

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

Eric R. Engdahl<sup>1</sup>, Eric A. Bergman<sup>1</sup>, Stephen C. Myers<sup>2</sup>, and Floriana Ryall<sup>2</sup>

University of Colorado<sup>1</sup> and Lawrence Livermore National Laboratory<sup>2</sup>

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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 southern Asia, in particular the region bounded by 20-44°N and 41-67°E, by providing information needed to develop and test more accurate travel time models for seismic phases that propagate in the crust and upper mantle. We have also incorporated phase picks from an experienced analyst who reviewed waveforms of particular interest for specific events. These in-country arrival times and analyst-reviewed picks have been associated with known earthquakes reported by international agencies, combined with existing bulletin readings, and relocated using the catalog EHB (Engdahl et al., 1998) methodology. Using in-country data we have formed new events, mostly at lower magnitudes that were not previously included in standard global earthquake catalogs. This has resulted in a catalog of earthquakes in the region for the period 1918-2006 for events larger than about magnitude 2.5. Catalog events larger than about magnitude 4.0 and well-constrained teleseismically have been highly reviewed. Events at lower magnitudes have been relocated with a standard procedure similar to the EHB procedure, but not all systematically reviewed.

The new catalog has been used to conduct detailed analysis of historic and recently occurring event clusters (often mainshock-aftershock sequences) using a multiple-event relocation technique and data sets of phase arrival times at distances from near-source to teleseismic. 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 information such as interferometric synthetic aperture radar (InSAR) or geological mapping. We have also developed a method for direct calibration of a cluster by using arrival time data only from local stations, with an appropriate crustal model, to locate the hypocentroid of the cluster. These studies have produced numerous events with epicenter absolute accuracy of 5 km and better (GT5). When both location and origin time can be calibrated for a cluster, we are able to estimate the unbiased 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 more accurate routine earthquake locations using regional seismic data.

To date we have performed hypocentral decomposition (HDC) calibration analyses on 27 earthquake clusters in the region. We present a synopsis of 8 new clusters that have been calibrated at GT5 or better, including information on the method of calibration and GT-level of calibration achieved. We also present several representations of absolute travel time information derived from the calibrated clusters, showing distance-dependence of different phases and map views to show the regional coherency of travel-time variations.

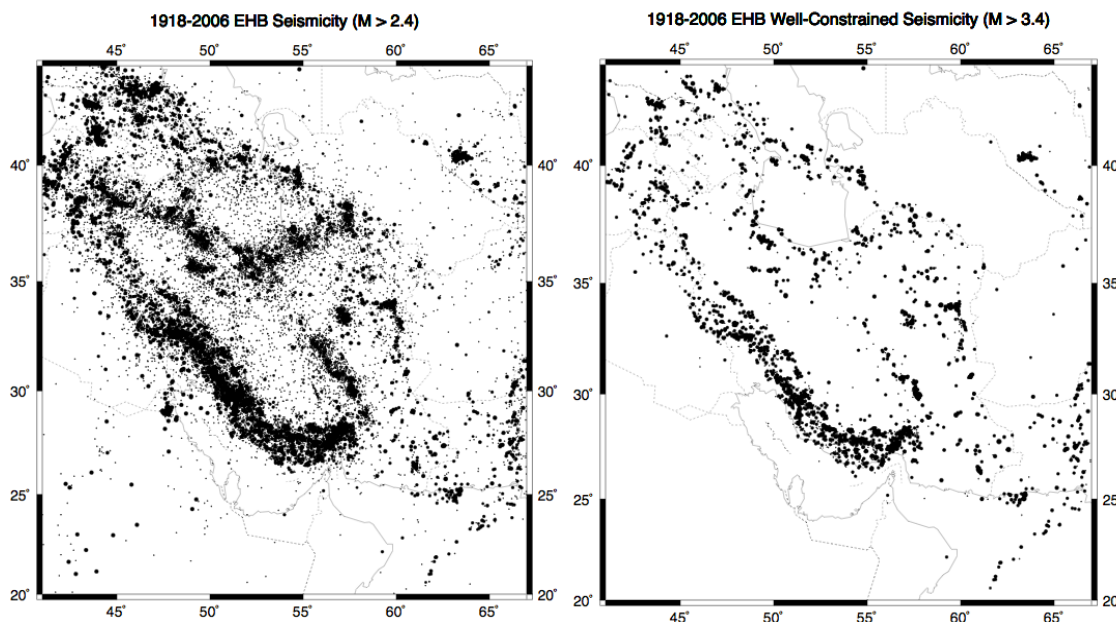
## **OBJECTIVES**

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, Pb, Pn, Sg, Sb and Sn; and (3) Application of advanced algorithms, specifically 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**

