Geological Society of America Special Papers

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Geological Society of America Special Papers 2007;425;319-327
doi: 10.1130/2007.2425(20)

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The Geological Society of America
Special Paper 425
2007

Seismic-reflection images of the crust beneath the 2001 M = 7.7 Kutch (Bhuj) epicentral region, western India

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ABSTRACT

Three short (~35 km) seismic-reflection profiles are presented from the region of the 2001 Mw = 7.7 Bhuj (western India) earthquake. These profiles image a 35–45-km-thick crust with strong, near-horizontal reflections at all depths. The thickness of the crust increases by 10 km over a distance of ~50 km from the northern margin of the Gulf of Kutch to the earthquake epicenter. Aftershocks of the Bhuj earthquake extend to a depth of 37 km, indicating a cold, brittle crust to that depth. Our results show that all of these aftershocks are contained within the crust. Furthermore, there is no evidence for offsets in the crust-mantle boundary associated with deep (mantle) faulting. The existence of a thick (~45 km) and highly reflective crust at the epicentral zone may be indicative of crustal thickening due to the compressive regime of the past 55 m.y. Alternatively, this crustal thickening could be attributable to magmatic intrusions that date back to Mesozoic rifting associated with the breakup of Gondwanaland.

Keywords: India, seismic reflection, crustal thickness, Bhuj earthquake.

INTRODUCTION

The 26 January 2001, Mw 7.7 Bhuj, western India, earthquake had a focal depth of 21 ± 4 km (Kayal et al., 2002; Antolik and Dreger, 2003; Mandal et al., 2004). Aftershocks outlined an ENE-trending S-dipping reverse fault (45°–50° dip) extending to a depth of 37 km (Raphael and Bodin, 2002; Kayal et al., 2002; Mishra and Zhao, 2003) with no obvious surface expression (Chandrasekhar et al., 2004; Rastogi, 2004). The largest amount of fault slip (10 m) was located close to the hypocenter and had an area of ~10 km × 20 km (Negishi et al., 2002). The area of the rupture zone (~40 km × 40 km) appears to be unusually small for a Mw 7.7 event, and suggests a high (13–25 MPa) static stress drop event (Negishi et al., 2002), similar to other

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Sarkar, D., Sain, K., Reddy, P.R., Catchings, R.D., and Mooney, W.D., 2007, Seismic-reflection images of the crust beneath the 2001 M = 7.7 Kutch (Bhuj) epicentral region, western India, *in* Stein, S., and Mazzotti, S., ed., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, p. 319–327, doi: 10.1130/2007.2425(20).

intraplate earthquakes (Schulte and Mooney, 2005). A tomographic study of the aftershocks showed a distinctly high P-wave velocity and low S-wave velocity (and thus a high Poisson's ratio) at the lower-crustal hypocentral zone (Kayal et al., 2002). Mishra and Zhao (2003) suggested that the 2001 Bhuj earthquake was characterized by high crack density, saturation rate, and porosity in the depth range of 23–28 km. According to Mishra and Zhao (2003), these mid-crustal anomalies indicate the presence of a fluid-filled, fractured rock matrix, and would thus constitute a local zone of weakness.

The 2001 Bhuj earthquake occurred ~130 km southeast of the epicenter of the 1819 Allah Band earthquake (Mw 7.8), which also ruptured on a reverse fault (Fig. 1; Rajendran and Rajendran, 2001). Based on paleoliquefaction studies, Tuttle et al. (2001) reported that another similar-sized event occurred in the Allah Band region 800–1000 yr ago. Kaila et al. (1972) computed a recurrence interval of 200 yr for Kutch earthquakes, which is comparable to the time interval between the 1819 and 2001 events. In addition, a smaller (Mw 6.0) earthquake occurred in 1956 near Anjar (Fig. 1). This event also had a reverse mechanism (Chung and Gao, 1995), which indicates a prevailing compression-dominated regime.

Kutch seismicity, like that of the New Madrid seismic zone of the eastern United States, is typified by a relatively short (200–500 yr) recurrence interval of major earthquakes, which does not readily conform to the statistics inferred from the rate of microearthquake activity (Mandal and Rastogi, 2005). However, Stein and Newman (2004) argued that the calculated recurrence interval of the larger New Madrid seismic zone events is consistent with microseismic activity if the magnitudes of the larger events are not overestimated (Stein and Newman, 2004). The seismicity of the New Madrid seismic zone is considered to be a classic example of intraplate seismicity related to a reactivated rift (Mooney et al., 1983; Chiu et al., 1992; Liu and Zoback, 1997; Newman et al., 1999; Schulte and Mooney, 2005; Li et al., 2007; McKenna et al., 2006). It has been hypothesized that the North

