GROUND TRUTH DATA IN INDIA AND CHINA FROM DENSE LOCAL NETWORKS AND CALIBRATION EXPERIMENTS

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ABSTRACT

Obtaining and interpreting qualified, regional geologic and geophysical data from countries such as India and China has been an important scientific and technical goal for many years. To aid in this effort, the U.S. Geological Survey has been building relationships with comparable government organizations throughout Asia. Here we present preliminary results from this interaction in the form of ground truth and crustal structure information for India and China.

We have successfully developed a cooperative program with Indian scientists over the past several years. During that time, delegations from Indian geophysical laboratories have made multiple visits to Menlo Park, CA, bringing with them new seismic data and crustal structure information. We have been very pleased to achieve such unprecedented access to data and their interpretation. During the most recent visit, shallow seismic refraction data from NE India (Kutch region), near the epicenter of the 2001 Bhuj earthquake and in close proximity to the Indian nuclear test site, were processed and interpreted. Another highlight of this cooperation has been the release of aftershock data. This data has relocated hypocenters determined from 18 local seismic stations and were obtained during a visit to India.

We continue our ongoing program of collecting crustal structure and ground truth information from China as well. This effort has likewise been a great success as delegations from many organizations within China have shared data and offered cooperation over the years. We are currently reprocessing data from a 1000-km-long seismic refraction profile centered at 36° N and 104° E. There are 9 borehole chemical shots on this profile, each with 3000-4000 kg charges. The resulting P-wave and S-wave arrivals are excellent. The large borehole explosions will likely have been recorded at seismic monitoring sites, and will serve as valuable ground truth events. In addition, we are working with Chinese seismic network catalog data that provide excellent ground truth seismic events.

OBJECTIVE

This research is aimed at continued cooperation between the U.S. Geological Survey and counterpart agencies in Asia to exchange data and interpretations of crustal structure, and hypocentral locations. With our colleagues from the National Geophysical Research Institute (Hyderabad, India) and the China Seismological Bureau (Beijing, China), we have been successful at initiating and completing a number of seismic studies in areas that are of great importance for nuclear test monitoring. The 2001 Bhuj (western India) earthquake has triggered widespread discussion in the scientific community about the nature and the causes behind such intra-plate earthquakes, and this, in turn, has led to joint work agreements between the USGS and NGRI. This is fortuitous as the Kutch region is just south of the Indian nuclear test site, and the joint study has yielded access to previously unavailable data in the region. In China, we have focused on obtaining the crustal structure of the 1000-km-long Project 973 profile through central China. In addition, large explosions along this line at close proximity to receivers provide excellent ground truth events.

Here, we first make an effort to summarize the available information about the destructive 2001 Bhuj and other major earthquakes in Kutch and their tectonic setting. We shall also try to assess the basic data gaps that need to be filled for understanding the Kutch crustal structure, and thereby will be in a better position to characterize events that occur in the region. Following this, we will describe the area of China where we have newly available information.

RESEARCH ACCOMPLISHED

India

The Kutch region forms a crucial geodynamic part of western continental margin of the Indian sub-continent, and falls in the seismically active Zone-V outside the Himalayan seismic belt. It extends for approximately 250 km (E-W) and 150 km (N-S), and is flanked by Nagar Parkar Fault in the north and the Kathiawar Fault in the south (Fig. 1). The portion bounded between these two faults also contains several E-W trending major faults including the Katrol Hill Fault, Kutch Mainland Fault, Banni Fault, Island Belt Fault and Allah Bund Fault (Biswas, 1987).

The Kutch tectonic setting owes its origin to Mesozoic tectonic events initiated during the break-up of Gondwanaland and the northward drift of the Indian plate. The rift basin evolved as a consequence of this break-up and was controlled by a series of normal faults, which are still exposed in the region. Movement along these faults under an extensional regime produced a number of horsts and grabens.

The Kutch landscape can be categorized into four major E-W trending geomorphic zones (Malik *et al*., 2000). They are: the coastal zone - demarcating the southern fringe, the Kutch mainland - forming the central portion of the rocky uplands, Banni-Plains marked by raised mud flats, and the Great Rann in the north and the Little Rann in east comprising vast saline-waste land. The boundaries of these geomorphic zones are bounded by major faults. The rocky mainland is characterized by the uplifts exposing folded Mesozoic rocks. All the major uplifts are bounded, at least on one side, by a fault or a sharp monoclinal flexure, on the other side by gently dipping Tertiary strata and the peripheral plains that merge gently into the surrounding residual depression.

The Kutch Mainland Fault marks the northern fringe of the rocky mainland. This fault is a vertical to steeply inclined normal fault, but changes upwards into a high angle reverse fault (Biswas, 1987). The central part of the rocky mainland has been upthrown along the longitudinal Katrol Hill Fault (Malik *et al*., 2000).

The Mw=7.6 Bhuj, western India earthquake occurred early in the morning of January 26, 2001. The epicentral coordinates of the main shock obtained from teleseismic data as reported by the USGS to be 23.36°N and 70.34°E. The focus of the earthquake was placed at 22 km. Aftershocks outline an ENE trending south-dipping thrust (45°-50° dip) to great depths (20-30+ km). Later results show concentrated patches of relocated aftershocks that dip to the south between 6 and 37 km deep (Raphael *et al*., 2001). The long-period source time function shows a relatively simple source of about 15 seconds duration. Mori *et al*., (2001) report that the largest area of slip was close to the hypocenter. This asperity is about 10 km x 20 km with a maximum slip of about 10 meters for a rupture velocity of 2.9 km/s. The area of the fault is small for such a large event.

