CONTINUING ANALYSIS OF EARTH STRUCTURE AND GROUND TRUTH DATA FROM THE MIDDLE EAST

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Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation

Contract No. DE-AI04-98AL66517

ABSTRACT

Middle Eastern countries have a very high level of seismic activity. For this reason, there are a large number of seismic networks in operation, and data from these networks have provided details of the crustal structure of the region. One such network, the Tehran Telemetry Seismic Network (TTSN), consists of twelve stations and is located around the city of Tehran. Nearly two years of local data are available from this array, and these data yield estimates of crustal thickness based on receiver function analysis. These results consistently show a crustal thickness of 44 – 50 km. This value is about 12 km thicker than has been measured in eastern Turkey, and 9 km greater than the global average for stable platform regions. The 45 km crustal thickness near Tehran is almost exactly the same as the 46 – 48 km thickness reported from receiver function analysis from the central Zagros mountains. The apparent uniformity of the crustal thickness implies that mountain building has only recently started in the region, and the crust beneath the Zagros mountains has not been appreciably thickened by compression. Despite the platform-like crustal structure, we find evidence that the upper mantle Pn velocity is lower than the typical value of 8.1 km/s. The relocated earthquakes of Engdahl et al. (2004) show a consistent pattern of longer (by several seconds) Pn travel times compared with the predictions of the global seismic velocity model ak135. The Pn velocity observations are confirmed by a new tomographic model that shows variation in seismic velocities in the uppermost mantle across the Middle East. The zone of low upper mantle velocity coincides with the region of high seismic activity, which indicates that the mantle anomaly is related to active tectonic processes.

OBJECTIVES

The structure of the crust and upper mantle of the Middle East is highly heterogeneous. We have integrated seismic and non-seismic data from this region to determine the properties of the crust and sub-crustal lithosphere. Available data and results include seismic networks data, receiver functions from permanent and temporary stations, Pn travel time residuals from regional earthquakes, seismic tomographic models, and recently-obtained strong motion waveform data. Our results allow us to compare crustal signatures across the region and to provide better-constrained velocity models for event locations.

RESEARCH ACCOMPLISHED

We have continued our existing program of collecting high-quality seismic data from the Middle East by capitalizing on newly-established research relations between the United States Geological Survey (USGS) and leading research institutions in the Middle East and overseas Middle Eastern scientists. These data include some local and regional phase and waveform data (especially strong motion waveforms). We also possess several hundred digital records from a regional 1500-station strong motion network.

These new research opportunities evolved as seismic hazards in the Middle East came to international attention following the devastating earthquake in the city of Bam, Iran, on December 26th, 2003. That event killed over 30,000 inhabitants and left 85 percent of the city in ruins, and has reignited efforts to study seismic events in the Middle East. In addition to the Bam earthquake, the Middle East has a long history of large-magnitude seismic events. The Tabas-e-Golshan earthquake of September 1978, and the Rudbar-Tarom earthquake of June 1990, are additional examples of strong earthquakes in the last 25 years. These type of events are extremely useful as ground truth data. We have obtained strong motion records from numerous events with magnitude greater than 5.0 that have occurred in the past ten years.

To record these regional events, a 1,500-station digital strong motion array has been built in the Middle East, and we have obtained 1813 high-quality digital strong motion records and associated meta-data for numerous events of varying size. Our work focuses on the larger magnitude (>M=6) events that have six or more records distributed over all azimuths.

The distribution of seismological stations and lack of national catalogs of events has limited the study of seismicity to a catalog of events published by international agencies such as the International Seismological Centre (ISC) and the USGS. Threshold magnitude of reporting of about 3.5 and poor location and depth accuracy for moderate and small events have been obstacles for realistic and quantitative assessments of seismicity in this region. Only recently have there been attempts to acquire better depth estimates by waveform modeling (e.g., Maggi et al., 2000) and improved locations (Engdahl et al., 1998, 2004). Although the installation of the National Broadband Network (Iran) and some regional telemetry networks commenced in the mid 1990's, there have been no concerted efforts towards preparation of a seismic catalog. Therefore, seismicity studies on a nation-wide or regional scale still rely heavily on information from international monitoring.

