PATH CALIBRATION STUDIES IN AND AROUND THE INDIAN SUBCONTINENT

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ABSTRACT

We have developed one-dimensional crustal models for the regions of Peninsular India, northeast India and parts of the northwest Pakistan by modeling regional seismograms recorded up to 12° distance. We modeled regional seismograms recorded at several stations in the Indian subcontinent, NIL (Nilore, Pakistan) and LSA (Lasha, China). We modeled teleseismic *pP* and *sP* phases to constrain depths and the amplitude variation of the *pP*, *sP* and *P* waves to constrain focal mechanisms of earthquakes. These crustal models are now being used to develop travel-time curves for seismic phases (*P* and *S*) so that they can be used in the seismic event location programs. We have also identified a set of possible GT10 and GT25 events using the data base from the ISC catalog and local contacts. For some events the locations determined using travel times from local networks and regionalized velocity models are found at several tens of kilometers away from the ISC and EHB hypocenters -- especially for small events. Often travel times exhibit residuals relative to a crustal structure used in their locations. To investigate how well this can be calibrated in the region surrounding the Indian subcontinent, we used a few GT10 events from the northeastern India and analyzed their travel times to the seismic stations that operate in the Indian subcontinent. We computed travel-time residuals by subtracting the IASP91 travel times from the observed travel times and by subtracting the IASP91 travel times from the travel times computed for 2D cross-sectional paths obtained from a preliminary 3D model of the region. This 3D model was constructed by placing the crustal model of Mooney and Laske on the mantle structure from Grand's tomographic model extrapolated to P wave velocities using a constant Poisson's ratio. We used a modified shortest path algorithm to calculate these travel times in this study. We computed travel times along many 2D profiles at 10 degree azimuth intervals from the earthquakes and interpolated these travel times to estimate the expected travel times for P waves to a given station using the cubic-spline interpolation method. We also did a similar calculation for travel times from the station GBA to the earthquakes that were identified as GT25 events. We a found a good correlation between the two sets of residuals suggesting that our 3D model of the region is a good initial one for the region.

Objective

The primary objective of this study is to develop crustal models for various regions of the Peninsular India, northeast India and parts of northwest Pakistan. To accomplish this goal we have identified several well located seismic events from the Indian subcontinent and used the arrival times of the impulsive P waves reported in the ISC and local bulletins by the seismic stations operating in regions. In this report we shall present results of regional path models which must be included in the final crustal model of the Indian subcontinent so that reliable theoretical travel times for seismic waves can be computed.

Research Accomplished

In our previous report we discussed preliminary crustal models developed for the northeast and central India. The northeast region of India is characterized by highly complex geology and a high rate of seismicity. In this ongoing investigation we further conducted an investigation of travel times for Pg, P* and Pn waves along various profiles using the time picks from the local networks. A study was conducted at RRL (Regional Research Laboratory, Jorhat) in order to obtain seismic velocities and thicknesses of the upper and lower crust and depth to the Moho discontinuity along the Main Central Thrust (MCT) and Main Boundary Fault (MBF) in the Arunachal Himalaya and the Brahmaputra lineament (BPL) in Assam (Sitaram *et al.*, 2000). The results of this investigation have yielded that the crust of the northeast India is primarily composed of two layers, but with varying thicknesses, along the above three profiles suggesting that the thickness of the Moho depth increases from 45.3±1.4 km to 51.8±1.4 km from the Brahmaputra lineament towards the north into the MCT. As the crustal structure extends into the Tibet region, the Moho depth increases to about 65 to 70 km as was determined from surface wave analysis (Gupta and Narain, 1967).

