IMPROVED GROUND TRUTH IN SOUTHERN ASIA USING IN-COUNTRY DATA, ANALYST WAVEFORM REVIEW AND ADVANCED ALGORITHMS

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ABSTRACT

Nearly 2,000 earthquakes occurring in the Iran region during the period 1909-2002 have been relocated with special attention to focal depth, using the EHB methodology (Engdahl, *et al*., 1998). We make a careful review of starting depths, association of teleseismic depth phases, and the effects of reading errors on these phases. When available, waveforms are examined. Uncertainties in EHB locations are, owing to Earth's lateral heterogeneity, on the order of 10-15 km in the Iran region. Uncertainties of reviewed EHB focal depth estimates are on the order of 10 km, as compared to about 4 km for waveform inversions. Nevertheless, these EHB depth estimates are sufficiently accurate to resolve robust differences in focal depth distribution throughout the Iran region. Most earthquakes in the Iranian continental lithosphere occur in the upper crust. In the Zagros Mountains most earthquakes are restricted to the upper crust (depths < 20 km). However, there is some evidence for infrequent earthquakes as deep as 30 km. In southeastern Iran, where the Arabian seafloor is being subducted beneath the Makran Coast, earthquakes occur in the upper crust as well as at intermediate depths within a northward dipping subducting slab. Near the transitional Oman Line, seismicity extends to depths of up to 45 km in the crust. In central Iran, along the Alborz Mountain belt, seismic activity occurs primarily in the upper crust but with some infrequent events in the lower crust.

Starting from this new catalog of Iranian seismicity, we further improve the relative accuracy of locations for recent large earthquakes through analyzing clusters of earthquakes simultaneously. Absolute locations of such clusters are still biased by departures of the Earth's structure from the one-dimensional (1-D) model (ak135) used in the location algorithm. This problem can be solved through the use of reference (or ground truth) event information, which provides independent evidence for the absolute location of the seismic source. If one or more reference events can be located jointly with a cluster of earthquakes, then the entire cluster's absolute location can be calibrated. There are three main sources of reference event information with which to calibrate the absolute locations of earthquake clusters. The first method is to compare the pattern of relocated earthquakes with mapped fault geometry. The second method is to find situations in which a cluster event has been accurately located by a local seismic network or aftershock deployment. The third method is to use InSAR data to determine the rupture zone of shallow earthquakes. For moderate-sized events, this zone is small enough to provide useful constraints on absolute location. Examples of all three kinds of reference information in Iran are shown in this paper. When both location and origin time can be calibrated for a cluster through use of reference event information, we are able to estimate the true travel times to all reporting stations. These estimates are the basis for improved models of the crust and upper mantle, which in the future will permit far more accurate routine earthquake locations using regional seismic data in Iran.

OBJECTIVES

This research seeks to improve the database of ground truth (GT) information and velocity models useful for calibration in southern Asia with the following objectives: (1) Aggressive pursuit of in-country data acquisition, especially the collection of ground truth at GT5 level or better for events of magnitude 2.5 and larger recorded by dense local networks, including associated velocity models; (2) Expanded analyst review of relevant regional waveforms for ground truth events by the comprehensive re-picking of phase arrival times from all available waveforms, with special attention to the regional phases Pg, P*, Pn, Sg, S* and Sn; and (3) Application of advanced algorithms, such as those used for multiple event relocation, to refine and validate all available ground truth data, to achieve the optimal selection of data for analysis, to better understand the uncertainties of the results, and to handle the error budget as realistically as possible.

RESEARCH ACCOMPLISHED

Nearly 2,000 earthquakes occurring in the Iran region during the period 1909-2002 that are well-constrained (secondary teleseismic azimuth gap < 180 deg) by phase arrival times reported to the International Seismic Summary (ISS), the International Seismological Centre (ISC) and the United States Geological Survey (USGS) have been relocated with special attention to focal depth using the EHB methodology (Engdahl, et al., 1998). The new locations are shown in Figure 1, along with seismotectonic features.