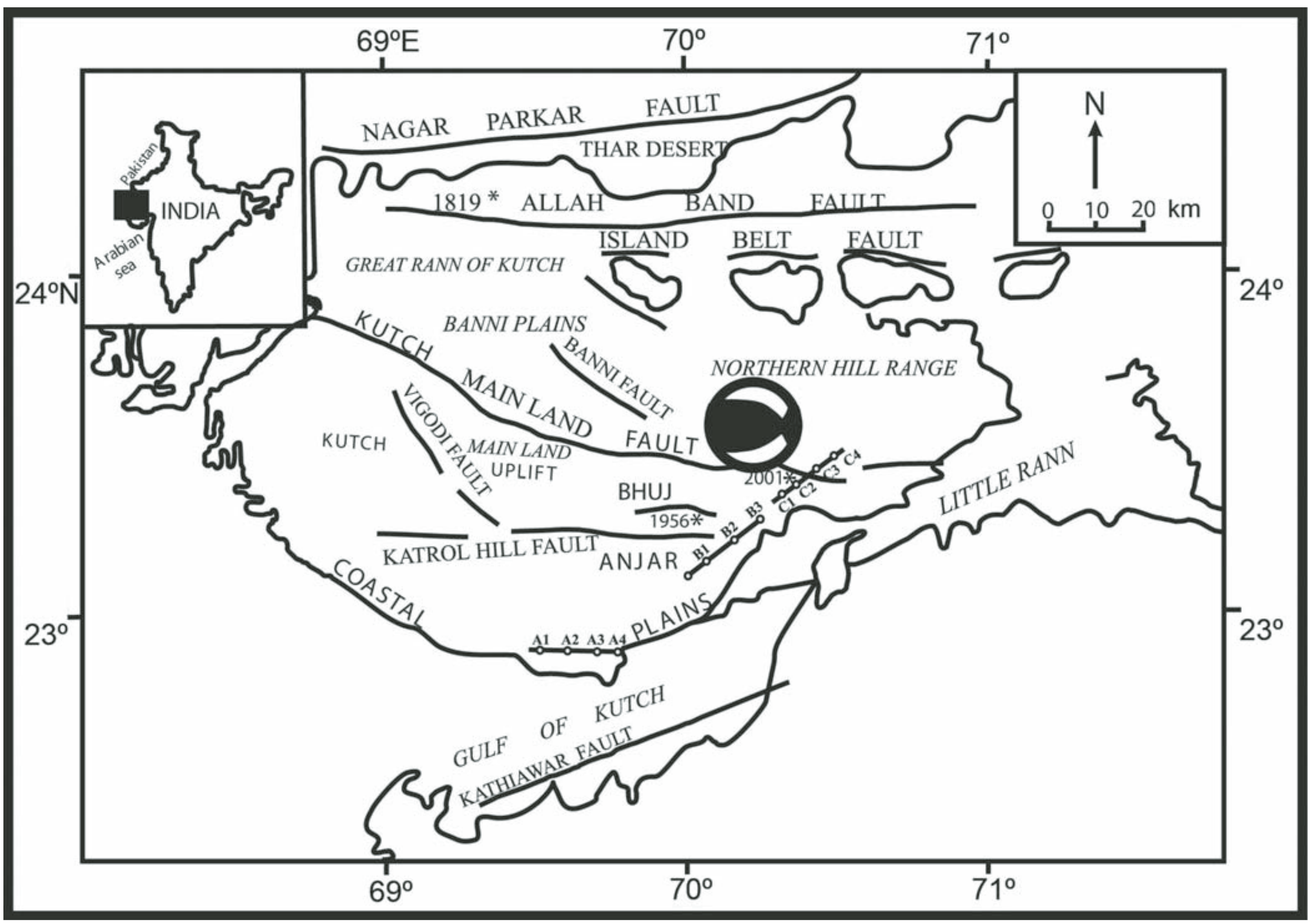

Figure 1. Tectonic map of Kutch showing major fault systems (adapted from Malik et al., 2000). The epicenters of the 2001 Bhuj earthquake (23.36°N, 70.34°E) as well as the two earlier events of 1819 and 1956 are indicated by asterisks. The focal mechanism of the 2001 earthquake is also shown. Three seismic lines (A, B, C) are shown as thick solid lines with corresponding shot points (open circles). Inset shows the study area.

American ambient stress field reactivates faults associated with the Reelfoot rift (Grana and Richardson, 1996).

Although the Kutch region has been rather well-explored by the oil industry, most studies have been limited to the shallow sedimentary formations and the Deccan volcanics overlying the granitic basement, and we still lack a well-determined crustal velocity model for this region. We have some knowledge of the geologically mapped faults but insufficient information regarding the disposition of blind faults in the crust. Such data are necessary in order to differentiate between the crustal structure of the seismogenic and nonseismogenic areas of the Kutch region.

In this study, we seek to determine the deep seismic structure of the crust at and adjacent to the epicenter of the Bhuj earthquake. Data from three seismic profiles within the region have been processed to determine crustal reflectivity patterns and to constrain the lateral variations in the crust that may be significant for understanding Kutch seismicity. With these objectives, we have depth-migrated seismic-refraction data collected in 1997 (NGRI, 2000) to produce a depth section similar to multichannel seismic data.

