J. Ind. Geophys. Union (March 2006)
Vol.10, No.1, pp.31-44

Relocation, Vp and Vp/Vs Tomography, Focal Mechanisms and other related studies using aftershock data of the Mw 7.7 Bhuj earthquake of January 26, 2001

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ABSTRACT

To comprehend the seismo-tectonic process of the aftershock zone of the 26 January 2001 Mw 7.7 Bhuj earthquake sequence of Mw 7.7, we relocated 999 aftershocks (M_w 2.0-5.3) using HYPODD relocation technique and the data from a close combined network (NGRI, India and CERI, USA) of 8-18 digital seismographs during 12-28 February 2001. These precisely relocated aftershocks (ERH < 30 meter, ERZ < 50 meter) delineate an east-west trending blind thrust dipping (~ 45°) towards south (named as North Wagad Fault, NWF), about 25 km north of Kachchh Main Land Fault (KMF), as the causative fault for the 2001 Bhuj earthquake of Mw 7.7. The aftershock zone confines to a 60 km long and 40 km wide region lying between the KMF to the south and NWF to the north, extending from 10 to 45 km depth. The P- and S-wave station corrections determined from the JHD technique show a consistent and clear pattern of positive and negative values associated with the SW and NE part of the study area. The station corrections vary from 0.20 to –0.24 sec for the P-waves and from -0.55 to 0.95 sec for the S-waves.

The tomographic inversion technique is used to invert 5516 P- travel times and 4061 S-P travel time differences from 600 aftershocks recorded at 8 to 18 stations. Tomographic results suggest a regional high velocity body (characterized by high Vp (7-8.5 km/s), high Vs (4-4.8 km/s) and small σ (0.24-0.55)) with a head extending 60 km in N-S and 40 km in E-W at 10-40 km depths. This high velocity anomaly is inferred to be a mafic pluton/rift pillow, which might have intruded during the rifting time (~135 Ma). Another important result of our study is the detection of a low velocity zone (low Vp (6.5-7 km/s), low Vs (3.6–4 km/s) and high σ (0.26-0.265)) within the mafic body at the hypocentral depth of mainshock (~18-25 km), which is inferred to be a fluid-filled (trapped aqueous fluid resulted from metamorphism) fractured rock mass. The depth-wise variation of anisotropic percentage, stress drops and b-values suggest an increase at 18-30 km depths corroborating the presence of a fluid filled fractured zone coinciding with low velocity zone (at 18-25 km depths). Thus, the observed increase in anisotropy, stress drops and b-values at 18-30 km depths could be explained in terms of alignment of numerous fractures present in the fractured layer.

The focal mechanism solutions of selected 444 significant aftershocks, which were recorded at 6-14 stations, suggest that the majority of the selected focal mechanisms ranged between pure reverse and pure strike slip; some pure dip slip solutions were determined. The stress inversion using the selected earthquake focal mechanisms in the aftershock zone of the 2001 Bhuj earthquake shows that the axis of maximum principal stress is oriented N181°E with a shallow dip (=14°). Stress ellipsoid is oblate (R = 0.4). Further, the crustal shear wave anisotropy study suggests that leading shear wave polarization directions (LSPDs) over the aftershock zone vary from N-S to N-E with a delay of 0.07 to 0.14 sec. The delays in the N-S to N-E direction suggest cracks parallel to the direction of maximum horizontal regional compressional stress prevailing in the region.

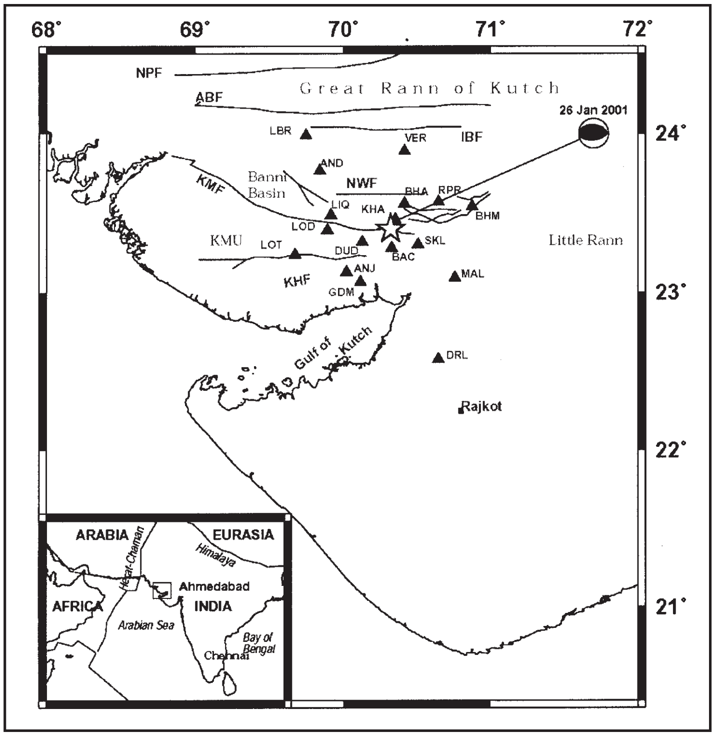

Figure 1. A plot showing 18 seismograph stations (seismograph stations marked by solid triangles (CERI, USA + NGRI, INDIA)) along with the mainshock epicenter (star symbol). The USGS focal mechanism solution for the 2001 Bhuj mainshock is also shown. KMU, Kachchh mainland uplift. Major faults (lines): ABF, Allah Bund Fault; IBF, Island belt fault; KMF, Kachchh mainland fault; KTF, Katrol fault; NPK, Nagar Parkar fault; NWF, North Wagad fault. The inset is showing the key map for the area with reference to Indian plate boundaries (dark lines). (After Biswas (1987)).