The crustal structure of Peninsular India is homogeneous and also consists of two layers above the half space (Saikia et al., 1998; Singh *et al.*, 1999; Saikia, 2000). A great deal of analysis was done using broadband seismograms that were recorded by the modern broadband stations deployed in the Peninsular India from the May 21, 1997 Jabalpur earthquake (origin times: 22h 51m 28.7s, 23.084^{o}N, 80.041^{o}E, h=36 km and M=6, PDE). Figure 1 shows the locations of these broadband stations, shown by triangles, that currently operate in India. Included in this figure are the locations of earthquakes occurring in the stable Indian subcontinent. We used digital seismograms recorded from this earthquake to calibrate the crustal model extending towards HYB (Hyderabad) – a Geoscope station and located 645 km away from the epicenter toward the southwest, BHPL (Bhopal) -- a broadband station operated by the India Meteorological Department (IMD) and is located 271 km west of the epicenter, and BLSP (Bilaspur) which is also a IMD broadband station and is located southeast of the epicenter at a distance of 237 km. The P- and S-wave timings of various phases at these stations required a slight adjustment of the velocity models. Figure 2 shows an example of the agreement between various seismic phases obtained by inverting the recorded data shown by the solid lines (Saikia, 2000). We used a focal depth of 35 km which was obtained by fitting the timings of the teleseismic depth phases, namely the pP and sP waves relative to P (Figure 3). The modeling of the regional refracted sPn and pPn phases relative to the Pn onset up to 15^o away from the epicenter also proved helpful in obtaining its depth.

In addition to working with digital data from this earthquake, we are also using the recorded Pn and Sn timings reported from 24 Indian seismic stations (IMD, 1998). This earthquake also generated 32 aftershocks which were located by the Indian scientists using local crustal models. We have collected the P and S times of these events and are in the process of relocating them using the IASP91 model.

We have further examined the epicenters of earthquakes that occurred in and around the Indian subcontinent during the period from 1964 to 1996 using the phase data published in the ISC catalog. Figure 4 identifies the events that satisfy the criteria of the GT25 and GT10 events (Yang and Romney, 1999). Figure 5 shows the distribution of stations that reported timings to the ISC catalog for these earthquakes. As expected the population of GT10 events decrease significantly and are mostly confined to the northwest Pakistan, Nepal and northeast India. Of these, the events in Nepal and northeast India are more recent because of the local networks that operate in these regions. For many of the events in the northeast India, we have also found in-common earthquakes whose locations are reported in the EHB catalog produced by Engdahl and his co-investigators. For small magnitude events (m_b<4.5) we find that locations published by the local network have moved from the EHB epicenters by several tens of kilometers. It is possible that the EHB locations for these small events are biased because of the crustal model used in locating them and due to the lack of data from local distances.

We have also examined the travel-time residuals using the GT10 locations of several events which occurred in the northeast India. Figure 6a shows the observed residuals for an event which occurred on the September 2, 1990 (m_b=5.2). The small circles represent the observed residuals reported in the ISC catalog at individual stations and are distributed over the entire globe. To investigate how well these residuals correspond to a three-dimensional crustal model of the region, we developed a preliminary model by placing the crustal model of Mooney *et al.* (1998) on the S-wave tomographic model of Grand for the mantle structure. The P-wave model at depth below 100 km was extrapolated using a constant Poisson's ratio. The mantle velocities specified in the crustal model of Mooney *et al.*, were extended to a depth of 100 km. Using this composite model we have computed theoretical travel times along profiles at 10^o azimuth intervals from the event using a modified shortest path algorithm. We also computed travel times for the 1D model (IASP91). These travel times were subtracted from the travel times computed using the composite model to compute the theoretical residuals. We used a cubic spline algorithm to interpolate travel times between the nearest two points taken from the profiles. The resulting residuals were used to contour the residual distribution over the study region (Figure 6). Clearly, there is a very good correlation between the observed and the theoretical residuals. Over the Peninsular India, both residuals have similar values, thus demonstrating the potential of our preliminary 3D composite crustal model. Such a model will yield travel-time corrections to relative to the one dimensional IASP91 model for earthquakes, especially of the small sized events, that occur in regions not been previously calibrated. Empirical estimates of travel-time corrections are generally the most desired data for the purpose of constructing correction surfaces as demonstrated in central Asia (Woods *et al.*, 2000).

A similar investigation conducted for the station Gauribidanur (GBA) in India using the GT25 locations indicated a poor correlation between the observed and the theoretical residuals also computed based on our preliminary 3D model (Figure 6b). This poor correlation strongly suggests that the locations of the GT25 events must be reviewed. We are now extending such station-specific investigations to other stations, namely NIL (Nilore) in Pakistan and DEL (Delhi) and KOD (Kodaikanal) in India.