### **Compilation of Arrival-Time Data and Relocation of Seismicity**

The aim of the present study is to produce a comprehensive catalog of all instrumentally recorded events, magnitude 2.5 and greater, that have occurred during the period 1918–2006 for the region bounded by 20–44°N and 41–67°E. Available bulletin arrival-time data from in-country seismic networks in the region, as well as phase picks from an experienced analyst who reviewed waveforms of particular interest for specific events, have been compiled and, where possible, associated with known earthquakes reported by international agencies. However, with the in-country data we have also formed many new events, mostly at lower magnitudes that were not previously included in standard global earthquake catalogs. This combined catalog of more than 22,000 events has been relocated using the EHB (Engdahl et al., 1998) methodology. Epicenters from the resulting catalog are plotted in Figure 1a. Significant scatter is evident in Figure 1a since events at lower magnitudes have not all been systematically reviewed, whereas most events that are well-recorded teleseismically (Figure 1b) have been highly reviewed.



**Figure 1. Seismicity maps of the study region, based on the new catalog assembled in this project, using in-country phase arrival time data that has been integrated with standard global bulletin readings. a) Over 22,000 earthquakes from 1918-2006 with magnitude 2.5 and greater, relocated using EHB methodology but most of the smaller events are unreviewed. b) Subset of events that are well-constrained with teleseismic readings, most of which have been reviewed.**

### 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. 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.

We are also in contact with several research groups developing ground truth locations from InSAR-detected ground displacement and other satellite-based location methods, as well as geological field work, that provide important constraints on earthquake location that are independent of seismic observations. Much new ground truth information is now being obtained from these sources as an ongoing activity.

### Location Calibration of Earthquake Clusters through Multiple Event Relocation

The HDC (Jordan and Sverdrup, 1981) method for location calibration 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. The HDC analysis includes further refinement of the data set by making empirical estimates of reading 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 have also developed a method for direct calibration of a cluster by using arrival time data only from local stations, with an appropriate crustal model, to locate the hypocentroid of the cluster. We have found a number of cases in which no individual earthquake in the cluster is well-recorded enough to be treated as a calibration event, but the cumulative local-distance readings of all events do provide sufficient location accuracy to calibrate the hypocentroid directly at GT5 or better. Many of the clusters presented below have been calibrated in this manner.

### Regional Path Anomalies

When both location and origin time can be calibrated for a cluster, we are able to estimate the unbiased 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 more accurate routine earthquake locations using regional seismic data.

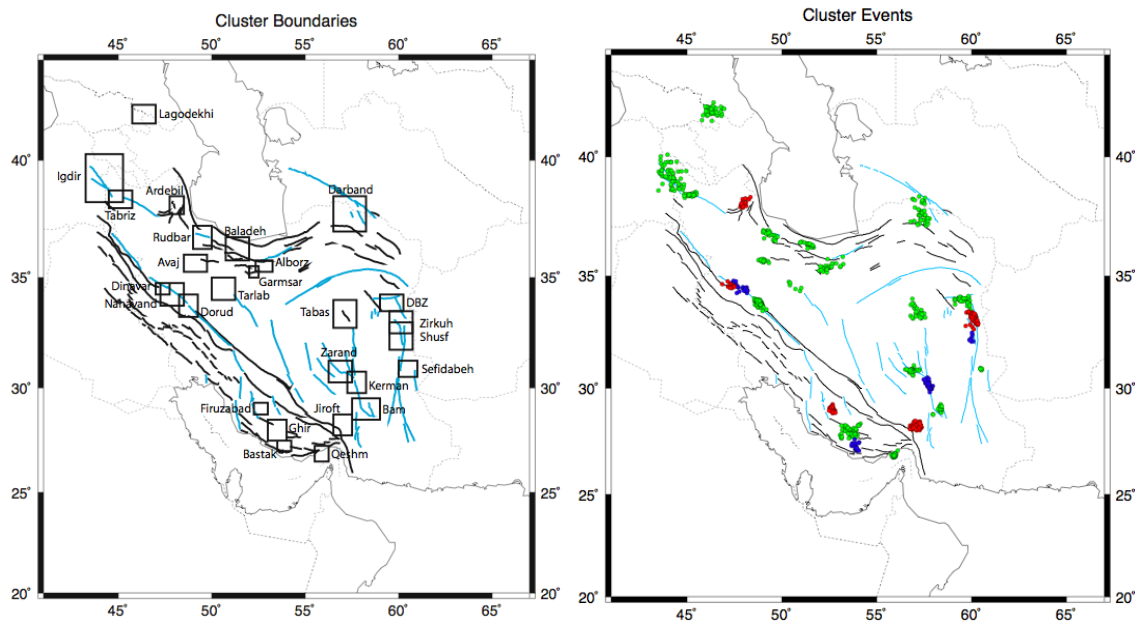
We use the calibrated cluster arrival time data to infer empirical path anomalies (relative to the global model ak135) from each cluster source region to surrounding seismic stations. The path anomalies can be the result both of variations in bulk velocity and differences in ray path geometry caused by lateral heterogeneity.