It is interesting to note that Antolik and Dreger's (2001) waveform inversion results also favor the presence of a second sub-event located at shallower depth above and slightly west of the rupture initiation containing as much as 6 m of slip. This sub-event occurs near an area of intense lateral spreading and ground deformation observed in the field, indicating the possible presence of shallow slip although the fault rupture appears not to have reached the surface. They, however, found the overall source parameters (short duration, high stress drop) in line with observations from other intra-plate earthquakes.

The recent Kutch event is about 50 km southeast of the 1819 Kutch (i.e. Allah Bund) event (Mw=7.8), which also originated on a thrust fault (Bilham, 1998). The inferred 50-70 deg N-dipping fault plane (slip>11m) beneath Allah Bund was unfavorably steep for reverse faulting, presumably requiring high fluid pressure in the nucleation zone, according to Bilham (1999). Rajendran and Rajendran (2001) concluded occurrence of another similar sized event 800-1000 years ago from paleo-liquefaction studies. Kaila *et al*. (1972) from statistical analysis computed a return period of 200 years, which is quite close to the time interval between 1819 and 2001 events. More recently, in 1956, a Mw=6.0 event occurred near Anjar town, which also had a thrust mechanism (Chung and Gao, 1995).

Looking at the possible origin of Kutch seismicity, we find that the focal mechanism studies of all the major earthquakes indicate thrust motions on nearly westerly striking planes and, as such, appear to reflect an approximately northerly compressive stress in the crust that would be expected with the ongoing northward collision of India into Eurasia. A change from rift-related extension to north-south compression probably occurred about 40 Ma ago, subsequent to the collision of India with Asia. Low-angle reverse faults exposed in this region provide geologic evidence for such a tectonic reversal, which is indicated also by the thrust-type focal mechanisms. The stress field oriented in the N-S to NNE-SSW direction is considered to be responsible for this reversal of movement and the ongoing deformation (Rajendran and Rajendran, 2001). As well, the Kutch region may be subjected to high and complex stress because of its proximity to the India, Arabia, Asia triple junction, which is located about 500km to the west (Gupta *et al*., 2001). An additional source of stress in the Kutch area might be loading by the Indus delta (Seeber *et al*., 2001).

A good velocity model will improve the hypocenter locations, and thereby identification of active faults. A well-planned seismic reflection study may also image the causative lower crustal fault of the 2001 event, which might have propagated down. If we can image the proper geometry of the fault system, we will be able to assess how the disposition of faults and their interconnection affect/perturb the ambient plate tectonic stress field.

At present, there is far too little information about the Kutch region to completely define the tectonic setting, however this has afforded us an excellent opportunity to share data and research techniques with our Indian counterparts. The data we present here are considered a continuing step in our efforts to work with the Indians. Several issues must be settled before an acceptable model for Kutch seismicity emerges, which will satisfy various observational data sets. We still lack a first order crustal velocity model of the Kutch region. Though we have some knowledge about the geologically mapped faults, we are totally unaware of the disposition of blind faults and thrusts in the crust. Very first information of immense importance is about the thickness, geometry and velocities of this complicated rifted crust. This information may tell us about the age of the crust and its later orogenic history. This will also tell us if there is any systematic difference in the crust between the seismogenic and non-seismogenic parts of the Kutch region. In turn, this information will aid us a great deal in creating accurate crustal models of the area for the purposes of nuclear test monitoring.

Velocity Modeling

In the Kutch region, seismic refraction data was collected, using two 60-channel DFS V recording stations up to a maximum shot-receiver distance of 48 km. The receiver spacing was maintained at 100 m, while the shot point interval was kept as 7 to 8 km. The shot holes drilled up to 20-30 m have been utilized to detonate high-energy explosives. The charge size varied from 50 to 500 kg, depending upon shot-receiver distance.

The data that had been selected for processing at USGS was initially processed at NGRI by utilizing only first arrival refraction data. No attempt was made to utilize near vertical and wide-angle reflection data. The hypocenters of the main and aftershocks of 2001 Bhuj earthquake reportedly lie mainly in the lower crust. After a detailed discussion, we have initiated an effort to reexamine data of some shot points, particularly for the seismic signatures coming from sub-basement features and the base of the crust. We have enhanced the signals of post 5s seismograms by applying automatic gain control (AGC) and suitable band-pass filters. A few intra-crustal reflections and the reflections from the Moho could be clearly identified. As an experiment, we have subjected this data to stacking, and Kirchhoff pre-stack depth migration. This experiment was done for a small segment with 4 shot points in the vicinity of the 2001 epicentral area (segment C), in addition to the other two segments (B, A) shown in Fig. 1. For depth migration, the aftershock derived sub-basement velocity-depth function (Rastogi *et al*., 2001) has been utilized for the main segment between Anjar and Adhoi, falling in the epicentral area. The average velocity model derived from first arrival refraction data has been used for the column down to the basement. Since one can expect shallower depths to the Moho near the coast, some alterations have been made in the velocity models of other segments for depth migration. Care has been taken to only process subbasement reflection data, as the upper sectional details are restricted.

