The 01/26/2001 Bhuj, India, Earthquake: Intraplate or Interplate?
Qingsong Li, Mian Liu, and Youqing Yang
Dept. of Geological Sciences, University of Missouri, Columbia, Missouri

The Mw=7.7 Republic Day (01/26/2001) earthquake near Bhuj in western India killed nearly 20,000 people and destroyed tens of thousands of homes. The cause and the tectonic implication of this earthquake have been the subject of intensive debate. Located ~400 km from the plate boundary, the Bhuj earthquake bears significant similarities with some intraplate earthquakes such as those in the New Madrid seismic zone in central United States. On the other hand, the plate boundary in western India is known to be diffuse, thus the Bhuj earthquake may reflect broad plate boundary deformation. To investigate the cause of the Bhuj earthquake and numerous other historic earthquakes concentrated in this part of the Indian plate, we have developed a viscoelastic finite element model to simulate the stress state within the lithosphere of western India. Our results indicate that the intracontinental thrusting and shearing along the northwestern Indian plate boundary may have caused deviatoric stresses to broadly diffuse into the Indian continent. When the internal rheologic heterogeneities of the Indian plate, such as the inherited mechanical weakening in the Kutch rift basin, is included, the model predicts a broad earthquake-prone zone extending hundreds of kilometers into the interior of the Indian plate that includes the Bhuj earthquake and most historic earthquakes in western India.

1. INTRODUCTION

The paradigm of plate tectonics predicts concentrations of earthquakes, volcanism, and other tectonic activity within narrowly defined plate boundaries, but no significant deformation within the rigid plates. Thus the infrequent, but often large intraplate earthquakes, such as the three \( M_w > 7.0 \) earthquakes that occurred between 1811-1812 in the New Madrid area in central United States [Johnston and Schweig, 1996; Hough et al., 2000; Ellis et al., 2001], have been enigmatic, and their rare occurrence has further hampered studies of intraplate earthquakes. Thus the \( M_w=7.7 \) earthquake near Bhuj in western India, which occurred on 1/26/2001, has stimulated considerable interests and debate (Fig. 1). This earthquake was one of the most devastating earthquakes in this region, causing > 19,000 fatalities and billions of US dollars of damage [Bendick et al., 2001]. Located ~400 km away from the nominal plate boundary, the Bhuj earthquake shared significant similarities with those in the New Madrid Seismic Zone (NMSZ), such as the extensive liquefaction and the lack of surface ruptures. Some workers regard the Bhuj earthquake as a new example of intraplate earthquakes that may provide a rare chance for understanding intraplate earthquakes in general and the large earthquakes in the NMSZ in particular [Bendick et al., 2001; Ellis et al., 2001]. Others, however, recognize the diffuse plate boundary zone deformation in western India and many other places in the world and suggest that the Bhuj earthquake resulted directly from the plate boundary processes and thus may provide more insight into the dynamics of diffuse plate boundaries than intraplate deformation [Stein et al., this volume]. Thus the debate of whether the Bhuj earthquake was an intraplate or an interplate event is by no means purely semantic; the
real focus of this debate is on the tectonic implications of this event.

Figure 1. Topographic relief and seismicity (Harvard CMT catalog 1976-2001, M≥5) of the Indian Peninsular and the surrounding area. The enlarged fault-plane solution is for the 01/26/2001 Bhuj earthquake [NEIC]. The white rectangle is the model domain.

To get to the heart of this debate, we need to address the question of what caused the Bhuj earthquake. Numerous hints have been provided by geological observations. The Bhuj earthquake occurred in a region of abnormally concentrated seismicities [Malik et al., 1999; Talwani and Gangopadhyay, 2001]; the 1819 Rann of Kutch earthquake (Mw=7.5-7.8) that caused considerable casualties and massive property damage occurred only 180 km north of Bhuj. Since 1668 there have been more than 10 major (M> 5) earthquakes in this region [Malik et al., 1999; Rajendran and Rajendran, 2001] (Fig. 2). Most of these earthquakes, including the Bhuj earthquake, occurred within an ancient rift complex and on reverse faults with roughly E-W strike (Fig. 2). The nearly N-S principal compressional stresses indicated by these events are consistent with the Indo-Asian plate convergence [Chung and Gao, 1995; Talwani and Gangopadhyay, 2001]. The specific questions we attempt to address in this work are: 1) Why did the Bhuj event and many historic earthquakes concentrate in this part of the Indian plate? 2) Were these earthquakes mainly controlled by plate boundary processes or by the rift complex?