### Cluster Studies Revisited

The influx of new data from in-country sources has required us to revisit all earthquake clusters that had previously been considered finished. The new data, when combined with existing ground truth datasets, is providing very useful constraints on true travel times through the crust and upper mantle of the region. Hence, we have performed further detailed analysis of historic and recently occurring event clusters using our standard multiple-event relocation technique and data sets of phase arrival times at distances from near-source to teleseismic.

### Synopses of New Calibrated Clusters

To date we have performed HDC calibration analyses on 27 earthquake clusters in the region (Figure 2). Not all clusters can be calibrated at GT5 levels of accuracy.

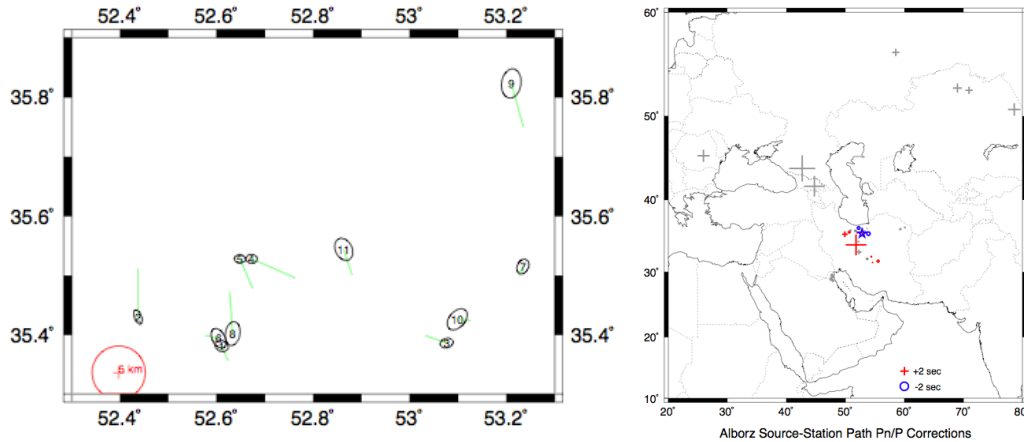


**Figure 2. Earthquake clusters studied for ground truth calibration. a) Boxes show the region of each cluster, with the name we have assigned. Major strike-slip faults (blue) and thrust faults (black) are shown. b) The earthquakes of each cluster are shown. Events in each cluster are color coded according those clusters that are calibrated (not necessarily at GT5 or better) in both location and origin time (green), clusters that are calibrated in location but not origin time (blue), and clusters for which we have as yet been unable to achieve any calibration (red).**

We present synopses of 8 clusters that have not been presented in previous Research Reviews and that have been calibrated in both location and origin time to GT5 or better, including information on the method of calibration and GT-level of calibration achieved. We also present several representations of absolute travel time information derived from the calibrated clusters, showing distance-dependence of different phases and map views to show the regional coherency of travel time variations.

#### *Alborz*

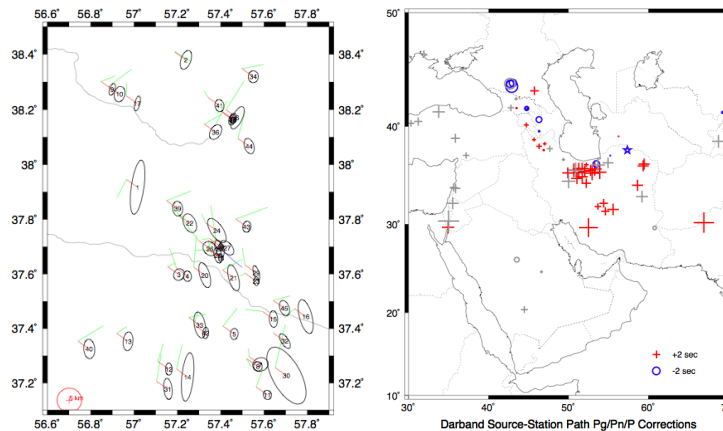
The Alborz cluster (Figure 3) is a small (11 events) cluster of relatively small ( $2.5 \leq M \leq 4.5$ ) earthquakes. Most of the arrival time data is from nearby stations, and we used 81 P arrivals out to  $1.5^\circ$  epicentral distance to locate the hypocentroid of the cluster (direct calibration), with an uncertainty of about 2 km. When this is combined with the cluster vector uncertainties shown in Figure 2b, most of the events will be calibrated at GT5 or better.