The 35-km-long main segment (C) of refraction profile between Anjar and Adhoi, shows significantly good reflectivity in the entire mid and lower crustal column (Fig. 2) with prominent reflection horizons at an average depth of 10 km,18-20 km and 30 km. The strong reflection horizon, identified as Moho, has a significant northward dip with depth of about 37 km at the southern end of the segment to almost 47 km at the northern end. At around common depth point (CDP) 200, one can notice a significant change in the pattern of Moho, with Moho assuming a thick lens-like structure. At the southern end of this lens, one can notice the emergence of a possible fault/thrust. From the surface this fault has a southward dip. Also, at the southern end of the segment one can notice the presence of a strong subcrustal reflector at a depth of ~ 57 km. The diffused and disturbed nature of reflectivity at the northern region of the profile has obliterated this reflector. The nearly 35-km-long southern coastal segment (A), depicts good reflectivity in the entire crust (Fig. 3), with the most prominent reflections occurring at an average depth of 5-6 km, and in patches at 10 km and 20 km. The third reflector horizon as a strong band of reflections has a clear eastward updipping trend, with the depth varying from 26 km at the western end to about 18 km at the eastern end of the profile. The Moho, identified as thick zone of 2-3 km thickness, is nearly horizontal all through the profile with an average depth of 35 km. As in the case of the main segment (C) one can notice reflectivity even at sub-Moho depths, with a reflection horizon at an average depth of ~ 47 km.

A close look at the Moho configuration along the three segments suggests that the subhorizontal Moho observed along segments A and B changes the pattern abruptly in the middle part of segment C, where the subsurface crustal structure is disturbed. Perhaps the most striking feature of segment C is the indication of two steeply dipping faults, which extend down to Moho (Fig. 2). The epicenter of 2001 main shock with a fault plane dipping south and a focal depth of 22 km lies very close to this segment.

Thin crust in the aseismic southern segment and a thick crust in the main segment suggest that the Kutch mainland uplift is probably associated with a crustal root, suggesting the significant role played by extensional and compressional tectonic activity. Data from the Banni basin is needed to have detailed subsurface configuration across the area.

China

We also investigate the tectonic process in the northern border of the Tibetan Plateau and the genetic mechanism of the 1920 M=8.6 Haiyuan earthquake, the largest earthquake in recent time in China. To accomplish this, we have interpreted data from what is known as "Project 973" (Funding for this project was established in 1997, March; thus "973."). This project incorporated a 1000-km-long deep seismic sounding, teleseismic observation, and magnetotelluric sounding profiles. This "tri-combination profile" was the first profile of its kind in China.

The formation and evolution of the Tibetan Plateau is closely related to the convergence of the Indian and Eurasian continental plates. At about 45 Ma, the Indian subcontinent collided with Asia, and has since continued to underthrust at a rate of about 5 cm per year (Molnar and Tapponnier, 1975). As a result, the widest and highest continental deformation zone in the world has been formed. In contrast to the few tens of km wide oceanic deformation zones, the Tibetan Plateau extends into the interior of the plate for more than one thousand km from the plate boundary. The mechanisms of these two kinds of deformation zones are completely different. Therefore, it is of great interest to study the crustal structure of the Tibetan continental deformation zone.

Many investigations in the Tibetan region have been conducted with the efforts of Earth scientists from around the world. As a result, many models have been proposed to describe the evolution of Tibetan Plateau, including the escape model (Molnar and Tapponnier, 1975; Tapponnier *et al*., 1990), the hydraulic pump model (Zhao and Morgan, 1985, 1987; Westaway, 1995), the underthrust model (Argand, 1924; Barazangi, 1989; Beghoul *et al*., 1993) and the accordion model (Dewey and Burke, 1973; England and Houseman, 1986; Wu *et al*., 1990). However, up to now, most of the field observations have been concentrated in the southern Tibetan region, and therefore most models are based on the data there. In northern Tibet, both observational and theoretical works are sparse and insufficient. Thus, the question remains as to the tectonic process that occur in the northern border of the Tibetan Plateau.

To investigate this question, the China Seismological Bureau, Research Center in Zhengzhou conducted a 1000-km-long geophysical profile crossing the northeastern border in 1999 (Fig. 4). Striking NE-SW, the seismic profile crosses the northeastern corner of Tibetan Plateau and penetrates into the Ordos Block, a very rigid and stable block in the North China Platform. Within the Tibetan Plateau, the profile passes across the Kunlun Fault that is bounded by the Kunlun and Qilian Blocks. The profile also passes through the epicentral area of the M=8.6 Haiyuan earthquake. Here we present the preliminary results from deep seismic sounding data of this profile.

Twelve shots were carried out at each of the 9 shot points along the profile, and for each shot 200 seismometers were deployed with 1-3 km spacing. Thus, a perfect overlapping and reversed observational system was formed.

