The Bhuj earthquake of 26 January 2001 (Figure 1) of $M_w 7.6$, with focal depth of 24–25 km was one of the most devastating earthquakes outside plate boundaries. Various seismological studies have suggested that it is caused by an E–W-oriented thrust$^{1,2}$. Kachchh rift basin basically developed during the Mesozoic period$^3$ and is therefore characterized by an extensional phase followed by a compressional phase during closure of the basin. In this respect, it is analogous to the New Madrid earthquake of 1811–12 in USA of almost the same magnitude, and both the events have often been compared with each other.$^4,5$

But there are also several differences between the two, the most important being their distance with respect to plate boundaries. The epicentre of the Bhuj earthquake is within 200–300 km of the plate boundary (inset, Figure 1) while that of the New Madrid earthquake is at least 2000 km away from any known plate boundary. However, the epicentral areas of both these earthquakes have been associated with Precambrian–Cambrian collision zones related to Aravalli–Delhi and Appalachian orogeny respectively. Such zones world over are weak, characterized by seismic activity.

The effect of the compressional phase on crustal structure can be seen in the crustal model computed along a gravity profile$^2$ from seismic studies$^1$ (Figure 2). It has produced thrusts in the upper crust (Figure 2a), which has affected the base- ment and sedimentary section above it accompanied by crustal thickening of 8–10 km (Figure 2b) under Wagad uplift (epicentral area of this earthquake). It may be noted that there is no topographic reflection of this thick crust showing an over-compensated crust, which causes upward buoyancy aiding local stress generation. The effect of these two major tectonics in this region, viz. thrusting and crustal thickening can be visualized well from the crustal seismic image$^4$. It shows N-verging reflectors, which primarily dip upward towards north in the upper crust up to about 20 km depth, while reflectors below 30 km primarily dip downwards towards north, causing crustal thickening. Between 20 and 30 km, both types of reflectors intermingle with each other, indicating interaction of these two distinct tectonic styles causing a weak crust. The hypocentre of this earthquake lies in the depth range of 24–25 km, as described above. Based on seismic tomography$^{10,11}$, presence of fluid in the hypocentral region has been suggested, which also indicates a fractured rock matrix in this section.

Gravity field observed at the surface is the best tool to delineate lithospheric flexure. However, due to signal from shallow sources, the effect of deeper sources such as lithospheric flexure is masked and requires some cosmetic operations to observe. Therefore, the gravity field observed over India is filtered using a low-pass filter$^{11}$ and the filtered Bouguer anomaly map is given in Figure 3. This map shows the largest linear gravity low gradient (L1) over southern side of Himalayas followed by linear gravity highs H1, H2 and H3, south of it over the Ganga basin. The Bouguer anomaly map of India$^{10}$ shows a linear gravity low over the Ganga basin due to the presence of low-density sediments and therefore, the gravity highs observed over this basin in low-pass filtered Bouguer anomaly map must be related to subsurface sources. The gravity low (L1) towards north over the Himalayas is attributed to crustal thickening$^{12}$ under it. In plate tectonic paradigm, subduction zones such as oceanic trenches or collision zones are characterized by flexure of the down-going plate due to weight of the overriding plate or collisional mountain belts. It is therefore, logical to expect a significant flexure bulge under Ganga basin south of the Himalayas, which formed due to collision of the Indian and Eurasian plates. The flexure bulge would produce linear gravity highs parallel to the collision zone such as gravity highs H1, H2 and H3 (Figure 3), which extend from the eastern boundary of the Indian plate to Delhi. The gravity high H4 in western India may represent a similar feature of lithospheric flexure due to the western part of the Himalayan belt (Karakoram–Kirthar–Sutlej ranges). The lithospheric flexure in Kutch may also be related to large-scale sedimentation in north Arabian Sea, west of Kutch since collision of the Indian and Eurasian plates and uplift of Himalayas during the Cainozoic period$^{13}$. Both these sets of linear gravity highs (H1–H3) and H4 intersect around Delhi and proceed NW, coinciding with the well-known basement ridge, Delhi–Sargodha ridge, which may represent shallow manifestation of the lithospheric flexure. It is interesting to note that H4 is located over Kachchh and H3 coincides with the Shillong plateau, which is also seismically active and has been the site of a major earthquake$^{14}$ in 1897. This earthquake is also considered to be associated with an N-verging thrust fault$^{15}$ similar to the Bhuj earthquake. Delhi and surrounding regions have also been the site of intermittent seismic activity, where the western and eastern lithospheric flexures intersect each other. Bilham et al.$^{16}$ suggested flexure bulge due to Himalayas under central India and attributed the earthquakes of central India along Narmand–Son lineament (NSL) to the lithospheric flexure due to the Himalayas. But this flexure under Ganga basin is north of NSL as stated above and may not have contributed much to seismic activity in central India. The topographic expression of Satpura fold belt along NSL in central India represents the old Proterozoic collision zone$^{17}$ and may not have much to do with present day lithospheric flexure. Lyon-Caen and Molnar$^{18}$ also visualized flexure bulge due to the Himalayas under the Ganga basin. Present-day lithospheric flexure can reactivate the old major thrusts in Kachchh and Shillong, resulting into seismic activity in those sections.