INTRODUCTION

The Kachchh region (Gujarat, India) is a unique intraplate seismic site in the Globe that has experienced two large (Mw 7.8 and 7.7) earthquakes within a time span of 182 years [Gupta et al., 2001]. The region lies in zone V (highest seismicity and potential for M8 earthquakes) on the seismic zoning map of India [BIS, 2002]. The latest earthquake of Mw 7.7 (intensity X+ on MM Scale) shook the whole of the Indian region at 8:46 (IST) on 26 January 2001 with an epicenter at (23.412°N, 70.232°E) in the Kachchh region, Gujarat, India [Figure 1, Rastogi et al., 2001]. Seismicity and first motion indicate that the Kachchh seismic zone is a zone of both strike-slip and reverse faulting [Chung and Gao, 1995]. Available GPS campaign data reveals at best a very weak signal and suggests very slow strain accumulation [Sridevi et al., 2001]. Thus, the most important question related to tectonics of Kachchh to be answered is how the large strains accumulate in this intraplate region (Himalayan plate boundary in the north is more than 1000 km away and Herat-Chaman plate boundary in the west is 500 km away) [Gupta et al., 2001]. Hence, the mechanism of stress concentration in the aftershock zone of 2001 Bhuj earthquake, is an important outstanding geodynamic problem, which perhaps can be clarified by focused investigation of subsurface velocity structures using reliable and accurate aftershock data that delineated a hidden E-W trending fault (NWF) about 25 km north of KMF, as the causative fault for the 2001 Bhuj earthquake of Mw 7.7 [Rastogi et al., 2001].

The geologic setting of Kachchh, Gujarat suggests a thick crust (≈42-45 km) of Paleozoic age, which is characterized by the presence of Mesozoic rifting, that has been reactivated by Cenezoic tectonism [Biswas, 1987; Gupta et al., 2001]. Prior crustal velocity investigations in Kachchh region are not very extensive but involve seismic refraction studies, receiver transfer function analysis of teleseismic P waves, regional surface wave dispersion study and regional earthquake tomography [Reddy et al., 2001; Gupta et al., 2001; Kumar et al., 2001; Singh et al., 1999; Kennett and Widiyantoro, 1999]. Integrated Geophysical modeling of seismic refraction, gravity,

Table 1. 1-D Velocity model for the Kachchh, Gujarat obtained from Joint hypocentral determination inversion of travel times.

Depth to the bottom of the layer (km)	Vp (km/s)	Vs (km/s)	Vp/Vs	Poisson's ratio	Geology
3.0	3.00	1.67	1.80	0.30	Sediments
6.0	5.43	3.14	1.73	0.25	Jurassic sediments and basement
10.0	6.00	3.47	1.73	0.25	Upper crust
15.0	6.45	3.73	1.73	0.25	Upper crust
20.0	6.48	3.75	1.73	0.25	Upper crust
25.0	6.72	3.88	1.73	0.25	Upper crust
30.0	7.15	4.13	1.73	0.25	Lower crust
35.0	7.49	4.33	1.73	0.25	Lower crust
42.0	7.88	4.55	1.73	0.25	Upper Mantle
∞	8.20	4.74	1.73	0.25	Half space

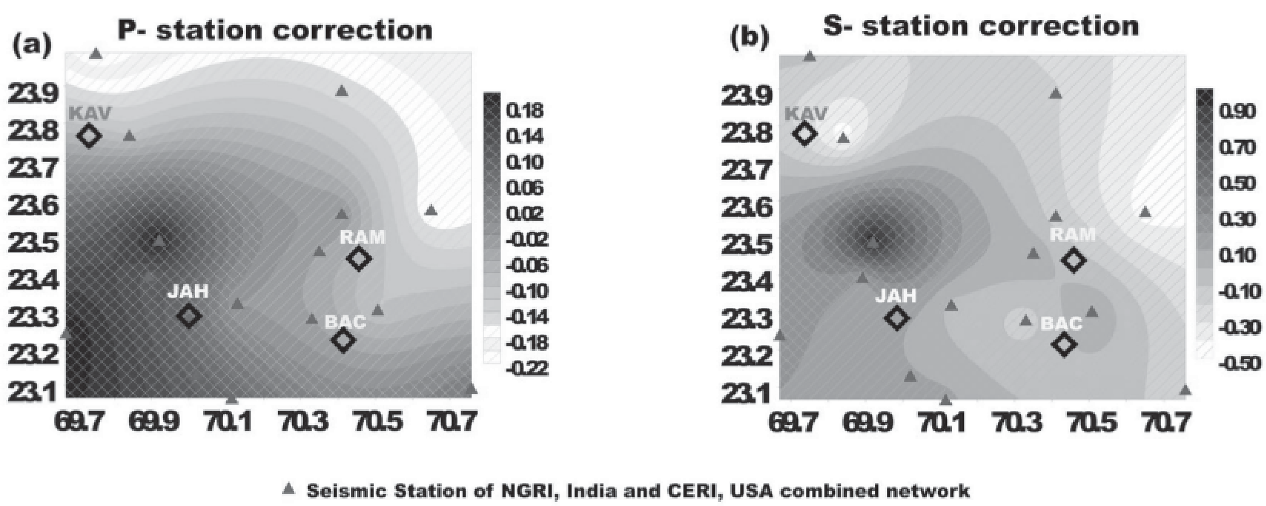

Figure 2. (**a**) Contour plot of P-Corrections and (**b**) Contour plot of S-corrections.

magneto-telluric and electrical data provided detailed information concerning velocity structure shallower than basement depth (3 – 6 km) [Gupta et al., 2001]. The controlled source seismic refraction and receiver transfer function studies have provided the estimation of Moho depth that varies from 37-45 km [Reddy et al., 2001; Kumar et al., 2001]. Further, marked crustal underplating has been seen in the form of high seismic velocity layer and/or reflector at the lower crustal depths [Reddy et al., 2001]. Surface wave dispersion study gave the average regional 1-D velocity structure of the area [Singh et al., 1999]. Regional earthquake tomography revealed that the deeper part of the lithosphere beneath the region is characterized by a marked low seismic velocity zone in the upper part of the mantle (~90-100 km) possibly related to the Deccan plume activity [Kennett and Widiyantoro, 1999]. Hence, there is an urgent need to investigate the detailed subsurface structure beneath the region.

In this paper, three-dimensional Vp and Vp/Vs models for the aftershock zone of 2001 Bhuj earthquake have been obtained using the Thurber's (SIMULPS12) travel time tomography method. The inversion involved 5516 P- travel times and 4061 S-P

Table 2. Station Locations and Results of S-wave Splitting Analysis.