Based on the characteristics of the recorded P-wave data, the following wave groups were identified: a diving wave (Pg) from the upper crust, reflected waves Pc and Pm from interface C and Moho discontinuity, respectively, and refracted wave Pn which penetrates into top of the upper mantle. The Pc wave, second only to the Pm wave in intensity, can be traced continuously. This indicates that interface C is a major interface of the crust. On these grounds, we deem that the crust can be vertically divided into the upper crust and the lower crust. In addition, we have observed some minor reflected phases, i.e. Pc1, Pc3, Pc4 and Pc5. However, most of these phases are weaker and less continuous than Pc, so the upper and lower crust can be further subdivided into inhomogeneous secondary layers.

The travel times of seismic waves were used to invert for the crustal velocity structures. First, the x^2-t^2 method was used to calculate the depth and average velocity of interface C and Moho discontinuity corresponding to each shot point. Then, the depth-velocity function for each shot point was extracted by 1-D inversion. On this basis, the initial model of 2-D velocity structure along the profile was constructed. The final 2-D velocity structure was ultimately revealed by travel time inversion. In the 2-D model calculation, a joint inversion technique was used for both interface location and velocity values (Zelt and Smith, 1992).

Since apparent seismic velocities are directly measured while the depth of refracting horizons are consecutively calculated (from the shallowest to deepest layer), seismic velocities generally have lower percent errors than interface depths. As is discussed by Mooney (1989), the errors for velocities and interface depths are about 3% and 10% respectively. Even so, the relative variation of velocities and interface depths, and the main features of the crustal structures can be seen from the velocity model.

Figure 5 presents the final 2-D velocity structure. The crust can vertically be divided into an upper crust and a lower crust, with interface C as the boundary. Lateral variation of the crust along the profile is considerable. On the whole, the crust gets gradually thicker from northwest to southwest. As the depth of interface C does not vary greatly along the profile, the variation of crustal thickness is mainly attributed to the gradual thickening of the lower crust from northwest to southwest. The Moho fluctuates significantly in the areas of the Maqin and Haiyuan blocks.

The number of secondary interfaces that exist in the upper and lower crust clearly varies along the profile. It increases gradually from northeast to southwest along the profile, indicating an increase of vertical heterogeneity of the crust.

Figure 5 also shows that a number of low velocity layers exist in the crust in the Maqin Region and one velocity layer exists near interface C in the Haiyuan Region. Moreover, in the vicinities of Maqin and Haiyuan anomalies also appear in the Moho and interface C. The two interfaces are no longer velocity interfaces, but they are complicated transitional layers. Furthermore, there are large offsets of the Moho in these two regions.

As can be readily seen from the record sections and the 2-D velocity model, several distinct anomalies exist in the crustal structure of the Maqin and Haiyuan regions. Two very large strike-slip faults, the Kunlun Fault and the Haiyuan Fault cross these regions respectively. These two faults are closely related to the large thrusts and growing mountain range, and play a very important role in accommodating Indo-Asia convergence (Tapponnier *et al*., 1990; Meyer *et al*., 1998). Their tectonic activity can be seen from the large slip-rates and strong seismicities. The average slip-rates of the Kunlun and Haiyuan faults in Late Pleistocene-Holocene are 11.5 mm/a (Woerd *et al*., 2002) and 11.7-19.2 mm/a (Deng *et al*, 1990) respectively.

As mentioned previously, several models have been proposed to interpret the tectonic evolution of the Tibetan Plateau. In general, these models can be classified into two groups (Tapponnier *et al*., 2001): (1) Continuous thickening and widespread viscous flow of the soft crust and mantle of the entire plateau, (2) Successive oblique subduction of Asian lithosphere mantle, leading to the growth of crustal accretion wedges.

The first model, the viscous Tibetan lithosphere model, ignores the existence of a series of large strike-slip faults within the plateau and at its border. Recent results from surface wave inversion are also not consistent with the soft Tibet paradigm (Griot *et al*., 1998). The phase velocities of Raleigh- and Love-waves show that between the depths of 100 and 300 km, the mantle is faster, and therefore colder, under Tibet than under adjacent regions.

It seems that recent studies of deformation, magnetism and seismic structure beneath the Tibetan plateau support the second model (Tapponnier *et al*., 2001). One important piece of evidence is the existence of magmatic belts becoming younger to the north. This implies that slabs of Asian mantle subducted one after another north of the Zongbo suture. The driving mechanism may be the compression of Indian and Pacific Plates, which results in sufficient stress to reactivate weakly-welded sutures, and thus cause new narrow shears within the Asian lithosphere.

Our 2-D velocity structure appears to support this time-dependent, localized shearing model. This evolution model can easily explain the anomalies of crustal structures in the Haiyuan and Magin Regions. In location, these two regions correspond to two mantle subducted slabs related to the Qilian and Kunlun Sutures. From our results we infer that the detachment zone may be shallower than suspected. One possibility is that the upper crust is decoupled along the top of low velocity layer in the middle crust. Due to subduction, the Moho is no longer a sharp discontinuity, but a very complicated transitional zone. The subduction zones also result in the large offsets of the Moho in these two regions. As the underthrusting action in the Kunlun Region lasted longer than that in the Qilian Region, the crustal structure is more complicated; there are more crustal low velocity layers in the Maqin Region than those in the Haiyuan Region. Furthermore, the crust is thicker and the average velocity is lower in the Maqin Region.

