

Subsurface stress analyses for the M_w 7.6 Bhuj earthquake, India: An insight from the integrated geophysical approach

D. V. Chandrasekhar*, B. Ramalingeswara Rao and B. Singh

National Geophysical Research Institute, Hyderabad 500 007, India

The M_w 7.6 Bhuj earthquake of 26 January 2001, associated with high stress drop indicates anomalous stress localization in the Kachchh rift basin, similar to regions in the plate margins. Although Kachchh is also postulated to be diffused and undergoing steady deformation, it cannot be related to plate boundary activity alone in the absence of any conspicuous seismogenic lineament. Further, nucleation of the earthquake in the middle-lower crust in a palaeo-rift environment, offers difficulty in evaluating the major tectonic cause for anomalous stress accumulation. A 2D finite element stress model constraining with the integrated geophysical results and distribution of aftershocks on the NNE–SSW-directed compressed Bhuj earthquake epicentral region of the Kachchh basin, indicate high shear stress dispersion (~ 70 MPa) at the hypocentral depth and accentuate the potential role of local tectonic elements in the Kachchh rift basin for anomalous stress distribution. Moderate strain rate (6.0×10^{-8}) and high pore fluid pressure (343 MPa) indicate the presence of serpentinite at greater crustal depth, whose dehydration causes brittleness, and release of fluids in a high-stressed zone triggers rock failure.

Keywords: Bhuj earthquake, crustal heterogeneity, pore fluid pressure, serpentinite, shear stress.

THE Bhuj earthquake of 26 January 2001 is the largest continental intra-plate earthquake globally known in more than 100 years and is not an isolated event in Kachchh rift basin. Understanding its source properties provides an opportunity to examine the mechanics of the earthquake-driving forces, active seismic deformation and stress fields in the Kachchh rift basin. The Bhuj earthquake occurred in a region ~ 600 km south of the crest of the flexural bulge of the Indian plate, where highest compressional stresses and associated ruptures are expected to occur at the surface and not in the lower crust¹. The focal depth ~ 22 km of the Bhuj earthquake and its aftershock extending through the entire crust with concentration in the lower crust at ~ 26 km and in the upper crust ~ 10 km, indicate its nucleation in the middle to lower crust^{2–5}. However, causes for such

stress concentration in this zone are enigmatic and underline the need to study its seismo-tectonic framework in the perspective of plate-tectonic forces in a hitherto stable intra-plate region.

Visco-elastic modelling results⁶ suggest that intracontinental thrusting and shearing along the western Indian plate boundary may have diffused some deviatoric stresses into the Indian plate. No attempt has been made so far to compute the shear stress and analyse the failure stress condition for the Bhuj earthquake of 26 January 2001. Using results of the different geophysical investigations in the Bhuj epicentral region, the present study delineates the plausible causative factors for the Bhuj earthquake and presents a model to understand the build-up of subsurface stresses in the epicentral region of M_w 7.6 Bhuj earthquake. Focal mechanism from teleseismic observation of body waves consistently indicates reverse faulting for Bhuj earthquake, which is accorded with the general North–South contraction of the Indian plate and their modelling suggests that most of moment was released from a small rupture area with high slip (≥ 10 m). The static stress drop of the Bhuj earthquake was found to be unusually high^{2,7–9}, about 16–46 MPa. Analysis of motions of historic triangulation monuments of the Great Trigonometric Survey (surveyed in 1856–60) also shows significant NNE–SSW-directed strain contraction in the epicentral zone^{9,10} (Figure 1). Similarly, other geophysical studies^{11–16} clearly demarcate the high density/conductive body and mass deficiency at greater depths in the epicentral region of the Bhuj earthquake. The tectonic forces¹⁷ probably induce uplift of blocks over the palaeo-rift region^{6,18}, which is also evident from an uplift of 157 cm observed in the epicentral region after the Bhuj earthquake¹⁹. These complexities act to destabilize the pre-existing faults^{11,20}. The present study delineates the plausible factors for anomalous stress distribution and presents a model to understand the build-up of subsurface stress in the hypocentral region of the M_w 7.6 Bhuj earthquake.