TECTONIC SETTING OF THE KUTCH REGION

The Kutch region forms a crucial tectonic segment of the western margin of the Indian subcontinent, and it falls within a zone of high seismic potential. The Kutch rift basin is flanked by the Nagar Parkar fault in the north and the Kathiawar fault in the south (Fig. 1). The Kutch basin contains several major E-W–trending faults, such as the Kutch Mainland fault on the northern fringe and the Katrol Hill fault in the central part of the Kutch Mainland uplift (Biswas, 1987; Malik et al., 2000).

The Kutch rift basin owes its origin to the Mesozoic breakup of Gondwanaland. Normal faulting within this extensional regime produced a number of prominent horsts and grabens. A change from rift-related extension to N-S compression probably occurred around 55 ± 1 Ma, subsequent to the collision of India with Eurasia (Ni and Barazangi, 1984; Gaetani and Garzanti, 1991; Klootwijk et al., 1992; Garzanti et al., 1996; Rowley, 1996; Leech et al., 2005). Most focal mechanism studies conducted in this area indicate E-W–striking reverse faulting and generally reflect N-S compressive stress (Rajendran and Rajendran, 2001). This region is subject to a high and regional stress field because of its proximity to the Indian-Arabian-Asian triple junction, located ~500 km to the west (Gupta et al., 2001), and is also affected by the plate-boundary zone (Li et al., 2002; Stein et al., 2002). The huge sediment load in the neighborhood of the Indus Delta is an additional source of stress on the Indian plate (Seeber et al., 2001). Since this is an active process of sediment loading, this stress has the opposite sign of the deglaciation hypothesis for the New Madrid seismic zone (Grollimund and Zoback, 2001).

REPROCESSING OF 1997 SEISMIC-PROFILING DATA

Seismic-refraction data were collected using two 60 channel Texas Instruments model DFS-V recording systems (NGRI, 2000). The geophone spacing was 100 m, and the shot interval was 7–8 km. Holes drilled to a depth of 20–30 m were used to detonate 50–500 kg explosives, depending upon the shot-receiver distances. The objective of the seismic survey was to delineate the basement configuration and to identify buried sediments that are often masked under higher-velocity Deccan volcanics. The refraction data, however, indicated some basement faults, either directly observable in the form of fault-plane reflections or in terms of an abrupt change in the basement depth. Here, we reprocessed the data to image the middle and lower crust.

The data presented here consist of three line segments: A, B, and C with 4, 3, and 4 shots, respectively (Fig. 1). We reprocessed these profiles using standard two-dimensional (2-D) Kirchhoff prestack depth migration from commercial software package ProMAX installed on a Sun Workstation. Prestack depth migration has become an important tool for obtaining quality images from seismic data acquired in geologically complex regions (Yilmaz and Doherty, 1987; Milkereit et al., 1990; Lafond and Levander, 1995; Audebert et al., 1997; Zelt et al., 1998; Pilipenko et al., 1999). The depth migration consists of an estimation of the velocity-depth model and the appropriate Green's function, which are used to relate times and amplitudes from each surface location to a region of subsurface points. Seismic traveltimes of selected phases are generally used to derive a large-wavelength velocity model, which, in turn, is used in prestack depth migration to derive the fine-scale structural image of a region.

For depth migration, we require an appropriate velocity model. Refraction velocity models derived from the same data set are only available for the basement (NGRI, 2000). In the absence of deeper refraction data, we calculated the subbasement models from the corresponding shot gathers. Application of automatic gain control and suitable band-pass filters enhanced the signals, which allowed us to identify intracrustal and Moho reflections.

Not all shot gathers allowed visual identification of deep reflection phases. The granitic basement, the Moho, and a third intracrustal phase were occasionally observed. We used the data from shot C3 to calculate the velocity-depth section for line C. Even though some intrabasin reflections were observed, they were used for this modeling. A mean sedimentary velocity, as obtained from earlier refraction analysis, was applied as far down as the basement level. The traveltimes of these phases were read and inverted to build a velocity model using a damped least-square technique (Sain and Kaila, 1994). The derived velocity-depth functions (Fig. 2) were sampled on a 200 m (horizontal) by 200 m (vertical) grid and used in the prestack depth migration for imaging crustal features. Since the migration procedure is sensitive to the crustal velocities used, particularly overestimations, a discontinuous velocity increase across the Moho was purposefully ignored. Instead, a smooth increase of crustal velocities was applied to avoid possible major distortions in the migrated section. On shot gathers from lines A and B, it was difficult to observe any clear and consistent phases. Therefore, we used the lower-crustal velocities for line C for the migration of data from lines A and B. Care was taken to process only subbasement

