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

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ABSTRACT

This research has the goal of developing in-country data sets that can be used to improve ground-based monitoring capabilities in Southeast Asia, by providing information needed to develop and test more accurate travel time models for seismic phases that propagate in the crust and upper mantle. These in-country arrival times have been associated with the arrival times of known earthquakes reported by international agencies, and relocated. This has resulted in a highly reviewed catalog of earthquakes in the Iran region for the period 1918-2005 for events larger than about magnitude 4.0. In collaboration with Cambridge colleagues, the new catalog has been used to assess focal depth distributions throughout Iran. A principal result of this study is that the geographic pattern of depth distributions revealed by the relatively small number of earthquakes (~167) with depths constrained by waveform modeling (+/- 4 km) are now in agreement with the much larger number of depths (~1229) determined using reanalysis of ISC arrival-times (+/-10 km), within their respective errors. This is a significant advance, as outliers and future events with apparently anomalous depths can be readily identified and, if necessary, further investigated.

The patterns of reliable focal depth distributions have been interpreted in the context of Middle Eastern active tectonics. Most earthquakes in the Iranian continental lithosphere occur in the upper crust, with the crustal shortening produced by continental collision apparently accommodated entirely by thickening and distributed deformation, rather than by subduction of crust into the mantle. In the Zagros Mountains nearly all earthquakes are confined to the upper crust (depths < 20 km), and there is no evidence for a seismically active subducted slab dipping northeast beneath central Iran. By contrast, in southeastern Iran, where the Arabian sea floor is being subducted beneath the Makran coast, low-level earthquake activity occurs in the upper crust as well as to depths of at least 150 km within a northward-dipping subducting slab. Near the Oman Line, a transitional region between inter-continent collision in the Zagros and oceanic subduction in the Makran, seismicity extends to depths up to 30-45 km in the crust, consistent with low-angle thrusting of Arabian basement beneath central Iran in this region. In north-central Iran, along the Alborz mountain belt, seismic activity occurs primarily in the upper crust but with some infrequent events in the lower crust, particularly in the western part of the belt (the Talesh), where the south Caspian basin underthrusts NorthWestern Iran. Earthquakes that occur in a band across the central Caspian, following the Apsheron sill between Azerbaijan and Turkmenistan, have depths in the range of 30–100 km, increasing northwards. These are thought to be connected with either incipient or remnant northeast subduction of the south Caspian Basin basement beneath the east-west trending Apsheron-Balkhan sill. Curiously, in this region of genuine mantle seismicity, there is no evidence for earthquakes shallower than 30 km.

In addition to uniform analysis of regional seismicity, we continue to conduct detailed analysis of historic and newly occurring event clusters (generally aftershock sequences) using multiple-event techniques and local data sets. These studies have produced numerous events with epicenter accuracy of 5 km and better (GT5). Absolute locations of such clusters are constrained using reference event information for one or more of the cluster events provided by local networks, aftershock deployments, or from non-seismic (e.g., InSAR or geological mapping) information. 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.

OBJECTIVES

This research seeks to improve the database of ground truth 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

Relocation and Assessment of Seismicity in the Iran Region

The aim of a recently published study (Engdahl et al., 2006) is to produce a comprehensive catalog of all instrumentally recorded events for the Iran region and to summarize the patterns seen in this relocated seismicity, in particular the patterns of reliable focal depth distributions, within their active tectonic context.

Engdahl et al. (1998) have shown that hypocenter determination can be significantly improved by using, in addition to direct P and S phases, the arrival times of core phases PKiKP (reflected off the inner core) and PKPdf (transmitted through the inner core), and the teleseismic depth phases (pP, pwP and sP) in the relocation procedure. Epicenter constraints are improved by the inclusion of S-wave and P-core phases because their travel-time derivatives differ significantly in magnitude from direct P, while depth-origin time trade-off is ameliorated by the inclusion of depth phases (pP, pwP, sP) because their travel time derivatives are opposite in sign to those of direct P. The Engdahl et al. (1998) methodology (hereafter referred to as EHB) is applied, with special attention to focal depth, to more than 2000 instrumentally recorded earthquakes occurring in the study region during the period 1918-2004 that are well-constrained by teleseismic arrival times reported to the International Seismological Summary (ISS), the International Seismological Centre (ISC) and the U.S Geological Survey's National Earthquake Information Center (NEIC).

EHB Epicenter and Depth Estimates

Engdahl and Bergman (2001) determined highly accurate relative locations for a number of teleseismically well-recorded earthquake clusters in Iran using a multiple event location method. When well-determined local-network (calibration) locations for a subset of events in the clusters are reconciled with the corresponding teleseismic relative locations, the absolute epicenter accuracy for many events in the clusters can be determined to 5 km or better. EHB epicenters for 80 earthquakes were compared to a set of these highly accurate absolute epicenters. The average and median mislocation errors were 9.2 +/- 5.2 km and 8.9 +/-4.9 km, respectively. The direction of EHB mislocation, though consistent for events in individual clusters, was variable across Iran. This can be accounted for by lateral variations in Earth structure and station coverage between individual clusters. We conclude that the EHB teleseismic epicenter bias for earthquakes in this region is ~10 km.

