little change as

compared to the left side which is attributed to the tectonic settings of the region. Almost all the active faults are located in the left region (Figure 2b). The most recent stress fields that developed during 2001 earthquake (Figure 2b), is significantly different from the past average stress field (Figure 2a). The difference of stress field is shown in Figure 2c. Significant changes in stress field are observed along the coastal region of Gulf of Kuchchh, and above the Kuchchh mainland fault (Figure 2c). Prior to the earthquake, stress direction was normal to the coastal boundary along the coast of Gulf of Kuchchh, after the earthquake stress direction changed in clockwise direction (Figure 2c).

[13] Aftershocks locations along with the mainshock focal mechanism indicate a reverse fault with a large left-lateral strike slip motion, with strike NE and dip around 50° [*Kayal et al.*, 2002]. If this subsurface fault plane is extended to the surface, it will intersect the ground surface near the southern edge of Runn of Kuchchh (Figure 2c, green line), west to the city of Ropar [*Negishi et al.*, 2002]. On the northern side of the fault plane (green solid line), the change in $S_{Hmax}$ is found to be positive and in the southern side of the fault line the change in $S_{Hmax}$ is found to be negative. The changes are likely due to because of left-lateral strike component of motion. The changes of stress direction observed in the present study support the visco-elastic finite element model which indicates that the inter-continental thrusting and shearing along the northwestern boundary may have caused deviatoric stress to broadly diffuse into the Indian continent.

[14] The analysis of local variations of stress field is not possible by earthquake focal mechanism because of unavailability of seismicity at every place and it is also very expensive by borehole breakouts. The similarity in the orientation of $S_{Hmax}$ as inferred from the lineament and regional stress direction highlights the utility of lineament for the analysis of change in stress direction $S_{Hmax}$, and also provides an understanding of regional tectonic. Generally, the direction of fluid flow is also controlled $S_{Hmax}$ which is usually parallel to the $S_{Hmax}$ [*Lynn*, 2004], this regional and local stress variations are considered as an important input in petroleum reservoir modeling.

## 6. Conclusions

[15] The present results confirm that the lineaments are related to fractures and faults and their orientation and density give an idea about the fracture pattern of rocks. Our results show a high level of correlation between the $S_{Hmax}$ deduced from the lineament and earthquake focal mechanism. The stress directions are always normal to the boundary, which suggests that the stress guide hypothesis is not only valid in subduction zone but also seems to be true for the shield region. The intercontinental thrusting and shearing along the northwestern boundary seems to play an important role in the Bhuj earthquake. Future study of lineaments throughout the world may yield further data on $S_{Hmax}$ orientation and add to the existing World Stress Map [*Zoback*, 1992]. The present paper shows the utility of remote sensing data in the evaluation of seismicity of the region and also providing the local and regional state of stress field.

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