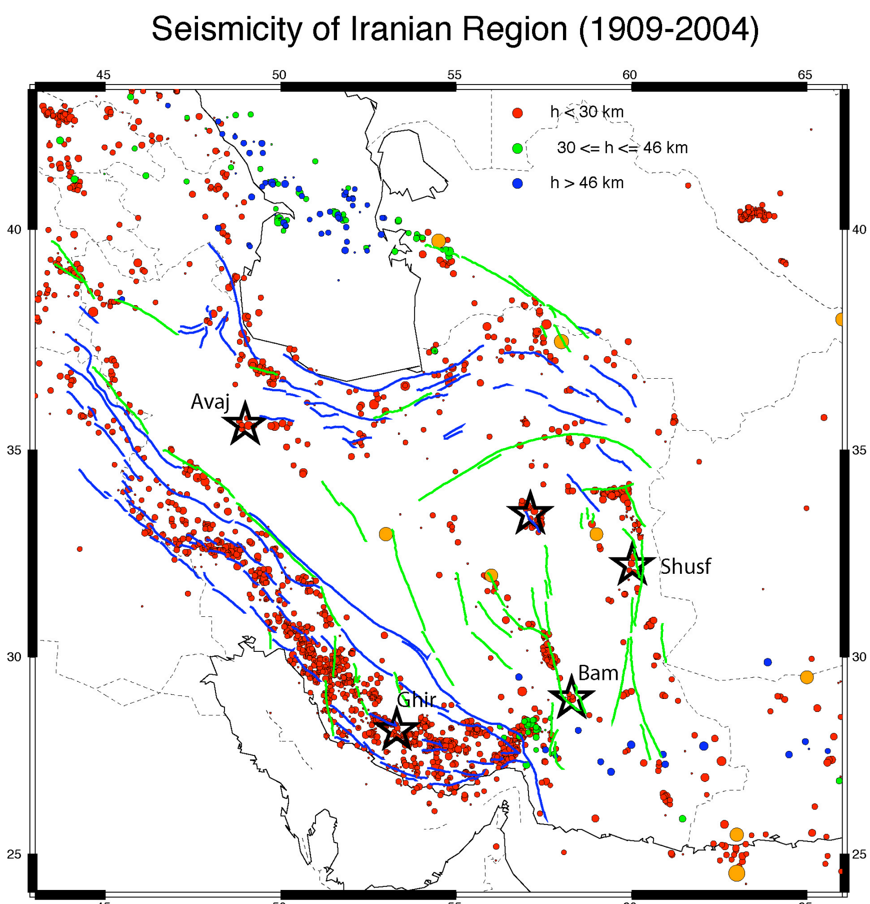

Figure 1. Seismicity in the Iran region relocated and color classified by depth. Filled yellow circles are historical earthquakes that need to be relocated. Faults are thrust (blue) and strike-slip (green). Stars are cluster locations analyzed and reported on later in this paper.

The EHB method uses the phase arrival times of P, S, PKP and depth phases (pP, sP and pwP) with a modern 1-D Earth model (ak135) to obtain improved estimates of locations and focal depths. The purpose of this study is to expand the work of Maggi et al. (2000) who re-assessed focal depth distributions in southern Iran using synthetic seismograms to analyze P and SH body waveforms. In this study, we rely on a careful review of EHB starting depths, the EHB assignment of teleseismic depth phases, and the effects of reading errors on these phases. Uncertainties in EHB locations are, owing to Earth's lateral heterogeneity, on the order of 10-15 km in the Iran region. Uncertainties of reviewed EHB focal depth estimates are on the order of 10 km, as compared to about 4 km for waveform inversions. These EHB depth estimates are sufficiently accurate to resolve robust differences in focal depth distribution within the crust and upper mantle throughout the Iran region. For the modern period (1964-2002) the data base is complete to at least M 5.5, but includes many events of smaller magnitude that are well constrained. Preliminary results indicate that most earthquakes in the Iranian continental lithosphere occur in the upper crust. In the Zagros Mountains of southern Iran, a linear intra-continental fold and thrust belt trending NW-SE between the Arabian shield and central Iran, most earthquakes are restricted to the upper crust (depths < 20 km). However, there is some evidence from this study and that of Tatar et al. (2003) for infrequent earthquakes as deep as 30 km. In southeastern Iran, where the Arabian seafloor is being subducted beneath the Makran coast, earthquakes occur in the upper crust as well as at intermediate depths within a northward dipping subducting slab. Where there is a change from continent to ocean near 57 deg in the Zagros-Makran transition zone, a region of complicated structure known as the Oman Line, seismicity extends to depths of up to 45 km in the crust. In central Iran, along the Alborz mountain belt, seismic activity occurs primarily in the upper crust but with some infrequent events in the lower crust. These differences in the focal depth distribution of Iranian earthquakes may have important implications about variations in the strength of the crust and uppermost mantle across the region.

Reported arrival times for depth phases from larger and even some smaller events, which may have a complex rupture, are often subject to misinterpretation. Shown in Figure 2 are waveforms from an Mw 5.2 Zagros event that was originally thought to be deeper than 40 km on the basis of a phase arrival (T2) widely reported as pP. By examination of the waveforms at a broadband station in Africa, we were able to determine that the coda of the T2 signal is a very good fit to the coda of the T1 signal (right panel), indicating that this earthquake is a double event. By virtue of this forensic seismology and waveform modeling we find the depth of this event to be on the order of 4 km, suggesting that the arrival T3 in the left panel is sP.