Two important scientific groups that conduct seismic research in the Middle East are the International Institute for Earthquake Engineering Seismology (IIEES) and the Geophysical Institute (GIUT) of the University of Tehran. The IIEES operates eleven broadband and many strong motion instruments. The GIUT operates more than 40 short-period digital stations, distributed into eight seismic networks. Management is within the National Center of Seismic Networks. The 12-station short period telemetered array around Tehran uses state-of-the-art Canadian Nanometrics equipment. This network is fully operational, and it provides the opportunity for obtaining excellent ground truth data. The IIEES has been making efforts to reach out internationally, and has hosted a series of international meetings in seismology and earthquake engineering. Table 1 lists the permanent seismic networks in our area of study which are also shown in Figures 1a-b.

Table 1. Five Permanent Networks
1. Broadband Network (11 stations)
There are presently 11 broadband seismic stations operating in our region of interest (Figure. 1a). The equipment consists of Guralp (CMG3T) sensors and Guralp 25 bit data loggers. The seismographs record continuously at the station sites. Selected time windows, on request of the analyzing seismologists, are sent to the central recording station in Tehran, IIEES, via satellite (VSAT).
2. Tehran Telemetry Seismic Network (12 stations)
The 12 station Tehran Telemetry network (Figure 1a) consists of short period seismographs connected to central recording station via telemetry. The recording is done on a triggering basis. Data available outside of Iran consist of teleseismic events with magnitude greater than 5.7 for the time period of 1996-2001 and local data for a period of over 22 months.
3. Azarbaijan Telemetry Seismic Network (8 stations)
The 8 stations of the Azarbaijan Telemetry network (Figure 1a) consist of short period seismographs connected to central recording station via telemetry. The recording is done on a triggering basis. Data available consists of two months of recording.
4. Iran Long Period Array (ILPA, 7 stations)
The seven stations of the ILPA (Figure 1a) consist of short period and long period borehole sensors located south and west of Tehran and transmits continuous data to a central recording station in Tehran. Available data consists of three years of long period and 17 months of short period recordings.
5. Strong Motion Network (ISMN, ~1500 stations)
The Iran Strong Motion Network (Figure 1b) in its present form consists of about 1500 stations. Digital waveforms for a large number of main shock and aftershock earthquakes in the Middle East have been obtained by the USGS-Menlo Park.

Although the identification and mapping of active faults in the Middle East have a long history (e.g. Berberian, 1976, 1977; Jackson and McKenzie, 1984; Baker et al., 1993; Jackson et al., 1995), the regional tectonics are poorly understood. In the face of poor locations of earthquakes and lack of slip measurements in the field, it is difficult to accurately associate earthquakes with known faults. To discriminate between earthquakes and suspected man-made events at teleseismic distances, such information is of paramount importance.

In the Zagros Mountains (Figure 2), a general absence of surface faulting further complicates this picture and leaves us to rely solely on seismological data. In the absence of terrestrial geodetic data, Jackson et al. (1995) used the modified method of Haines and Holt (1993) to construct a velocity field based on strain rate data obtained from scalar moment tensors of earthquakes. A major breakthrough has been the deployment of global positioning system (GPS) instruments in the late 1990's for a series of measurements. The results (e.g, Nilforoushan et al., 2003; Vernant et al., 2004) depict strain rates across the study area and show that north-south shortening from Arabia to Eurasia is about 2-2.5 cm/year less than previously estimated by global plate tectonic models (Figure 2), and that the transition between the Makran subduction zone and the Zagros system is sharp. The transition between the two regimes is accommodated along faults bordering the Lut Block.

The installation of new broadband stations and Incorporated Research Institutions for Seismology (IRIS) temporary deployments in Saudi Arabia and Turkey has resulted in a new series of tomographic imaging of Pn, Sn, Lg, and Q values across the Arabian, Eurasian, and African plates (e.g., Sandvol et al., 2001; Al-Damegh et al., 2004; Al-Lazaki et al., 2004). Earlier the Lg and Q values for the region were based primarily on the work of Jih and Lynnes (1993) (who expanded upon the earlier work of Nuttli (1980), Kadinsky-Cade et al. (1981) and the pioneering work of Asudeh (1982)) on Pn velocity mapping across the region. Recent findings show that Central Iran is, in contrast to the Caspian Block and Arabian Shield, characterized by low Pn velocities (< 8.1 km/s; e.g., Al-Damegh et al., 2004; Al-Lazaki et al., 2004) (Figure 3). According to these studies, the region also shows inefficiency for Sn propagation, compared with neighboring Arabia and Eurasia. These fundamental structural differences have further been confirmed by recent and ongoing body wave tomography studies (e.g., Alinaghi et al., 2004) showing that the Arabian and Eurasian plates generally have higher P- and S-wave velocities than other regions of the Middle East. Hearn and Ni (1994) and Rodgers et al. (1999) have noted that Sn propagation is very weak near the IRIS ABTK (Turkmenistan) station.