Station	Lat. (oN)	Long. (oE)	Elev. (m)	LPSD. (deg.)	DT. (sec)	No. of Events used
Samkhiyali (SKL)	23°18.20′	70°30.39′	170	265	0.09	20
Bhachau (BCH)	23°17.79′	70°20.76′	2	10	0.10	06
Gandhidham (GDM)	23°03.60′	70°06.00′	150	38	0.08	10
Vondh (VND)	23°17.56′	70°24.19′	6	180	0.08	20
Rapar (RPR)	23°34.24′	70°38.89′	120	40	0.09	20
Lodai (LOD)	23°23.60′	69°53.52′	-48	320	0.14	10
Chopdwa (CHP)	23°16.39′	70°17.35′	3	350	0.07	25
Chobari (CHB)	23°31.38′	70°20.37′	-11	180	0.09	20
Adhoi (ADH)	23°23.34′	70°30.33′	50	40	0.10	20
Ramvav (RAM)	23°32.85′	70°28.37′	-11	8	0.07	05

travel time differences from 600 aftershocks recorded by 8 to 18 digital, three-component stations deployed in the aftershock zone over the time period 13 February - 07 March 2001. An effort has also been made to obtain a possible model for lower crustal Bhuj earthquake in terms of velocity anomalies and seismo-tectonics of the region. Further, an attempt has been made to characterize the fault zone in the light of source mechanism, crustal shear wave splitting and stress tensor orientation.

Local Seismic Network

The aftershock activity of the 2001 Bhuj earthquake has been monitored by National Geophysical Research Institute, Hyderabad since 4 February 2001 with a local digital network consisting of eight 24-bit recorders with an external hard disk (2 GB) and GPS timing system. Out of these six were equipped with short period seismometers (Frequency range 1-40Hz) and two were equipped with broadband seismometers (Frequency range 0.01-40Hz). The distance between station and epicenters varies from 14 km to 90 km. Recording was done in a continuous mode at 100 sps. Some station locations were shifted during the study period making a total of 12 station sites. Further, we used data from seismic network of CERI, Memphis (from 13.02.2001 to 27.02.2001) and Hirosaki University, Japan (from 28.02.2001 to 7 March 2001). With a view to obtain a better understanding of seismic hazard, attenuation and source processes, NGRI deployed a new network consisting of ten strong motion accelerogrphs and five seismographs in August 2002. The aftershock activity has been very intense. Until January 2005, 11 earthquakes of magnitude exceeding 5, over 170 earthquakes of exceeding 4 and several thousand earthquakes of magnitude ≤ 4 have occurred.

Relocation of aftershocks using Joint Hypocentral Determination (JHD) Method

Joint hypocentral determination (JHD) has been performed using the P and S travel times from 1234 aftershocks (during February –May, 2001) recorded at 8 to 18 three-component digital stations (error in epicentral location (ERH) < 0.5 km, error in focal depth (ERZ) < 1km; azimuthal gap between recording stations (GAP) < 180^o and root mean square error in P-residual (RMS) < 0.1s). The initial model used for

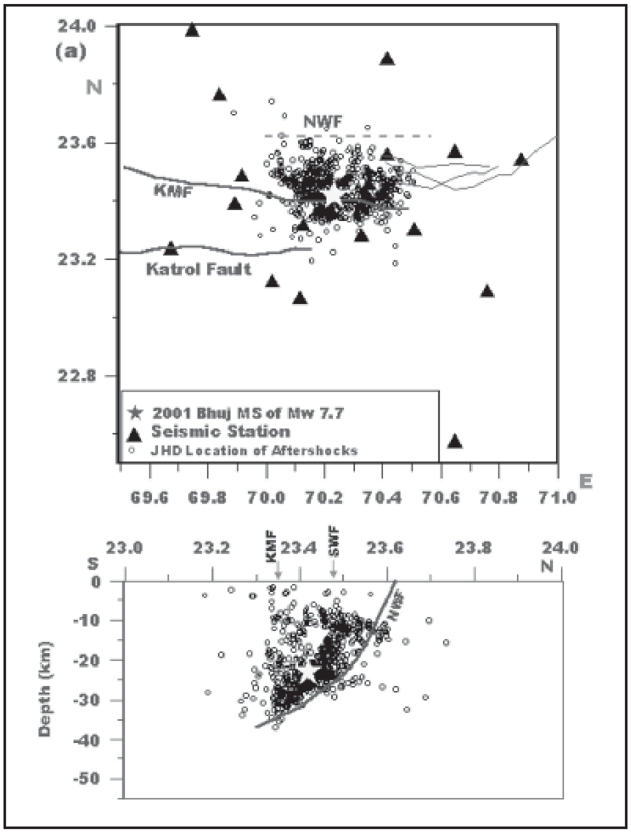

Figure 3: (**a**) Epicenters of selected 1238 aftershocks by using Joint Hypocentral Determination, which have occurred during 12-28 February 2001. A solid star shows the epicenter for the 2001 Bhuj mainshock. The inferred causative fault is shown by dotted line and marked as NWF. (**b**) Hypocentral depth plots of selected earthquakes in N-S direction (Inferred fault trace is shown by dotted line and marked as NWF. Surface traces of KMF and SWF are marked by arrows (after Biswas, 1987)).

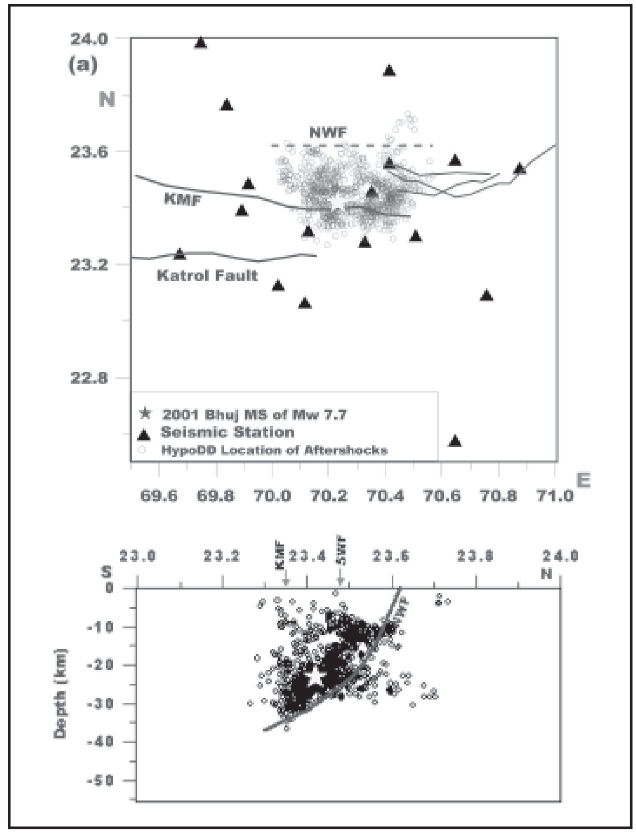

Figure 4: (**a**) Relocated epicenters of selected 999 aftershocks by using HYPODD, which have occurred during 12-28 February 2001. A solid star shows the epicenter for the 2001 Bhuj mainshock. The inferred causative fault is shown by dotted line and marked as NWF. (**b**) Hypocentral depth plots of selected earthquakes in N-S direction (Inferred fault trace is shown by dotted line and marked as NWF. Surface traces of KMF and SWF are marked by arrows (after Biswas, 1987).