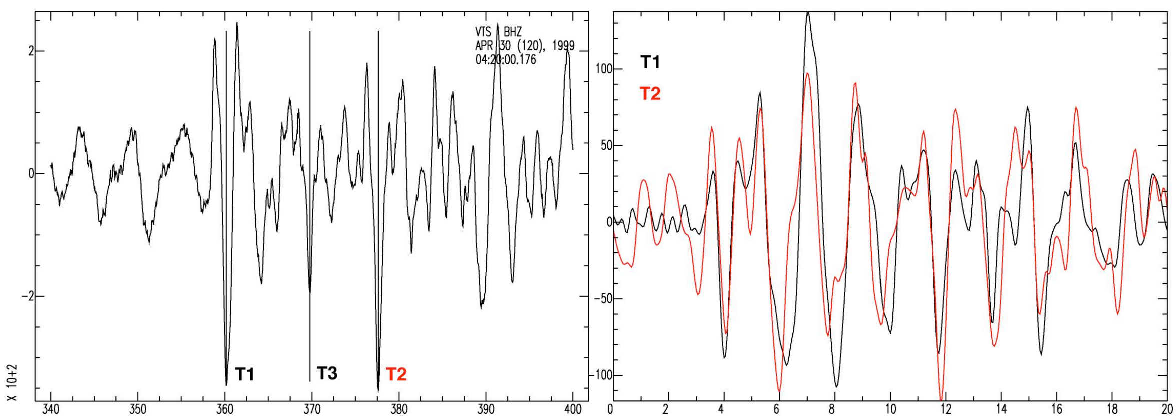

Figure 2. Left panel shows original seismogram with phase arrivals T1, T2 and T3. Right panel shows coda of T2 signal (red) overlying coda of T1 signal (black).

Waveform depths accurate to ~ 4 km for Iranian earthquakes, as determined by the Cambridge research group, were a valuable resource for this project. Waveform depths were used as EHB starting depths for over 100 events in the Iran region. For events, which had more than five phases that could be identified as pP or sP, we compare the differences in depth estimation as functions of depth and magnitude in Figure 3. The EHB depths for most events were within 10 km of the corresponding waveform depths, with a maximum difference no larger than 15 km (left panel). There does not appear to be a significant magnitude to depth dependence (right panel). EHB depths are slightly deeper than waveform depth estimates because different reference models were used (ak135 vs. Cambridge generalized source velocity model).

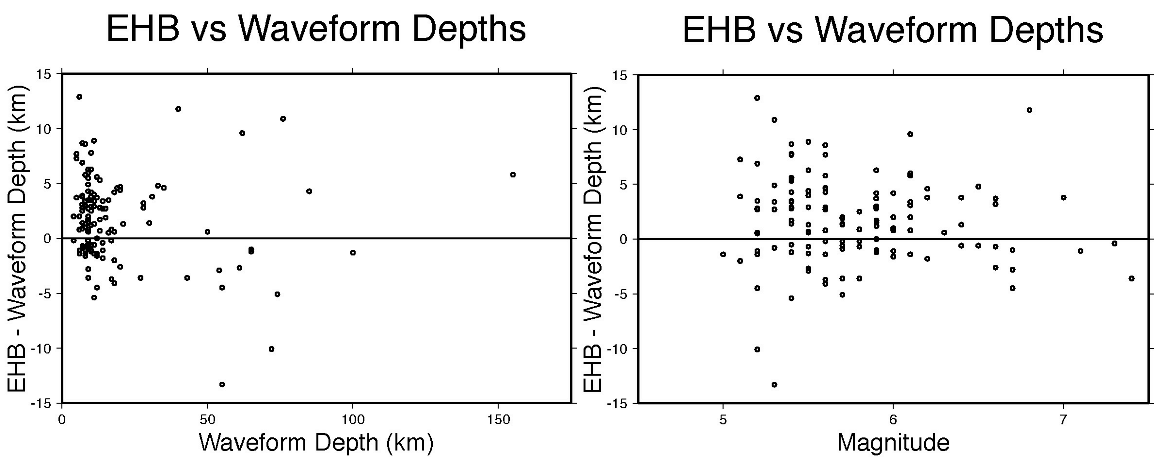

Figure 3. EHB versus waveform depth differences plotted as function of waveform depth (left panel) and magnitude (right panel).

The band of earthquakes crossing the central Caspian shown in Figure 4a is unusually deep focus, with depths ranging from about 30 to 100 km. Jackson et al. (2002) suggest that these events are related to the NE subduction of the south Caspian lithosphere or possibly to the detachment of a sinking slab.