The EHB procedure was used to determine unconstrained depth solutions of 151 events that were also modeled using long-period P and SH waveforms for the time period post-1962. Each event had more than five reported short-period arrivals that could be identified as pP or sP depth phases. Starting depths were set at the waveform depths, which have an estimated accuracy of ~4 km in the Iran region, to avoid secondary minima in the depth determination. Differences between the waveform and EHB depths for most events were within 10 km of the corresponding waveform depths, with a maximum difference no larger than 15 km. To process the entire database, we relied on a careful review of the EHB starting depths, the EHB assignment of teleseismic depth phases, and the effects of reading errors on these phases. The reviewed EHB depth estimates were sufficiently accurate to resolve robust differences in focal depth distribution within the crust and upper mantle throughout the study region, and showed patterns in agreement with the more accurate, though numerically far fewer, long-period body-wave inversion depths. One principal result of this study is that the patterns of depth distributions revealed by the relatively small number of earthquakes (~167), whose depths (+/- 4 km) are confirmed by waveform modeling, are now in agreement with the much larger number (~1,229) whose EHB depths (+/-10 km) have been reassessed, within their respective errors.

Regional Distribution of Seismicity

There are 2,227 earthquakes that occurred in the Iran region that have well-constrained (secondary teleseismic azimuth gap < 180 degrees) epicenters for the period 1918-2004 based on phase arrival times reported to the ISS, ISC, and USGS/NEIC. Of these events, 1,226 have depths estimated from EHB-associated depth phases or from waveforms (primarily during the post-1964 period). EHB events with unconstrained depths based on first arriving P arrival times alone are usually poorly determined and have been set to default depths based on the regional medians of nearby better determined depth estimates. This ensures that, when other depth constraints for an event are not available, the use of an inappropriate depth does not unduly bias the relocated epicenter. The new locations for all events (color coded by depth) are plotted in Figure 1a, along with known major faults. Figure 1b is similar except only events having depths determined by P and SH body wave modeling are shown. The comparison is important because it shows the geographical coverage, and also reveals places where EHB depths do not have direct waveform confirmation and hence are particularly interesting for future earthquakes.

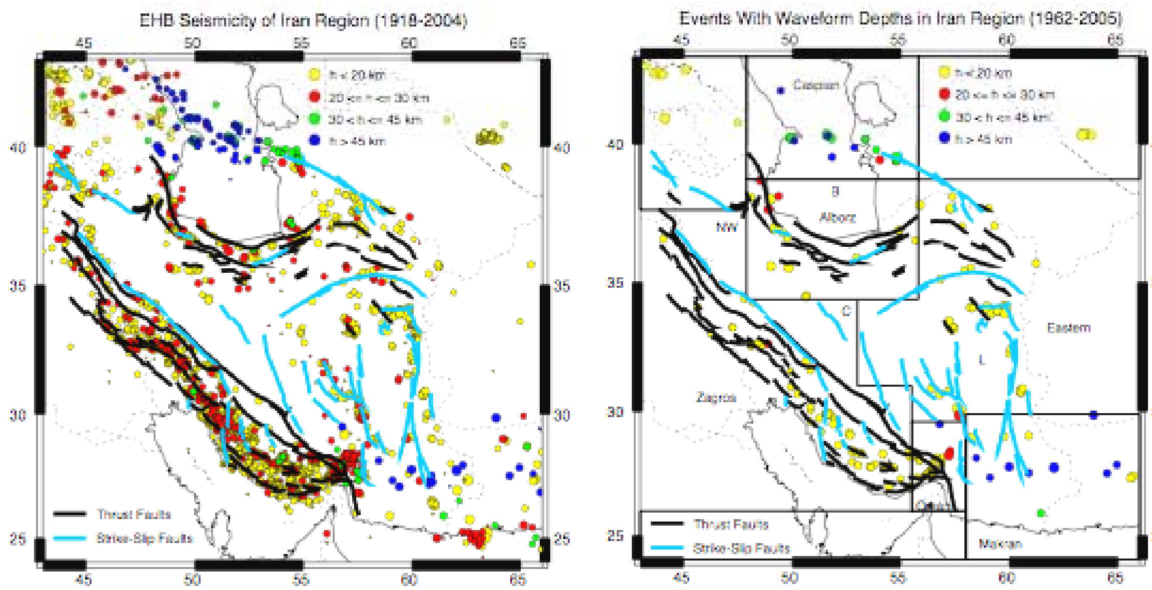

Figure 1. (a) EHB regionalized seismicity in the Iran region (1918-2004). (b) Regionalized seismicity in the Iran region for events with depths determined by P and SH body-wave modeling (1962-2004). The boxes outline the six regions (Caspian, Alborz, Zagros, Oman Line, Makran and Eastern) in which the patterns of seismicity and depth distribution will be discussed Also shown in both figures are thrust (black) and strike-slip (blue) faults.