Historical seismicity and strain rate

The Kachchh rift basin has been experiencing earthquakes for quite some time (1820–35, 1910–35 and 1956–96) and its

*For correspondence. (e-mail: go4sekhar@yahoo.com)

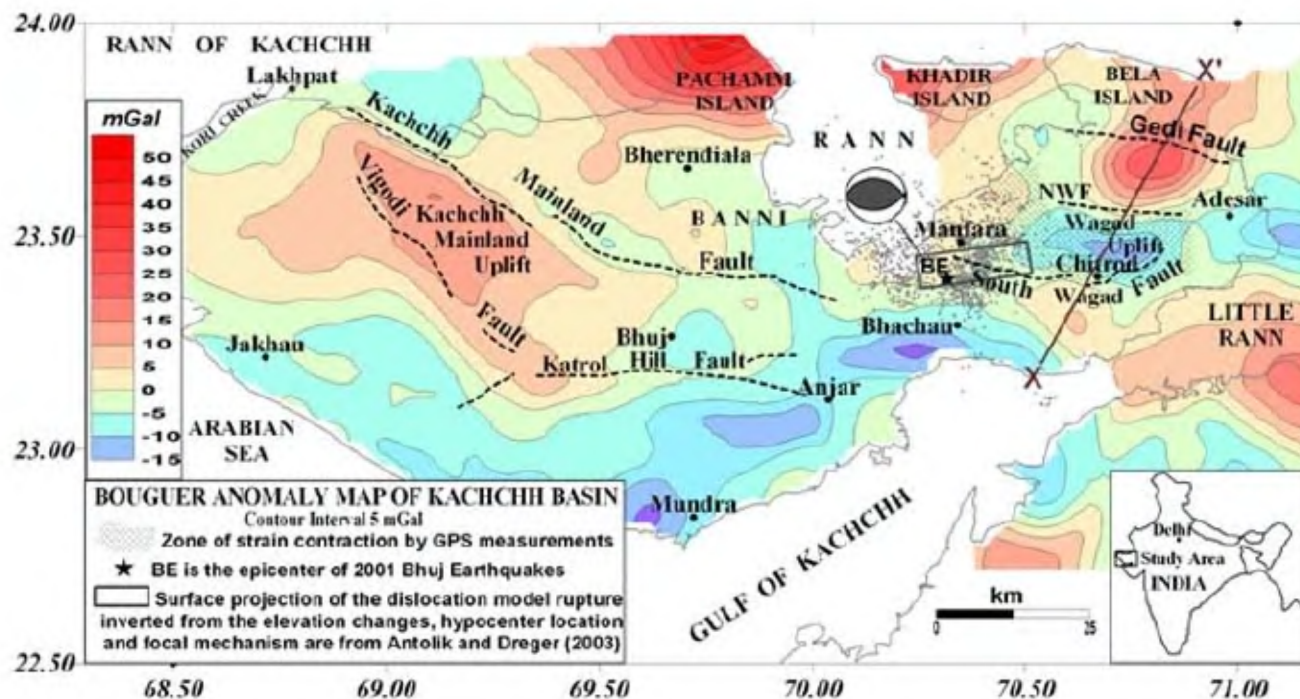


Figure 1. Bouguer anomaly map of Kachchh¹² showing major tectonic elements of Kachchh rift basin, zone of strain contraction demarcated by GPS measurements^{9,10} for the 1856–2001 epoch in the epicentral region and a profile XX' across the Wagad uplift for integrated analysis. Grey dots indicate aftershock distribution of the Bhuj earthquake^{3,4,7}.

historical seismicity has been studied by several authors^{21–25}. Seismicity on the principal faults of the Kachchh rift is not clear, as the two boundary faults Nagar Parker and North Kathiawar may not be active since early Jurassic, knowing that the basement is deeper within the rift than outside; whereas the Kachchh mainland, South Wagad and the Island belt fault do present clear topographic expression and were active since Mesozoic, as rocks of this period are displaced along these faults. However, their activity level is indecipherable, as being prominent on both the surface and tectonic maps, none of them was responsible for the 2001 Bhuj earthquake.