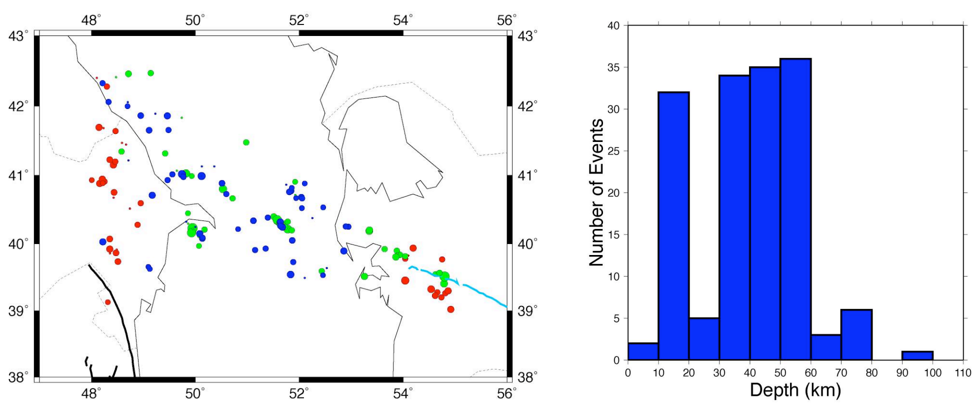

Figure 4a. Seismicity (left panel) and depth distribution (right panel) plotted for the central Caspian region. Color classification by depth as in Figure 1.

Most earthquakes along the southern Caspian Basin active border region (Figure 4b) are less than 20 km in depth. However, there are a few slightly deeper events (e.g., the filled green circle is nearly 35 km in depth).

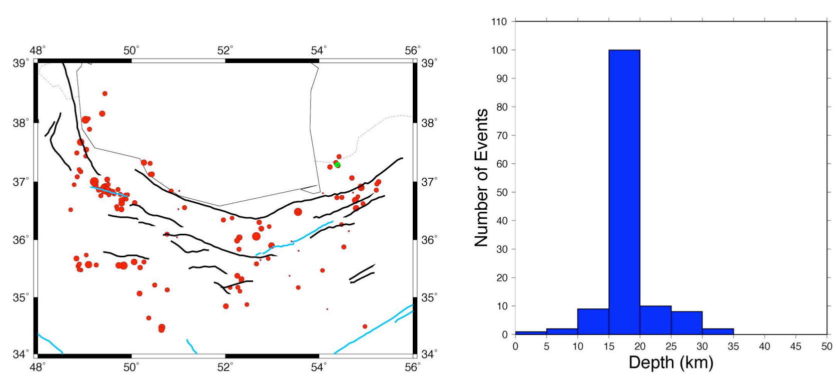

Figure 4b. Same plots as Figure 4a for the southern Caspian Basin active border region.

Nearly all earthquakes in the Zagros (Figure 4c) are less than 30 km in depth, largely confined to an upper crust with a lower boundary at about 19 km (Hatzfeld, et al., 2003). A few are deeper, but with the 10 km depth uncertainty.

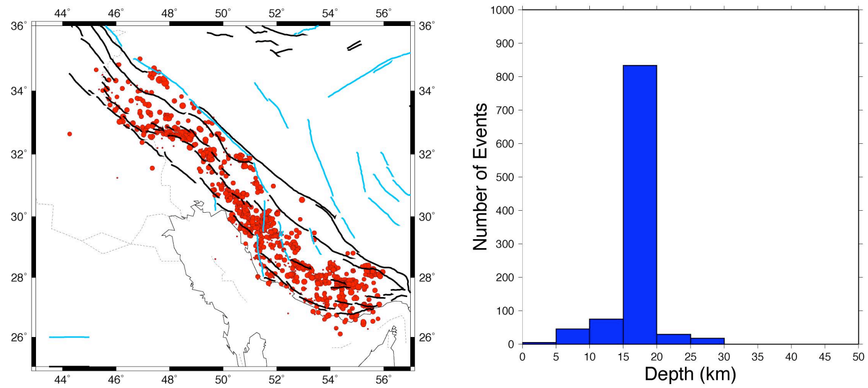

Figure 4c. Same plots as Figure 4a for the Zagros mountains region.

Near the transitional Oman line (Figure 4d) the Zagros seismicity extends to greater depths. Earthquake focal depths of more than 30 km are common, with a few quite deep that are probably related to subduction in the Makran.

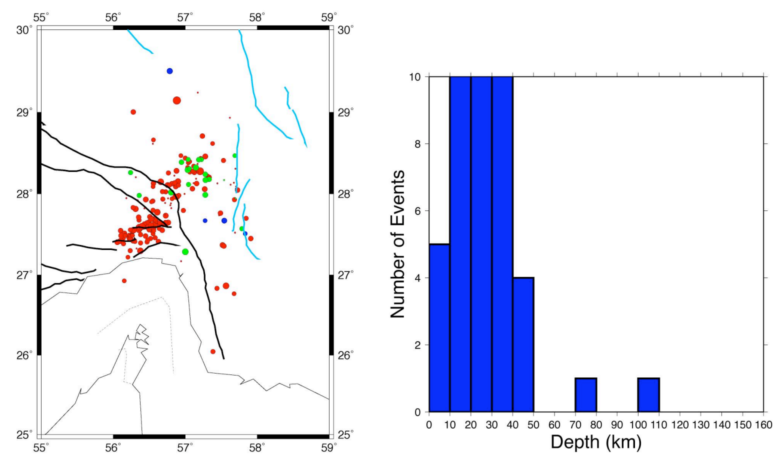

Figure 4d. Same plots as Figure 4a near the Oman Line.