Central Caspian Region – Offshore Deep and Onshore Shallower Seismicity

Earthquakes in this region occur over a wide range of depths (Figure 2a) with a median depth of 40 +/-15 km, but this generalization hides a clear geographical pattern to the distribution of focal depths. A band of earthquakes crossing the central Caspian beneath the Apscheron-Balkhan sill and continuing onshore in the east includes many earthquakes in the mantle, some as deep as 80 km but none shallower than 30 km. The deepest earthquakes are on the northern side of this zone, but there are an insufficient number of them to define a dipping mantle slab (Jackson et al., 2002). South of this trans-Caspian band, the South Caspian basin itself is apparently aseismic. Crustal thickness varies across the region. Given the uncertainty about the nature of the high-velocity basement beneath the thick sediments of the South Caspian basin, the events at depths between 30 and 50 km beneath the Apscheron-Balkhan sill, whose focal mechanisms show predominantly normal faulting with an ESE strike (Jackson et al., 2002), are difficult to interpret. Several events that lie on the north side of the sill between 70 and 80 km depth are clearly in the mantle, and are thought to represent either the last oceanic remnant of subduction of a now-closed ocean basin or the incipient northeast subduction of the South Caspian basin basement beneath the sill (Jackson et al., 2002). This subduction is a process that appears to occur aseismically at shallow depths, with the lack of earthquakes in the basin indicating that it behaves as a roughly 300 x 300 km^2 relatively rigid block within the

Eurasia-Iran-Arabia collision zone. There is no evidence for seismicity deeper than 100 km, suggesting that the subduction is either slow or young (Jackson et al., 2002).

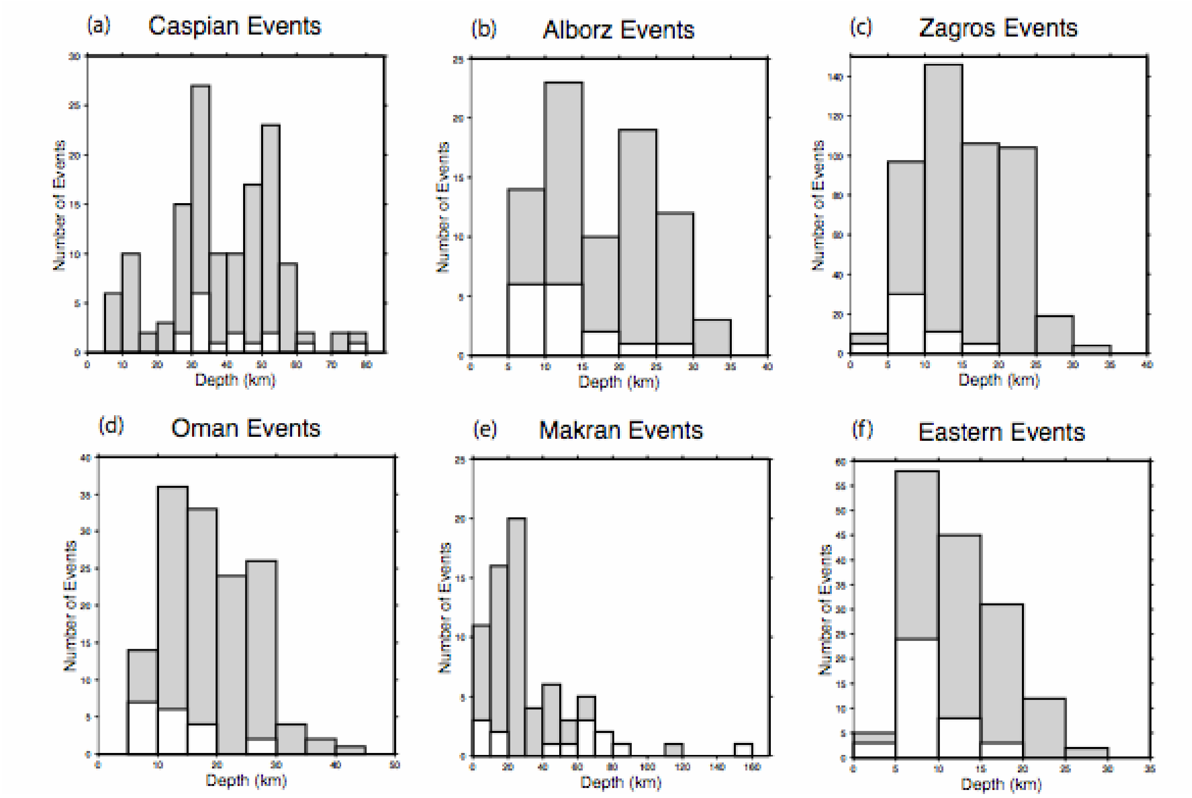

Figure 2. Earthquake depth distribution by region (depths determined by waveform modeling are not shaded): (a) Caspian, (b) Alborz, (c) Zagros, (d) Oman Line, (e) Makran, (f) Eastern.