Internal strain might be progressively building up from the onset of Allah Bund earthquake²⁶ of 1819. We estimate strain rate by Anderson's method²⁷, as several faults having different orientations are embedded within the Kachchh rift basin. The regional strain rate can be computed as:

$$\varepsilon^* (\text{strain_rate}) = \frac{\sum M_0}{2.67 \mu A h t}, \quad (1)$$

where A is the geographical area ($60,000 \text{ km}^2$), $\sum M_0$ is the rate of seismic moment estimated for a period t (182 years), h is the average thickness of the seismogenic layer (20 km) and μ is the rigidity of the material ($3.6 \times 10^{11} \text{ dyne-cm}$). The strain rate is estimated as 6.0×10^{-8} per year for the entire Kachchh region, which is equivalent to strain

rate obtained using GPS measurements^{9,10}. The strain rate in Kachchh basin is much higher than that in the Indian shield (6.01×10^{-10} per year) and comparable to North America (6.8×10^{-10}), one of the highest in stable continental regions of the world²⁸. The average slip rate computed using historical earthquake data comes to $\sim 5\text{--}6 \text{ mm/yr}$. The maximum expected slip for the period of 182 years' inter-occurrence of two catastrophic events of 1819 and 2001 is found to be $\sim 10 \text{ m}$ and agrees well with seismic studies^{29,30}.

Failure stress criterion and fluid pressure

Failure criterion at any point for any formation, is the maximum shear resistance of the material (shear strength τ) which equals the cohesive shear stress on a failure plane plus internal frictional resistance ($\psi \sigma_n$), where ψ is the coefficient of internal friction and σ_n is the normal stress orthogonal to the fault plane. Several workers^{16,31,32} have suggested the presence of fluids at the hypocentral region of the Bhuj mainshock of 26 January 2001. Presence of pore fluid at a depth of 7–20 km in the active fault zone can develop hydrostatic/suprahydrostatic fluid pressure which reduces the normal stress abnormally to brittle failure stress conditions³³.

According to Streit and Cox³⁴, the stress difference of about 100 MPa and fault dip angles of $45\text{--}55^\circ$ may activate

failure at 7–20 km depth with hypocentral pore fluid factors (λ_v) of 0.8–1.0 for reverse faults, 0.6–0.9 for strike slip faults and <0.8 for normal faults. Applying the same for estimating the pore-fluid pressures in this region, the effective overburden pressure (σ_{v-eff}) at a location on a fault plane can be expressed as:

$$\sigma_{v-eff} = \rho_r gh - P_f, \quad (2)$$

where P_f is the ambient pore-fluid pressure, ρ_r is the rock density, g is the gravitational acceleration and h is the depth of the focus. An average rock density of $\rho_r = 2700 \text{ kg/m}^3$ has been used for granitic/gneissic rocks.

It is assumed that one of the principal stresses is vertical and the intermediate stress lies within the fault plane. For reverse/thrust fault, effective least principal stress is equal to effective vertical overburden stress. Fluid pressures on faults can be expressed as the difference between the overburden pressure imposed by the rock mass and the effective vertical stress. Thus the pore fluid factor (λ_v) is

$$\lambda_v = P_f / \sigma_v = 1 - \frac{\sigma_{v-eff}}{\rho_r gh}. \quad (3)$$

The effective principal stresses for reactivation of reverse fault in the present study for the Bhuj mainshock have been considered. Parameters obtained from different studies^{33,34} are considered as focal depth $h = 22 \text{ km}$, reverse fault dip angle $\theta = 50^\circ$, assumed values of cohesive fault strength (C_0) are 60 bars, and internal coefficient friction $\mu_2 = 0.8$. For compressional shear failure along the reverse fault, the pore fluid factor³⁴ is expressed as:

$$\lambda_v = 1 - \frac{-2C_0 + (\sigma_1 - \sigma_2)(1 - \mu_2 \tan \theta) \sin 2\theta}{2\rho_r gh\mu_2}. \quad (4)$$

From eq. (4), we have computed the pore fluid factor (λ_v) as 0.81–0.89 for the dip of the fault, i.e. 60° . Thereby the pore fluid pressure estimated as $P_f = 343 \text{ MPa}$ will reduce the normal stress of 185 MPa at the focus. The reduced normal stress shifts the Mohr's circle towards failure stress condition (left of the original circle) and effective coefficient of friction as obtained from the Mohr's diagrams are 135 MPa and 0.24–0.34 respectively. The shear stress at this point of failure is about 50 MPa as shown in Figure 2.