The Makran region (Figure 4e) has earthquakes with depths well in excess of 40 km. These events occur within a northward shallow dipping slab, but are also accompanied by earthquakes at shallower depths in the upper crust.

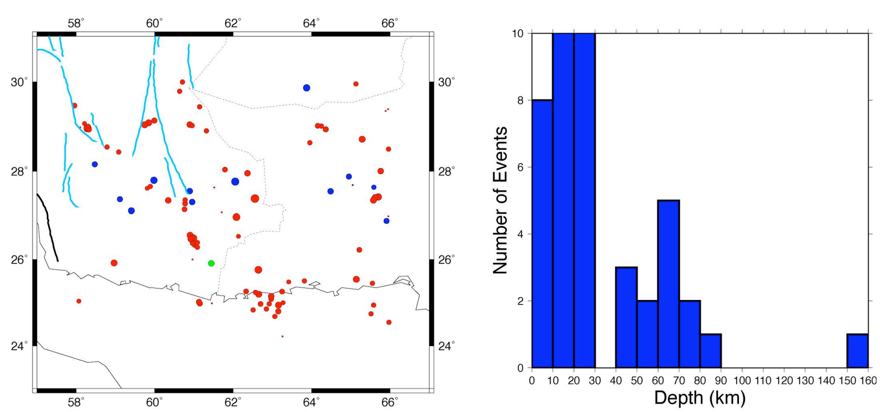

Figure 4e. Same plots as Figure 4a for the Makran region.

Multiple Event Relocations and Ground Truth Studies

We relocated several clusters of earthquakes in Iran with a recently developed technique that yields improved accuracy for both the relative and absolute locations of clustered earthquakes. The gist of the method is to use a multiple event relocation method with regional and teleseismic phase arrival times to constrain relative locations of clustered earthquakes and then to calibrate the absolute location of the cluster by obtaining independent information on the absolute location of one or more members of the cluster. For the multiple event relocation (cluster analysis) we use a version of the Hypocentroidal Decomposition (HDC) method first proposed by Jordan and Sverdrup (1981), which has been developed specifically for this kind of "ground truth" research. Further explanation of the methodology may be found in Bondar et al. (2004). For each cluster there is independent information on location that helps to calibrate the absolute locations. The clusters shown here illustrate several approaches to this important problem.

The clusters of earthquakes used in these analyses were extracted from the new catalog of Iranian seismicity presented earlier in this paper. For multiple event relocation, it is necessary to keep the dimensions of the cluster small enough (typically 50-75 km across) to avoid the effects of lateral heterogeneity in the crust and upper mantle.

The HDC analysis includes further refinement of the data set by making empirical estimates of readings errors and using these estimates to help identify outliers. These steps yield significant improvements in accuracy and resolution for the relocations. Of course, the main benefit of HDC analysis is to largely remove the biasing effects (path anomalies) of lateral heterogeneity in the Earth, which permits much better resolution of the relative locations of cluster earthquakes.

Changureh (Avaj): Calibration Using Aftershock Survey Data and Comparison with Geological Mapping and Remote Sensing Data

The cluster consists of the June 22, 2002 Mw 6.4 Changureh mainshock, aftershocks, and several earlier events, 17 events in total. The result of our HDC analysis of the Changureh earthquakes is shown in Figure 5. The relative locations of events are plotted with respect to the hypocentroid or geometrical center of the cluster vectors that describe the relative locations.

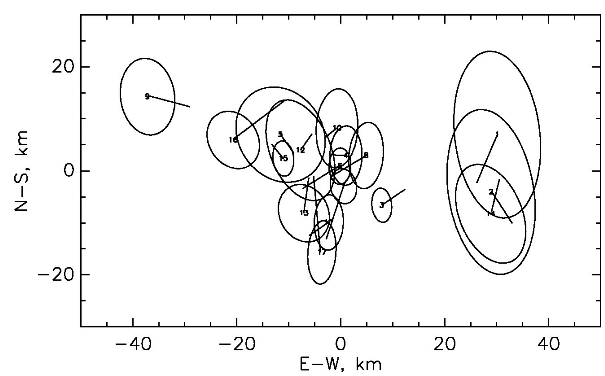

Figure 5. Relative locations of the Avaj cluster. Confidence ellipses (90%) are shown. Line to each event shows change in relative location from starting (EHB single event) location.