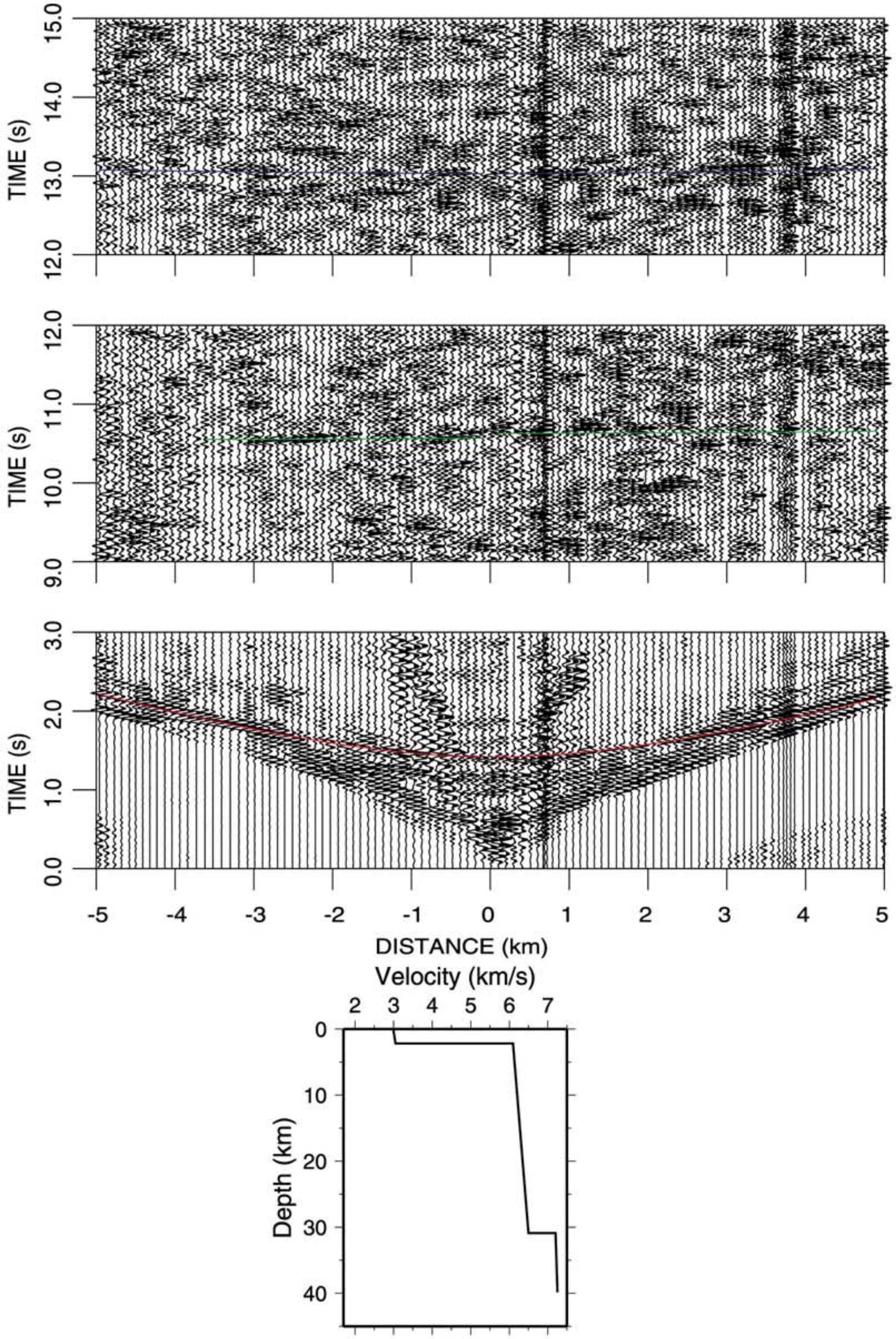

Figure 2. Record section (in three time windows) showing intracrustal reflections for shot point C3, along with corresponding velocity model that was used in prestack depth migration.

reflection data because the upper sectional details are proprietary to natural resource exploration.

RESULTS AND DISCUSSION

The nearly 35-km-long southern coastal segment (line A) depicts strong reflectivity throughout the entire crust, starting from the reflections at a depth of 5–6 km (Fig. 3). A clear W-dipping (20–25 km depth) horizon with a strong band of reflections marks the top of the prominent lower crust. This is noted in Figure 3 at 25 km depth from ~2 km east of shot point (SP) A1 and continues to between SPs A2 and A3. The Moho, the bottom of the lower-crustal reflective zone, shows a high-reflectivity signature and is nearly horizontal along the entire profile at an average depth of 35 km. The crust is evidently thinner here than most other crustal depth estimates (40–42 km) for the western coast of India (Sarkar et al., 2001, 2003). There is noticeable but relatively incoherent reflectivity in the mantle at a depth of 10–15 km below the Moho.

The seismic section along line B, which crosses a part of the E-W–trending Kutch Mainland Uplift, depicts reflectivity at depths of ~5, 10, 18, and 27–29 km, the latter of which represents the top of the lower crust (Fig. 4). N-dipping subhorizontal Moho reflection bands are weakly observed at 37–40 km depth. There is also a strong subcrustal reflection horizon at 50 km. The ~40-km-thick crust of the northern portion of the profile is consistent with the tectonic model of Stein et al. (2002), and it has been host to a number of historical earthquakes. A blind basement fault, nearly coinciding with the geologically known Kutch Hills fault, was inferred from earlier refraction analysis (NGRI, 2000) at ~10 km north of the town of Anjar. This fault could be associated with the 1956 Mw = 6.0 Anjar earthquake, a rupture that showed 1 m of offset along the fault and was the most severe earthquake prior to the 2001 Bhuj event.