Our opportunity to calculate a crustal and upper-mantle model for the Middle East using seismic tomography is due to the work recently completed by (Engdahl et al., 2004). Their work was based on a careful analysis of phase arrival times reported to the International Seismic Summary (ISS), the International Seismological Centre (ISC), and the USGS. This effort has resulted in the relocation of nearly 2,000 earthquakes that occurred in the study area during the period 1909-2004 (Figure 4). The "EHB" methodology of Engdahl et al. (1998) was applied, and special attention was given to focal depths. The "EHB" method uses phase arrival times of P, S, PKP and depth phases (pP, sP, and pwP) with the 1-D Earth model Ak135 (Kennett and Engdahl, 1991). In general, the relocated earthquakes of Engdahl et al. (2004) show a consistent pattern of longer (by several seconds) Pn travel times compared with the predictions of the global velocity model ak135. These authors estimate the uncertainties in "EHB" locations to be 10-15 km owing to lateral heterogeneities in the Earth's structure. Previous studies of the seismicity of the region include the work of Maggi et al. (2000), who used synthetic seismographs to model P- and SH-waveforms. The uncertainties in "EHB" depths are estimated to be 10 km, in comparison with 4 km for the depth estimates derived from an analysis using synthetic seismograms.

There are numerous limitations to performing the inversions using only regional phase data. For example, such a tomographic inversion would mainly provide estimates of only regional crustal thickness and Pn velocity. However, since there are several independent estimates of crustal thickness of the region (e.g., Doloei and Roberts, 2003; Hatzfeld et al., 2003), it is possible to fix the initial crustal model based on these estimates in order to obtain a better constraint on lateral variations in Pn velocity. In addition, some phase data, which provide valuable regional travel time constraints are available for local stations. Also useful are data from a number of temporary deployments of broadband seismographs (e.g., East Turkey, 1999-2001, Turkmenistan, 1992-1994, Saudi Arabia, 1995-1997).

Some limited phase data has been obtained from the Tehran Telemetry Seismic Network (TTSN). This 12-station, short period digital network (Figure 1a) has been in operation in its present configuration since the mid-1990s. Teleseismic waveform data from this network has previously been released to overseas Iranian nationals for use in tomographic and receiver function studies. For example, in order to determine the crustal structure beneath the array, some 129 teleseismic waveforms recorded between 1997 and 2001 were compiled at the GeoForshungsZentrum (GFZ) in Potsdam, Germany. Receiver functions determined from these data have shown clear P-to-S conversions from the Moho ranging in time from 5.4 s (station QOM) to 6.3 s (station MHD), corresponding to depths of approximately 44 km to 50 km, respectively. A mid-crustal boundary is evident at ~20 km depth, and the Vp/Vs ratio appears to be close to 1.76, a rather typical value for the crust.

The Iran strong motion network has grown steadily over the past decade and consists of more than 1,500 stations. The instrumentation is mainly SMA-1 and SSA-2 Kinemetrics recorders. Analog recorders were replaced by digital recorders following the 1990 Manjil earthquake. Instruments are concentrated in the Zagros fault zone where seismicity levels are very high (Figures 2 and 4), and in the Tehran region where the population density is highest.

An example of strong motion data is provided by the data recorded from the Mw = 6.0 Golestan village earthquake of 28 February 1997, located SW of the city of Ardebil. (Approximate event location: 38º N by 48º E; Figure 5) We have 16 local strong motion records for this event within the distance range of 20 km to 150 km (city names: Haris, Nir, Niaragh, Razi, Ardebil (2 stations), Astara, Bilehsavar, Meshkinsharahr, Germi, Hir, Mianeh, Namin, Sarein, Khalkhal, and Karigh; Figure 5). Peak acceleration is 0.6 g recorded at a distance of 25 km. Data quality is very high, as can be seen in two examples (Figure 6). Although a surface rupture was not identified for this event, the focal mechanism determined by IIEES indicates that the causative fault was most likely an extension of the well-known Bozghosh fault (Figure 5). Additional examples of waveform data from other seismic events are shown in Figure 7.