JHD was obtained from the RTF study of the teleseismic P-waves recorded at 10 broadband stations deployed during 2001-2003 in Kachchh and Saurashtra, India [Mandal and Langston, 2005], which suggests a 9-layered crust beneath the region. The detailed of inversion of RTFs can be found in Mandal and Langston [2005]. The P- and S- station corrections were also estimated using JHD of 1234 aftershocks, which are shown in Figures 2 (a & b).

1234 events are relocated during February-March 2001, using JHD (ERH < 1 km, ERZ < 1 km and RMS 0.02 to 0.1 s), delineating an EW trending plane extending from 10 to 40 km depth with southward dip of 45^{o} and covering an area of 60 x 40 km^2 (Figures 3 a-d). Most of the earthquakes continue to occur between the NWF, responsible for January 26, 2001 earthquake and the KMF [Mandal et al. 2004a]. The surface expression of NWF is hidden beneath the Banni plains comprising soft sediments and extending along Wagad uplift [Biswas, 1987]. Focal mechanism solutions of a few of the major aftershocks obtained from waveform inversion of broadband data indicates a dominant reverse movement on the NWF [Mandal et al. 2004a].

Station Corrections Estimated using JHD

The P- and S-wave station corrections determined from the JHD inversion [Pujol, 1988] show a consistent and clear pattern of positive and negative values associated

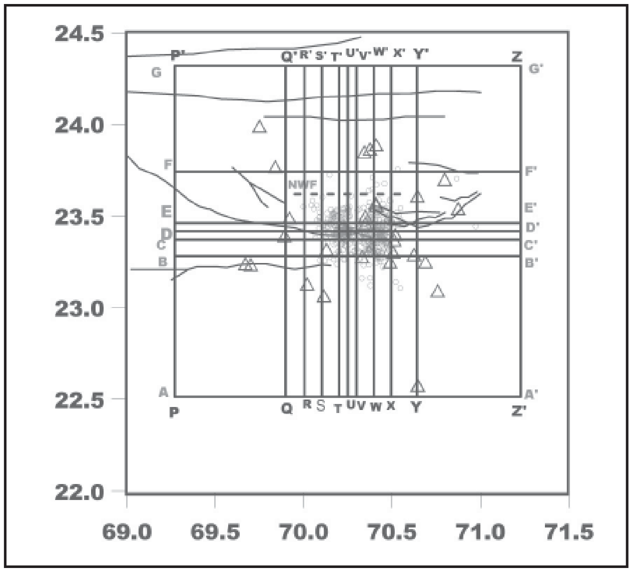

Figure 5. A plot showing the grid parameterization used for Vp and Vp/Vs tomography.

with the SW and NE part of the study area (Figures 2 a & b). For the SW part stations, all corrections are positive. On the contrary, the NE part stations have negative corrections. The station corrections vary from 0.20 to –0.24 sec for the P-waves and from 0.95 to -0.55 sec for the S-waves. A positive (negative) station correction indicates that the observed travel time is larger (smaller) than that calculated from a given velocity model, suggesting that the actual velocity structure is lower (higher) than given velocity model used in earthquake location. Therefore, patterns of station corrections suggest that the SW part of the study area is characterized by low velocity, while relatively higher velocities characterize the NE part of the study area. The contours of station corrections are aligned in a NE-SW orientation, which suggests an east-west lateral variation closely related to the trends of major tectonic units in the region.

Relocation of Aftershocks using Double-difference Algorithm

The HYPODD algorithm was developed to optimally relocate seismic events in the presence of measurement errors and earth model uncertainty [Waldhauser and Ellsworth, 2000]. Although, Waldhauser and Ellsworth [2000] used the cross-spectral method of Poupinet et al. [1984] to measure the differential travel times, however, this method is found to be unstable for radically dissimilar events. Hence, in this study a cross-correlation technique has been used which is found to be quite stable [Horton et al., 2005]. This method has been discussed in detail by Mandal and Horton [2005, personal communication). The waveforms of two events, which are to be analyzed, are band-passed filtered between 0.6 and 30 Hz. Then, 1.28 –second windows are selected from both the waveforms, which are centered on the same specified time relative to the origin time of each event. The specified time corresponds to the travel time of the phase in question for the first event. Finally both the waveform windows are cross-correlated. The differential travel-time corresponds to the lag time of the peak in the cross-correlation function. Only those measurements, which are having a correlation coefficient equal to or larger than 0.8, are used in the double difference earthquake location. The correlation coefficients are used to weight the uncertainty of the observations. The method has a precision of one sample (0.01 s in this study), and it is a stable estimator since non-similar signals do not satisfy the correlation coefficient threshold.

We performed waveform cross-correlation on 1238 aftershocks of 2001 Bhuj earthquake of Mw 7.7 as recorded by the local seismological networks of National Geophysical Research Institute, Hyderabad, India and CERI, Memphis, USA, during 12 – 28 February, 2001. Approximately 10 to 40% of the events belong to similar event clusters, depending upon the similarity criteria that are applied.

First, all aftershocks were relocated using least squares inversion of arrival times of P and S waves recorded at 8 – 18 stations. Then, the cross-correlated P and S arrival times were included to improve the relocations. Finally, the manually as well as cross-correlated picked P and S arrival times were used to