**Figure 3. Alborz cluster. a) Results of the HDC analysis. Confidence ellipses are 90% level for relative locations. A circle of 5-km radius is shown in red for reference in the lower left corner. Green lines show change in relative locations from starting locations (EHB single event locations). b) Map of empirical path anomalies, relative to ak135. The blue star is the location of the cluster hypocentroid. Anomalies are calculated when there are two or more readings of the same phase at a given station. If there are 5 or more readings the symbol is in color (red for positive anomalies, blue for negative); otherwise the symbol is plotted in gray. Crosses indicate positive (late arrival) anomalies, circles indicate negative (early arrival) anomalies. The scale of path anomalies is shown at the bottom right of the figure.**

#### *Darband*

The Darband cluster (Figure 4) contains 45 events scattered over a fairly large area. There are many readings at local distances and the hypocentroid was located with 144 P readings at distances less than 2.5 degrees (direct calibration), with an uncertainty of about 3 km. It was necessary to go out further than is desirable in epicentral distance in order to achieve adequate azimuthal coverage. Many events in the cluster will qualify as GT5 locations.

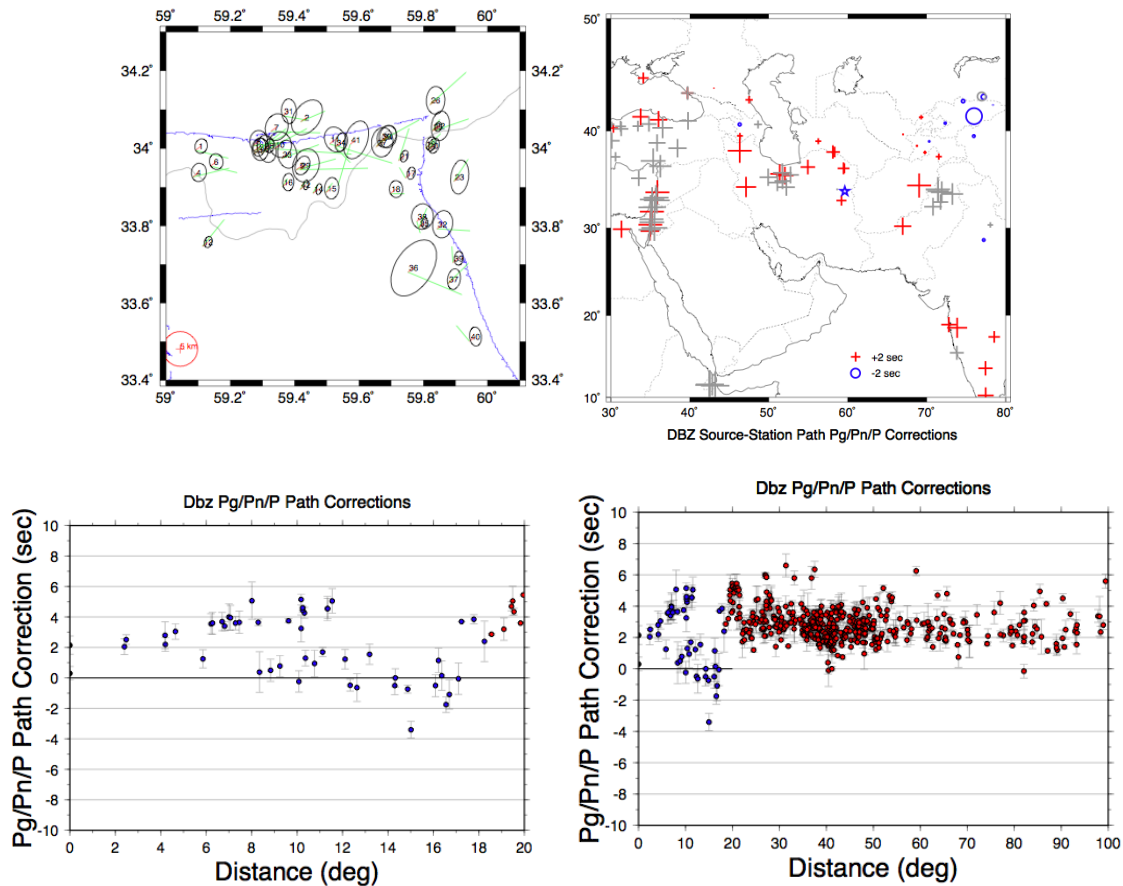


**Figure 4. Darband cluster. See Figure 3 for explanation.**

#### *Dasht-e-Bayaz-Zirkuh*

The Dasht-e-Bayaz-Zirkuh cluster (Figure 5) is composed of 42 events near the intersection of two major strike-slip fault systems, shown in blue in Figure 5a. The cluster contains several very large events and their aftershocks. To calibrate this cluster we used two calibration events that were very well located by a temporary seismic network studying aftershocks of a large earthquake in November 1979. Thus, we located the hypocentroid of this cluster using teleseismic P readings and shifted the cluster to best match the calibration

locations of these two events, with an uncertainty of the calibration of about 3 km. When the cluster vector uncertainty is added, over half of the events in the cluster qualify as GT5.

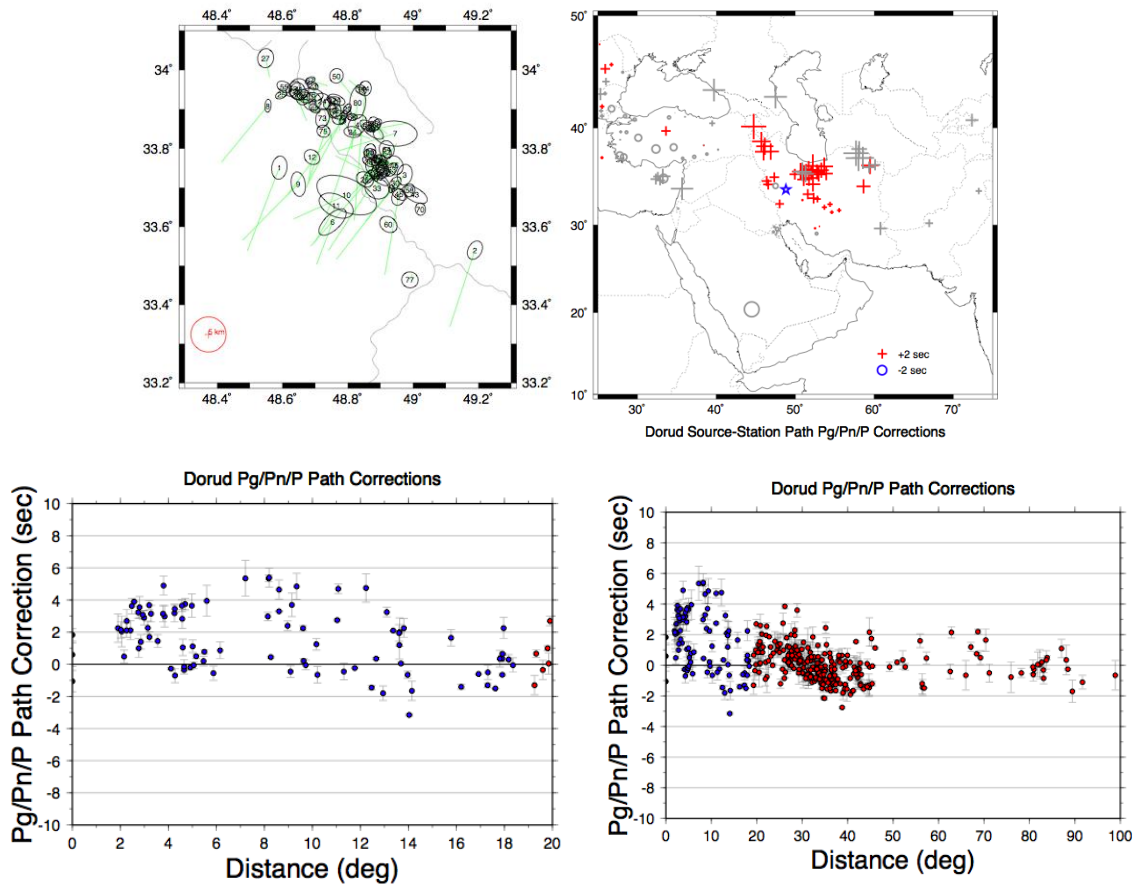


**Figure 5. Dasht-e-Bayaz-Zirkuh cluster.** See Figure 3 for explanation of a and b. c) Empirical path anomalies and spread of each measurement, over the regional distance range. d) Empirical path anomalies and spread of each measurement, over the regional and teleseismic distance range.