The Changureh mainshock (#3) is isolated from the other earthquakes. Most of the aftershocks occurred to the northwest of the mainshock. These results support a fault model in which rupture initiated in the southeast end of the rupture zone and propagated unilaterally to the northwest for 20-25 km. This would be consistent with the source time function duration of about five seconds, derived from body wave modeling by the Cambridge group.

We obtained arrival time data for one of the cluster events (#12) from an aftershock study by a group of IIEES (International Institute of Earthquake Engineering and Seismology) scientists, and also a crustal model derived from the aftershock study of Changureh (Farahbod, personal comm.). We relocated the event using the HYPOSAT code of Schweitzer (2001) and used this location to calibrate the absolute location of the HDC cluster. The mislocation vector was among the largest we have observed, 17.3 km at an azimuth of 78°, with an origin time shift of -2.55 seconds.

After correction of the cluster event locations, we can compare them with the seismotectonic analysis of the Cambridge group (Richard Walker and James Jackson, personal comm.), summarized in Figure 6. Numbers 1-14 are the HDC cluster locations from an earlier study (before events 15-17 were added). The dashed line is an inferred "Abdarreh fault" based on mapping of surface rupture. Remote sensing data and analysis of stream offsets support a model in which the seismogenic faulting extends to the southeast, to the location of the mainshock epicenter, but did not break the surface. Most of the aftershocks would have occurred in the hanging wall of the essentially "blind" thrust event.

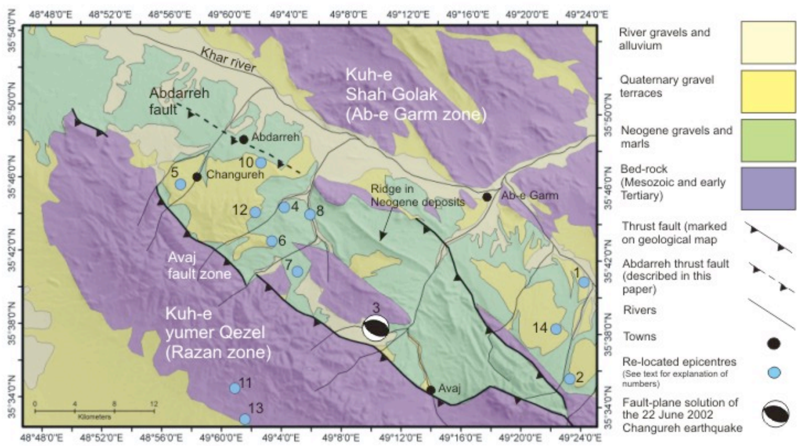

Figure 6. Seismotectonic map of the Avaj earthquake sequence

Finally, we use the calibrated cluster arrival time data to infer empirical path anomalies from the Changureh source region to seismic stations. Figure 7 shows the results for Pn and P phases at regional distances. The path anomalies are relative to the ak135 global model. There is broad consistency of longer travel times at most azimuths. The early arrivals at stations in Saudi Arabia reflect propagation across the Arabian shield. The path anomalies can be the result both of variations in bulk velocity and differences in ray paths caused by lateral heterogeneity.

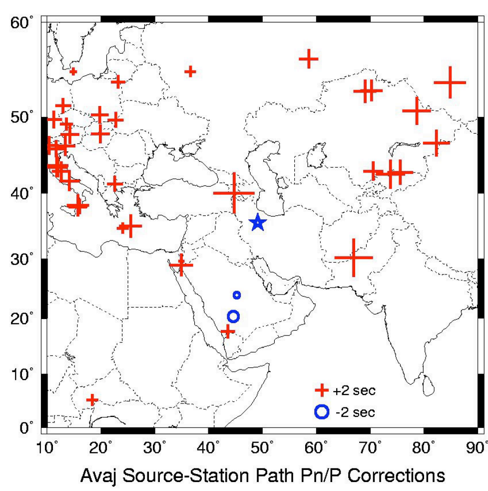

Figure 7. Empirical path anomalies for Pn and P phases from Avaj

This example illustrates the usefulness of combining carefully conducted aftershock surveys and analysis of regional and teleseismic data with geological mapping and remote sensing data.

Ghir: Calibration Using Two Types of Ground Truth Data

The Ghir cluster contains 65 events in a region of active and complex earthquake activity. Figure 8 (left panel) shows the relative locations of the Ghir cluster events.