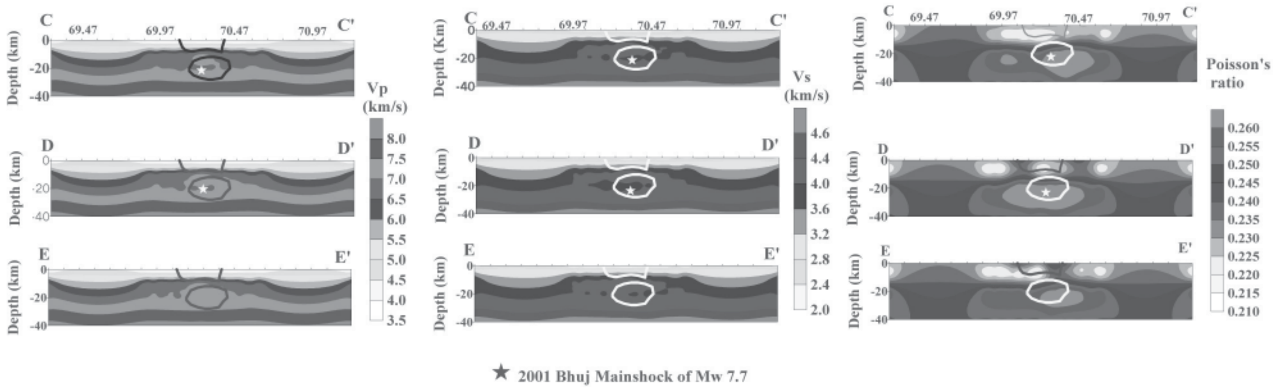

Figure 6: Depth sections of Vp, Vs and Poisson's ratio along three E-W profiles across the aftershock zone (CC′, DD′ and EE′ as shown in Figure 5): (a) Vp along CC′, (b) Vp along DD′, (c) Vp along EE′, (d) Vs along CC′, (e) Vs along DD′, (f) Vs along EE′, (g) Ã along CC′, (h) Ã along DD′ and (i) Ã along EE′. The zone of maximum primary slip as obtained by teleseismic body wave inversion at 12-26 km depth is shown by solid line (Antolik and Dregar, 2003). Star marks the hypocenter of the 2001 Bhuj mainshock.

relocate 999 aftershocks out of 1238 events using conjugate gradient method (LSQR). We used 100% weighting for manually picks and 50% for cross-correlated picks. The condition numbers obtained for 6 iterations are ranging from 41 to 80. This suggests that the damping used for LSQR inversion scheme were proper. The average uncertainties obtained for relocated 999 aftershocks are 30 m for epicentral location and 50 m for focal depth estimation.

Finally, in order to check the uncertainties of LSQR inversion technique, the whole aftershock data set was divided into 23 subsets consisting of 48 to 96 events for relocating them using SVD. We checked each of the location obtained by LSQ as well as SVD techniques, which showed almost same hypocentral locations. Thus, it can be said that the uncertainties in the aftershock locations obtained by HYPODD are minimum.

The relocated epicenters using HYPODD (marked by 'o' symbols) are plotted in Figure 4a that suggests only modest differences in epicentral locations in comparison with the earlier location by JHD (Figure 3a). But, the mean of epicetral location uncertainty has been reduced from 1000 to 30 meters. The distribution of epicenters still defines an E-W trending aftershock zone covering almost 40 km x 60 km area, which is about 8^{o} from the WSW-ENE striking nodal plane of the mainshock (Figure 1). However, a substantial compressing of the vertical distribution of hypocenters in comparison to earlier JHD hypocentral location (Figure 3b) is apparent in the transverse cross-section as shown in Figure 4b. The relocated hypocenters delineate a sharp and distinct south dipping aftershock zone extending up to 35 km depth. However, there is no significant difference in pattern of focal depth distribution estimated from JHD and HYPODD. The mean of focal depth uncertainty has been decreased from 2000 to 50 meters.

Three-Dimensional Vp and Vp/Vs Tomography

The grid configuration (with an origin at 23^{o}25′N and 70^{o} 15' E) was used for tomographic inversion that showed the most pronounced diagonal element resolution (Figure.5). This configuration was aligned parallel to the major tectonic features in the area (like KMF, Katrol, NWF, Wagad uplift, Banni and mainland where much of the seismicity is concentrated) extending 200 km in E-W x 200 km in N-S directions. The grid separation is 2-5 km within the seismic zone and 15-20 km for the rest of the modeling volume (Figure.5). The detail of resolution and reliability tests results of 3-D Vp and Vp/Vs tomography can be found in Mandal et al. [2004b].

Three-dimensional Vp and Vp/Vs structures at 0-3, 3-6, 6-20, and 20-40 km depths are obtained by using Thurber's [1983] tomographic inversion (SIMULPS12) of 5516 travel times of P-waves and 4061 S-P time differences from 600 aftershocks recorded at 8 to 18 stations during 6 February - 7 March 2002. Finally, Vp and Vp/Vs information are used to compute tomograms of Vs and Poisson's ratio (Ã). Here, we will present results of Vp, Vs and Ã for three E-W profiles (CC′, DD′ and EE′) (Figures 6(a-i)) and results of only Vp for three N-S profiles (TT′, UU′ and VV′) (Figures 7 (a-c)). These profiles are selected because

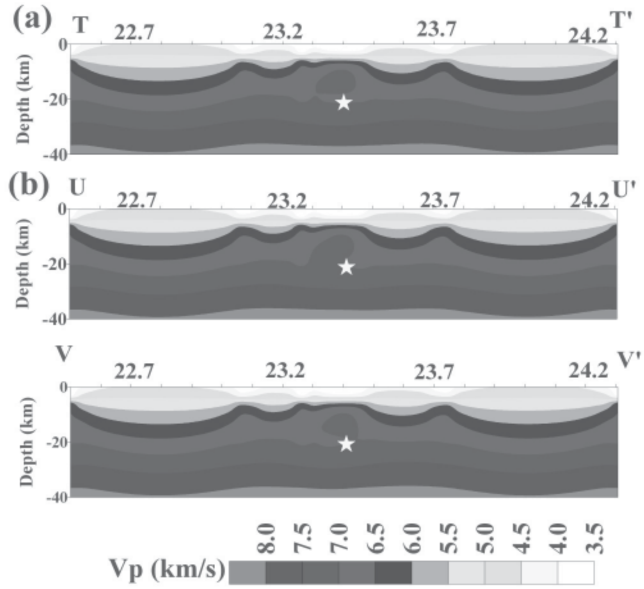

Figure 7. Vp depth sections along three N-S profiles across the mainshock epicenter near Bhachau as shown in Figure 5: (a) TT′, (b) UU′, and (c) VV′. Star marks the hypocenter of the 2001 Bhuj mainshock.

they pass through the main aftershock zone (Figure 5). These profiles clearly brought out a bell-shaped high velocity body (100 km x 100 km) at 10 – 40 km depths within the rupture zone, with a head extending about 60 km in E-W (69.87° to 70.57°E) and about 20 km in N-S (22.25° to 22.45°N) directions (Figures 6 & 7). A combination of high Vp (7-8.5 km/s), high Vs (4-4.8 km/s) and low σ (0.24-0.255) characterizes this body, which suggests a mafic composition for the body. Hence, the high velocity body has been inferred as a mafic pluton probably intruded during the rifting time (~ 135 Ma). Depth sections of tomograms also delineate a low velocity patch at 18 – 25 km depths extending about 40 km in E-W (70° – 70.37°E) and about 15 km in N-S (22.3° to 22.45°N) directions (occupying 20% area of high velocity body) which is characterized by low Vp (6.5-7 km/s), low Vs (3.6-4 km/s) and large Ã (0.26-0.265). This combination of low Vp, low Vs and large Ã enabled us to infer this zone as a fractured fluid filled rock matrix.

