Interpretation of post-geodetic and seismic data of the 2001 Bhuj earthquake, M_w 7.7

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A devastating earthquake (M_w 7.7) struck Bhuj area, Gujarat, western India on 26 January 2001. Using Global Positioning System (GPS) data that were collected over three years (2001–03), displacement vectors in the Bhuj region were estimated. The local horizontal displacement vectors represent a general southwestward movement and the regional horizontal displacement vectors were in the northeast direction, parallel to the NE–SW trending major lineament and the major axis of the isoseismal of the 2001 earthquake. This observation is in conformity with the reverse faulting of the main shock and aftershocks due to the dominant compressional stress of the NNE-ward movement of the Indian plate. Some anomalous displacement vectors during the GPS epoch 2002–03 could be the result of a rebound of the southern block subsequent to the earthquake.

Keywords: GPS, displacement vectors, focal mechanism, seismic data.

THE Bhuj earthquake occurred on Republic Day, i.e. 26 January 2001, in the middle of the Kutch rift basin (Figure 1), a seismically active region that falls in Zone V in the seismic zoning map of India. The moment magnitude M_w 7.7 was estimated with focal depth at 25 km, and a reverse fault-plane solution was obtained; the maximum intensity reached X in the MSK scale[1] (Figure 1). This was one of the largest intraplate earthquakes in the world and has been compared with that of the 1811–12 New Madrid earthquake M_w 7.8 in central United States[2]. A detailed study of the 2001 Bhuj earthquake and its aftershocks was given by Kayal *et al.*[3] and Mandal *et al.*[4]. Among the past significant earthquakes in the region, the largest event was the 16 June 1819 Kutch earthquake (M_w 7.8)[5] which occurred at the northern boundary of the basin (Figure 1). The other significant event, the Anjar earthquake (M_s 6.1), occurred on 21 July 1956, close to the epicentre of the 2001 devastating Bhuj earthquake (Figure 1). Chung and Gao[6] studied the source mechanism of the 1956 event using the teleseismic long period *P*- and *SH*-waveforms. A reverse fault mechanism was suggested, which is comparable with that of the 2001 Bhuj earthquake (Figure 1). The maximum intensity of the 1956 event was reported to be IX (MM scale)[7]. The major axis of the elliptical isoseismals was in the NE–SW direction, similar to that of the Bhuj 2001 earthquake.

Campaign-mode GPS surveys were carried out by the Indian Institute of Technology, Bombay (IITB) during three years 2001–03, after the 2001 Bhuj earthquake to study the post-earthquake crustal deformation/adjustment in the area. Results of this survey are highlighted here.

The Kutch Rift Basin (KRB) in the present study area is distinguished by EW-oriented highlands (uplifts) and low-lying basins or 'Ranns' ('Ranns' mean uninhabited salt flats that are neither sea nor land, and are flooded periodically). A number of E–W faults control the structural trend of the Kutch rift. These are: the Nagar Parkar Fault (NPF), the Allah Bund Fault, the Island Belt Fault (IBF), the Kutch Mainland Fault (KMF) and the North Kathiwar Fault (NKF; Figure 1). The NPF is the northern boundary and NKF the southern boundary fault of the KRB. The basin is filled with sediments ranging in age from middle Jurassic to Tertiary. The Deccan trap lavas, late Cretaceous to early Paleocene, divide the Mesozoic and Tertiary stratigraphy of the Kutch basin. After the initial period of extension[8], the KRB has been subjected to N–S compression by the resultant back push of the Himalaya at least since 20 ma. The structure of the basin is styled by a series of uplifts, master faults and upthrusts[9]. Uplifts are the results of differential movements of discrete basement blocks due to compression along these faults. The Bouguer gravity anomaly in the Kutch basin is high and the contours have an E–W trend[10]. In addition to the major E–W faults, the basin is transected by major N–S to NE–SW and NW–SE tectonic lineaments that include a structural 'Median High' (Hinge Zone) to the west of Bhuj, a NE–SW lineament near Anjar through Rapar (hereafter called A–R lineament), a NW–SE lineament from Bhachau to the NW (hereafter called Bhachau lineament), NW–SE Banni fault and various short lineaments and faults[11] (Figure 1).