We explore the answers to these questions by numerically simulating stress evolution in the lithosphere of western India in a three-dimensional finite element model. Systematic numerical experiments were conducted to evaluate each major factor that may have contributed to the concentration of seismicity in this region. Our results indicate that the intracontinental
thrusting along the north-western corner of the Indian plate is the major cause of broad diffusion of deviatoric stresses into the Indian continent. A number of factors, including the contrast in mechanical strength between the oceanic and continental part of the Indian plate and structural weakening of the rift basins, may have contributed to the concentration of seismicity into a broad zone extending hundreds of kilometers into the Indian plate.

2. THE BHUJ EARTHQUAKE AND ITS TECTONIC SETTING

The $M_w=7.7$ earthquake occurred in the morning of January 26, 2001, on the Republic Day of India. The epicenter is located at 23.40°N and 70.32°E [NEIC: http://neic.usgs.gov], near Bhuj in the province of Gujarat, India (Fig. 2). The official death toll from the India government was close to twenty thousand [Bendick et al., 2001]. Thousands of houses were destroyed and more than half million of people were left homeless. Initial results indicate a shallow (~20 km) focal depth, with a roughly E-W trending thrust fault plane [NEIC; Gaur et al., 2001]. Based on the aftershock data, the rapture was estimated to have occurred along a plane with a 50-100 km along-strike length and 15-30 km down-dip rupture width. The slip was 1-4 m, reaching ~12 m near the hypocenter [Antolik and Dreger, 2001; Bendick et al., 2001]. This event apparently caused few surface scarp[s [EERI, 2001; Rajendran et al., 2001].

The Bhuj earthquake occurred in the Kutch (Kachchh) rift basin, part of a Mesozoic rift complex formed during the break-up of the Gondwana and subsequent northward drift of the Indian plate [Biswas, 1982; Rajendran and Rajendran, 2001; Talwani and Gangopadhyay, 2001] (Fig. 2a). It is bounded by the Nagar Parkar fault to the north, the Kathiawar fault to the south, and the nearly north-trending Cambay rift basin to the east. A shallow seismic reflection survey in the Gulf of Kachchh shows an E-W trending offshore basin parallel to the southern boundary of the Kutch rift basin. The basin is filled with sediments ranging in age from Middle Jurassic to recent. Around 65 Ma extensive flood basalts erupted in this part of the Indian plate when it passed over the Deccan/Reunion hotspot [Courtillot et al., 1986], forming the enormous flood basalt province known as the Deccan Traps. The Mesozoic sediments in the Kutch rift basin were intruded and covered by the Deccan basalts [Biswas, 1982]. Seismic tomography indicates a pronounced low-velocity structure in the upper mantle under the Kutch region [Zhou and Murphy, manuscript in prep.], probably a relic of the thermal perturbation by the mantle.
plume. Following the Indo-Asian collision ~50 million years ago, the Kutch rift basin, like other parts of the Indian plate, was subjected to north-south compression, resulting in roughly E-W trending fold-thrust structures within the rift basin [Malik et al., 2000; Rajendran and Rajendran, 2001]. The rift complex in western India has been the site of numerous large earthquakes [Malik et al., 1999; Talwani and Gangopadhyay, 2001]; most of these earthquakes occurred in the Kutch rift basin and surrounding regions (Fig. 2b).