Conclusions and Recommendations

So far, we have completed developing 1D crustal models for various regions in and around the Indian subcontinent. These models need to be included in our preliminary model of 3D structure of the region. We have collected regional seismograms from earthquakes that span the entire seismicity depth range extending to about 200 km for the earthquakes that occur in the northwest Pakistan around the Pakistani nuclear test site and along the India and Mayanmur border. These seismograms need to be analyzed for identifying characteristics that would separate the deep earthquakes from those that occur at a shallow depth. We have also compiled regional seismograms recorded at LSA, which is a broadband station in China, from earthquakes that occurred in the Indian subcontinent. A preliminary analysis of these waveforms has indicated that they are influenced by the local structure. Although we have succeeded in yielding the observed travel-time residuals from earthquakes in this region using our preliminary composite model, this model should be updated so that time-domain features in the regional seismograms can be simulated using the crustal models. We also found that locations of GT25 events are not reliable because they yield inconsistent travel-time residuals relative to the IASP91 model. For a selected set of events, it is therefore necessary that locations of the GT25 events need improvement. To this end, we propose that regional and teleseismic seismograms are to be analyzed so that depths are reliably estimated in order to relocate them using a fixed depth. This way the trade-off between the depth and the origin time can be significantly reduced and origin times can be improved.

Key words: regional, event location, GT10 and GT25, 1D and 3D models.

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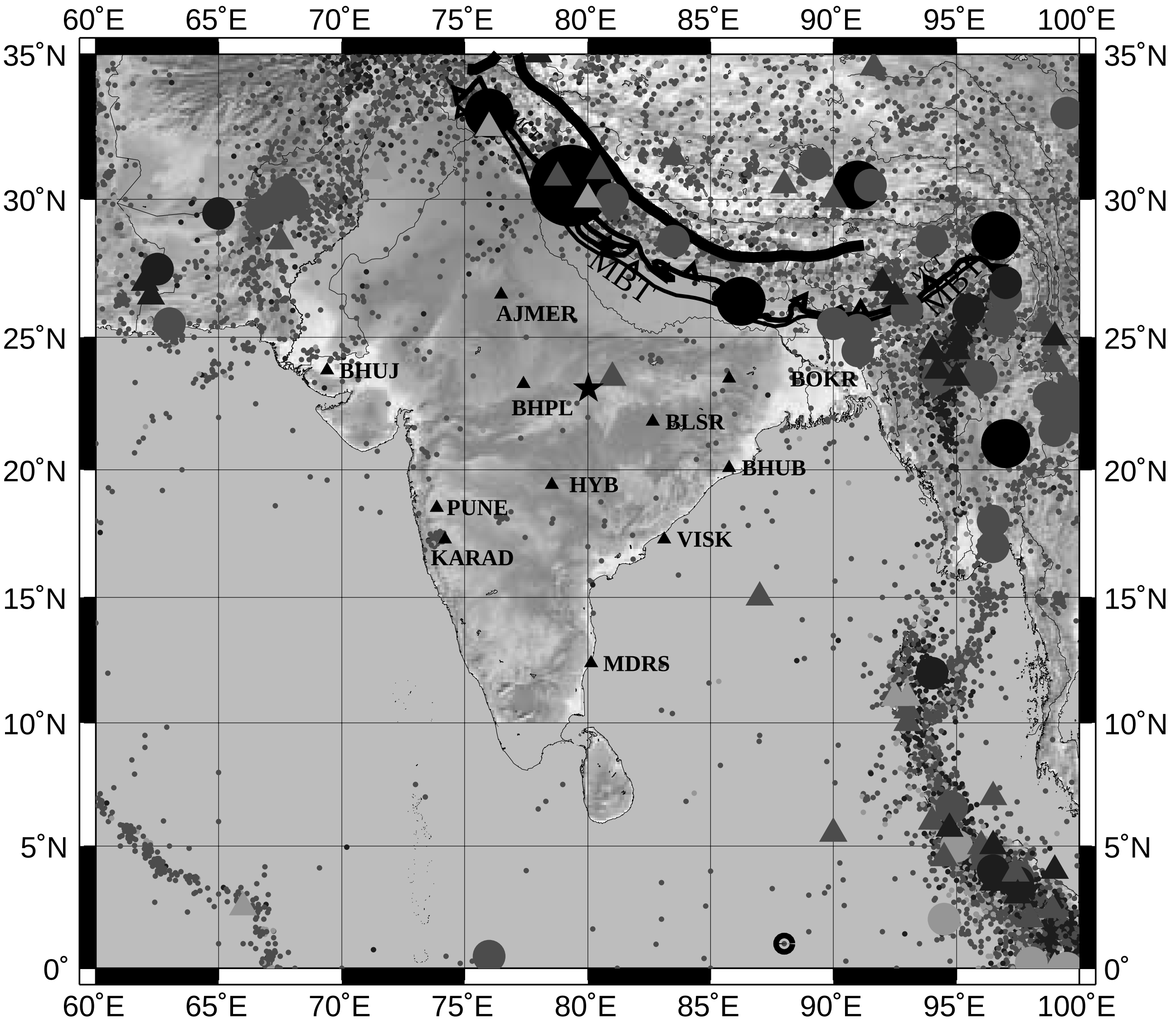