Seismic line C is located ~15 km east of the 2001 Bhuj earthquake epicenter. This profile shows strong reflectivity in the entire crust, with reflection horizons at average depths of 5, 10, and 19 km (Fig. 5). The reflection Moho is clearly imaged as the base of the reflective crust, and it has a significant northward dip, from 38 to 45 km, within a distance of 35 km. A seismic reflection within the upper mantle is visible at a depth of 56–58 km near the southern end of the profile. This reflection gets partially obliterated due to the diffused and disturbed reflectivity farther north. The central portion of the profile, between distances of 10 and 20 km, shows a significant increase in crustal reflectivity, while the Moho appears as a thick reflection band.

The 2001 Bhuj earthquake had a S-dipping fault plane and a focal depth of 21 ± 4 km, and it occurred very close to the southern edge of increased reflectivity. The proximity of the fault plane with this reflective portion of the crust may not be coincidental. The laterally varying crustal reflectivity pattern exhibits enhanced reflectivity of the middle and lower crust beneath the epicenter of the 2001 earthquake. We hypothesize that the reflective zone consists of anastomosing shear zones created within a highly compressive stress regime (Lueschen et al., 1987; Hamilton, 1989; Smithson and Johnson, 1989; Mooney and Meissner, 1992). This observation of high reflectivity, along with the observance of a high Poisson's ratio (Kayal et al., 2002; Mishra and Zhao, 2003) in the hypocentral region, may also be indicative of enhanced fluid concentrations in a highly sheared zone (Mishra

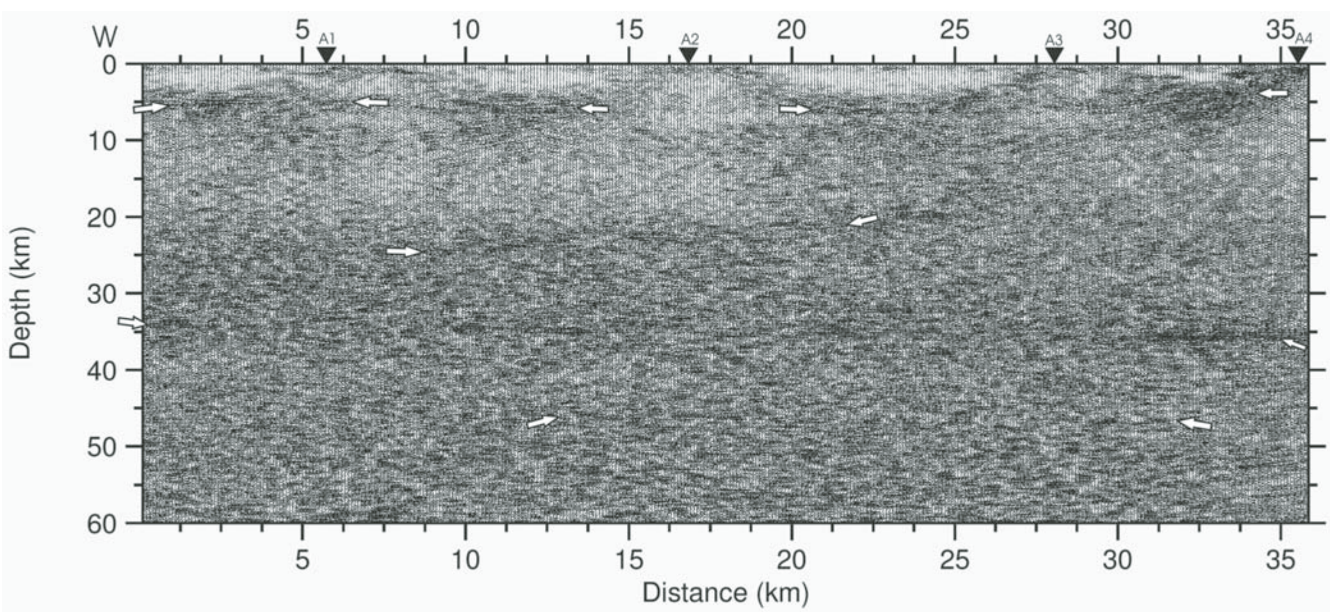

Figure 3. Prestack depth-migrated section for line A (Fig. 1). Prominent reflection boundaries are indicated by white arrows. Shot locations are indicated by inverted triangles along the axis. The top of the reflective lower crust is at a depth of ~22 km, and the Moho is at a depth of 35 km.