According to the result of Zeng *et al*. (1998) from teleseismic receiver functions and Pn waves, the Moho in the Kunlun and Qilian Blocks dips southward while that in the Qangtang Block dips northward, which is consistent with the evolution model mentioned above. Results from reflection profiling in young (post-Mesozoic) orogens also show that the lower crust usually dips toward the center of the root from both sides and shows seismic laminated structures (Mooney and Meissner, 1992). The long durations of Pc and Pm waves in our Haiyuan and Maqin record sections may therefore reflect a laminated lower crust.

CONCLUSIONS AND RECOMMENDATIONS

The available data from the Kutch, India, region shows the deep-seated effect of the recent seismic activity. We suggest proper imaging of the deep-seated blind thrusts/faults is essential to obtain a meaningful seismicity model for the region.

The Bhuj earthquake has placed the Kutch peninsula and the Little Rann of Kutch west and east of the Bhuj epicenter under increased stress, and it is anticipated that these regions are likely to experience heightened seismicity in the next several decades. Thus, it is imperative that we continue to monitor seismicity and understand the crustal structure so that we will be able to discriminate seismic events. The mapping of potentially active faults with likely increased stress concentration thereby assumes great importance from a monitoring point of view, and seismic surveys are needed to refine the determination of crustal structure in Kutch mainland.

Further experiments are also needed to define the P- and S-wave velocity structure of China. In addition to limited information in other regions of China, we would also seek to verify the step-wise underthrusting evolution model of the Tibetan Plateau. We need better definition of deeper structures, especially within the lithospheric mantle in the northeastern corner of the Tibetan Plateau. Due to the limited observational distance in our refraction profile, we could not image the structures below the Moho. Therefore, further experiments based on teleseismic methods are needed. One possible way is to deploy dense seismic stations in this region for teleseismic observation. By seismic tomography, a 3-D velocity model to a sufficient depth can be obtained which will permit us to refine geologic models of the evolution of this region.

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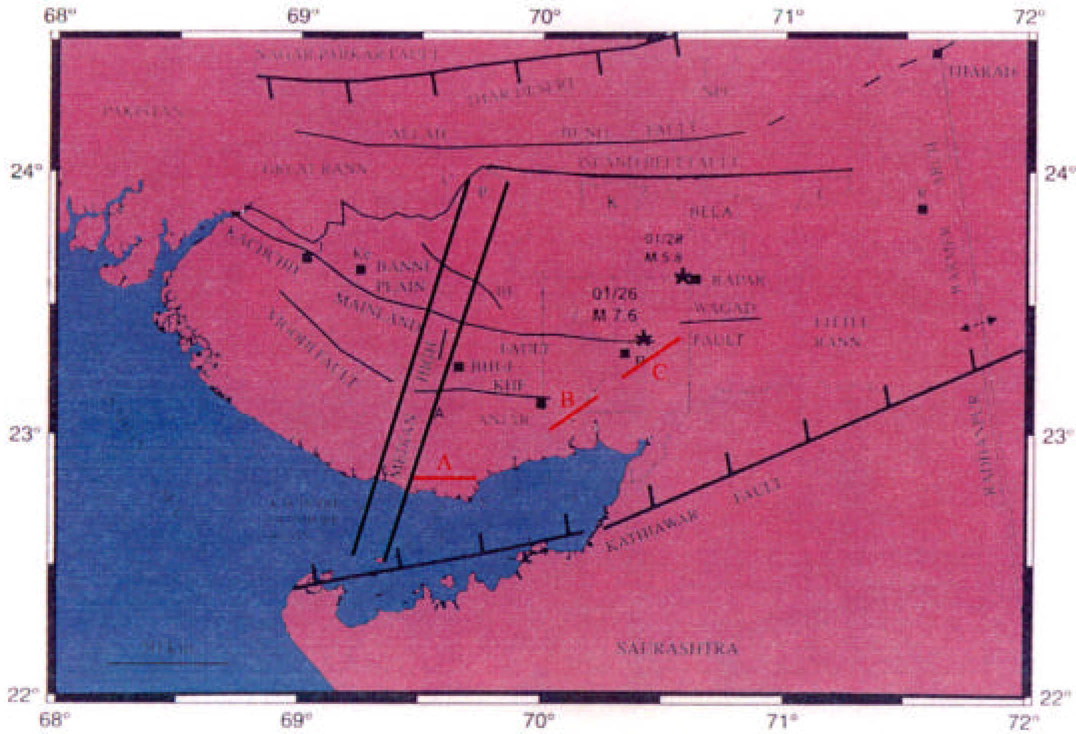

Figure 1. Structural elements in the Kutch basin. Asterisks show the USGS location of the 2001 main and one aftershock events (after Talwani and Gandopadhyay, 2001). Three seismic refraction segments (A, B, and C) are shown in red.