Shear stress model

In deciphering the real cause of stress concentration in the epicentral zone of the Bhuj earthquake, here we present a model whose geometry and associated parameters mimic the crustal configuration of Kachchh. We have adopted 2D cross-sectional stress modelling through finite element

method, whose fundamental aspects are meshing, material properties and boundary conditions. Meshing involves well-structured geometry and all the elements must be interconnected and their finite element equations be formed at each node. The model represents the structured mesh, wherein 400 elements are ordered in a consistent pattern depicting regions, namely upper crust, shallow intrusive plug-like igneous body, middle-lower crust, crustal root-like serpentinized body (Figure 3) and the whole block conforms to the linear elastic model. The proportionality

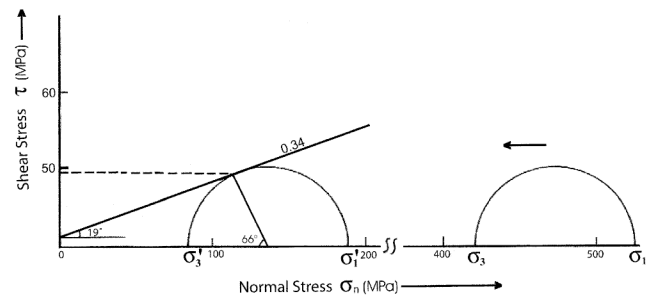


Figure 2. Mohr's circle moves towards failure stress condition and effective coefficient of friction as obtained from the Mohr's diagram. The shear stress at this point of failure is ~50 MPa.

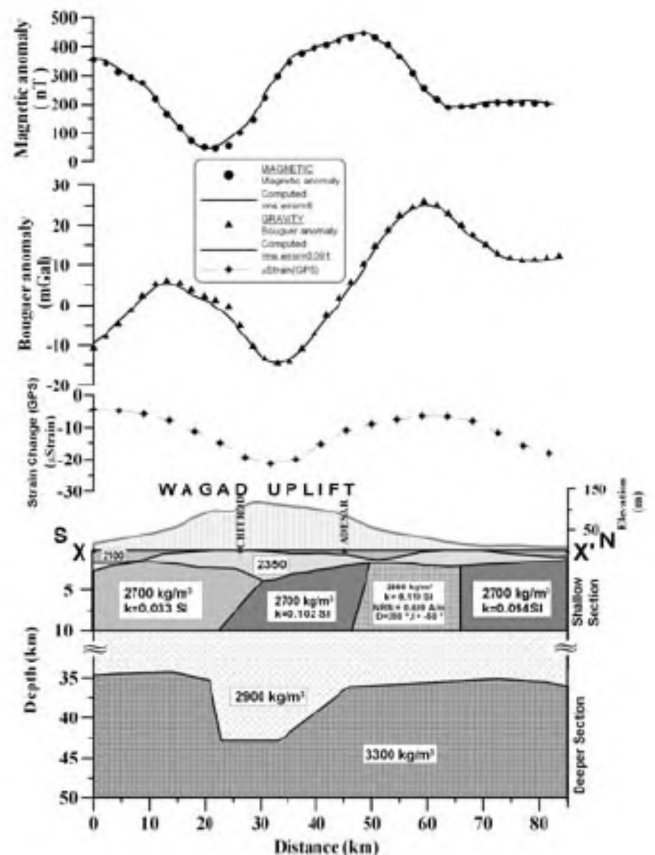


Figure 3. Crustal cross-section derived from 2D simultaneous modelling of total intensity magnetic and Bouguer gravity anomaly along profile XX'. It also shows strain contraction in the epicentral region as deduced by GPS measurement for the epoch (1856–2001)^{9,10}.

constants are Young's modulus, E and Poisson's ratio ν . The stresses and strains are related by the equation as follows:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xz} \end{Bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 \\ \nu & 1-\nu & \nu & 0 \\ \nu & \nu & 1-\nu & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix} \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{xz} \end{Bmatrix} \quad (5)$$