A magnitude M_w 7.5 was initially estimated for the 2001 Bhuj earthquake by the US Geological Survey (USGS) and Earthquake Research Institute (ERI), Japan and then updated to M_w 7.7 with more data (USGS). The India Meteorological Department (IMD) has well estimated the focal depth at 25 km using the 'converted phases' recorded by the national broadband network. Numerous fissures, ground fractures, coseismic surface ruptures, slumping, liquefaction, ground subsidence and craters are reported in the main shock epicentre area[1,12].

The fault-plane solution of the mainshock shows reverse faulting with a strike-slip component (Figure 1). The south-dipping ENE–WSW plane is the inferred fault plane, which indicates left lateral strike-slip movement[3]. Based on waveform modelling, Yagi and Kikuchi[13] estimated fault dimension of the order of 90 km × 30 km and a maximum static displacement of 6.2 m at the hypocentre.

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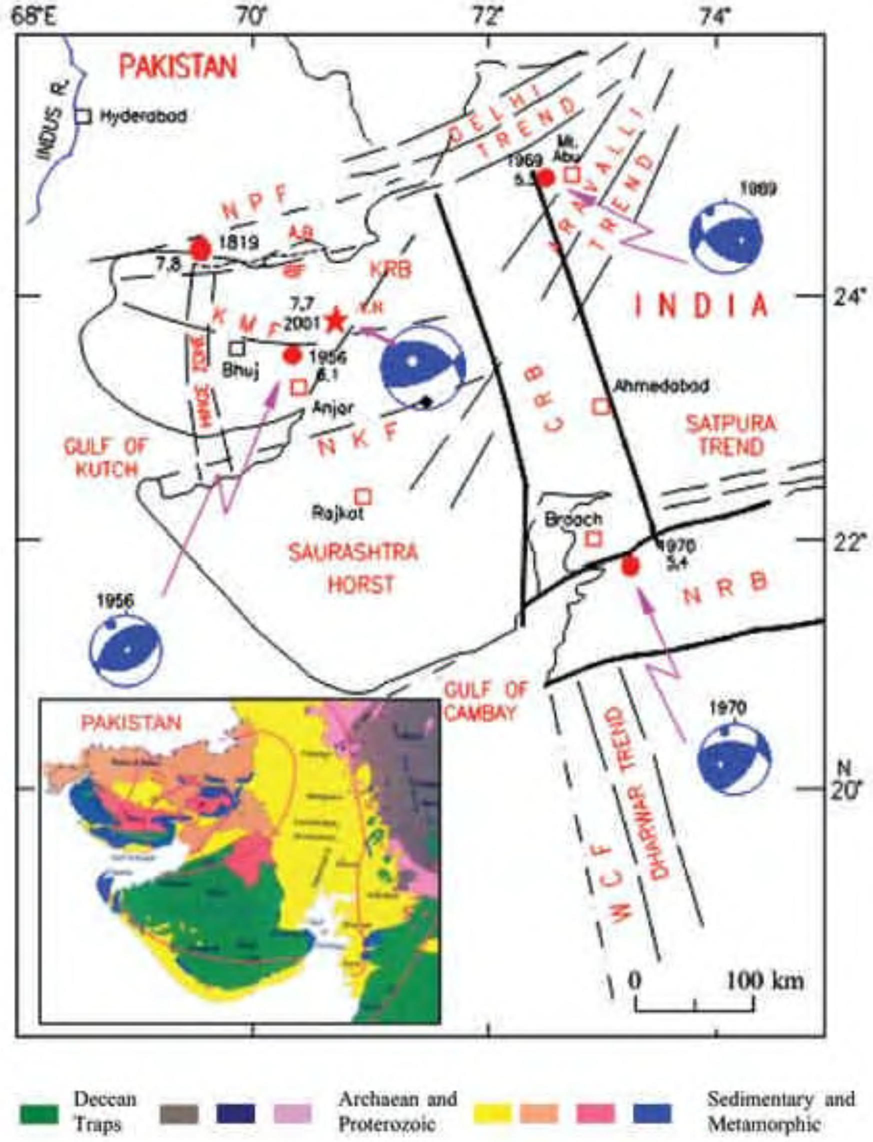