Figure 1. Map showing the locations of broadband stations, shown by triangles, operated by the India Meteorological Department (IMD). Included in this map are the earthquakes occurring in the stable Indian subcontinent.

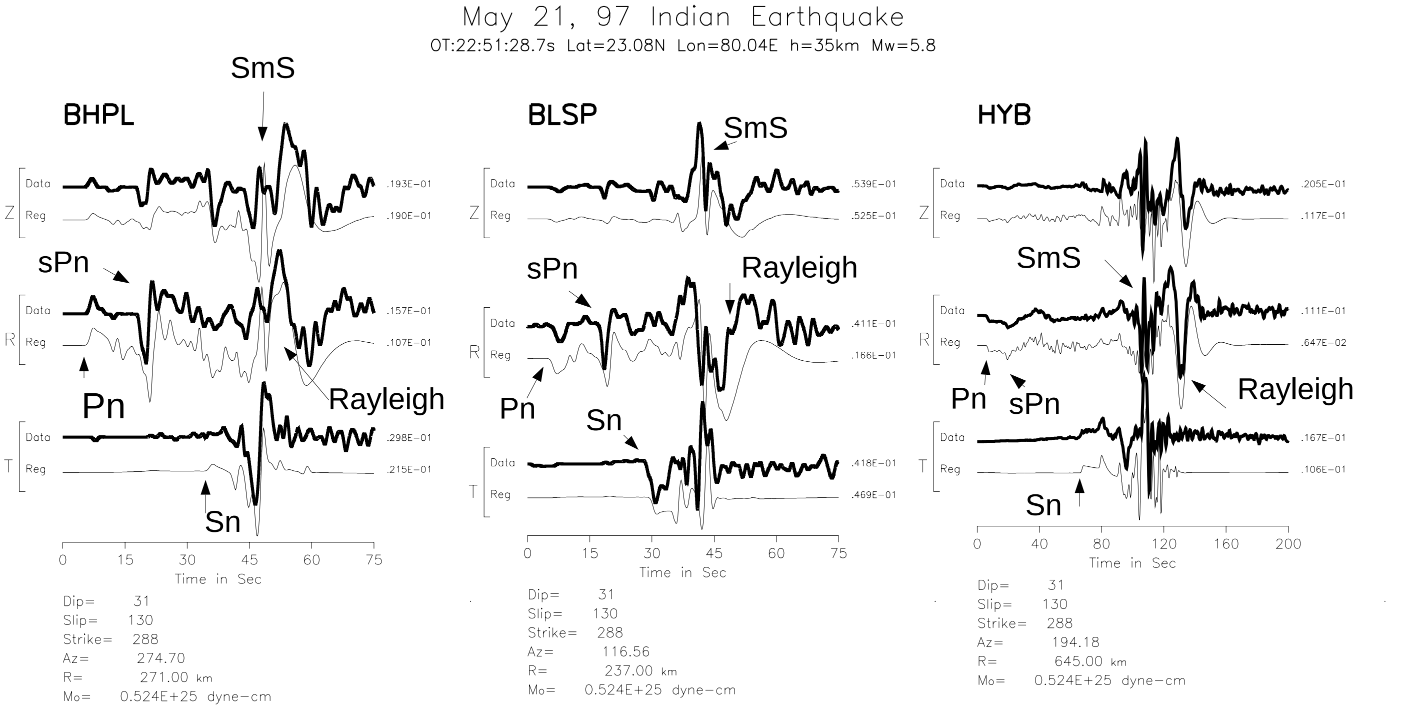


Figure 2. Comparison between the data and the synthetic regional seismograms at stations BHPL (Bhopal), BLSP (Bilaspur) and HYB (Hyderabad). Note the agreement in travel times of sPn, Sn and surface waves relative to the Pn onset. The Pn onsets are aligned in absolute travel times for both the data and synthetics.