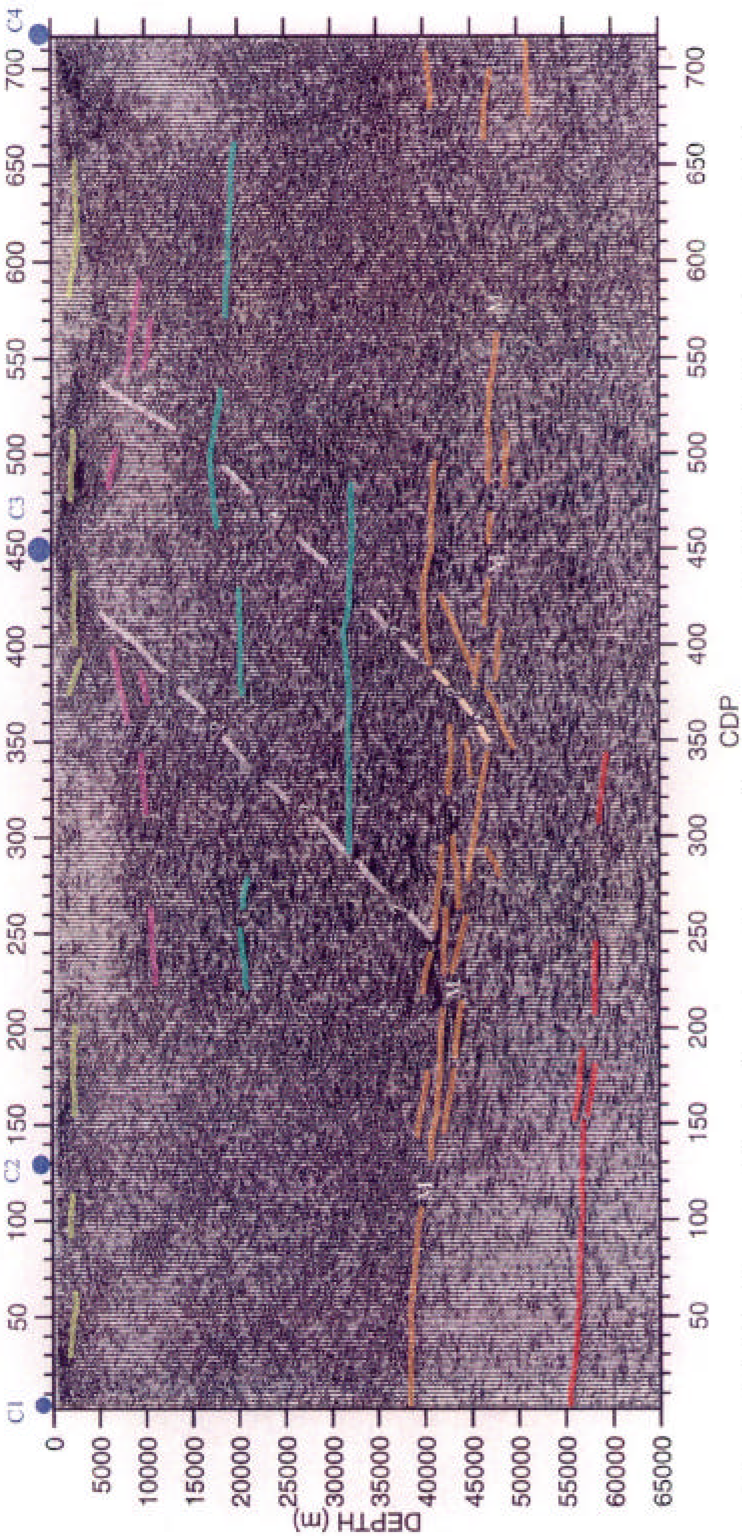

Figure 2. Kirchhoff pre-stack depth migrated crustal cross-section along segment C. CDP interval is 50 m. Interpreted horizonas are superimposed. Dots above represent shot point locations.