Figure 1. Tectonic map of Kutch region, fault plane solutions of the 2001 Bhuj earthquake and the significant earthquakes in the region. Shaded area indicates zone of compression and open area zone of dilatation. Solid circles indicate *P*-axes and open circles *T*-axes (after Kayal *et al.*[3]). NRB, Narmada Rift Basin; CRB, Cambay Rift Basin; KRB, Kutch Rift Basin; AR, Anjar Rapar lineament. (Inset) Isoseismal map of 2001 Bhuj earthquake with lithounits in the area[17].

They also gave a fault-plane solution, which depicts a reverse fault movement on the south-dipping fault plane.

About 600 aftershocks ($M \geq 2.0$) were located in an area 60 km × 30 km, between 70.0–70.6°E and 23.3–23.6°N, which reflects the source area of the main shock and aftershocks at depth[3]. The aftershocks show two major trends, NE and NW. Fault plane solutions of the best-located aftershocks were studied by Kayal *et al.*[3]. The NE cluster of events show left-lateral strike-slip mechanism and those of the NW cluster show right-lateral strike-slip solutions. Based on the aftershock investigation, Kayal *et al.*[3] gave a schematic fault-interaction model, which explains the fault-plane solutions and the co-seismic left-lateral and right-lateral ground movement[1,12]. The aftershock activity is continuing in the area, which suggests post-earthquake crustal adjustment.

Campaign-mode GPS surveys were carried to study the post-earthquake crustal deformation/adjustment in the area. GPS data were collected in three epochs, February 2001, February 2002 and February 2003, using the 4000 SSI and 5700 dual frequency geodetic receivers[14]. GPS data were analysed using the Bernese software[15]. During GPS data processing, IGS stations (IISC, BAHR, LHAS and KIT3) were tightly constrained to obtain precise GPS station