Modeling of Teleseismic Waveforms
97/05/21 22:51:23.088s (23.08N 80.04E)
h=35.0 km Mo=5.88e+24 dyne−cm
Time Delay : 0.0s 0.6s
T.F: (0.1 0.0 0.2s) (0.5 0.0 0.5s)
dip=65.0 rake=68.0 strike=70.0

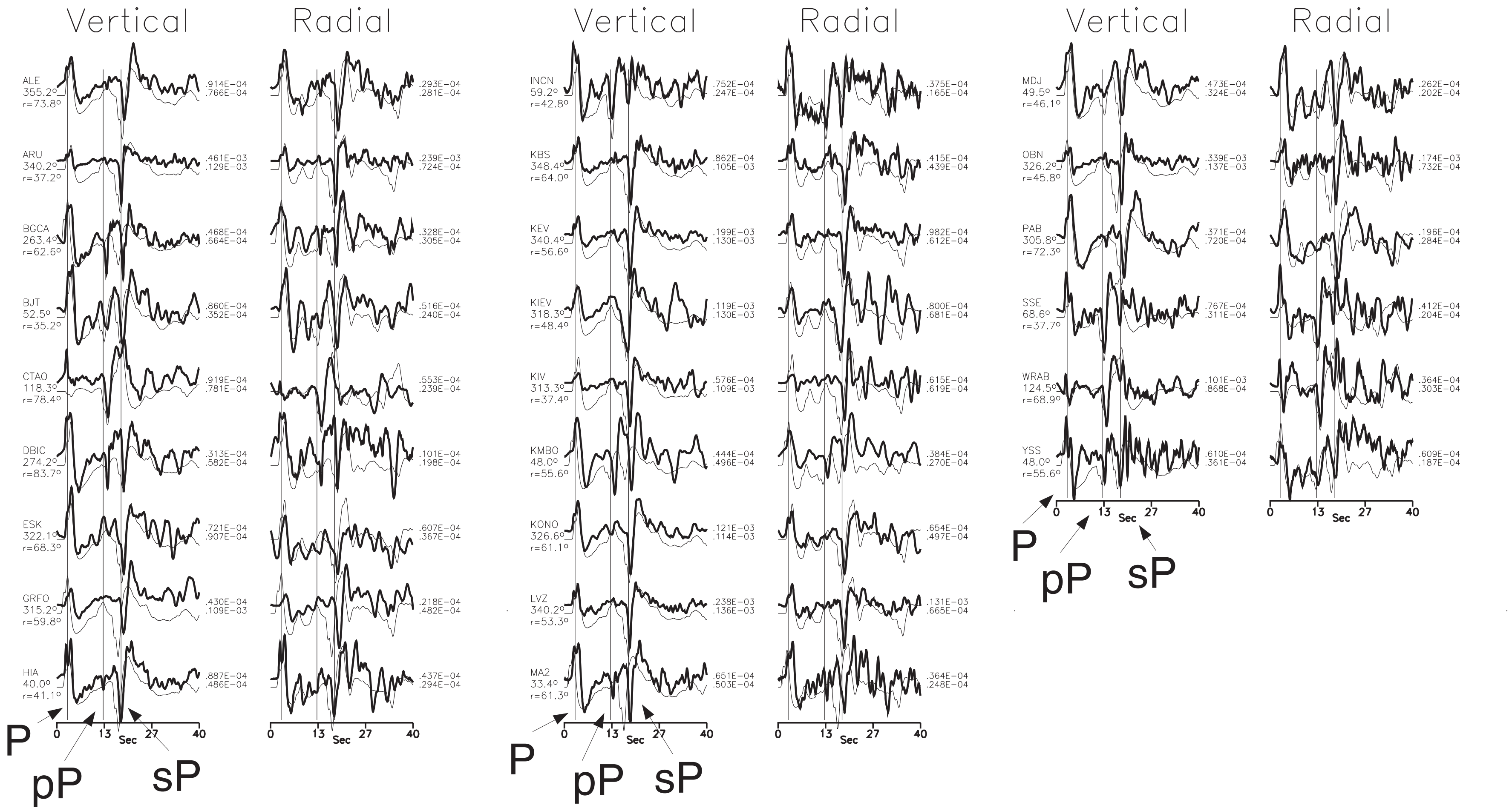
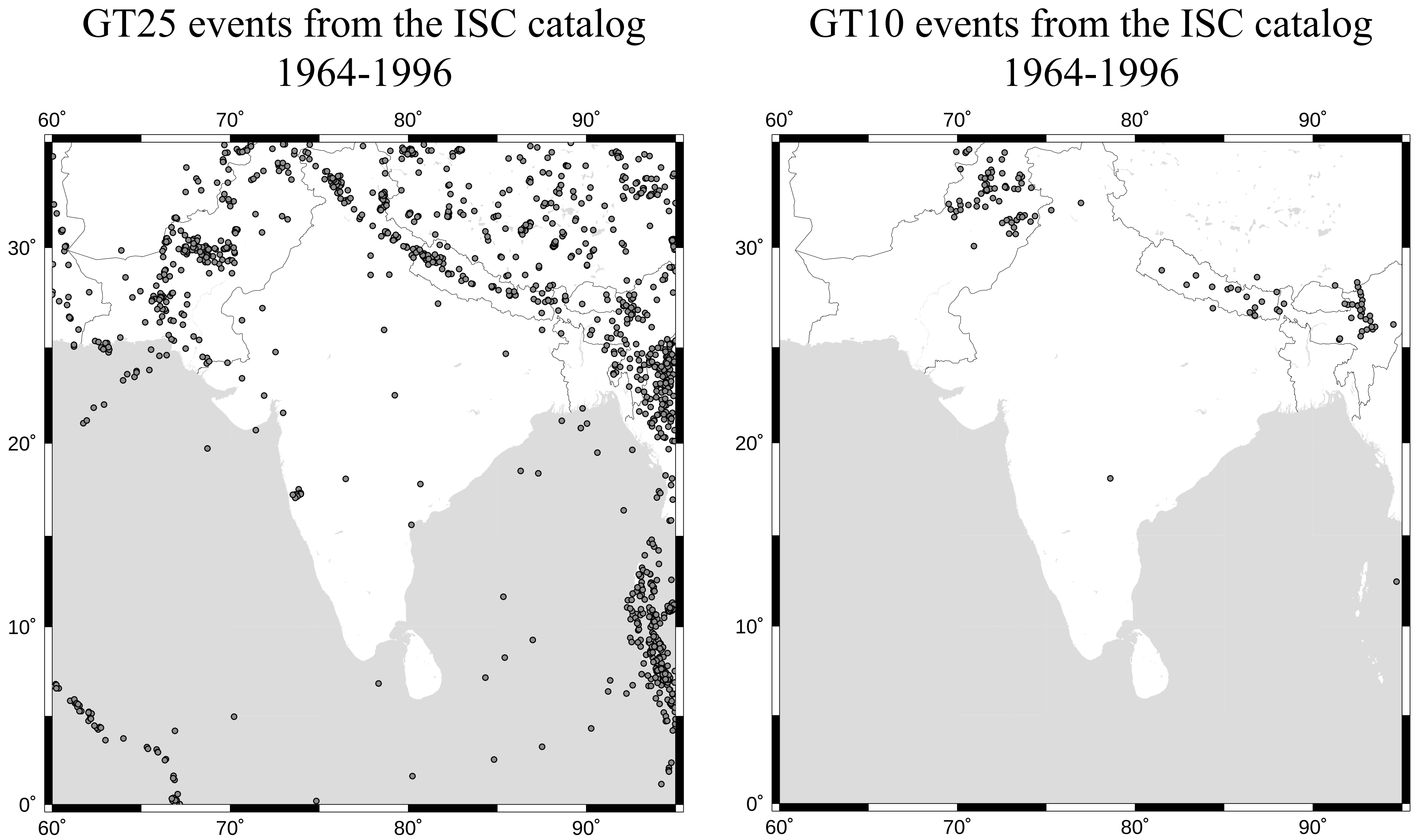


Figure 3



GT25 events from the ISC catalog 1964-1996

GT10 events from the ISC catalog 1964-1996

Figure 4. Location of events from the ISC catalog that conform to the GT25 (left panel) and GT10 (right panel) criteria, as discussed in Yang and Romney, 1999.