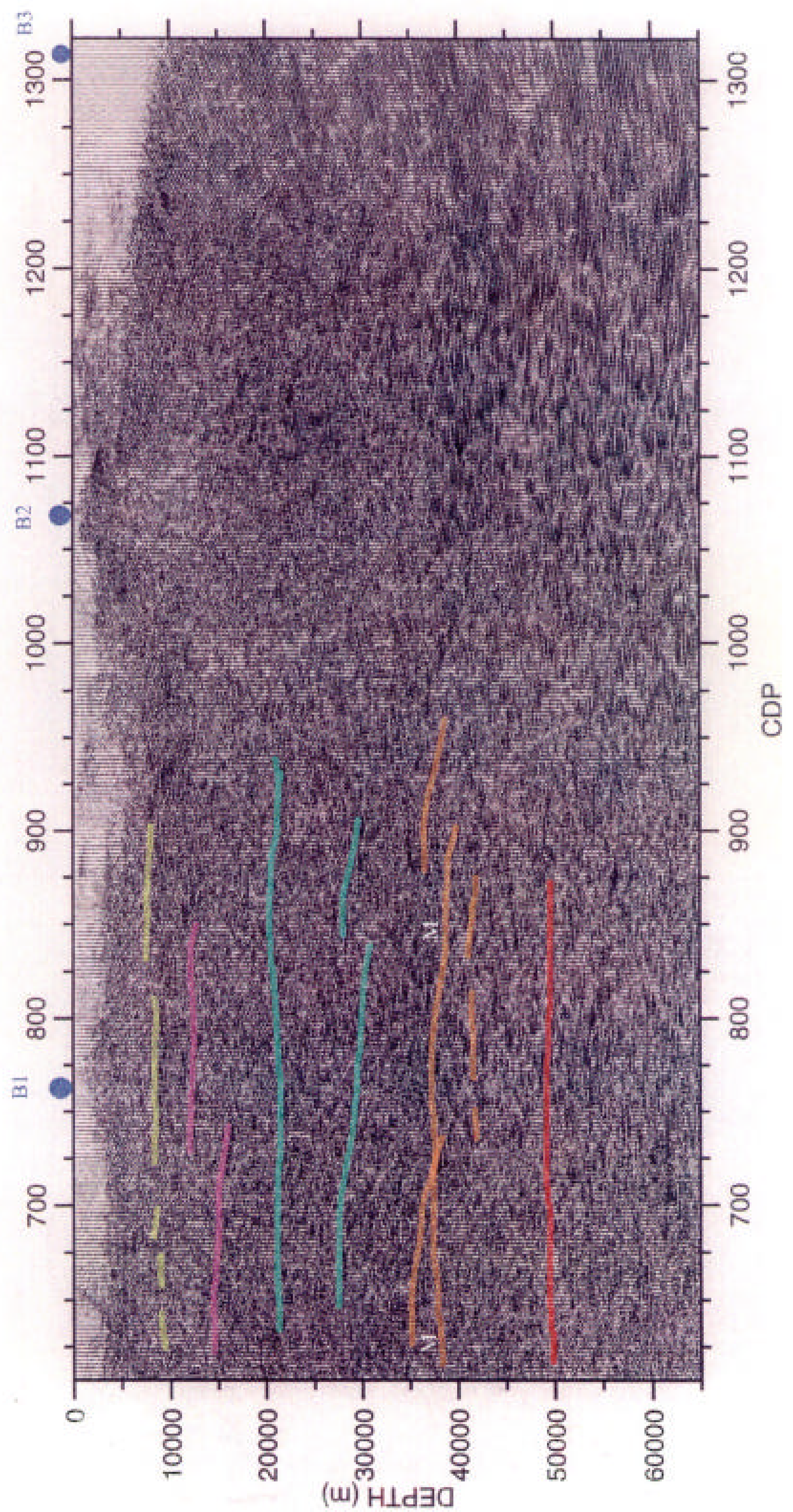

Figure 3. **Kirchhoff pre-stack depth migrated crustal cross-section along segment B. CDP interval is 50 m. Interpreted horizons are superimposed. Dots above represent shot point locations.**