Automatic moment tensor inversion of Middle Eastern earthquakes at teleseismic distances, which is done routinely by agencies such as Harvard and USGS, has been limited to large events (M > 5.5 and beyond). Although automatic determination of moderate earthquakes is becoming more and more a routine process, the uncertainties involved make the results not very useful for seismotectonic investigations, where we must determine the association of events with known active faults. For moderate and small events, inaccuracies concerning location, depth, and nodal planes render the events unfit for ascertaining their significance or possible association with known active faults versus suspected nuclear test events.

This work is responsive to the goals of (1) determining regional 3D Earth structure in the Middle East, and (2) collecting high-quality seismic data for reference events and determining source parameters using waveforms for a specific area of interest (the Middle East). Temporary deployments of seismological stations across the region (e.g. Tatar et al., 2004; Hatzfeld et al., 2003; Figure 2) have provided new insights into lithospheric structures and seismicity. These ongoing studies have provided the first body wave tomographic results which not only delineate large-scale tectonic structures, but provide better-constrained velocity models for event locations.

CONCLUSIONS AND RECOMMENDATIONS

Seismic velocities in the crust and uppermost mantle vary across the Middle East. The zone of low upper mantle velocity coincides with regions of high seismic activity, indicating that the mantle anomaly is related to tectonic processes. To enhance the existing catalog of moment tensor inversions, systematic waveform inversions at local (strong motion data), regional and teleseismic distances, should continue to be developed. This would provide more reliable estimates of source parameters. For local and regional distances, we recommend using Dreger's method (Time-Domain Moment Tensor INVerse Code, release 2002) which evaluates the complete waveform inversion for seismic moment tensor. This is a "tried and true" method and has been used extensively in the past. In this process we have relied heavily on data from the Iran Strong Motion Network (Fig. 1b), however it has been shown (D. Dreger, pers. comm., 2004) that using IRIS stations in neighboring countries produce promising results. At teleseismic distances a number of revisited earthquakes prove that waveform inversion can provide better constraints, vital for seismotectonic studies (Berberian et al., 1999). Therefore, we perform waveform inversions using both locally recorded strong motion data and teleseismic data using Nabelek's approach (Nabelek, 1984).

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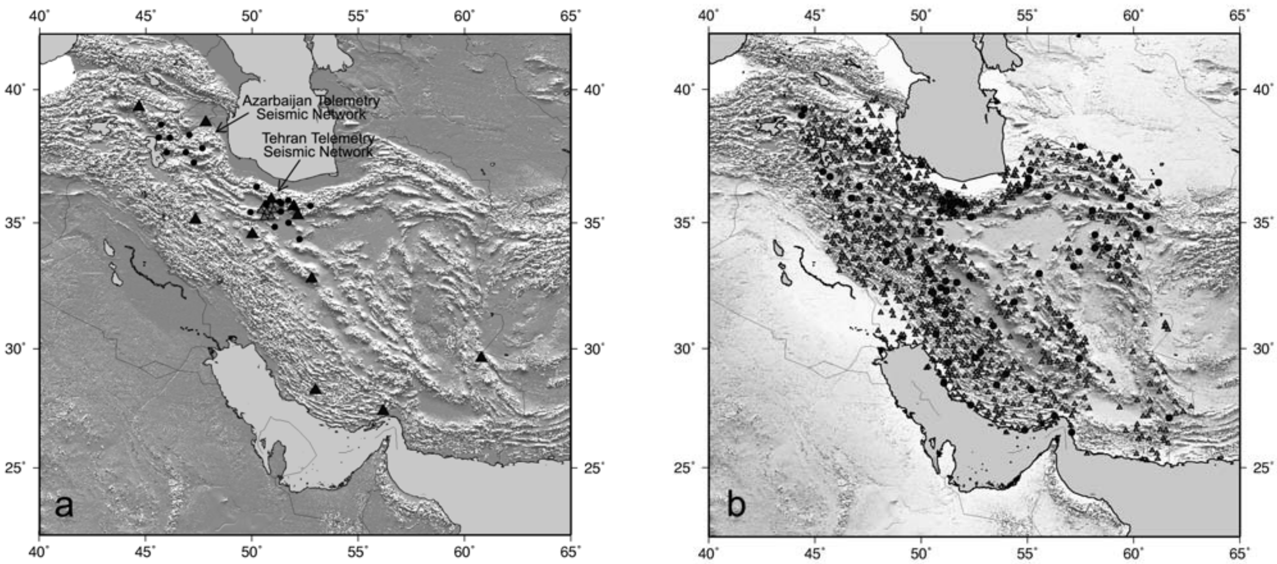

Figure 1. a) Distribution of stations of the Iran Broadband Network (black triangles), the short-period stations of Tehran and Tabriz (Azarbaijan Province) (black circles), and stations of the Iranian Long Period Array (grey triangles). b) Distribution of stations of the Iran Strong Motion Network (ISMN) with about 1000 stations. The triangles represent SSA2 digital Kinemetrics instruments whereas the circles are SMA-1 analog recorders.