3. NUMERICAL MODEL

To investigate why many of the large earthquakes concentrated in the Kutch rift basin and surrounding regions, we developed a three-dimensional finite element model to simulate stress distribution and evolution in western India. Fig. 3 shows the model geometry and boundary conditions. The low-relief Indian plate is approximated by a flat viscolastic plate. The rheologic parameters for the basic model include a $2.0 \times 10^{10}$ Pa Young’s modulus, a 0.3 Poisson’s ratio, and a $1.0 \times 10^{23}$ Pa s effective viscosity. These are conventional values [Turcotte and Schubert, 1982; Williams and Richardson, 1991; Flesch et al., 2001], and because our focus here is on stress patterns instead of absolute stress values, our general conclusions are not sensitive to the chosen parameters. In some cases the rheologic difference between continental and oceanic parts of the Indian plate and the rheologic effects of the rift complex are considered. The southern side of the model domain is a velocity boundary, and viscous damping is imposed on the northern side to produce internal shortening within the India continent consistent with the GPS data, which is $2-7 \times 10^{-9}$ yr$^{-1}$ [Paul et al., 2001]. To be conservative, we used a value of $2 \times 10^{-9}$ yr$^{-1}$ in the model, whereas using a greater shortening rate will enhance the stress patterns shown below. We used 35 mm yr$^{-1}$ on the southern side of the model based on the GPS measurements of the Indian plate [Holt et al., 2000; Paul et al., 2001; Sella et al., 2002]. However, we produced similar results using 50 mm yr$^{-1}$ as indicated by the plate motion models [DeMets et al., 1990; DeMets et al., 1994]. This is because that, in either case, the viscose damping on the northern side of the model was adjusted to produce the same shortening rate within the model Indian plate, which is constrained by the GPS data. The right side is in the middle of the Indian plate and can be viewed as a symmetric boundary; we used viscous damping elements to resist motion normal to this boundary. The left side represents the western boundary of the Indian plate, which changes from strike-slip between the Indian and Arabian plates to a complex of strike-slip motion and intracontinental thrusting north of the poorly defined triple junction (Fig. 1). Considerable thrusting and crustal shortening along the festoon-shaped Sulaiman range and other ranges are reflected in high seismicity in this region, and 5-14 mm yr$^{-1}$ of N-S motion between India-Eurasia is accommodated here by intracontinental thrusting [Bernard et al., 2000]. We used additional viscous damping to simulate resistance to the northward motion of the Indian plate along this boundary (Fig. 3) and will show that this boundary is important for deviatoric stresses to diffuse into the Indian plate.

**Figure 3.** Finite element mesh and boundary conditions of the numerical model. M1, M2, M3 are model domains for the continental part of the Indian plate, oceanic part of the Indian plate, and the Kutch rift basin, respectively. See text for discussions.

Deviatoric stresses within the model Indian plate result from the northward motion imposed on the southern side and resistance on the north-
ern and northwestern sides of the model domain. Flexural stresses due to loading of the Himalayas and stresses acting on the base of the plate arising from the asthenosphere are not included. The distribution and evolution of the deviatoric stresses are obtained by solving the force balance equation:

$$\frac{\partial \tau_{ij}}{\partial x_j} + F_i = 0$$

(1)

using the finite element method. Here $\tau_{ij}$ is the stress tensor, $F_i$ is the body force, and $i,j=1,2,3$. In this model no topographic loading is assumed because of the low relief of the Indian plate, and lithostatic body force is removed when calculating the deviatoric stresses [Liu et al., 2000a]. We build the numerical model using the commercial finite element package FEPG (www.fegensoft.com/English/index.htm).

4. MODEL RESULTS

Systematic numerical experiments were conducted to evaluate the effects of boundary conditions and major factors that may have contributed to the concentration of deviatoric stresses in the Kutch region. Fig. 4 shows the predicted pattern of the principal compressional stress ($\sigma_1$). As expected, $\sigma_1$ is horizontal and nearly parallel to the direction of plate convergence. The slightly westward rotation in the northwestern part of the Indian plate was caused by the resistive boundary condition in the model simulating the effects of intracontinental thrusting along this part of the Indian plate boundary (Fig. 3). The rotation would be larger if the resistance was greater; however, the resistance used here is the same as that along the northern side of the model – the Himalayan front, where the value is constrained by the GPS-measured strain rate within the Indian plate and is likely greater than the resistance along the northwestern plate boundary. The general pattern of $\sigma_1$ remained similar when other reasonable boundary conditions and model rheology were used, so the results will not be discussed below. The stress pattern in Fig. 4 is consistent with Late Miocene-present structures and the focal mechanisms of earthquakes in the Kutch region that indicate predominate N-S compression (Fig. 2).

Figure 4. Predicted principal compressional stress ($\sigma_1$) within the crust at 20 km depth. The fault-plane solution is for the Bhuj earthquake.