Alborz Region - Seismicity Throughout the Crust

Roughly 50% of the ~20 mm/yr north-to-south convergence between Arabia and Iran is accommodated in the Alborz region, between the southern Caspian and central Iran. Earthquakes in this region along the Alborz Mountains and other southern Caspian basin active border regions to the southwest and east occur at all depths in the crust (Figure 2b) with a median depth of 20 +/-8 km. However, this generalization hides a clear geographical variation in the known depths. Along the western side of the South Caspian basin, beneath the western Alborz, earthquakes occur to depths of ~30 km, generally on low-angle thrusts, indicating underthrusting of the Caspian sea floor beneath the coast (Jackson et al., 2002). East of 50^{o}E all waveform-modeled depths are shallower than 15 km, but there are a few EHB depths of up to 35 km (Figure 1a). A receiver function result in the central Alborz Mountains shows that the crust is ~35 km thick, with a structure typical of continents. The western Alborz, with its low-angle underthrusting, is tectonically distinct from the central and eastern Alborz, which is dominated by strike-slip and high-angle reverse faulting at shallower depths.

Zagros Region - Seismicity Mostly in the Upper Crust

The Zagros Mountains of SW Iran form a linear intracontinental fold-and-thrust belt about 1,200 km long, trending northwest-southeast between the Arabian shield and central Iran, with a width varying between 200 and 300 km. Roughly 50% of the convergence rate between the Arabia Plate and the continental crust of central Iran is accommodated in the Zagros by north-south crustal shortening oblique to the strike of the belt over much of its length. Of particular interest is whether or not the earthquake depths in this region show any evidence for intracontinental subduction. In their review of waveform-modeled depths in the Zagros, Talebian and Jackson (2004) found no earthquakes deeper than 20 km anywhere except near the Oman Line in the extreme SE Zagros. In the revised EHB database presented here, nearly all earthquakes in the Zagros are less than 30 km in depth (Figure 2c), a result consistent, given the expected uncertainty of 10 km, with the waveform-modeled data. The median depth in Figure 2c is 15 +/-7 km. However, EHB depths may be slightly overestimated in this region because of slower velocities at depth-phase bounce points in comparison with the faster crustal velocities of the ak 135 model. Moreover, with a 10 km uncertainty in EHB depth estimates, most of these events probably occur within the upper crystalline crust but beneath the sedimentary layer. Hence, beneath the Zagros there is no evidence in the form of mantle earthquakes or structure for present-day active subduction of continental crust, with shortening apparently accommodated entirely by crustal thickening and distributed deformation (Talebian and Jackson, 2004).

Oman Line Region - Transition from Shallow Zagros to Subcrustal Makran Seismicity

The Oman Line is a geological syntaxis, where the faults and folds of the Zagros bend dramatically to connect with those of the Makran. The region is a transition from the continent-continent collision of the Zagros to the subduction of the Arabian plate beneath the Makran coast, and is geologically complex. Global Positioning System (GPS) measurements indicate north-to-south convergence between Oman and central Iran of about 11 mm/yr, expressed as a mixture of shortening and north-to-south right-lateral strike-slip on the eastern side of the syntaxis. In the west and central part of the syntaxis, waveform modeling shows earthquakes increasing in depth northwards, from typically 8-12 km near the coast to as much as 28 km at a location 50 km north of the geological suture (the Main Zagros Thrust) that represents the join between Arabian and Iranian rocks (Talebian and Jackson 2002). The deepest earthquakes are all low-angle thrusts, dipping gently northwards, and represent one of the few places where a case can be made for underthrusting of the Arabian basement beneath central Iran; but only by a distance of 50 km to a depth of ~30 km. The eastern limit of the Oman Line region in Figure 1b is drawn so as to exclude most of the Makran subduction zone, but one earthquake at 100 km is included in its northern part. EHB seismicity within the box extends to depths of about 40 km (Figure 2d), consistent with the waveform data summarized above, with a median depth of 20 +/-8 km. The EHB dataset contains earthquakes on the eastern side of the syntaxis at 30–40 km (Figure 1a), but these have not been confirmed by waveform modeling.

Makran Region - Low-Level, Upper-Crustal, and Subduction-Celated Cantle Seismicity

East of 57.3^{o}E, most of the ~30 mm/yr shortening produced by Arabia-Eurasia convergence is accommodated by the Makran subduction zone. The Makran region has earthquakes both at upper crustal depths and at depths well in excess of 40 km (Figure 2e) with a median depth of 25 +/-19 km. The deeper events apparently occur within a shallow (~26^{o}) northward dipping slab. These mantle-depth events in the Makran result from subduction of the Indian ocean beneath the relatively stable Lut and Afghan continental blocks. The Afghan block east of 60^{o}E is now effectively part of undeforming Eurasia, separated from the Lut by the north-to-south right-lateral Sistan shear zone. An along-strike plot of seismicity (Figure 3) shows how earthquakes in the Oman Line zone merge at ~57.3^{o}E into lower-level seismicity beneath the Makran coastal ranges.