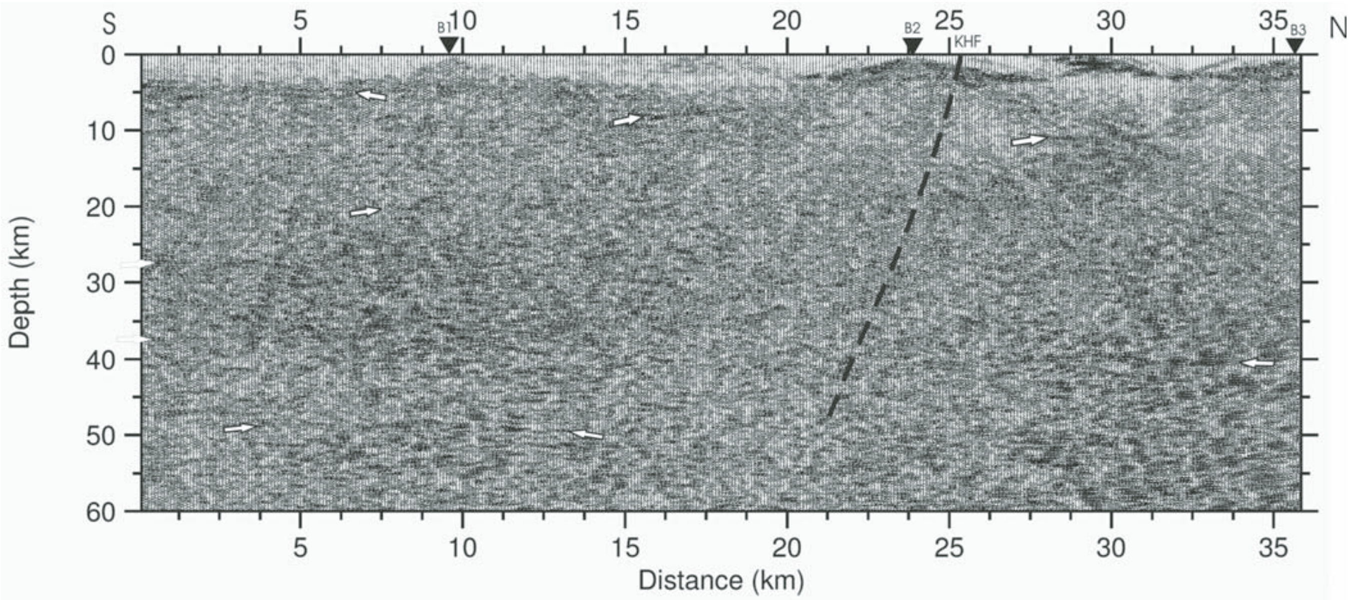

Figure 4. Prestack depth-migrated section for line B (Fig. 1). Prominent reflection boundaries are indicated by white arrows. Shot locations are indicated by inverted triangles along the axis. The Katrol Hill fault (KHF) is indicated by a thick dashed line but is not clearly imaged by the data. The Moho is at a depth of 38–40 km.