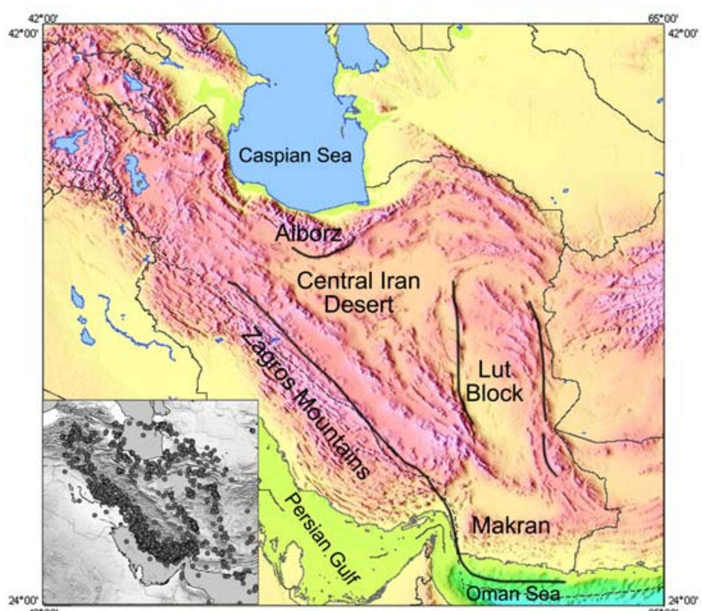

Figure 2. Tectonic province map of Iran showing the Zagros and Alborz mountains, the Lut block, and the Makran subduction zone. Inset shows significant seismic events in Iran (for detailed seismicity see Figure 4).

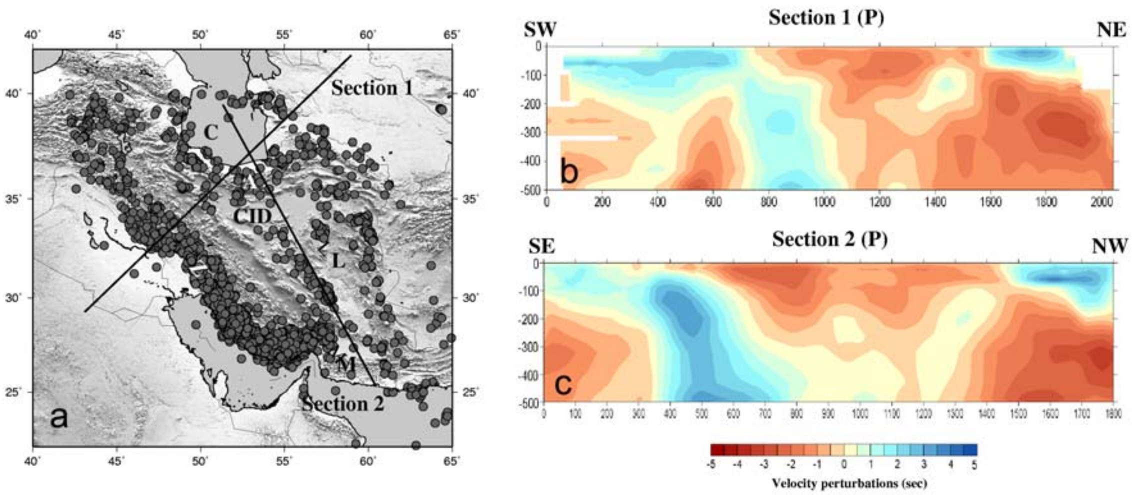

Figure 3. Instrumental Seismicity of Iran (a) for time period of 1964-2002 (updated catalog of Engdahl et al, 1998). The seismicity is concentrated mainly along Zagros Mountains (Z) extending from northwest to southeast, along Alborz Mountains (A) which lie adjacent to the southern shore of the aseismic southern Caspian Block (C). The borders separating the Lut Block (L) from the rather aseismic Central Iranian Desert (CID) and Afghanistan are marked by seismicity along major strike-slip faults. The Makran (where the oceanic plate of the Oman Sea subducts under the Iranian Plateau) is almost aseismic. (b and c) show the latest results of P-wave tomography using Iranian earthquakes along two sections 1 and 2 crossing the Zagros and Makran, respectively (Alinaghi et al., 2004). Central Iran is characterized by low velocity whereas the Caspian Block is a high-velocity domain.