For this cluster we show the empirical path anomalies both in map view (Figure 5b) and as a function of distance (Figures 5c and 5d). Figure 5d shows empirical path anomalies over the regional distance range, while Figure 5d shows the anomalies over the regional and teleseismic range.

#### *Dorud*

The Dorud cluster (Figure 6) is based on a mainshock-aftershock sequence that began in March 2006 and a few events prior to that.

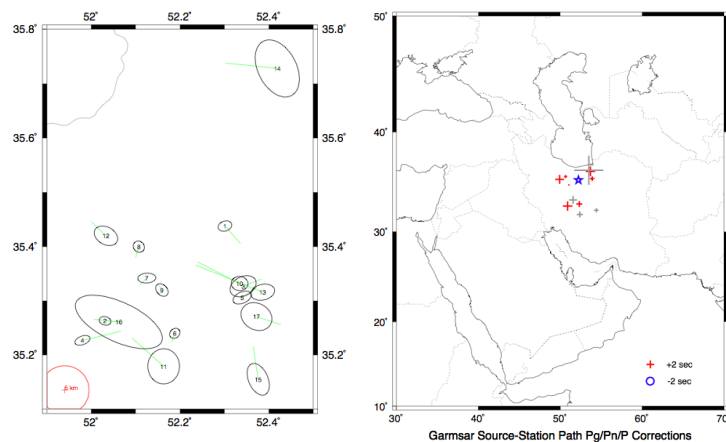


**Figure 6. Dorud cluster.** See Figure 3 for explanation of a and b, Figure 5 for explanation of c and d.

Our ability to analyze this cluster is strongly dependent on the availability of a large number of readings from local stations that were carefully repicked by one of our colleagues. The cluster contains 80 events, most of which are very well-constrained in relative location. We used direct calibration for this cluster because none of the individual events was well-recorded enough by local stations to be treated as a calibration event. Cumulatively, however, we had 344 P readings at distances of less than 2.0 degrees to locate the hypocentroid, which gave us a calibration with about 3 km uncertainty. When the uncertainty of the cluster vectors is added, many of the events in the cluster qualify as GT5.

#### *Garmsar*

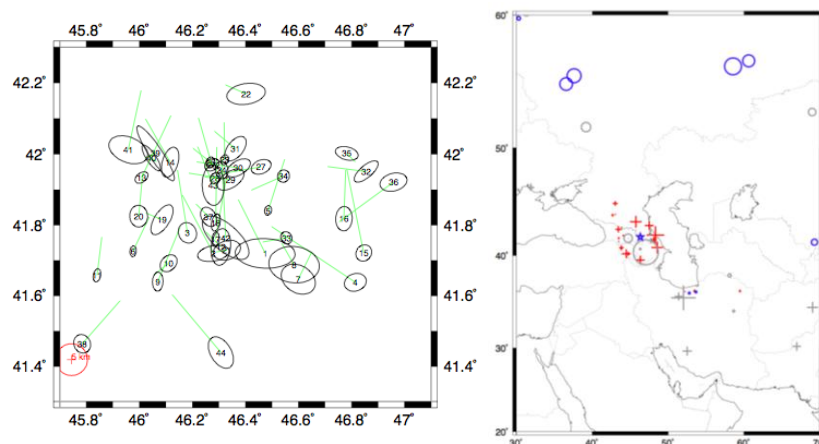
The Garmsar cluster (Figure 7) is composed of 17 small events, maximum magnitude 3.9, for which there is little arrival time data beyond about 5.0 degrees. In-country data was vital in being able to analyze this cluster. We used direct calibration with 105 P readings at distance no more than 1.3 degrees, achieving an uncertainty in calibration of about 2 km. 15 of the events qualify as GT5.



**Figure 7. Garmsar cluster. See Figure 3 for explanation.**

### Lagodekhi

The Lagodekhi cluster (Figure 8) contains 44 events in a somewhat diffuse pattern, but not so large as Iğdir. We used direct calibration because none of the individual events were suitable as calibration events. With 158 P arrivals at distances less than 1.3 degrees we achieved an uncertainty in the calibration of 3 km and about half the events in the cluster would qualify as GT5.