For a two-dimensional (XZ-plane) strain analysis, ϵ_y is zero. The stresses and strains are directly related by a constant, which is representative of pure volumetric strain. Furthermore, the term $E/((1+\nu)(1-2\nu))$ tends towards infinity as $(1-2\nu)$ approaches zero. Physically, this means that the volumetric strain tends towards zero as ν approaches 0.5. The structured model is subjected to horizontal stress field collectively with pure elastic-linear properties. Material properties such as Poisson's ratio and Young's modulus were constrained from earlier geophysical studies^{31,32}, horizontal tectonic forces (tectonic stress due to northeastward movement of the Indian plate) with an assumed ridge compression³⁵ (push force) of 30 MPa/km, uniform overburden load of 60 bars and load of 274 MPa due to high density intrusive body (ρgh). The stress at failure point of ~50 MPa, as discussed in the previous section and the reported high stress drop^{2,7-9} of 20 MPa (approximately) suggest at least ~70 MPa of shear stress at the hypocentral zone. The parameter ranges required to obtain the acceptable solution were as follows: ν , 0.25–0.32, E , 2×10^{10} – 11×10^{10} N/m². The best-fit shear stress model (Figure 4) obtained for the buoyant forces (~130 MPa) acting on the crustal root (serpentinite body) shows the south-dipping shear stress concentration (~70 MPa) oriented in the fault plane construed by geodetic¹⁹ and teleseismic studies⁸, and also well contained in the mainshock and after-shocks zone.

Discussion and conclusion

The 2001 earthquake and other historic earthquakes were reverse-faulting events, consistent with NE–SW-directed compression and evidence of deep crustal seismogenesis with inference that elevated fluid pressures may have weakened, deep-seated faults. However, it is difficult to conceive presence of water in the fault zone down to 35 km and seems more likely that any fluid involved would be something more exotic. Kachchh presents a thick seismogenic crust (10–35 km), as seen by recent and historic earthquakes. Thickness of seismogenic crust is representative of the strength of the continental lithosphere or the effective elastic thickness³⁶. In such a case, the mass deficiency

identified in the form of crustal root (Figure 3) may unlikely be a product of isostatic compensation for a small topography of ~150 m. Besides, there is no evidence of any rapid and large-scale erosion in this region. The instability of crustal blocks, presence of high pore fluid pressure³⁷, high strain rate^{9,10} and high heat flow (55–93 mW/m²) over patches of gravity high (>30 mGal) or regions falling in seismic zone V, viz. Bhuj earthquake region^{38,39} indicate maximum likelihood of serpentinite at focal depth.

Dehydration of serpentinite generates pore-fluid pressure and plays an important role in thrust faulting^{40,41}. It increases hydrostatic pressure P_{H_2O} , until it attains P_{total} (litho-static pressure). Further increase in P_{H_2O} with enhanced litho-static load will expel water from the rocks. Expulsion of fluids will dilute solutes other than H₂O water and will maintain $P_{H_2O} \sim P_{total}$ ^{42,43}. The peculiar characterization of serpentinite rocks indicates that its volume changes fast with change in composition (decrease in density increases the volume and results in cleavage development). The bimodal nature of the crust, inferred from after-shock studies, indicates that rigidity in the upper/middle crust, in contrast to lower crust, differs mainly due to serpentinitized bodies. Considering serpentinites at deeper crustal level may be worthwhile; as causative fault associated with earthquake may compose serpentinite gouge⁴² and also embrittlement associated with dehydration of serpentinites extends up to greater depths^{44,45}.

Analyses of different geophysical studies such as gravity-magnetic¹²⁻¹⁴ and magneto-telluric^{15,16}, indicate unstable structure at the focal depth of the Bhuj earthquake, and anomalous mass deficiency^{13,14} causing differential uplift

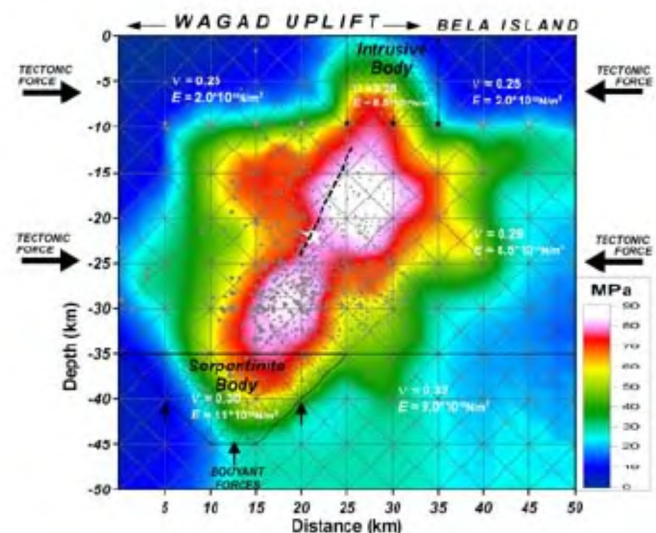


Figure 4. Two-dimensional shear stress distribution along a part of profile XX'. Computed model shows the south-dipping anomalous shear stress (~70 MPa) oriented in the construed fault plane^{8,19}. Hypocentre of Bhuj earthquake shown by white star and grey dots indicates after-shock depth distribution^{3,4,7}.