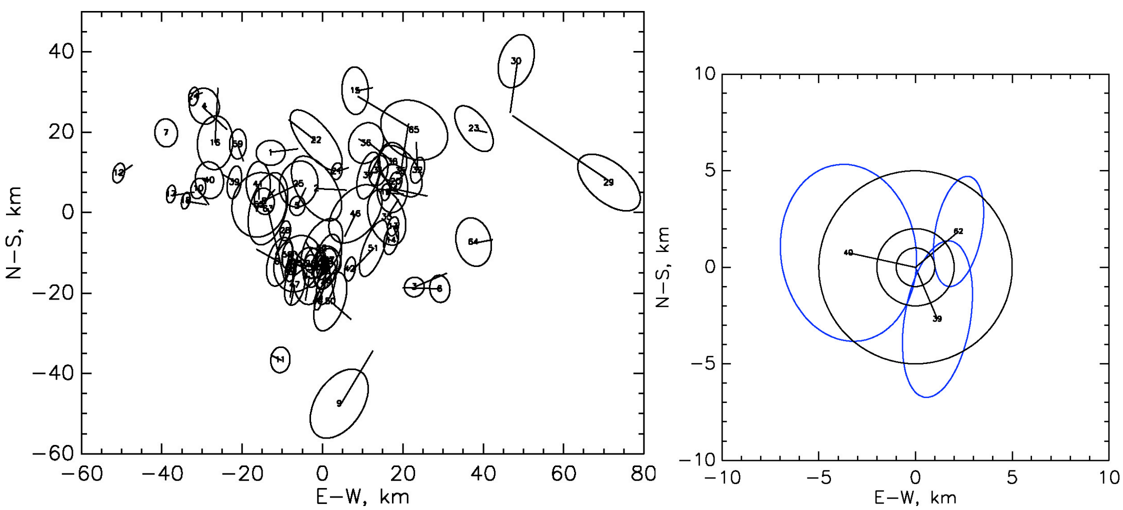

Figure 8. (left) Relative locations of the Ghir cluster. See Figure 5. (right) Consistency of estimates of mislocation vector for three reference events, after the average vector is subtracted. Confidence ellipses (90%) are shown. Concentric circles of radius 1, 2, and 5 km are shown.

For this cluster we had three reference events from two different kinds of data: two events for which good quality aftershock network data were available, and an epicentral location based on InSAR analysis. InSAR provides no constraint on origin time but a surprisingly tight constraint on depth. A moderate-sized earthquake cannot create a detectable InSAR signal unless it is quite shallow.

When we have more than one reference event for a cluster, there are separate estimates of the mislocation vector for each case. We average them to obtain a best estimate of the shift needed to calibrate the cluster location (6.2 km at 66°, -2.80 seconds in origin time), and also as an internal consistency check, both on the HDC analysis and the reference event data. In this case there is good agreement between all three reference events. Figure 8 (right panel) shows the residual mislocation vectors after the average has been removed. These results show that our calibration of this cluster is accurate at 1-2 km at a 90% confidence level. Events 39 and 40 have aftershock network locations and event 62 is the InSAR event. The origin time shift is estimated only from events 39 and 40.

Bam: Preliminary Results

The Mw 6.5 Bam earthquake on December 26, 2003 is of great interest because of the terrible loss of life and the damage that it caused. It is not a strong candidate for multiple event relocation, however, because no other earthquakes of any significance have occurred near Bam in the instrumental seismology period. Nevertheless we formed a small cluster from the mainshock and 7 of the larger aftershocks. The data available immediately from the USGS National Earthquake Information Center (NEIC) are not complete and we expect to be able to constrain relative locations more precisely in the future when more data is available. This preliminary HDC analysis provides useful improvement in resolution over the single event locations. In Figure 9 (left panel), the mainshock is event #1. The location for event #5 is rather suspect. Data coverage to the south is poor for this small event and it has the appearance of a "flyer" caused by some late readings at European stations. It is worth noting that the relative location of events 1 and 2 (and, to a lesser extent, #6) strongly suggest faulting on more than one fault strand in that area.

A shift of 5-10 km to the northeast would bring the HDC cluster into close agreement with the aftershock study. We are hopeful that it will be possible to obtain a local network solution for one or more events that we can locate with HDC, so that a full calibration of this important earthquake series can be done.