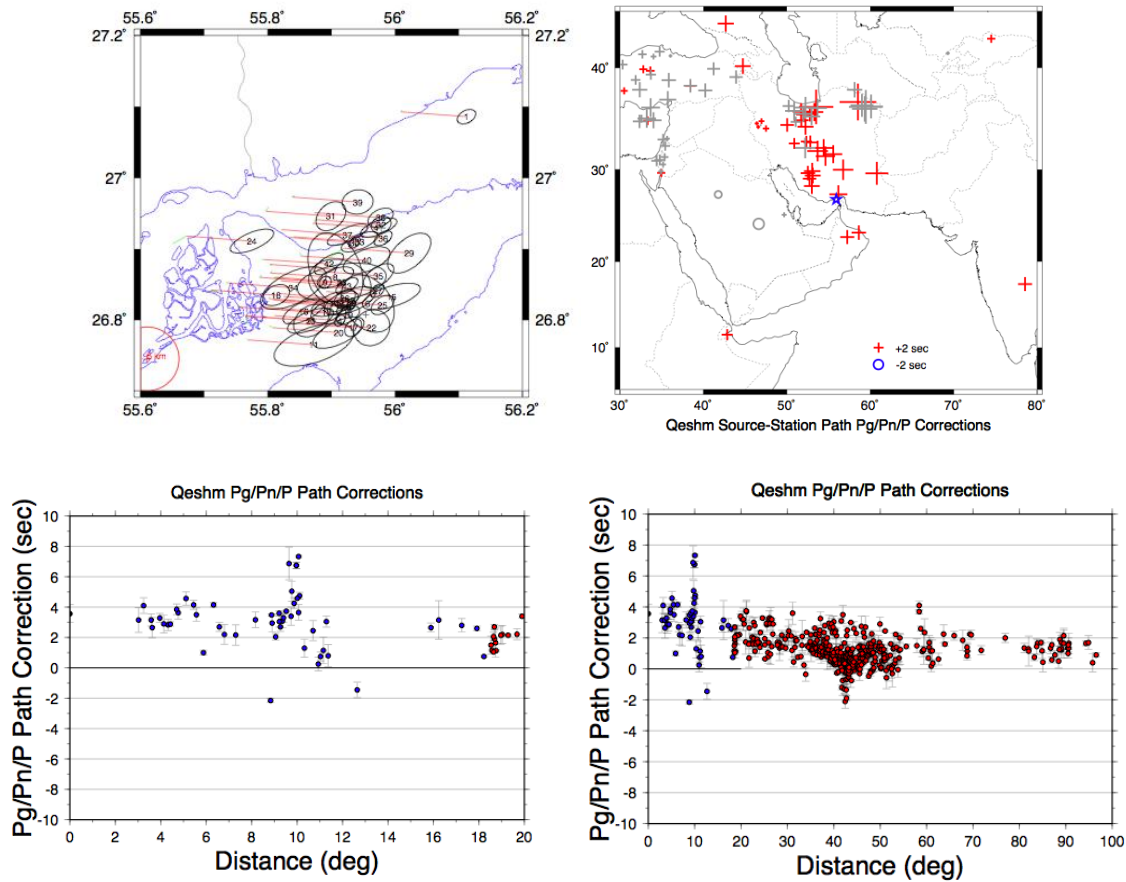


**Figure 8. Lagodekhi cluster. See Figure 3 for explanation.**

### Qeshm

The Qeshm cluster (Figure 9) is based on a mainshock in November 2005 and an extended aftershock sequence.



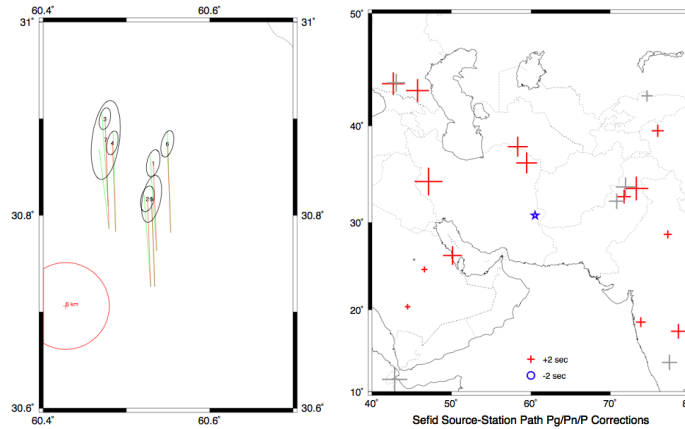


**Figure 9. Qeshm cluster.** See Figure 3 for explanation for a and b. See Figure 5 for explanation of c and d. The red lines in 9a indicate the shift needed to bring the cluster into alignment with the calibration data. The starting locations for this run were taken from the prior run to aid convergence, so there is almost no change in relative location (green lines).