having abnormal (high) conductivity at middle to lower crustal zone (1–30 Ohm-m)¹⁵. Poisson's ratio (0.32)^{31,32}, seismicity pattern and bi-modal nature of the crust in the backdrop of regional tectonic stress indicate that seismicity in this region could be fluid-driven^{31,32}. Further, the reduced static coefficient of friction (0.24–0.34) and the presence of high pore-fluid pressures (343 MPa) can at best be explained by the presence of fluids. Both fluids and high pore pressure play a major role in greasing the fault planes. These observations in concurrence with the high Poisson's ratio are strong indicators of the presence of serpentinite⁴⁶. In the process of serpentinization, Moho is likely to restore to new equilibrium position⁴⁷ and undergo deformation depending on the geological and tectonic setting. In the present case it deformed at the focal depth giving rise to deep crustal tectonics. These observations and the processes governed by serpentinization are the most likely causal factors for the Bhuj earthquake.

A 2D shear stress model using finite element method constraining with the Bhuj aftershocks, shallow to deep crustal heterogeneity and ambient tectonic forces consistent with NE–SW-directed compression of this basin, indicate high shear stress in the hypocentral depth of the Bhuj earthquake, thereby emphasizing the dominant role of local tectonic elements for the anomalous shear stress in the hypocentral region of the Bhuj earthquake. The computed shear stress model also shows south-dipping anomalous shear stress dispersion (~70 MPa) oriented in the construed fault plane^{8,19} and found running into a structural barrier² (intrusive body) at the top, which might have abruptly stopped the powerful rupture. The intrinsic tectonic complexities as discussed above in the Kachchh rift basin may have facilitated the causative factors for the intraplate earthquake.