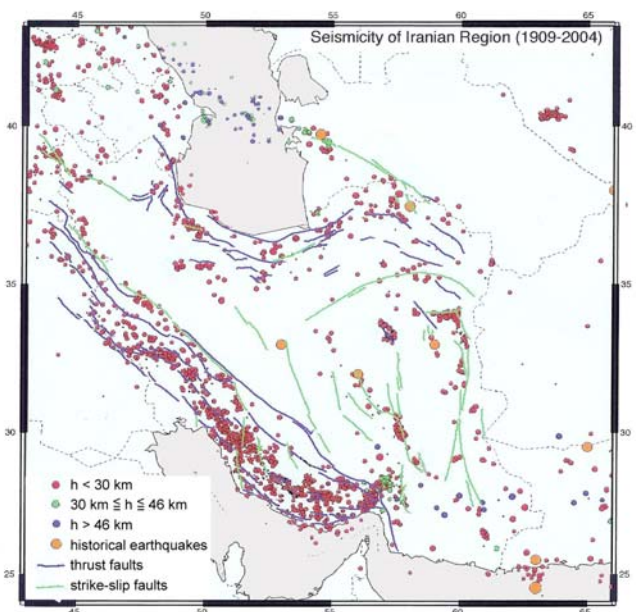

Figure 4. Detailed seismicity of Iran from 1909 to 2004. Note the majority of seismic events occur in the Alborz and Zagros mountains. Hypocentral depths are given as are orientations of faults.

Figure 5. Location map of the Mw=6.0 Golestan earthquake for which we have high-quality strong motion data (see Figure 6). Sixteen local strong motions records are available for this event. Peak ground acceleration is 0.6 g recorded at 25 km distance.

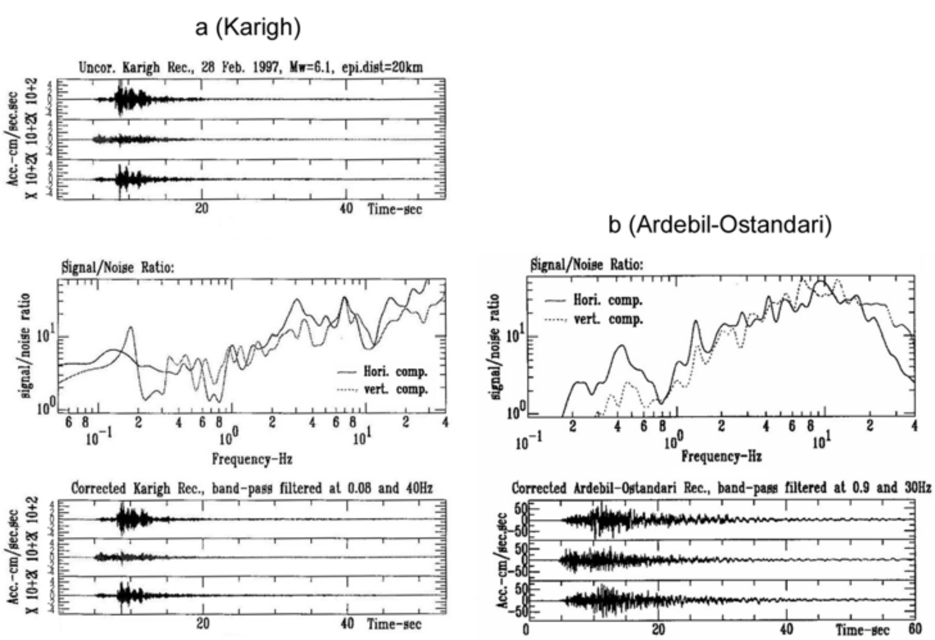

Figure 6. Strong motion waveforms for the Mw=6.0 Golestan earthquake recorded at Karigh (a) and Ardebil (b) see figure 5 for location. Data quality is very high. Additional data are shown in Figure 7.