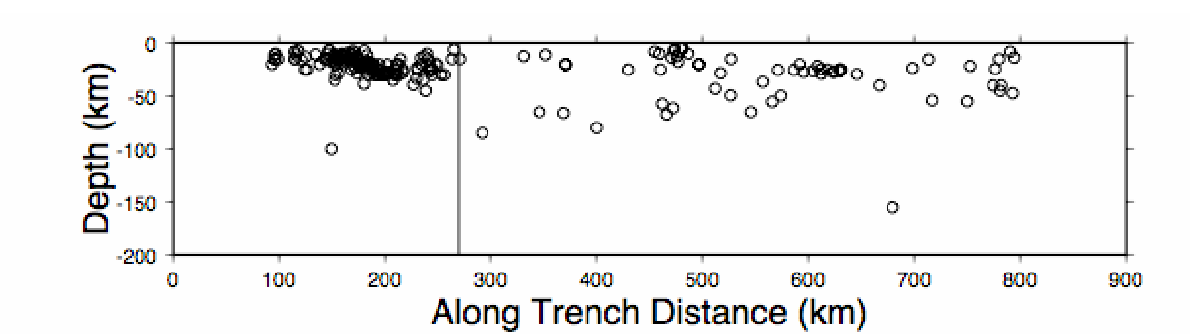

Figure 3. Earthquakes in the Oman Line and Makran regions of Figure 1 plotted along trench strike.

Eastern Iran - Upper Crustal Seismicity Surrounding the Aseismic Lut and Central Iran Blocks

Seismicity in eastern Iran mostly surrounds the stable aseismic blocks of central Iran (Figure 1a). North-south right-lateral shear between central Iran and Afghanistan is about 10-12 mm/yr, mostly accommodated by north-to-south strike-slip faults on the east and west sides of the Lut block. It is probable that most of this shear occurs on the eastern side, whereas north of the Lut the shear is taken up by east-west left-lateral faults that rotate clockwise (Walker and Jackson, 2004). This whole region has been the source of many large earthquakes, many producing surface rupture, in both modern and historic times (Walker and Jackson, 2004). Earthquakes with waveform-modeled depths are all shallower than ~20 km in this region, a pattern seen also in the larger EHB database (Figures 1 and 2f), which has a median depth of 12 +/-5 km.

Iran Ground Truth Data

Critical to our ground truth data discovery and acquisition process are collaborative arrangements that have been made with key organizations in southern Asia. These arrangements are built on exchanges that are mutually beneficial to the parties involved, usually based on our applying advanced techniques to refine locations of the host country's natural seismicity in return for access to in-country ground truth information. In Iran, informal arrangements have been established with the International Institute of Earthquake Engineering and Seismology (IIEES) and the University of Tehran, Institute of Geophysics, during several visits. These arrangements provide a forum for gathering and assessing potential ground truth data, and collecting waveform and phase reading data for events of interest from local and regional stations in Iran. We are also in contact with several groups developing ground truth locations from InSAR-detected ground displacement and other satellite-based location methods that provide important constraints independent of seismic observations. Much new ground truth information in Iran is now being obtained from these sources as an ongoing activity.

Validation through critical examination of the data and procedures that were used in the local network or InSAR location of a proposed ground truth event is an internal process. Therefore, an external validation process, one that utilizes other information as a crosscheck on the reported or derived (using HYPOSAT) local network location, is highly desirable. We use Hypocentroidal Decomposition (HDC), a powerful algorithm for multiple event relocation, as a tool for discovery and validation of ground truth data. HDC is applicable in situations in which several candidate ground truth events and/or InSAR signals are located in a limited region, and in cases where other seismic activity in the area can be localized to known faults and other geologic features. The essence of the validation process is to compare the relative locations in space and time of events based on their ground truth locations, and the relative locations revealed by HDC. An added bonus of the validation process is the generation of additional ground truth events that are of GT5 quality.

Validation of Iran Ground Truth Data

The HDC method for validation 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 each cluster there is independent information on location that helps to calibrate the absolute locations. 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.

We have recently extended the calibration process to take into account the uncertainties in calibration data in estimating an optimal calibration shift for the cluster. We also estimate a term to account for the inconsistency between multiple calibration events. Our final estimate of local accuracy for events in calibrated clusters includes all these sources of uncertainty, as well as the uncertainty in relative locations derived from the HDC analysis.