1. Bilham, R., Bendick, R. and Wallace, K., Flexure of the Indian plate and intraplate earthquakes. *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 2003, **112**, 315–329.
2. Bodin, P. and Horton, S., Source parameters and tectonic implications of aftershocks of the M_w 7.6 Bhuj earthquake of 26 January 2001. *Bull. Geol. Soc. Am.*, 2004, **94**, 818–827.
3. Kayal, J. R., De, R., Ram, S., Sriram, B. V. and Gaonkar, S. G., Aftershocks of the 26th January 2001 Bhuj earthquake in western India and its seismotectonic implications. *J. Geol. Soc. India*, 2002, **59**, 391–417.
4. Mandal, P. *et al.*, Characterization of the causative fault system for the 2001 Bhuj earthquake of M_w 7.7. *Tectonophysics*, 2004, **378**, 105–121.
5. Mandal, P. and Johnston, A., Estimation of source parameters for the aftershocks of the 2001 M_w 7.7 Bhuj earthquake, India. *Pure Appl. Geophys.*, 2006, **163**, 1537–1560.
6. Li, Q., Liu, M. and Yang, Y., The 01/26/2001 Bhuj earthquake: Intraplate or interplate? In *Plate Boundary Zones* (Stein, S. and Freymueller, J.), American Geophysical Union, Geodynamics Series, 2002, vol. 30, pp. 255–264.
7. Negishi, H., Mori, J., Sato, T., Singh, R., Kumar, S. and Hirata, N., Size and orientation of the fault plane for the 2001 Gujarat, India earthquake (M_w 7.7) from aftershock observation: a high stress drop event. *Geophys. Res. Lett.*, 2002, **29**, 1949.
8. Antolik, M. and Dreger, D. S., Rupture process of the 26 January 2001 M_w 7.6 Bhuj, India, earthquake from teleseismic broadband data. *Bull. Seismol. Soc. Am.*, 2003, **93**, 1235–1248.
9. Wallace, K., Bilham, R., Blume, F., Gaur, V. K. and Gahalaut, V., Geodetic constraints on the Bhuj 2001 earthquake and surface deformation in the Kachchh Rift Basin. *Geophys. Res. Lett.*, 2006, **33**, L10301.
10. Jade, S. *et al.*, Pre-seismic, co-seismic and post seismic displacements associated with the Bhuj 2001 earthquake derived from recent and historic geodetic data. *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 2003, **112**, 331–345.
11. Gupta, H. K. *et al.*, Bhuj earthquake of 26 January 2001. *J. Geol. Soc. India*, 2001, **57**, 275–278.
12. Chandrasekhar, D. V. and Mishra, D. C., Some geodynamic aspects of Kachchh basin and seismicity: An insight from gravity studies. *Curr. Sci.*, 2002, **83**, 492–498.
13. Mishra, D. C., Chandrasekhar, D. V. and Singh, B., Tectonics and crustal structures related to Bhuj earthquake of 26 January 2001: Based on gravity and magnetic surveys constrained from seismic and seismological studies. *Tectonophysics*, 2005, **396**, 195–207.
14. Chandrasekhar, D. V., Singh, B., Firozishah, Md. and Mishra, D. C., Analysis of gravity and magnetic anomalies of Kachchh rift basin, India and its comparison with the New Madrid seismic zone, USA. *Curr. Sci.*, 2005, **88**, 1–8.
15. Arora, B. R., Gautam, R. and Singh, A. K., Mid-crustal conductor below the Kachchh rift basin and its seismogenic relevance to the 2001 Bhuj earthquake. *Deep Continental Studies in India, DST News*, 2002, **12**, 22–24.
16. Ramlingeswara Rao, B., Harinarayana, T., Chandrani Singh, Chandrasekhar, D. V. and Rao, V. K., Triggering of seismicity by pore-fluids due to Bhuj earthquake of 26 January 2001, Gujarat, India. *Tectonophysics*, 2007 (under review).
17. Storetved, K. M., The Tethys Sea and the Alpine–Himalayan orogenic belt: Mega-elements in a new global tectonic system. *Phys. Earth Planet. Inter.*, 1990, **62**, 141–184.
18. Stein, S., Sella, G. and Okal, E., The 26 January 2001 Bhuj earthquake and the diffuse western boundary of Indian plate. In *Plate Boundary Zones* (eds Stein, S. and Freymueller, J.), American Geophysical Union, Geodynamics Series, 2002, vol. 30, pp. 243–254.
19. Chandrasekhar, D. V., Mishra, D. C., Singh, B., Vijayakumar, V. and Bürgmann, R., Source parameters of the Bhuj earthquake, India of 26 January 2001 from height and gravity changes. *Geophys. Res. Lett.*, 2004, **31**, L19608.
20. Mishra, D. C., Singh, B., Tiwari, V. M., Gupta, S. B. and Rao, M. B. S. V., Two cases of continental collision and related tectonics during the proterozoic period in India – Insights from gravity modeling constrained by magnetotelluric studies. *Precambrian Res.*, 2000, **99**, 149–169.
21. Oldham, T., Catalogue of Indian earthquakes. *Mem. Geol. Surv. India*, 1883, **19**, 163–215.
22. Malik, J. N., Parag, S., Sohoni, Karanth, R. V. and Merh, S. S., Modern and historic seismicity of Kachchh peninsula, western India. *J. Geol. Soc. India*, 1999, **54**, 545–550.
23. Rajendran, C. P. and Rajendran, K., Characteristics of deformation and past seismicity associated with the 1819 Kachchh earthquake northwestern India. *Bull. Seismol. Soc. Am.*, 2001, **91**, 407–426.
24. Talwani, P. and Gangopadhyaya, A., Tectonic framework of the Kachchh earthquake of 26 January 2001. *Seismol. Res. Lett.*, 2001, **72**, 336–344.
25. Ramalingeswara Rao, B. and Sitapathi Rao, P., Historical seismicity of the Peninsular India. *Bull. Seismol. Soc. Am.*, 1984, **74**, 2519–2534.
26. To, A., Bürgmann, R. and Pollitz, F., Postseismic deformation and stress changes following the 1819 Rann of Kachchh, India earthquake: Was the 2001 Bhuj earthquake a triggered event?. *Geophys. Res. Lett.*, 2004, **31**, L13609.