Location of seismic stations reporting to the ISC

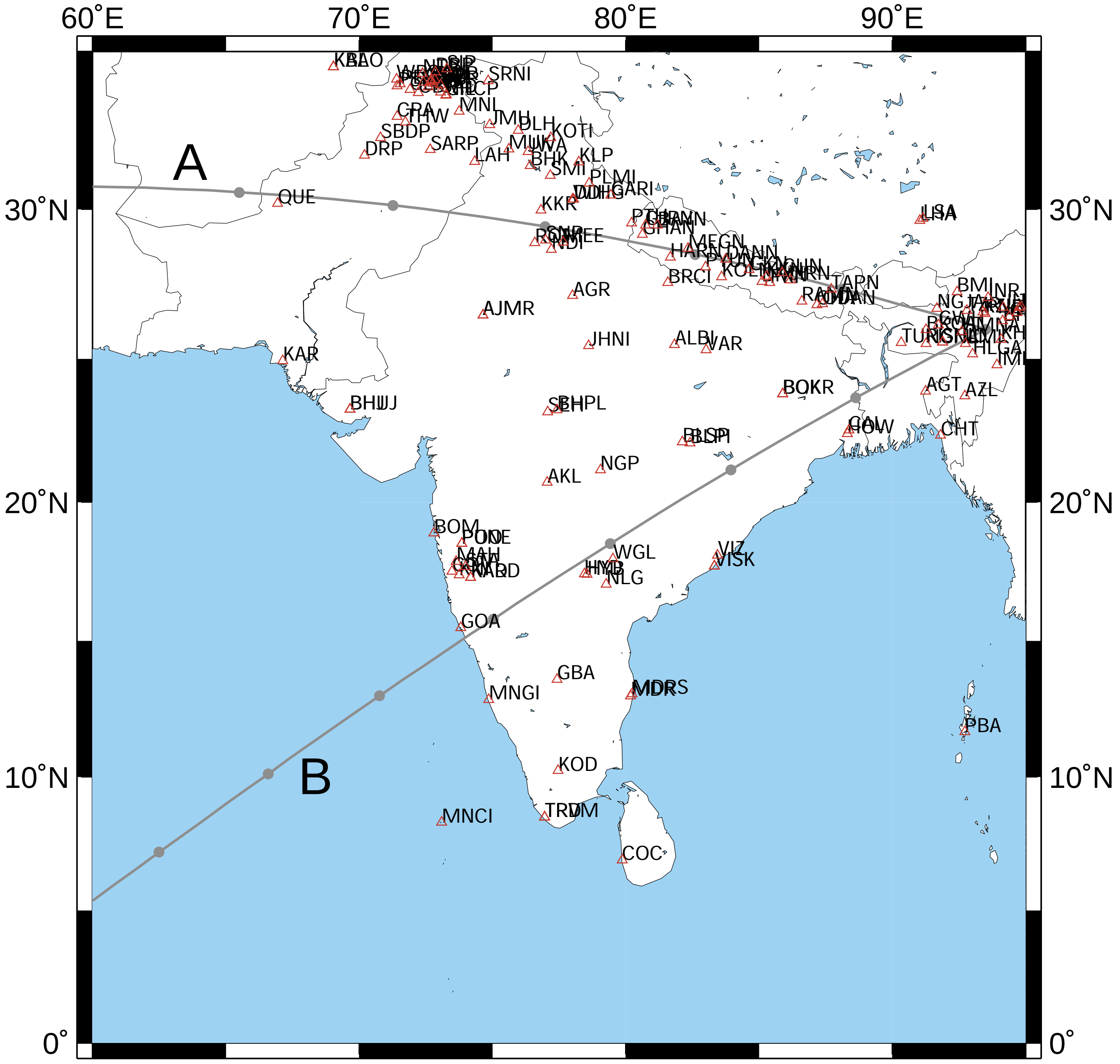


Figure 5. Map of stations on the Indian subcontinent that are included in the ISC bulletins.