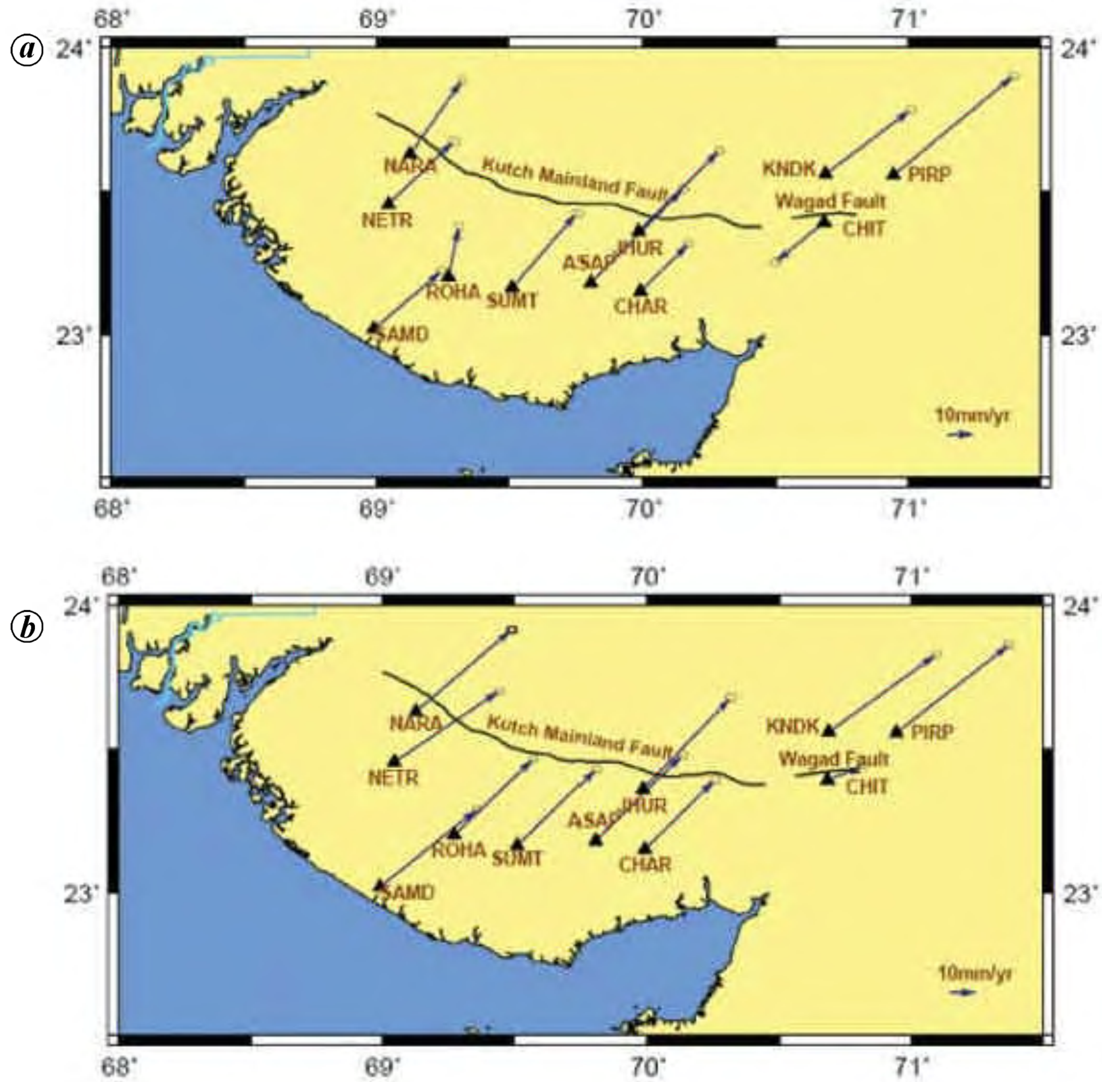

Figure 2. Regional displacement vector for period 2001–02 (***a***) and 2002–03 (***b***).

coordinates. Horizontal displacement vectors were estimated from the difference in coordinates obtained from GPS data processing[16].

The regional displacement vectors for the period 2001–02 and 2002–03 are given in Figure 2 *a* and *b* respectively, and the local displacement vectors for the period 2001–02 and 2002–03 are given in Figure 3 *a* and *b* respectively. The local displacement values were estimated by subtracting IISC station displacement from regional displacement values.

A significant post-earthquake crustal movement is observed in the Bhuj earthquake epicentre area after the main shock on 26 January 2001. The regional displacement (Figure 2 *a* and *b*) and local displacement (Figure 3 *a* and *b*) are parallel to the NE–SW trending A–R lineament and the major axes of the isoseismals of the 2001 Bhuj earthquake (Figure 1). These trends are parallel to the regional trend, the Delhi–Aravalli fold belt (Figure 1). It appears that the NE–SW trending Delhi–Aravalli fold belt plays a major role in controlling tectonics of the region[1,17]. The 2001 main shock rupture and the meizoseismal trends are governed by this major structure[17]. The 1956 Anjar earthquake also had similar effects; the inferred fault plane and the meizoseismal followed this major structural trend[3,17].