We report here on ground truth studies of four clusters in Iran that are based on recent large earthquakes: Bam (December 2003), Baladeh (May 2004), Zarand (March 2005), and Qeshm (November 2005). In comparison with our previous HDC studies in this region, the data sets of arrival times for these clusters have many more readings from Iranian seismograph stations at near and regional distances. We have obtained these readings through our enhanced collaborative relationship with colleagues at several institutions. The in-country readings have three main advantages:

- They provide critical azimuthal coverage for some events that greatly improves the resolution of relative locations.
- They make it possible to include additional events in the clusters, to improve the statistical power of the HDC analysis and derived parameters, such as empirical path anomalies.
- They provide new paths for which empirical travel times can be estimated, paths that are especially useful for studies of crustal and upper-mantle velocity heterogeneity in the study region.

The four clusters that have been calibrated are shown in Figure 4:

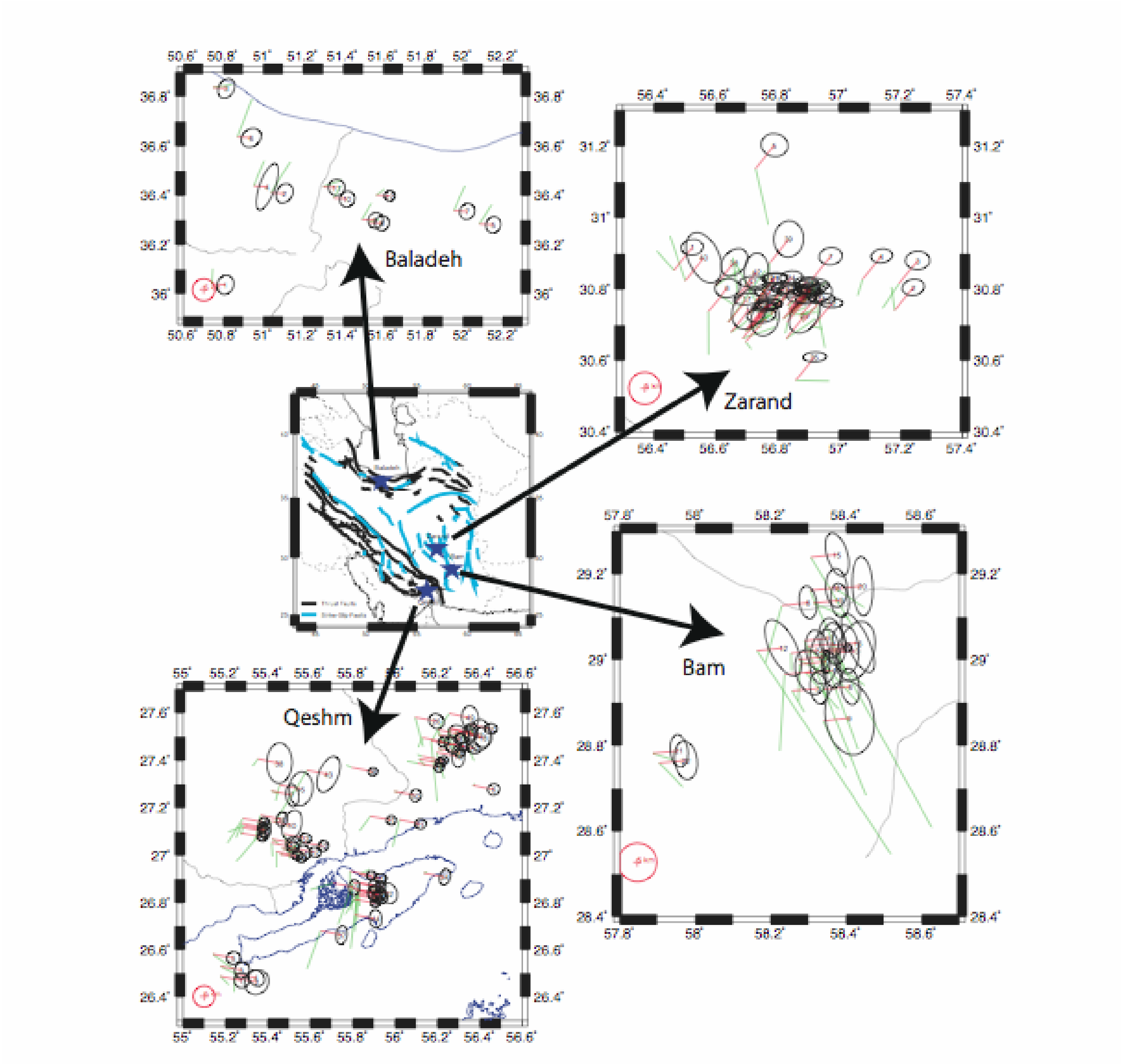

Figure 4. Location map of four earthquake clusters in the Iran region that have been calibrated, and detail maps of the HDC analysis for each cluster. Each figure contains a red circle with 5 km radius in the lower left corner for scale. Green lines show the change in location through the HDC analysis. Red lines show the shift applied to the hypocentroid (thus, the same for each event) to best match the calibration data. Confidence ellipses are at 90% confidence level and include the contribution of uncertainty in relative location from HDC analysis, the calculated uncertainty of the calibration shift, and a component that accounts for discrepancy between multiple calibration data.