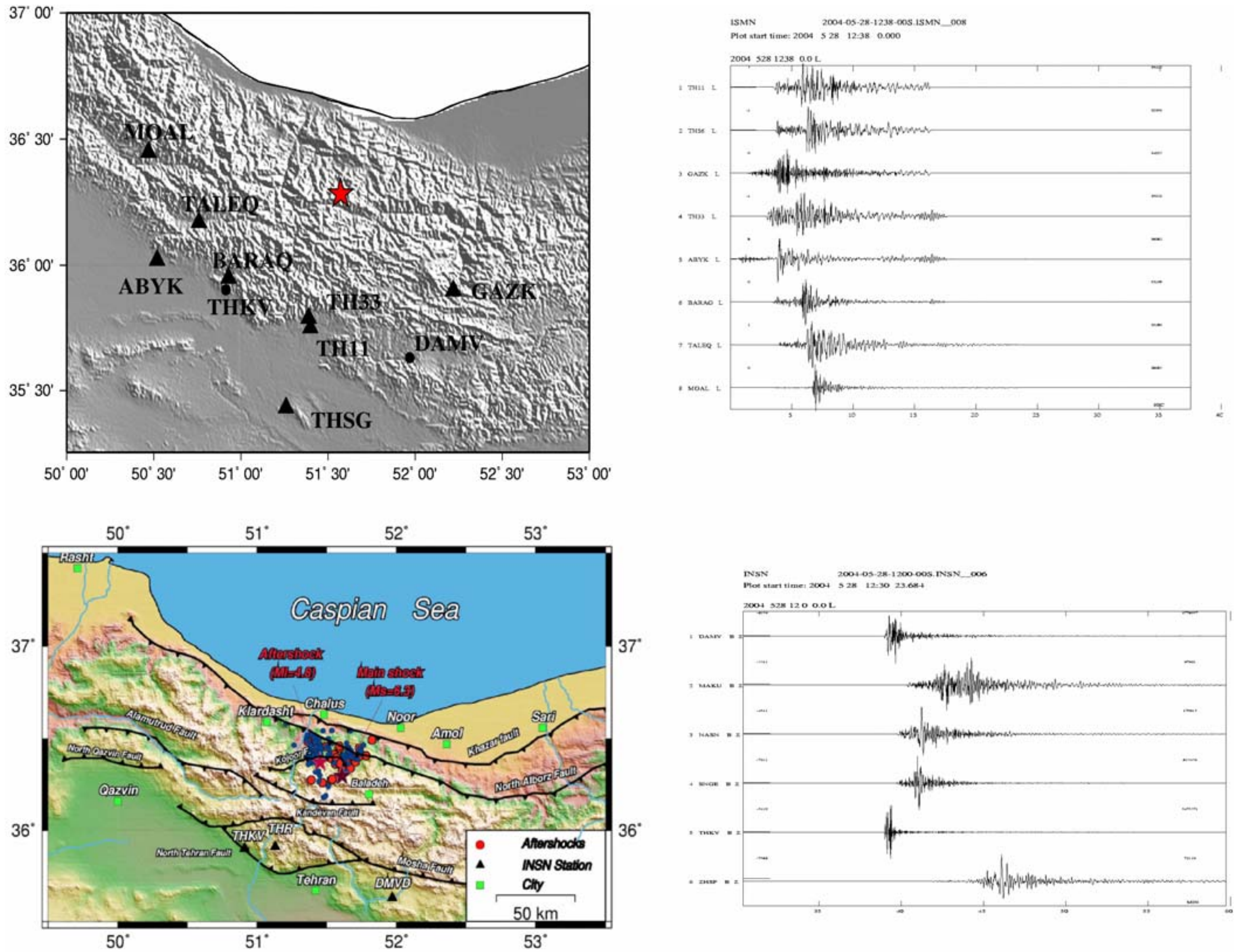

Figure 7. Samples of data from the Baladeh earthquake of 28 May, 2004 (M=6.2) in northern Iran. The top right panel shows waveforms from some representative stations of the ISMN (filled triangles in top left map). The bottom right panel are waveform data from six representative stations of the Iran broadband network (two of the stations are shown in the top left map as filled circles). The bottom left map shows the distribution of aftershocks as have been recorded by a temporary network of ten stations deployed by IIEES, Iran.