Crustal Shear – Wave Splitting study

We carefully chose 156 split shear wave paths from 1500 well recorded aftershocks in the magnitude range 2.5-5.3 for our present study based on the observation that shear waves arrive at free surface at an incidence angle less than the critical ($\sin^{-1}$ Vs/Vp) resulting in undistorted waveforms of the incident wave, whereas, if the incidence angle is greater than the critical then waveforms are distorted [Evans, 1984]. Most of our selected events have occurred within the 6-42 km depth range where estimated i_d varies between 33° to 36° suggesting that selected events are well within the shear window. The predominant directions of polarization are found to vary from N-S to NE (Table 2). At Bhachau, Chopdwa, Vondh and Chobari, LPSDs are found to be N-S suggesting cracks parallel to the direction of the regional maximum horizontal compression prevail in the region. This correlation suggests that the cracks whose orientations are controlled by the regional tectonic stress are the origin / source of anisotropy. However, at Samkhiyali and Lodai, the LPSDs are found to be E-W and NW-SE, respectively, which are quite different (i.e.) in comparison to other stations. This could be explained in terms of orientation of local stress or cracks. The DTs are estimated to varying from 0.07s to 0.14s with an average of 0.091s. The maximum delay of 0.14s is observed at Lodai, whereas, minimum delay of 0.07 is found at Chopdwa as well as Ramvav (Table 2).

The anisotropic percentage is estimated using the following equation,

$$\text{Anisotropy} = (Vf - Vs)/Vf * 100\ \%$$
$$= (DT/R) * Vf * 100\ \%$$

where $DT = R*(Vf-Vs)/(Vs*Vf)$

where, Vs and Vf are velocity of slow and fast shear waves, respectively. R represents the hypocentral

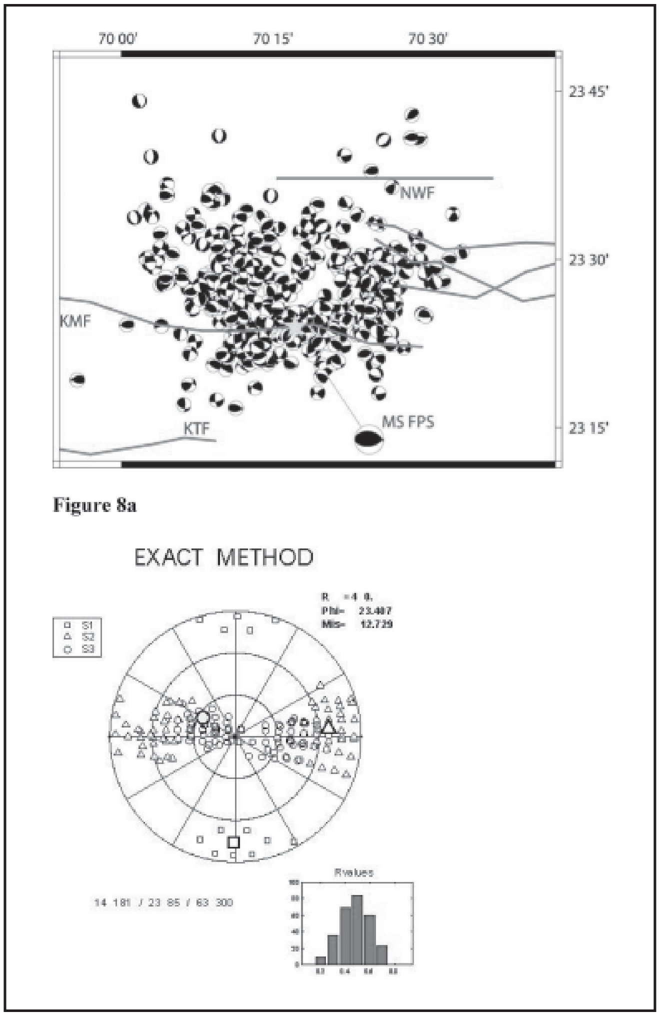

Figure 8. (a) Spatial distribution of aftershock focal mechanisms inferred from first motion of P-waves using FPFIT and (b) Maximum principal stress axis, Ã1 (square), intermediate axis, Ã1 (triangle), and least principal axis, Ã3 determined from inverting the P and T axes of focal mechanisms of selected 444 aftershocks using the Exact method. Star marks the hypocenter of the 2001 Bhuj mainshock.

distance / path length in the anisotropic media. The estimated anisotropy percentages are varying from 0.4 % to 10.76% with an average of 2.4% (Table 2).

Aftershock focal mechanisms

In the present study, we used 991 focal mechanism solutions for Bhuj aftershocks estimated using the first motions of P-wave from 10-18 stations with the help of FPFIT techniques [Reasenberger and Oppenheimer, 1985]. The estimated uncertainties in the dip and strike of these focal mechanism solutions are as small as ten degrees. Out of these 991 FPSs, 444 solutions were selected for detailed stress tensor analysis, which have misfit less than 0.2 and less than 30^o in estimating dip, rake and azimuth.

Our study shows that the majority of the selected focal mechanisms ranged between pure reverse and pure strike slip; some pure dip slip solutions were determined (Figure 8a). For each focal mechanism solution, the fault plane was chosen as that nodal plane which agrees with the orientation of faults in the vicinity mapped or compiled by Biswas [1987]. In most cases, the faulting type was the same regardless of which nodal plane was assumed to be the fault plane. A total of 143 events were found to oblique reverse, 106 reverse, 102 strike-slip, 65 oblique normal, and 28 normal. Hence, these solutions suggest a dominant reverse movement with a strike slip component on a south-dipping plane, which agrees with the causative nodal plane of the mainshock focal mechanism as shown in Figure 8a [Antolik and Dregar, 2003].