Plate reconstruction model and sea-floor spreading anomalies suggested a velocity of about 4.7 cm/yr for the Indian plate$^{19}$ with respect to Eurasia. However, the present-day geodetic measurements suggest a convergence of about 3.8 cm/yr between India and Tibet. Bilham et al.$^{21}$, however, suggested convergence of 2 cm/yr between India and Nepal, which is absorbed along the active thrusts in the southern part of the Himalayas such as Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT). Based on this convergence rate and known rupture during major earthquakes in this region,
Bilham et al. predicted that several great earthquakes are due to occur along the Himalayan foothills in future. The convergence in Himalayas is known to be accommodated by the following mechanisms: (i) movement on regional thrust faults, both upwards and downwards associated with plate tectonic forces; (ii) uplift due to compression over a large area of about 2000 km in width, and (iii) continental extension along E-W.

However, Bilham et al. considered only one aspect, viz. slip of the Indian plate to account for the total observed convergence. Bhuj earthquakes of 2001 and Shillong earthquake of 1897 occurring slightly away from plate boundaries, have always been a subject of discussion about whether they are connected to plate boundaries or not. Several other major earthquakes have also been reported in western India and Pakistan and east India close to the Himalayan front. Mishra et al. have shown that major tectonic elements of Kachchh are connected to the plate boundary towards west and NW. They also suggested that seismic activity of Kachchh may not represent, in the true sense, plate boundary seismicity but this region may be deriving some regional stress related to plate boundary activity. Interaction with local stress caused by buoyant crust and mafic intrusives is primarily responsible for major seismic activity in this region. The same may be true for the Shillong earthquake of 1897, as it also lies within 200–300 km of the plate boundaries towards north and east and important tectonic elements of Shillong plateau and neighbouring regions extend up to the plate boundaries. Gravity data in this case suggest under-compensated crust, which however, also implies isostatically unstable condition. These earthquakes should therefore also be considered for budgeting the convergence between the Indian and Eurasian plates. A similar situation has been reported in case of San Andreas fault system, where motion between Pacific and North American plate (4.8 cm/yr) cannot be accounted only by slip along San Andreas transform fault (3.4), and a significant part of it (1.4 cm/year) is accounted by other faults in the surrounding region. Strain rate for Kachchh appears to be almost same (10^-7/yr) as that for New Madrid seismic zone, which compares well for plate boundaries. Large-scale co-seismic uplift and subsidence have been common to the Bhuj, Shillong and New Madrid.

**Figure 1.** Geology of Kachchh showing various formations and faults referred to as F1–F4. The Nagar Parker Ridge and Island Belt Fault (IBF) form the northern margin of the basin with several uplifts due to Mesozoic sediments south of it. BE, KE and AE are epicentres of Bhuj, Kachchh and Anjar earthquakes of 2001, 1819 and 1956 respectively, KMU, Kachchh Mainland Uplift and WU, Wagad Uplift. C and M denote Chobari and Manbara villages respectively, where large lateral displacement and strike slip movement were reported after Bhuj earthquake. (Inset) Regional tectonics of this are with different plates and plate boundaries. Grey dots show epicentre of earthquakes since 1968 (USGS, 2001). KA, Karachi arc; KF, Karachi fault; KL, Kachchh-Lakhpat lineament; KR, Kirthar range; MR, Murry ridge; OFZ, Owen fracture zone; SF, Sonae fault of Ormara micro-plate between OFZ and Makran SZ (shear zone).

**Figure 2.** a. Shallow cross-section up to basement derived from 2.5-D modelling of residual gravity anomaly and total intensity magnetic field along a profile XX’. Basement contact (F’4) between Chitrod and Adesar shows variation in susceptibility across it and its projection on the surface coincides approximately with north Wagad fault (F4). MI, mafic intrusive similar to a volcanic plug. A, Regional field along the same profile is modelled for mass deficiency at Moho of about 8 km thick crust for density contrast of 400 kg/m³ between lower crust and upper mantle under the Wagad uplift. Susceptibility and density of different bodies are given in SI units and kg/m³ respectively. Computed and observed fields show r.m.s. error much less (1–2%) than the observed anomaly, indicating good match between them.
earthquakes followed by a large number of aftershocks in both cases. These are another indication of their relation to plate boundary activity.


ACKNOWLEDGEMENTS. We thank CSIR, New Delhi for Emeritus Scientist Scheme. We also thank the Director, NGRI, Hyderabad for permission to publish this work. Thanks are also due to our colleague Mr Ch. Ramaswamy for help rendered.

Received 17 February 2005; revised accepted 23 November 2005

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