Bam Cluster

The Bam cluster begins with the December 26, 2003 mainshock (Mw 6.6) that heavily damaged the city of Bam, and includes 21 subsequent earthquakes through October 7, 2004. Most of the subsequent events can be considered aftershocks, but the last two events in the cluster, on October 6 and 7, 2004 (#21 and 22 in the corresponding panel of Figure 4) are located about 40 km southeast of the seismicity directly associated with the 2003 mainshock.

Calibration of this cluster is based on locating the December 26, 2003 mainshock on the fault revealed by analysis of InSAR data (Talebian et al., 2004; Jackson et al., 2006) and the aftershock survey (M. Tatar, personal comm.). The position along the fault (near the southern end) is constrained by the S-P time of a strong motion instrument in the city of Bam, at the north end of the fault (Bouchon et al., 2006). The depth is well-constrained by waveform modeling at 6 km, but we have no constraint on origin time for this event (the strong motion instrument clock is not calibrated). Fortunately, the aftershock survey provided a reliable location and origin time for an aftershock on January 11, 2004 that is also included in the cluster, and this provides the calibration for origin time. Calibration of the Bam cluster required a shift of 6.9 km at an azimuth of 84° and a shift of -0.24 s in origin time. Ten of the events in the cluster have calibrated locations at GT5 accuracy or better.

Baladeh Cluster

The Baladeh cluster is a small cluster based on the destructive earthquake of May 28, 2004 (Mw 6.3), in the Alborz Mountains north of Tehran (#7 in the corresponding panel of Figure 4). The cluster includes 5 aftershocks, two of which were well-located by a temporary deployment of seismographs (M. Tatar, personal comm.). To increase the resolution of the HDC analysis, we expanded the size of the cluster to include some earlier earthquakes within about 50 km of the May 2004 sequence. The shifts required to satisfy the two calibration events were rather consistent; the weighted average shift that was used to calibrate the cluster is 6.1 km at an azimuth of 93°, and +0.92 s in origin time. Eleven of the events in the cluster have calibrated locations at GT5 accuracy or better.

Zarand Cluster

The Zarand cluster is based on the destructive earthquake of February 22, 2005 (Mw 6.4) and its aftershocks (#8-42 in the corresponding panel of Figure 4). Events 1-7 are earlier events in the area, some of which were also large and damaging.

Calibration of the Zarand cluster is based on the analysis of InSAR, geological, and seismological data by Talebian et al., 2006. This provides a strong constraint on the location and depth of the mainshock hypocenter, but unfortunately does not constrain origin time. There was a temporary deployment to record aftershocks of this earthquake and we are presently waiting for this data to be made available. We are optimistic that the temporary deployment captured one or more of the lengthy and energetic aftershock sequences of this event, allowing improved calibration of the cluster's location, and also providing calibration for origin time. A shift of 9.3 km at an azimuth of 39° is needed to bring the cluster into agreement with the calibration location. Thirty-six of the events in the cluster have calibrated locations at GT5 accuracy or better.

Qeshm Cluster

The Qeshm cluster is based on the Mw 6.0 earthquake of November 27, 2005, and aftershocks that have continued until very recently (#52-62 in the corresponding panel of Figure 4). To gain statistical power for the HDC analysis and gain a better perspective on the seismicity patterns in this region, we enlarged the cluster to include earlier events within about 70 km (Figure 4).

Calibration of the Qeshm cluster is based on a preliminary analysis of InSAR data (J. Jackson, personal comm.) that provides constraint on the location and focal depth of the November 27, 2005 mainshock. There was a very successful aftershock deployment to which we will have access, but analysis of the data has not yet been completed. We are optimistic that these data will provide additional constraint on location calibration, and also provide calibration data for origin time. A shift of 10.1 km at an azimuth of 101° is needed to bring the cluster into agreement with the calibration location. Fifty-two of the events in the cluster have calibrated locations at GT5 accuracy or better.

Regional Path Anomalies

We use the calibrated cluster arrival time data to infer empirical path anomalies (relative to the global model ak135) from each cluster source region to surrounding seismic stations. Figure 5 shows the results for Pg, Pn, and P phases at regional stations for the four clusters in Figure 4. There is broad consistency of path anomalies at most azimuths, including those observed at stations in Iran. 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 path geometry caused by lateral heterogeneity.