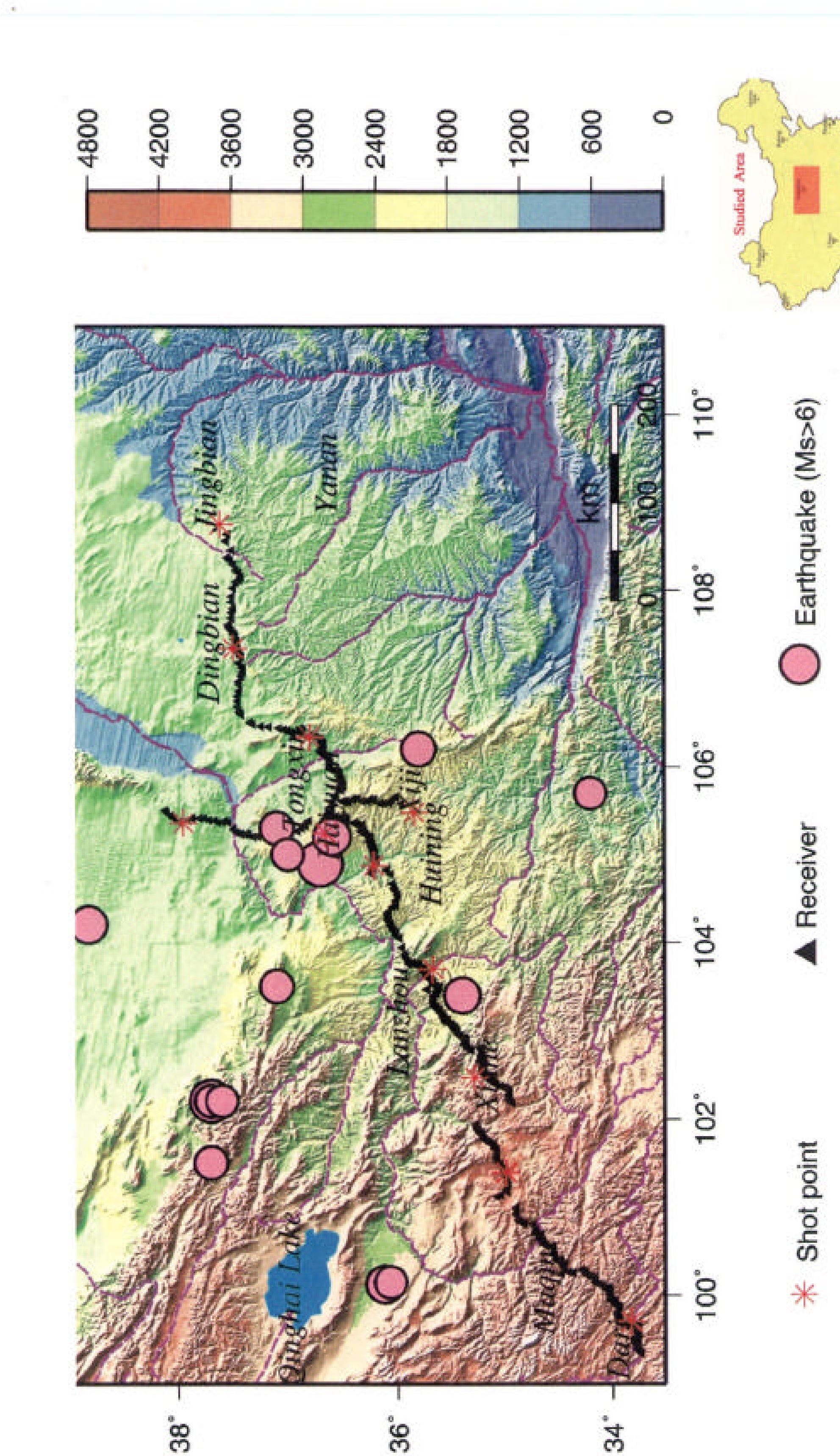

Figure 4. Geological setting and position of the "tri-combination profile."

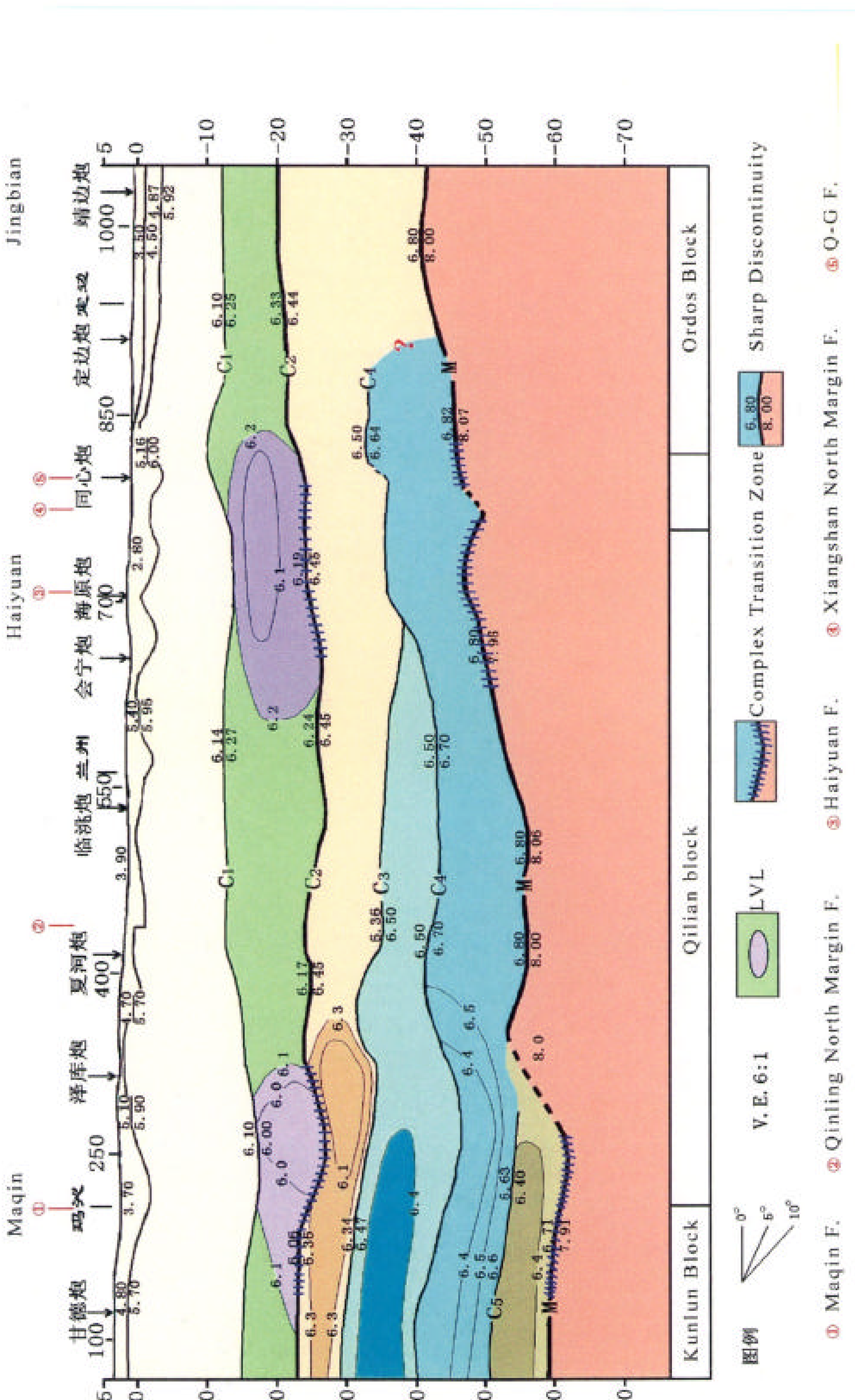

Figure 5. 2-D crustal seismic velocity structure of the Maqin-Jingbian DSS profile.