Figure 5. (a) Arrows are the predicted surface velocity. The gray background shows the northward velocity contour. The black line indicates
the coastline, and the star marks the epicenter of the Bhuj earthquake. (b) The resulting shear stress ($\sigma_1-\sigma_3$) contour in the crust (at 20 km depth).

Fig. 5a shows the predicted surface velocity and deviatoric stresses within the upper crust. The intracontinental thrusting along the northwestern boundary of the Indian plate slows the plate motion near it, distorting the velocity field. The results are analogous to those of a moving glacier slowed near its margins by friction. The deviatoric stresses, which would be uniformly distributed at a given depth without the resistive northwestern boundary, diffuse into the Indian plate with the maximum centered near the triple junction (Fig. 5b).

The results in Fig. 5a may be regarded as an instantaneous velocity field, because displacement associated with earthquakes was not considered. In nature, the deviatoric stress would be released by earthquakes or aseismic slip when its value is greater than the yield strength of the lithosphere. We simulated such processes in the model by capping the deviatoric stresses below the lithospheric strength. Whenever the deviatoric stress grows beyond the lithospheric strength at a point in the model, a small, instantaneous displacement is added to dissipate the strain energy during a time-step, effectively simulating a seismic (or aseismic) slip. This process is repeated till the deviatoric stress at this point drops below the yield strength at the same point. The resulting velocity field is shown in Fig. 6a. Calculated over a period of a few thousand years with many cycles of stress accumulation and release, these results represent the averaged velocity field. Whereas the general pattern is similar to that in Fig. 5a, a high velocity gradient is localized near the plate boundary just north of the triple junction. The cumulative seismic slips lead to increased average velocity near the western coastal area while reducing the velocity north of it, roughly at the location of the Sulaiman range (see Fig. 2a). This velocity pattern indicates concentrated crustal contraction near the Sulaiman range, consistent with observations there [Bernard et al., 2000] (Figs. 1-2). The resulting deviatoric stresses are shown in Fig. 6b.

Comparison with Fig. 5b shows that diffusion of deviatoric stresses is further inland. In other words, the high seismicity near western Indian plate boundary facilitates inland diffusion of deviatoric stresses. The physical process may be analogous to earthquake-triggered stress migration along strike-slip faults [Stein, 1999].

**Figure 6.** (a) Predicted northward surface velocity similar to Fig. 5a, but in this case incremental strain (slip) was added to release the shear stress when it is greater than the yield strength of the lithosphere. Other symbols are the same as in Fig. 5. (b) The resulting shear stress ($\sigma_1-\sigma_3$) in the crust (at 20 km depth). The line A-A’ indicates the location of the vertical section in Fig. 7b.

The strength envelope of the model for the western Indian plate is shown in Fig. 7a. We calculated the yield strength assuming a 40-km thick granitic crust and a geotherm characterized by a steady-state surface heat flux of 60 mW m$^{-2}$.
[Pollack et al., 1993]. Given the paucity of heat flow data and the uncertainty of lithospheric structure in this region, this strength envelope is used only as a general guide for vertical stress distributions. The predicted vertical distribution of the deviatoric stresses is shown in Fig. 7b in an E-W section. The stresses are concentrated near the plate boundary (left side) but diffuse broadly into the plate interior. The high stresses are in the competent layers: the upper-middle crust and the uppermost mantle. To better delineate seismic zones we define an index parameter called fault intensity: fault intensity = deviatoric stress / lithospheric yield strength. Given the uncertainty of lithospheric strength and physical mechanisms controlling earthquakes, the fault intensity provides a useful indication of the likelihood of having earthquakes in a given region. Using the fault intensity, we re-plot the results of Figures 5 and 6 in Fig. 8a and 8b, respectively. The results show a diffuse seismic zone extending hundreds of kilometers into the Indian plate, enhanced by high seismicity near the western Indian plate boundary.