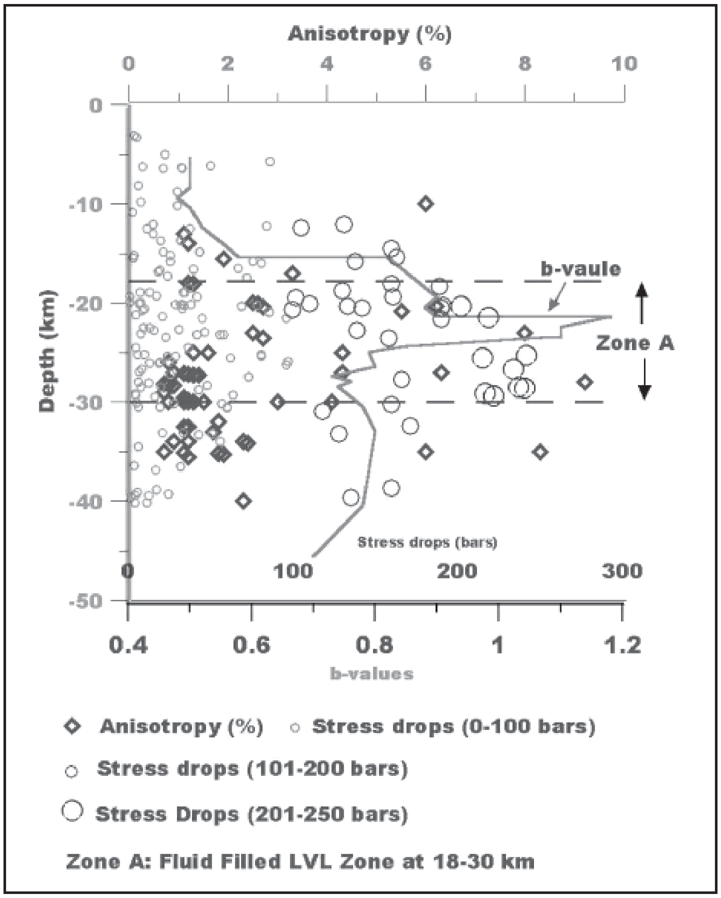

Figure 9. Depth-wise distributions of estimated anisotropy percentage (marked by open diamond symbols), b-values (marked by solid lines) and stress drop values (marked by graded circles). And, the low velocity zone A at 18 – 30 km depth is shown by dotted lines.

Stress Inversion using Focal Mechanism Estimates:

For the stress inversion study, we used Gephart's [1990] method to invert P and T axes data (trend and plunge) from 444 well-constrained focal mechanisms obtained from FPFIT. The qualities of the solutions were judged by the standard deviation obtained by FPFIT for each focal mechanism solution. Thus, the focal mechanism data for stress inversion were weighted according to the above-said standard deviations. The inversion was done using three methods viz. pole rotation, minimum rotation and exact method. The misfit obtained by pole rotation, minimum rotation, and exact methods are 48.23^o (R=0.6), 21.358^o (R=0.4) and 12.729^o (R=0.4) respectively [Mandal and Horton, 2005]. Finally, the solution obtained by the exact rotation method (Figure 8b), which gave minimum misfit, was considered since this method provides more robust solution as suggested by Gephart [1990].

DISCUSSIONS

The 2001 Bhuj earthquake located in the Mesozoic Kachchh basin which has been experiencing large intraplate earthquakes [Rajendran and Rajendran, 2001; Gupta et al., 2001]. Existing seismological data suggests that the majority of Kachchh intraplate earthquakes can be attributed to the sudden movement along the E-W trending pre-existing reverse / thrust faults in response to the prevailing N-S compression due to the northward movement of the Indian plate [Gao and Chung, 1995; Biswas, 1987]. In accordance with the above-mentioned seismological observations, precise and accurate relocated aftershocks (by HYPODD) delineate an E-W trending south dipping aftershock zone extending up to a depth of 35 km. The spatial distribution of relocated aftershocks suggests a tight E-W trending cluster involving an area of 60 km x 40 km. In comparison to locations determined by JHD technique, the uncertainty in epicentral location and focal depth estimation have been reduced significantly from 1000 to 30 meters and 2000 to 50 meters, respectively. The N-S hypocentral depth distribution reveals a distinct south-dipping plane, which agrees well with the nodal plane of the manishock focal mechanism [Antolik and Dregar, 2003].

Our tomographic results clearly delineate a regional high velocity body (low Vp (6.5-7 km/s), low Vs (3.6-4 km/s) and large Ã (0.26-0.265)) beneath the aftershock zone at 10-40 km depths existing in most of the 100 km x 100 km area of Kachchh with a prominent head extending 60 km in N-S and 40 km in E-W directions. This body is inferred to be a mafic pluton / rift pillow that might have intruded during the previous episodes of rifting (~ 135 Ma). The controlled source seismics results in the area also confirm the underplating beneath the aftershock zone in the form of high seismic velocity layer and/or reflector at the lower crustal depths [Reddy et al., 2001]. Further, the gravity modeling along two profiles in the near vicinity of the aftershock zone revealed two regional intrusive bodies / mafic plutons associated with two marked gravity highs namely Patcham and Wagad uplifts [Chandrasekar and Misra, 2002]. The gravity highs associated with Patcham, Kadir, and Bela uplifts are circular, similar to those observed over volcanic plugs of Deccan traps in the Saurashtra [Chandrasekhar and Mishra, 2002]. Presence of E-W trending dykes of about 20-40 km long and patches of Deccan basalts have been reported in the Wagad uplit evidencing the magmatic / volcanic activity in the region [Biswas and Deshpande, 1970]. It is well known that the presence of this type of mafic pluton / frozen rift pillow could also explain the occurrence of large earthquakes in the lower crust beneath the intraplate regions [Kane, 1977; Cambell, 1978]. Similar type of causative mechanism has already been proposed for lower crustal intraplate earthquakes like 1811-1812 New Madrid (USA) earthquakes [Pollitz, 2002], 1997 Jabalpur (India) earthquake [Rajendran and Rajendran, 1998] and Amazonian earthquakes [Zoback and Richardson, 1996]. The mafic pluton / rift pillow may be acting as an asperity in response to NNE compression due to northward movement of the Indian plate, which can explain the reason for large strain accumulation at the 2001 Bhuj aftershock zone.