The relative locations of the 43 events are well-constrained by in-country data and also by readings at a critical azimuth from a neighboring country, which we were able to obtain through colleagues. Calibration of this cluster is based on a combination of InSAR and seismic data. The InSAR study provides strong constraint on the location of the mainshock and our local colleagues provided us with two calibration events based on an aftershock survey, which confirms the InSAR location and also provides calibration for the origin times. The uncertainty of the calibration is about 2 km, and when cluster vector uncertainties are added, 36 of the events qualify as GT5.

#### *Sefidabeh*

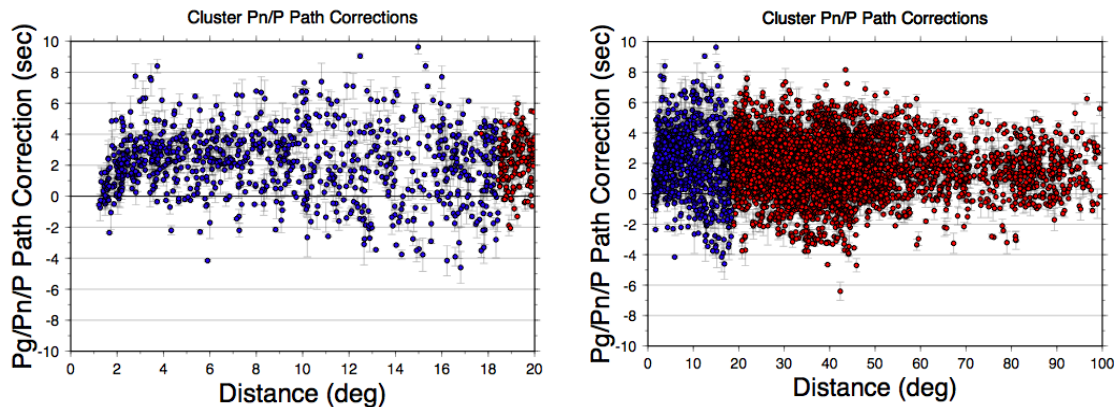
The Sefidabeh cluster (Figure 10) is a quite unusual episode of seismic activity, a series of moderate-sized earthquakes over a few days in early 1994 in a place with no prior or subsequent seismic activity. The tectonic significance of the seismicity is discussed in Parsons et al., 2006. The cluster contains 7 events that are all well-recorded, and the cluster vectors uncertainties are quite small (Figure 10a). Calibration is done with a combination of InSAR and seismic data. InSAR analysis (Parsons et al., 2006) places strong constraints on the locations of the cluster events, with about GT3 calibration uncertainty. Through the help of one of our colleagues we obtained P and S readings from two stations at very short epicentral distance, a few tens of km. Although these readings were insufficient to locate the events, we could use them to calibrate the origin time of the cluster. six of the events in the cluster qualify as GT5.



**Figure 10. Sefidabeh cluster. See Figure 3 for explanation. The red lines in 10a indicate the shift needed to bring the cluster into alignment with the calibration data. The starting locations for this run were taken from the prior run to aid convergence, so there is almost no change in relative location (green lines).**

### Summary of Travel-Time Anomalies

We have combined the empirical path anomalies of all the clusters that are calibrated in both location and origin time to produce a summary plot of P arrivals as a function of epicentral distance (Figure 11).



**Figure 11. Empirical path anomalies, relative to ak135, and spread for P phases from 12 earthquake clusters that are calibrated both in location and origin time. a) Regional distance. b) Regional and teleseismic distance.**

The empirical path anomalies for individual clusters (e.g., Figures 5, 6, and 9) show evidence both for departures from the average earth model used for reference (ak135), and for lateral heterogeneity. When the path anomalies are combined however, most structure is lost in a cloud of impressive width, a range of 10–12 seconds for P phases over the regional and teleseismic distance range (Figure 11). Even here there is a suggestion of about 2–3 seconds baseline offset from ak135 in the study region. This can be accounted for with a crustal structure that is both thicker (40–45 Km Moho depth, vs. 35 km for ak135) and slower in bulk velocities. It is clear, however, that accurate earthquake location in this region will require the use of crustal models that are more specific to the source regions.

### CONCLUSIONS AND RECOMMENDATIONS

We have relocated more than 22,000 earthquakes of magnitude 2.5 and greater, occurring between 1918 and 2006, in the region bounded by 20–44°N and 41–67°E. From this catalog we have acquired new or improved ground truth events and calibrated earthquake locations in the region, based on detailed multiple event relocation and use of calibration data, both from local seismic network data and from InSAR and geological 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 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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