27. Anderson, J. G., Seismic strain rates in the central and eastern United States. *Bull. Seismol. Soc. Am.*, 1986, **76**, 272–290.
28. Ramalingeswara Rao, B., Historical seismicity and deformation rates in the Indian Peninsular Shield. *J. Seismol.*, 2000, **4**, 247–258.
29. Mori, J., Negishi, H. and Sato, T., Slip distribution of the 2001 West India earthquake from inversion of teleseismic data. In International Conference on Seismic Hazard with Particular Reference to Bhuj Earthquake of 26 January 2001, DST and IMD, New Delhi, 3–5 October 2001, pp. 6–8.
30. Yagi, Y. and Kikuchi, M., Western India earthquake website, 2001; <http://www.eic.eri.u-tokyo.ac.jp/vuji/southindia/index.html>.
31. Kayal, J. R., Zhao, D., Mishra, O. P., De, R. and Singh, O. P., The 2001 Bhuj earthquake: Tomographic evidence for fluids at the hypocenter and its implications for the rupture nucleation. *Geophys. Res. Lett.*, 2002, **29**, 2152.
32. Mishra, O. P. and Zhao, D., Crack density, saturation rate and porosity of the 2001 Bhuj, India, earthquake hypocenter: A fluid driven earthquake? *Earth Planet. Sci. Lett.*, 2003, **212**, 393–406.
33. Sibson, R. H., Fault rocks and fault mechanisms. *J. Geol. Soc., London*, 1977, **133**, 191–213.
34. Streit, J. E. and Cox, S. F., Fluid pressures at hypocenters of moderate to large earthquakes. *J. Geophys. Res.*, 2001, **106**, 2235–2243.
35. Mandal, P., Intraplate stress distribution induced by topography and crustal density heterogeneities beneath the South Indian Shield, India. *Tectonophysics*, 1999, **302**, 159–172.
36. Maggi, A., Jackson, J. A., McKenzie, D. and Priestley, K., Earthquake focal depths, effective elastic thickness, and the strength of the continental lithosphere. *Geology*, 2000, **28**, 495–498.
37. Padhy, S. and Crampin, S., High pore-fluid pressures at Bhuj, inferred from 90°-flips in shear-wave polarizations. *Geophys. J. Int.*, 2006, **164**, 370–376.
38. Ravi Shanker *et al.*, *Geothermal Atlas of India*. Geol. Surv. India. Spec. Publ., 1991, vol. 19, p. 144.
39. Roy, A. B., Geological and geophysical manifestations of the Reunion plume-Indian lithosphere interaction: Evidence from north-west India. *Gondwana Res.*, 2003, **6**, 487–500.
40. Kerrick, D., Serpentine and subduction. *Science*, 2002, **298**, 1344–1345.
41. Rubey, W. W. and Hubert, M. K., Role of fluid pressure in mechanics of overthrust faulting. *Bull. Geol. Soc. Am.*, 1959, **70**, 167–206.
42. O'Hanley, D. S., Serpentinities, records of tectonics and petrological history. In *Oxford Monographs on Geology and Geophysics*, Oxford University Press, New York, 1966, vol. 34, p. 277.
43. Ramalingeswara Rao, B. and Rao, V. K., Influence of fluids on deep crustal Jabalpur earthquake of 21 May 1997: Geophysical evidences. *J. Seismol.*, 2006, **10**, 301–314.
44. Floyd, J. S., Mutter, J. C., Goodliffe, A. M. and Taylor, B., Evidence for fault weakness and fluid flow within an active low-angle normal fault. *Nature*, 2001, **411**, 779–783.
45. Ralieggh, C. B. and Paterson, M. S., Experimental deformation of serpentinite and its tectonic implication. *J. Geophys. Res.*, 1965, **70**, 3965–3985.
46. Rao, V. K. and Prasad, S. N., Fluid genesis through serpentinites and the origin of subsurface electrical conductors in northwest India and adjoining regions. *Earth Planet. Sci. Lett.*, 2001, **190**, 79–91.
47. Rosendahl, B. R., Meyers, J. and Groschl, H., Nature of the transition of continental to oceanic crust and the meaning of reflection Moho. *Geology*, 1992, **20**, 721–724.

ACKNOWLEDGEMENTS. We thank Dr V. P. Dimri, Director, National Geophysical Research Institute, Hyderabad for support and permission to publish this work. We also thank the anonymous reviewer for constructive suggestions.

Received 24 March 2006; revised accepted 12 December 2006