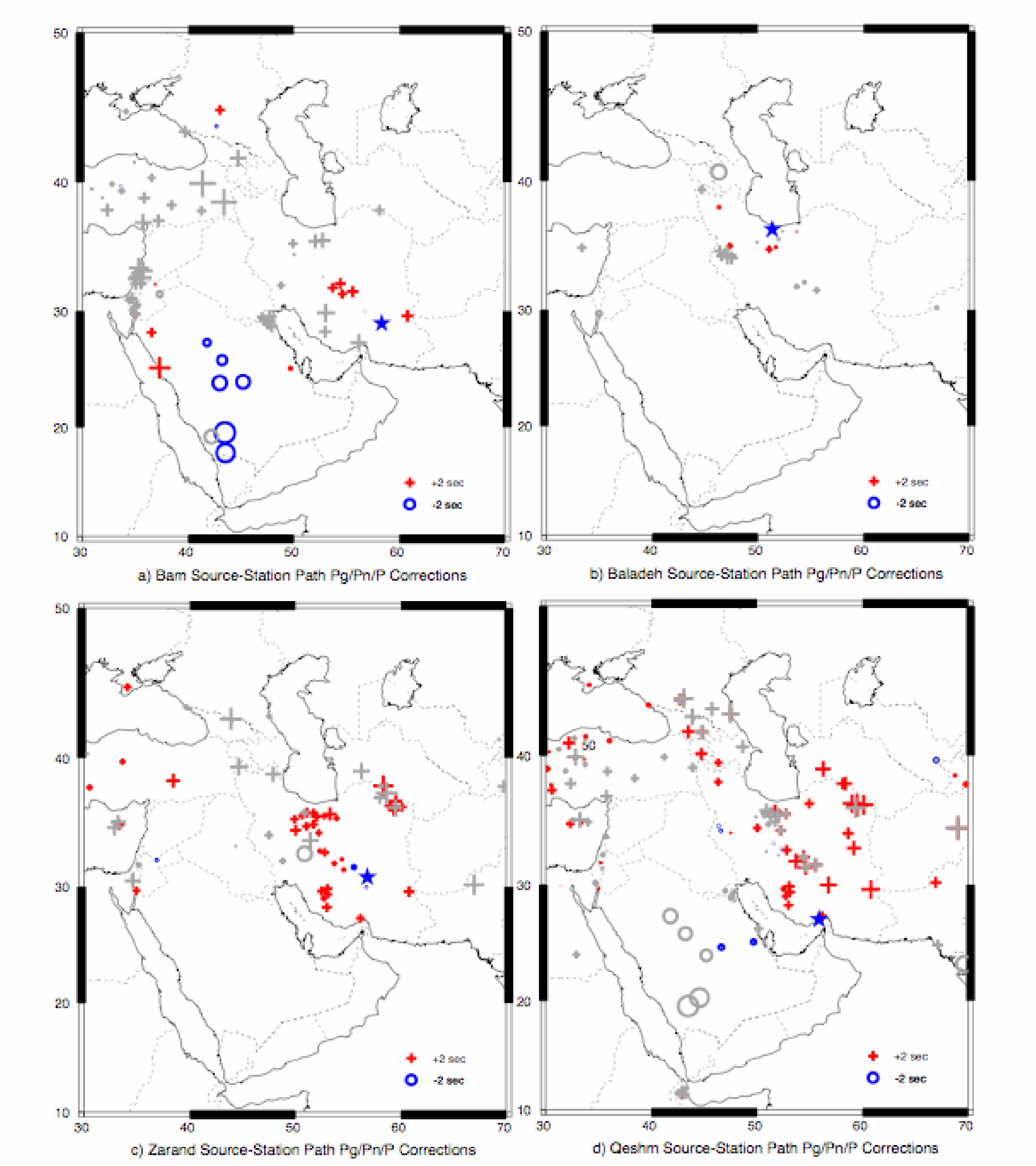

Figure 5. Empirical path anomalies (relative to ak135) for Pn and P phases from (a) Bam, (b) Baladeh, (c) Zarand, and (d) Qeshm clusters. Blue stars show cluster centroids. See Figure 4 for details of clusters. Crosses are late arrivals; circles are early arrivals. Symbol size scales with anomaly. Symbols in color are median anomalies based on 5 or more readings. Grey symbols are based on 2-4 readings.

CONCLUSIONS AND RECOMMENDATIONS

We have relocated Iranian earthquakes occurring between 1918 and 2004. The image of seismic activity occurring at the boundaries between distinct tectonic blocks is sharpened, and event depths are refined. This is a significant advance, as outliers and future events with apparently anomalous depths can be readily identified and, if necessary, further investigated. Our results suggest that the vast majority of Iranian events occur in the upper crust. Lower crustal locations are confirmed in the Oman Line and Alborz regions. Mantle events are associated with the Makran subduction zone and in remnant subduction north of the southern Caspian Sea. Iranian seismicity is the result of the early stages of continent/continent collision between the Arabian Peninsula and Eurasia. Distinct tectonic blocks are responding to the nascent collision through relative motion, resulting in seismicity at the boundaries. Areas of heightened strain (collision with the Oman Peninsula and drastic variations in crustal structure around the southern Caspian) result in lower crustal seismicity.

We have developed new ground truth events and calibrated earthquake locations in Iran, based on detailed multiple event relocation and use of calibration data, both from local seismic network data and from InSAR data. We have been able to include substantial numbers of phase readings at in-country seismograph stations that have improved the quality and quantity of calibrated earthquake locations in this region. 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.

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