Although we have shown that intracontinental thrusting along the northwestern Indian plate boundary can cause broad diffusion of deviatoric stresses into the Indian plate, the patterns shown in Figs. 8 a-b do not resemble the distribution of seismicity in the Kutch region (Fig. 2b). One possible reason is the simplified plate boundary geometry used in the model. As shown in Fig. 2a, the thrust zone along the northwestern Indian plate boundary is very irregular. This is true especially for the extruding Sulaiman lobe and range, which accommodate 5-14 mm yr$^{-1}$ N-S plate convergence between the Indian and Eurasian plates [Bernard et al., 2000]. Using more realistic plate boundary geometries may predict more concentrated stresses in front of the Sulaiman range. Another reason may be the contrast between oceanic and continental lithospheric strength. It is well known that the oceanic lithosphere is generally much stronger than continental lithosphere [Kirby and Kronenberg, 1987; Lynch and Morgan, 1987]. Fig. 8c shows the results when we assume the oceanic part of the Indian plate is 10 MPa stronger than the continental part of the Indian plate. Such a rheologic contrast causes further inland diffusion of seismicity, and the predicted seismic zone is now more defined around the Kutch rift basin and surrounding regions. A better-defined seismic zone can be obtained if we assume the crust under the Kutch rift basin has been structurally weakened (Fig. 8d). In this case we predicted a distinctive seismic zone extending hundreds of kilometers into the Indian continent that is centered on the Kutch rift basin and includes most of the historic earthquakes in western India.

![Figure 7](image)

**Li et al.: Fig. 7**

**Figure 7.** (a) The strength envelope of the model lithosphere of western India. (b) Vertical distribution of the deviatoric stress along the A-A’ profile in Fig. 6b.

The 10 MPa structural weakening of the Kutch rift basin used in Fig. 8d is arbitrary. There are no reliable constraints on the extent of crustal weakening in the rift complex. One may argue that, with sufficient structural weakening of the Kutch rift basin, a seismic zone similar to that in Fig. 8d can be predicted without requiring changes in plate boundary conditions along the western side of the Indian plate and/or rheologic contrast between the continental and oceanic
Indian plate. However, we suggest that mechanical weakening in the rift system is unlikely the dominant cause of the concentrated seismicity in western India. Although a few moderate earthquakes indeed occurred in the Cambay and the Narmada rifts [Chung, 1993; Chung and Gao, 1995], suggesting that structural weakening of the rifts may be a factor triggering earthquakes, structural weakening alone cannot explain why most of the large earthquakes are concentrated in the Kutch rift basin, which should have the similar amount of structural weakening as the other rifts in western Indian because of their similar origin and evolution history.

**Figure 8.** Predicted fault intensity in the crust (at 20 km depth). The black line indicates the coastline, the star shows the Bhuj earthquake, and the white dots mark the epicenters of the historic earthquakes in the Kutch region (from Malik et al., [1999]). (a) Fault intensity for the basic case (Fig. 5). (b) Fault intensity similar to those in (a), but stress release by earthquakes or aseismic slip is considered (Fig. 6). (c) Fault intensity similar to those in (b), but also assuming that the oceanic part of the Indian plate is stronger than the continental part of the Indian plate. (d) Fault intensity similar to those in (c), but also assuming the Kutch rift basin to be a weak zone.
We also ran a case with a thinner and weaker mantle lithosphere under the Kutch rift basin as suggested by seismic tomography [Zhou and Murphy, manuscript in prep.] and found its contribution to the Kutch seismic zone is likely minor, because most deviatoric stresses can be supported by the strong upper-middle crust.

5. INTERPLATE VS. INTRAPLATE PROCESSES

We have shown that the Bhuj earthquake and many historic earthquakes in the Kutch region may have resulted from interactions between the diffuse plate boundary processes and the mechanical heterogeneity within the Indian plate. Intracontinental thrusting along the northwestern Indian plate boundary impedes the northward motion of the Indian plate relative to stable Eurasia, distorting the velocity field and causing deviatoric stresses to diffuse over a broad zone into the Indian plate. High seismicity near the western boundary of the Indian plate limits the deviatoric stresses that can be supported by the lithosphere near the plate boundary, thus leading to further inland diffusion of deviatoric stresses. On the other hand, mechanical heterogeneity within the Indian plate, mainly the contrasting mechanical strength between the continental and oceanic parts of the Indian plate and the inherited mechanical weakening of the Kutch rift basin, causes seismicity to concentrate in the Kutch rift basin and surrounding regions.