The observed regional as well as local crustal movement observed in this study (Figures 2 and 3) is comparable with the inferred fault-plane solution of the main shock, which shows a reverse faulting with left-lateral strike-slip motion. A significant horizontal crustal movement, local displacement vector, to the ENE direction during the GPS epoch 2002–03 (Figure 3 *b*), particularly in the western part of the KRB is noted. Such differential movement, temporal and spatial variation, is not uncommon in an earthquake-affected area[18]. It may be mentioned that different coseismic crustal movements, right lateral as well

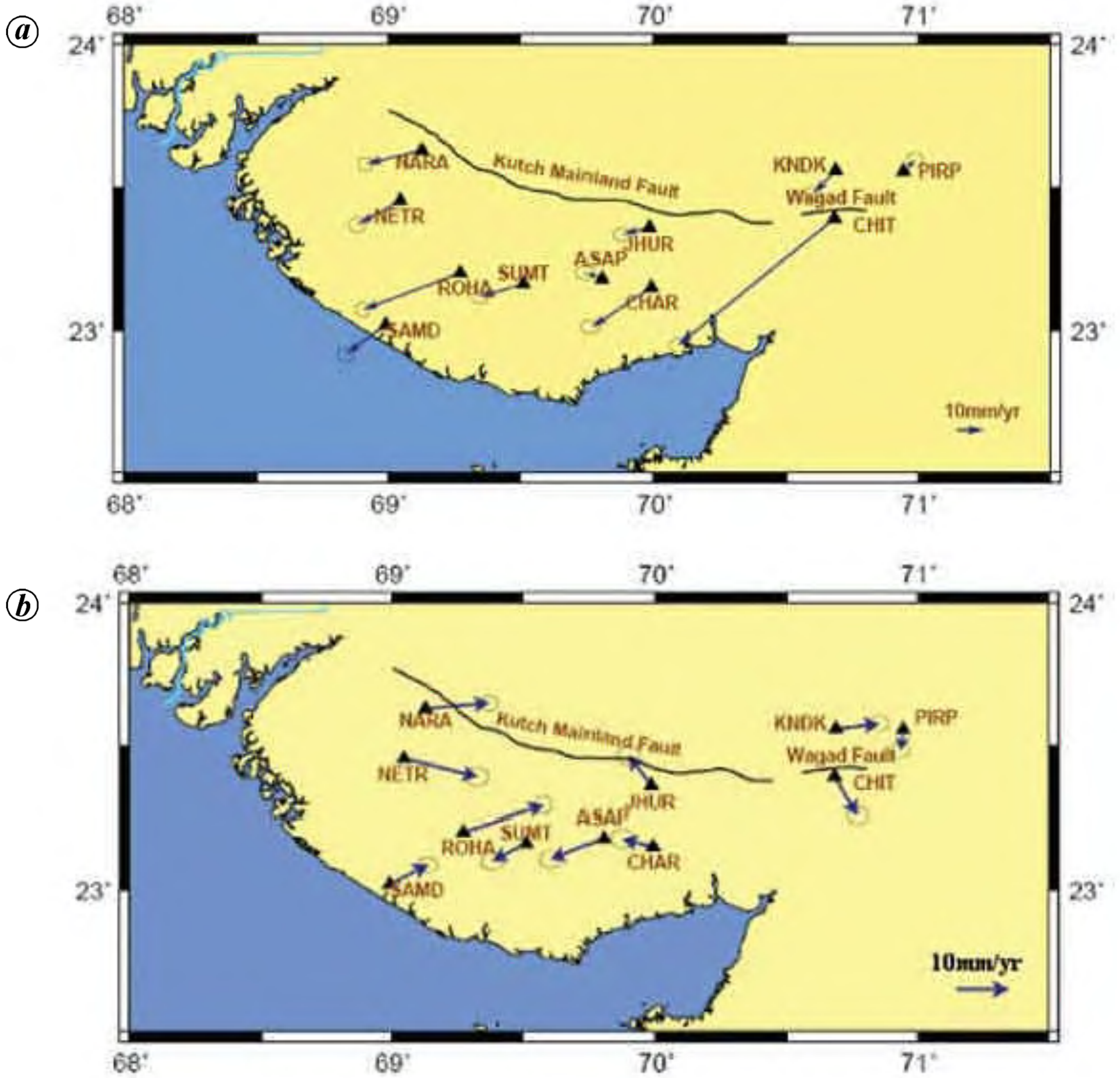

Figure 3. Local displacement vector for period 2001–02 (***a***) and 2002–03 (***b***).