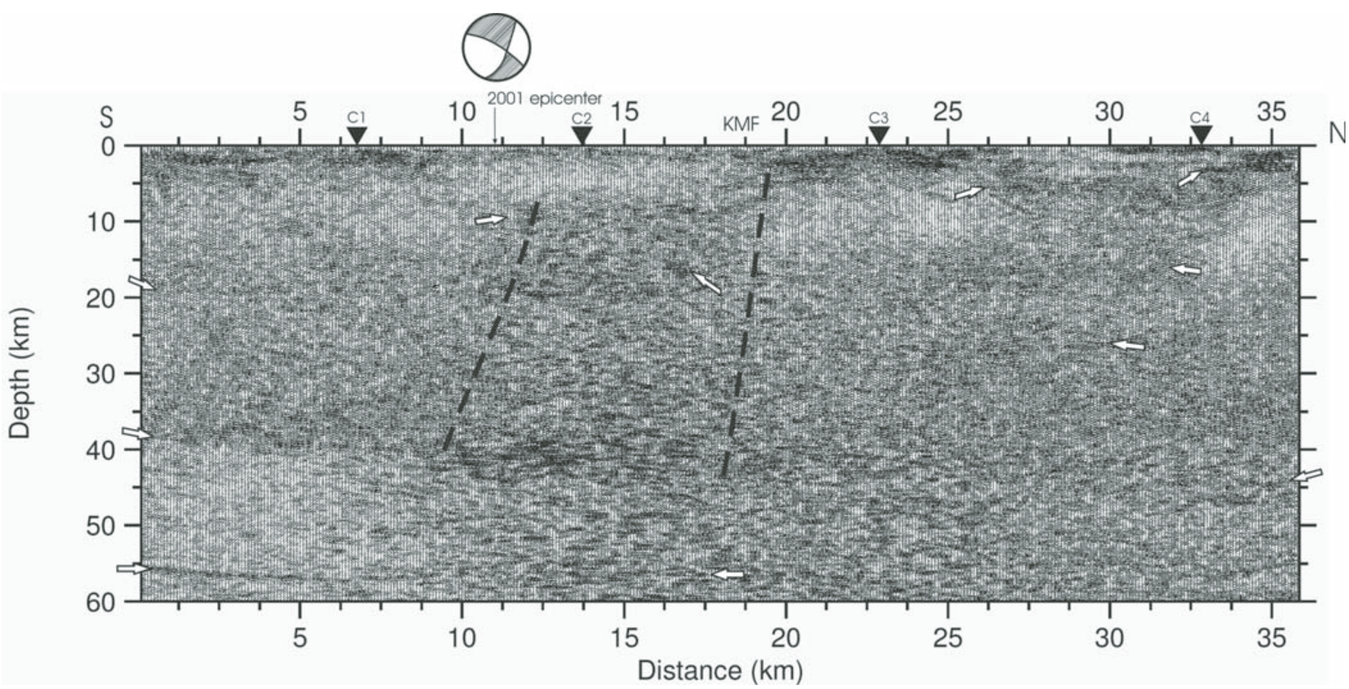

Figure 5. Prestack depth-migrated section for line C (Fig. 1). Prominent reflection boundaries are indicated by white arrows. Shot locations are indicated by inverted triangles along the axis. The hypocenter of the 2001 Bhuj earthquake along with the focal mechanism, as viewed on a vertical cross section, is superimposed on the depth section. Though not clearly imaged by the data, the Kutch Mainland fault (KMF) and the fault associated with the 2001 Bhuj earthquake are indicated by thick dashed lines. The Moho is at a depth of 38–45 km. A strong mantle reflector is imaged at a depth of 55 km.

and Zhao, 2003; Mandal and Rastogi, 2005). High fluid pressures would have the effect of reducing the effective normal stress on the Bhuj fault plane and would thus reduce the shear resistance of the fault (Sibson, 1994, 2002).

Figure 6 shows all three seismic-reflection profiles in three dimensions, along with the most prominent reflectors. The thinner (35 km) crust in the aseismic southern crustal profile (A) and the thick (45 km) crust in the northern segment (C) suggest that the Kutch Mainland uplift is associated with a crustal root. One possible tectonic explanation for such a thickened crust under the epicentral region (the Kutch Mainland uplift) is the prevailing N-S compression generated by the India-Eurasia collision. Alternatively, the crust may have been thickened by igneous intrusions during rift formation, signatures of which are visible in the form of strong sub-Moho reflectors. The aftershocks from the Bhuj earthquake and the location of the Kutch Mainland fault are also shown.

CONCLUSIONS

Three 35-km-long seismic-reflection profiles from the region of the 2001 M = 7.7 Bhuj earthquake provide images of the regional crustal structure and depth to the Moho. A zone of high reflectivity is observed in the lower crust starting at a depth of ~22 km. The crust-mantle boundary, defined as the base of the zone of strong reflectivity, deepens from 35 km at the coast to 45 km in the immediate epicentral region. Thus, the crustal thickness in the Bhuj epicentral region is approximately equal to the average value for continental India (40–44 km; Kaila and Sain, 1997). This observation contradicts the suggestion that seismic activity in the Kutch region is due to thin, rifted crust, such as that found along the East African Rift (Mechie et al., 1994; Mooney and Christensen, 1994). The 45 km crustal thickness compares favorably with the 42–46 km crustal thickness of the New Madrid seismic zone. Furthermore, the 22 km depth to the top of the reflective lower crust in the Bhuj region agrees well with the 26 km depth of the 7.3 km/s lower crust beneath New Madrid (Mooney et al., 1983). Thus, the Bhuj region appears to have a rifted crustal structure that is comparable to the New Madrid rift, but not the East African Rift.

High-angle reverse faults and near-vertical strike-slip faults are rarely imaged on seismic-reflection profiles. It is therefore not surprising that these data do not image the fault associated with the 2001 Bhuj earthquake (Biswas, 2005). The geometry of this