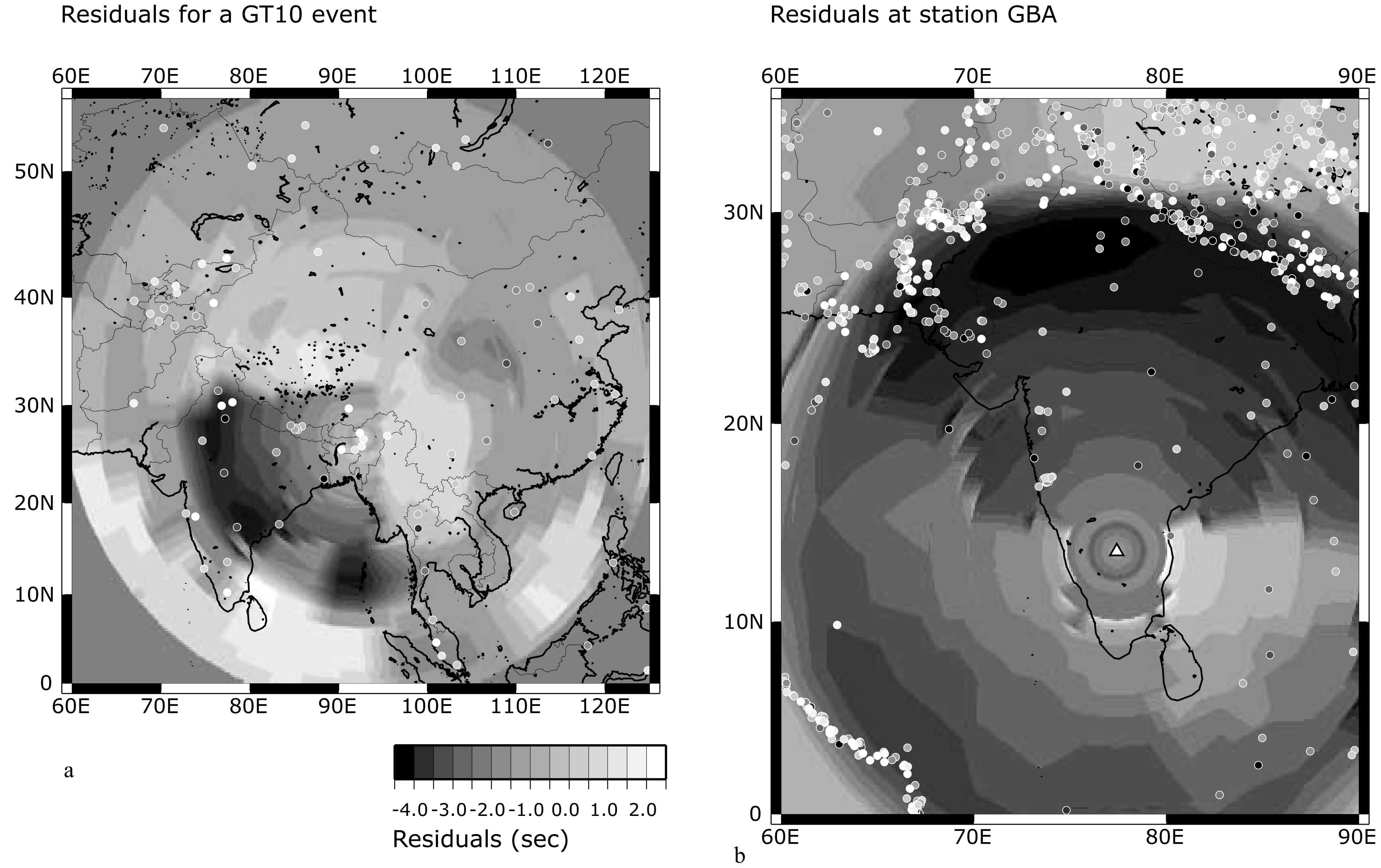


Figure 6. Observed travel-time residuals (dots) plotted on top of maps of synthetic residuals, computed for a composite model based on the Mooney et al (1998) crustal model and the Grand tomographic model below 100 km. The grey shading for the observed and synthetic residuals are identical. a - residuals for a GT10 event in NE India recorded at the ISC stations. b - residuals observed at station GBA for GT10 + GT25 events from the ISC bulletin.