as left lateral, were observed in the 2001 Bhuj earthquake epicentre area[1,3,12]. The southwestward movement by left lateral strike-slip along the A–R lineament in the epicentre area was more dominant. This was observed by the fault-plane solutions of the main shock and NE cluster of aftershocks[3]; these observations are conformable with GPS measurements (Figures 2 *a* and 3 *b*). Kayal *et al.*[3], based on aftershock trends and fault-plane solutions, presented a fault-interaction model. They suggested that the main shock rupture propagated along NE–SW by left-lateral strike-slip, and a conjugate rupture propagated along NW–SE by right-lateral strike-slip; these observations were conformable with the coseismic ground movements. The major displacement vectors and the spatial/temporal variations observed in this study are compatible with the main shock ruptures in the NE and NW directions by differential ground movement in space (Figure 3 *a* and *b*). It appears that there is post-seismic adjustment, as evidenced by GPS measurements as well as by the continuing aftershock activity; although frequency of aftershocks has reduced, the shocks are still continuing (IMD, pers. commun., 2005).

It was suggested that a south dipping hidden fault, parallel to the A–R lineament and Delhi–Aravalli fold belt, generated the main shock[3,17]. If we accept the south-dipping ENE–WSW modal plane, parallel to the A–R lineament, as the fault plane of the 2001 main shock (Figure 1), which is conformable with the major rupture/aftershock cluster[3], then we can speculate that the footwall (northwestern block) has moved to the left. A subsequent conjugate rupture to the NW, along the Bhachau lineament, on the other hand, caused a right-lateral movement[3,17]. This complicated tectonic movement is reflected in the GPS measurements (Figure 3 *a* and *b*); the western stations showed differential movement with time and space. This opposite movement could be the result of rebound of the footwall subsequent to the conjugate rupture/fault.

Further, although the fault-plane solutions of the aftershocks show different mechanisms, reverse faulting with right-lateral as well as left-lateral strike-slip movement, the observed compressive stress (P-axis) in all the solutions is dominantly in the N–S or NNE–SSW direction[3]. Gowd *et al.*[19] also reported similar compressive stress by *in situ* stress measurements. The P-axis and the observed GPS displacement vectors in the area are in good agreement. The KRB, which is developed due to dominant tensional stress in the geological past, is under the present compressive stress due to NNE-ward movement of the Indian plate and back push thrust force from the Himalaya[8]. This observation is similar to that of the Narmada Rift Basin (NRB) earthquakes[20]. The 1997 Jabalpur earthquake in the NRB was also generated by left-lateral reverse faulting; a NNE–SSW compressive stress (P-axis) is dominant in the NRB[20].

The GPS results of temporal and spatial variations of the horizontal crustal movement in the Bhuj area possibly indicate post-earthquake adjustment, which is also evident from the ongoing aftershock activity. These results encourage further investigations and to increase stations to the northwest in the area.

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Observation of seismogenic ultra low frequency electric field fluctuations detected as a burst in the ionosphere during tsunamis over the Andaman and Nicobar Islands

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Natural ultra low frequency (ULF) geomagnetic pulsations are mainly caused by wave plasma processes in the terrestrial magnetosphere and ionosphere. Earth crust processes may influence the parameters of geomagnetic noises and pulsations owing to the generation of additional noise or variation of local geo-electric properties. Electromagnetic disturbances of lithospheric origin observed before earthquakes are believed to become a physical background for short-term forecasting of seismic hazards. Among a large variety of seismo-electromagnetic phenomena, considerable in-

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