Results also suggest a distinct low velocity zone of 40 km x 15 km within the mafic high velocity body at the hypocentral depth of manishock (18 –25 km). This zone can be interpreted as a highly fractured fluid-filled rock matrix, which contributed 70% of the primary slip due to the 2001 Bhuj mainshock (Antolik and Dregar, 2003). Further, the depth distribution of b-values suggests a marked increase in b-values in the depth range of 15 to 25 km indicating presence of more fractures. The heat flow values measured in Cambay and Rajasthan suggest a high heat flow of ~ 50-70 mw/m^2 for the Kachchh area indicating the crustal thermal state for Mesozoic basin [Panda, 1985]. Thus, source of fluid at 18-25 km depths could be of deeper origin representing trapped aqueous fluid released during metamorphism/partial melt intruded in the crust during K/T plume activity. It will be important to note here that the teleseismic and regional earthquake tomography showed low velocity zones in the upper part of the mantle (~90-100 km) possibly indicating the presence of plume-head centered on Cambay-Kachchh region and the overlying continental lithosphere [Kennett and Widiyantoro, 1999]. Hence, it is inferred that the presence of fluids (trapped aqueous fluids released from metamorphic reactions) at hypocenteral depth of the mainshock may have been further facilitated the occurrence of 2001 Bhuj earthquake [Zhao et al., 1995]. The confinement of maximum primary slip and large stress drops in the 18-25 km depth range could also be explained in terms of the significant pore fluid pressure at those depths.

Hence, it would be interesting to combine all the above mentioned important findings from shear-wave spitting and 1-D as well as 3-D velocity inversion studies to infer about the prevailing structure and source responsible for generating the Mw 7.7 2001 Bhuj earthquake in the lower crust. Figure 9 shows that the depth-wise distribution of estimated anisotropy (%), b-values and stress drop values reaches a maximum at 18 – 30 km depths (Zone A), which is already inferred as a fractured fluid filled layer having a large b-value of 0.75-1.1 and a marked concentration of large stress drop values [Mandal et al, 2004 a & b; Mandal and Johnston, 2005]. Further, it is important to note here that our tomographic results also revealed a low velocity (low Vp, low Vs and large Poisson's ratio) fractured layer at 18-25 km depths (Figs. 6 & 7). Thus, the presence of numerous fractures could be the explanation for the observed increase in anisotropy at 18-30 km depths.

Analysis of selected 444 focal mechanisms in the aftershock zone of the 2001 Bhuj earthquake shows that the axis of maximum principal stress is oriented N181^{o}E with a shallow dip (=14^o), which exactly agrees with the P-axes orientation obtained from the focal mechanism solution of mainshock as suggested by waveform inversion of teleseismic body waves (Figures 1 and 8b). The stress ellipsoid is oblate (R = 0.4). The pattern of stresses obtained from stress inversion suggests that the prevailing compressive stress regime in the region will prefer thrust mechanism. This result is in good agreement with the available seismological, geophysical and geological information of the area. This indicates that the stress field in Kachchh, Gujarat, India is relatively uniform and that the maximum principal stress has an orientation that might be predicted on the basis of current plate motions or from the directions of the P-axes of the earthquakes.

CONCLUSIONS

Major E-W trending faults characterize the seismotectonics of the Kachchh region. Available earthquake data reveals that dominant deformation mode for the region is south dipping thrust faulting. In accordance with dominant E-W trends, precise relocations of 999 aftershocks using HYPODD technique suggest an E-W trending south dipping aftershock zone extending up to 35 km depth. The mean error in epicentral location and focal depth estimates has been reduced from 1000 to 20m and 2000 to 50m, respectively. The aftershock zone involves a crustal volume of 60 km x 40 km x 35 km. The N-S hypocentral depth plot clearly reveals a south dipping plane, which agrees well with the south-dipping causative nodal plane of 2001 Bhuj mainshock.

Results suggest that the presence of a high velocity body (inferred to be a mafic pluton/frozen rift pillow) characterized by high Vp (7-8.5 km/s), high Vs (4-4.8 km/s) and low σ (0.24-0.255) beneath the aftershock zone extending from 10 km depth to the deep in the lower crust (~ 40 km depth) must be contributing significantly in accumulating large crustal stresses resulting in the generation of large lower crustal intraplate earthquakes in the Kutch area. Another important finding of this study is the detection of a low velocity anomaly (inferred to be fluid-filled fractured rock matrix) at 18 –25 km depths characterized low Vp (6.5-7 km/s), low Vs (3.6-4 km/s) and large Ã (0.26-0.265) beneath the aftershock zone where the mainshock had occurred. This zone A contributed 70% of the primary slip due to the 2001 Bhuj mainshock (Antolik and Dregar, 2003). This low velocity body is further supported by a large b-value of 0.75-1.1 and a marked concentration of large stress drop values at 18-30 km depth indicating the presence of numerous fractures (zone A). Hence, the confinement of maximum primary slip and large stress drops in the 18-30 km depth range could also be explained in terms of the significant pore fluid pressure at those depths. From the above discussion, it can be inferred that the large stress/strain accumulation associated with asperities within this rigid mafic body in response to NNE compression due to the northward movement of the Indian plate must have provided the large strain energy required to generate the Mw 7.7 2001 Bhuj earthquake in the lower crust. This may have been further facilitated by the presence of fluids (aqueous fluid) at the hypocentral depths (18-25 km) might have facilitated the occurrence of 2001 Bhuj earthquake.

In accordance with the prevailing N-S compressive stress regime, the stress inversion study of selected 444 focal mechanism solutions in the aftershock zone of the 2001 Bhuj earthquake shows that the axis of maximum principal stress is oriented N181^{o}E with a very shallow dip (=14^{o}). The stress ellipsoid is oblate (R = 0.4). This indicates that the stress field in Kachchh, Gujarat, India is relatively uniform and that the maximum principal stress has an orientation that might be predicted on the basis of current plate motions or from the directions of the P-axes of the earthquakes. The minimum principal stress directions suggest an E-W extension agreeing well with the trend of major large-scale extensional tectonic trends of the region. However, the distribution of P-axes orientations suggests a significant variation over the aftershock zone indicating a heterogeneous local tectonic stress regime. Hence, from these results it can be inferred that the coupled force system induced by the regional N-S compression and heterogeneous local tectonic forces has caused a sudden movement along the pre-existing south dipping fault to cause the 2001 Mw7.6 Bhuj minshock.

ACKNOWLEDGEMENTS

The authors are thankful to Dr. V. P. Dimri, Director, NGRI for his encouragement and kind permission to publish this work. This study was supported by the Department of Science and Technology, New Delhi. Authors are grateful to CERI, Memphis, USA and Hirosaki University of Japan for providing their aftershock data. Authors are grateful to Profs. Arch Johnston and C.A. Langston of CERI, MEMPHIS, USA and Drs. B.K. Rastogi and R.K. Chadha for their useful scientific discussions.

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