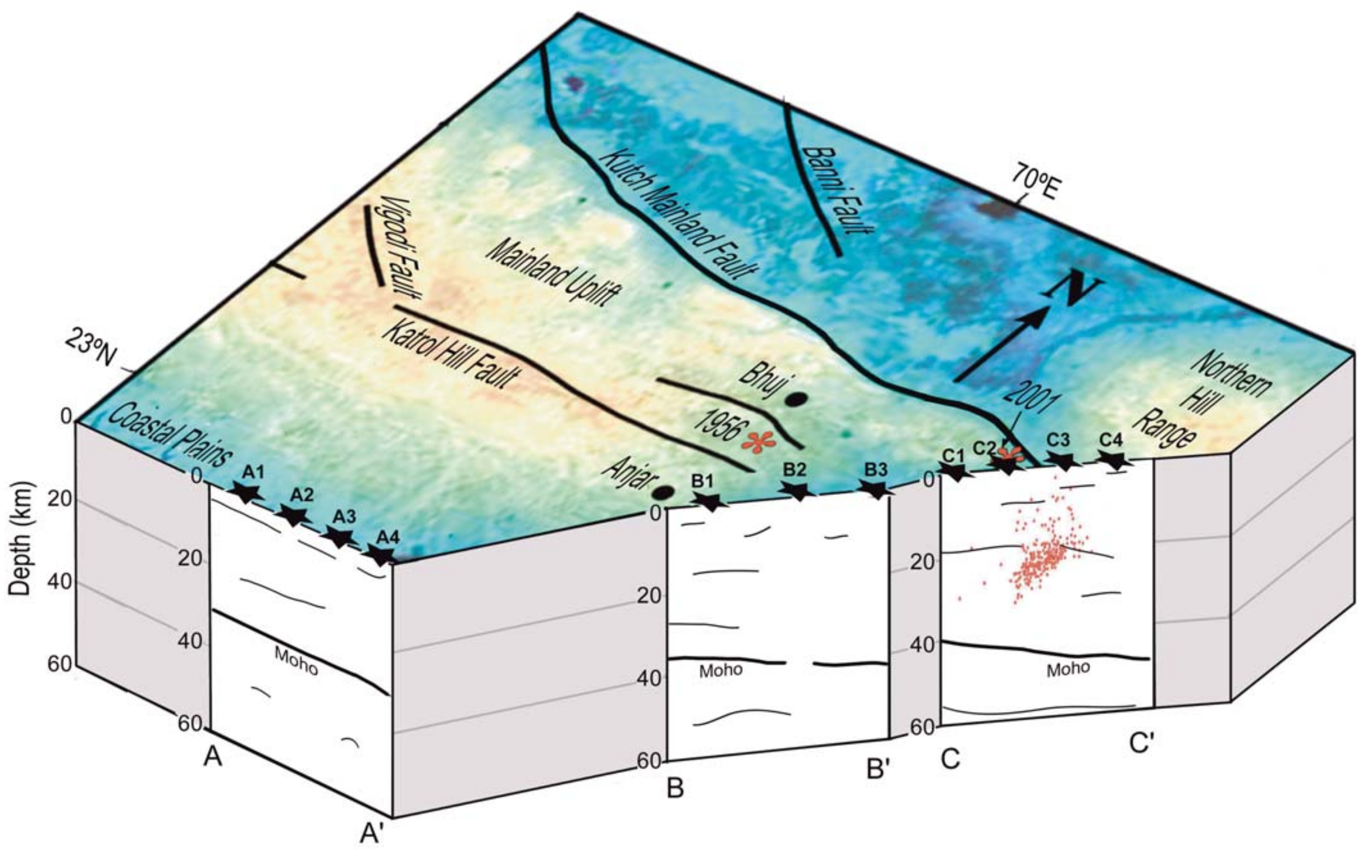

Figure 6. Pie-slice diagram of the Bhuj epicentral region. The three seismic-reflection profiles (A, B, C) are shown along with prominent reflectors. The aftershocks from the Bhuj earthquake have also been plotted as red dots, showing the location of the Kutch Mainland fault.

fault is best defined by the aftershocks, as reported by Kayal et al. (2002), Negishi et al. (2002), and Mishra and Zhao (2003). These aftershocks reach depths as great as 37 km, and our seismic profiles demonstrate that all of this seismicity is contained within the crust. However, there is no evidence on our seismic profiles for offsets in the crust-mantle boundary. On the contrary, the Moho appears to be flat, with a smooth dip from the coast to the interior of the continent.

The presence of seismic reflections some 10–15 km below the Moho is an unexpected and relatively rare observation on such profiles. We interpret these sub-Moho reflections as either mantle shear zones or mafic igneous intrusions that are associated with the rifting that occurred as India separated from Africa in the late Mesozoic.

The crustal properties associated with the epicentral region of the 2001 Kutch earthquake are significant in light of the regional seismicity. Our seismic image allows us to distinguish between the seismic structure at and adjacent to the 2001 Bhuj earthquake epicenter. Furthermore, a high Poisson's ratio, along with a laterally varying crustal velocity structure, has previously been linked to fluid-filled and highly fractured fault segments (Kayal et al., 2002; Mishra and Zhao, 2003), which are a plausible explanation for the high seismic moment release in the Kutch region.

ACKNOWLEDGMENTS

We thank the directors of the National Geophysical Research Institute and U.S. Geological Survey for their support of collaborative work and approval of this publication. We furthermore acknowledge I.M. Artemieva, G.S. Chulick, S. Detweiler, M. Coble, and S.T. McDonald for critical reviews of the manuscript. D. Eaton, H. Sato, S. Seth, S. Mazzotti, and an anonymous reviewer have provided constructive criticisms to improve this paper. Oil Industry Development Board (India) sponsored the Crustal Structure Studies Project (P.I.P.R. Reddy) of NGRI for undertaking the shallow seismic-refraction survey in Kutch to delineate its basinal structure and basement configuration. We thank the field party chief B. Rajendra Prasad and other members of the C.S.S. field party for data collection. Imaging of subbasement deep structure of two crustal segments was carried out under an India-U.S. bilateral collaboration between NGRI and the U.S. Geological Survey.

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Manuscript Accepted by the Society 29 November 2006