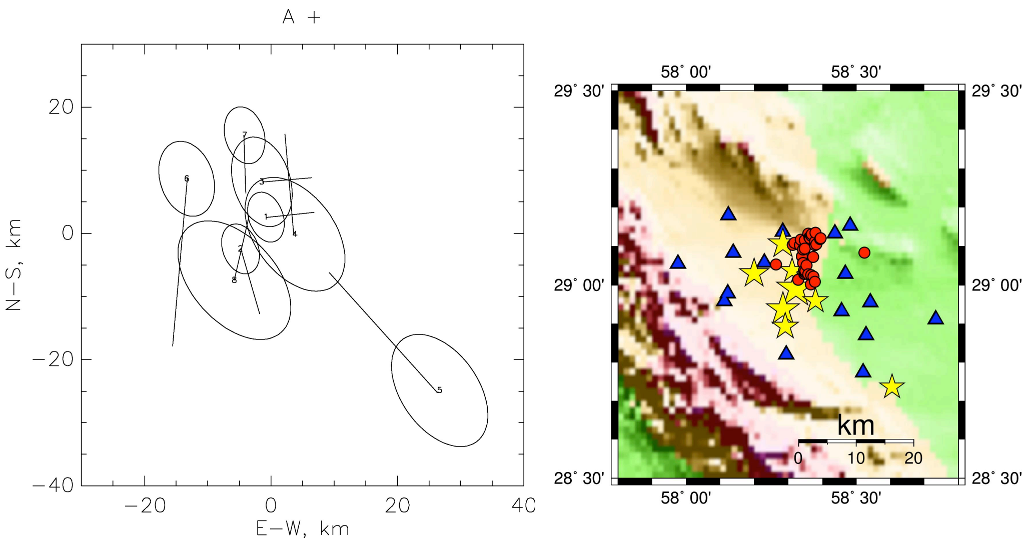

Figure 9. (Left) Relative locations of the Bam cluster. See Figure 5. (Right) Locations of aftershocks (red circles) from a temporary deployment (blue triangles). Yellow stars are the locations of the main shock and larger aftershocks from HDC analysis.

South Zirkuh (Shusf): Ambiguity in the use of InSAR Locations for Ground Truth

We formed this cluster (Figure 10) to take advantage of InSAR data that reveal deformation related to a moderate sized earthquake in the late 1990s. The situation is complicated by the fact that there are two candidate earthquakes during the InSAR time window, the Mw 5.6 "Chakhu" event on 6/20/1997 (Event 8), and the Mw 5.8 "Sahlabad" event on 4/10/1998 (Event 13). InSAR data reveal one very strong signal and a much weaker signal about 20 km north. Our calibration of this cluster is based on associating the Chakhu event with the stronger InSAR signal and the Sahlabad event with the diffuse signal to the north. We use only the Chakhu location for calibration because it is much better defined. In this case we find a mislocation vector of 5.8 km at an azimuth of 13°. Of course, no calibration of origin time is possible with InSAR data alone. Eric Fielding, Cambridge University provided us access to the preliminary results of his InSAR study of these events.

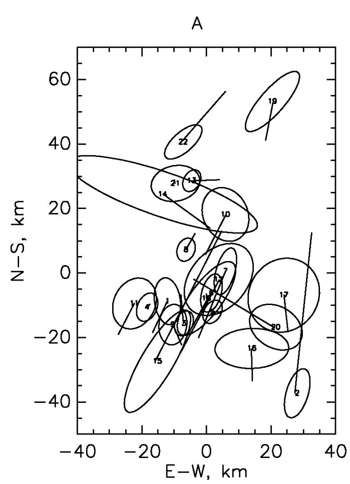

Figure 10. Relative locations of the Shusf cluster. See Figure 5.

In an initial phase of this study we associated the strongest InSAR signal with the Sahlabad event, which led to a mislocation vector of length 25 km, much larger than we have ever seen and barely credible. This emphasizes the need for caution in associating InSAR data with a particular event. When dealing with moderate-sized earthquakes, the "before-after" time window for InSAR often encompasses more than one event that could be the source.

CONCLUSIONS AND RECOMMENDATIONS

Our results for deeper earthquakes that occur beneath the central Caspian along the Apsheron- Balkhan sill support the view of Jackson et al. (2002), i.e., these events most likely "indicate the onset of subduction of the South Caspian Basin beneath the central Caspian, a process that appears to occur aseismically at shallow levels". In the earthquake belts of northern Iran (Talesh-Alborz-Kopeh Dag) surrounding the South Caspian Basin most events are less than 20 km in depth, but there is some evidence for a small number of events occurring at a greater depth (up to 35 km). In the Zagros region earthquake focal depths do not exceed 30 km. Thus, within the uncertainty of EHB depth estimates, there is no evidence (in the form of mantle earthquakes) to support active subduction of continental crust. In southeastern Iran, the continent-continent collision in the Zagros merges along strike with the subduction of the Arabian Sea floor beneath the Makran coast. The change from continent to ocean occurs in a region of complicated structure known as the Oman Line. Tomographic images confirm the existence of subducted slab. Our results support the view of Maggi et al. (2000), i.e., a "continental lithosphere in which a lower crust of relatively low strength, where aseismic ductile deformation predominates, is sandwiched between relatively strong upper crustal and uppermost mantle seismogenic regions".

We have developed several new ground truth events in Iran, based on detailed multiple event relocation and use of reference events, both from local seismic network data and from InSAR data. We have found that the use of analyst reviewed picks is extremely helpful in some circumstances, and the practice should be expanded. We are continuing to develop resources for local network data inside Iran and expect these efforts to lead to new ground truth events and resulting data on empirical path anomalies that will substantially improve location capabilities in this region.

ACKNOWLEDGEMENTS

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