The predictions of this study may be testable. In our model the major cause of broad inland-diffusion of deviatoric stresses is the impeding intracontinental thrusting zone along the Sulaiman range and other ranges in the northwestern part of the Indian plate boundary. This plate boundary process would cause an E-W velocity gradient for the motion of the Indian plate (Fig. 5a). Within the Sulaiman Range and the neighboring region such a velocity gradient is suggested by the crustal strain rates inferred from seismicity [Bernard et al., 2000]. Kinematic data away from the plate boundary in this region are lacking. Fig. 5a predicts up to 4-5 mm yr\(^{-1}\) short-term velocity difference between Delhi and areas near the Sulaiman Range, and Fig. 6a indicates a greater long-term velocity difference. This could be tested by future geodetic measurements.

Our results suggest that the Bhuj event and the historic earthquakes in this region cannot be adequately described by any narrowly defined “interplate” or “intraplate” earthquakes. Whereas its epicenter is located ~400 km away from the nominal plate boundary and shares some common characteristics with other intraplate earthquakes like those in the NMSZ [Bendick et al., 2001; Ellis et al., 2001], there is a fundamental difference: the Bhuj event and other historic earthquakes in the Kutch region were strongly influenced by the plate boundary processes. The same cannot be said for the 1811-1812 New Madrid earthquakes, which were located nearly 2000 km from plate boundaries and showed no clear link to plate boundary processes [Stein et al., this volume]. On the other hand, the diffuse plate boundary deformation reflected by earthquakes in the Kutch region is significantly different from that on the northern side of the Indo-Asian plate boundary, where the weak Asian plate caused broadly diffusing seismicity and crustal deformation. Because of the high rigidity of the Indian plate [Paul et al., 2001; Yang and Liu, 2002], the diffuse plate boundary deformation here is strongly controlled by intraplate rheologic heterogeneities.

With the continued refinement of relative motion of the Earth’s crust, the definition of a plate boundary has become increasingly blurred [Gordon and Stein, 1992; Gordon, 1998]. Although many oceanic plate boundaries indeed appear to be well defined, other plate boundaries, especially those in continents, are characterized by diffuse deformation that may extend thousands of kilometers into the plate interior, such as in the Himalayan-Tibetan plateau and western United States. Attempts to understand the diffuse plate boundary deformation have propelled geoscience to advance from the kinematic plate tectonics approximation towards a more comprehensive understanding of the Earth’s dynamic system [Molnar, 1988]. We now understand that tectonic plates are essentially the top thermal boundary layer of the Earth’s convection system powered by heat transfer from the Earth’s inte-
rior [Parsons and McKenzie, 1978]. The tectonic plates behave as rigid plates because they are cold and therefore hard. However, rigid-plate definitions are only an approximation of the lithospheric rheology, which is timescale dependent and spatially heterogeneous [Ranalli, 1995; Liu et al., 2000b]. The internal rheologic heterogeneity, either inherited from previous tectonic history or resulting from differential thermal perturbations and tectonic stresses, can cause significant differential motion within the plates. Within the relatively rigid oceanic plates the internal rheologic change usually occurs over narrow zones, sometimes causing a rigid block to move at a significantly different rate from the rest of the plate, or in other words, to behave as “microplates” [Engeln and Stein, 1988]. Similar rheology-controlled differential motion is also common within continental plates, for instance the rigid Tarim block has experienced considerably differential motion with respect to the surrounding Asian continent [Avouac et al., 1993; Neil and Houseman, 1997]. However, in continents the lateral change of lithospheric rheology is usually more gradual, so the boundary of microplates is less well defined. The Indian plate is an exceptionally rigid plate with an overall rigidity similar to typical oceanic plates [Yang and Liu, 2002]. If part of the Indian plate breaks up, a distinct microplate may result. Stein et al. [this volume] suggest that such a microplate is forming around the Kutch Peninsula, and the Bhuj earthquake may be part of the breaking-up process. However, the present kinematic data are insufficient to verify this hypothesis. Our results suggest that the diffuse deviatoric stresses associated with plate boundary processes, in conjunction with the rheologic heterogeneity within the Indian plate, caused the Bhuj earthquake and other historic seismicity to concentrate in the Kutch region. Further studies of the Bhuj earthquake may lead to a better understanding of why earthquakes occur within stable plates and how diffuse plate boundary processes may interact with rheologic heterogeneity of tectonic plates.

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Qingsong Li, Mian Liu and Youqing Yang. 101 Geological Sciences Building, Columbia, Missouri, 65211. (lium@missouri.edu)