A REFERENCE DATA SET FOR VALIDATING 3-D MODELS

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ABSTRACT

High-resolution cluster analysis (multiple-event relocation) of earthquakes and other seismic sources has been developed as a tool for assembling catalogs of reference events, especially those whose locations can be determined with an accuracy of 5 km or better (ground truth [GT] 5). We use the Hypocentroidal Decomposition (HDC) method of Jordan and Sverdrup (1981), which is well suited to the rigorous statistical analysis required for this task. An ongoing task is the identification and collection of potential reference events monitored by local seismic networks or recorded during temporary aftershock deployments. Cluster analysis is used with arrival-time data reported to the International Seismological Centre (ISC) and United States Geological Survey National Earthquake Information Center (USGS/NEIC) at regional and teleseismic distances to validate these reference events and to generate new GT5 reference events. The resulting catalog and derived parameters, such as empirical estimates of source-station path anomalies, provide a reference data set that can be used in experiments designed to validate three-dimensional (3-D) models of the region of interest.

To date HDC analyses have been performed on 26 earthquake and explosion sequences across Eurasia and North Africa. We examine the characteristics of our cluster data using, for example, plots of combined Pn/P residuals (corrected for origin time offset) at regional distances. For residuals in the range +/-15 sec, both raw and trimmed data show similar variations of median and spread as a function of distance, with a maximum spread near 12-13 degrees. Similar plots of empirical source-station path anomalies show a range of -7.5 sec to +5.0 sec, with maximum differences occurring at distances of 11 to 18 degrees where the influence of interfering travel-time branches makes phase identification difficult.

The University of Colorado (CUB) group has constructed from surface wave dispersion data a global 3-D S-wave velocity model of the crust and the upper mantle. S-wave speeds were converted into P-wave speeds based on laboratory-measured properties of mantle minerals and an average compositional model of the upper mantle. Regional path anomalies predicted by the CUB 3-D model are in much better agreement with empirical path anomalies derived by cluster analysis than with predictions made using a 1-D reference model (AK135). Moreover, agreement with the 3-D model predictions is significantly improved by re-identification of Pn and P phases (set during cluster analysis) based on the insights gained by ray tracing through the CUB model.

The CUB 3-D model is also used to relocate reference events either known exactly or validated by cluster analysis as GT5 or better. Culled Pn/P arrival-time data at regional distances are used with a grid search technique and with Source-Specific Station Corrections (SSSC's) derived from the CUB model to relocate the events. In a preliminary validation test, we find that the 3-D model improves locations relative to locations based on the 1-D model AK135 in 70-85% of all cases, with details depending on the number of reported phases used for relocation. Typically, the 3-D model reduces the location errors to about half the values attained with the 1-D model.

OBJECTIVE

The primary objective of this research effort is to develop a comprehensive reference event database with validated travel-time information for regional seismic phases recorded by International Monitoring System (IMS) and surrogate stations in Asia and North Africa. This database can be used to support the calculation of regional travel-time curves and source-specific station corrections (SSSC's).

RESEARCH ACCOMPLISHED

Introduction

There is a fundamental need for a validating data set of seismic events above the International Data Centre (IDC) event definition threshold (currently mb~3.75) with minimal systematic error of event location and from which reliable empirical estimates of source-station path anomalies with respect to a reference model can be determined. In this report, we first discuss the development of such a database by cluster analyses of earthquake and explosion sequences in Eurasia and northern Africa. We use primarily phase arrival-time data reported to the International Seismological Centre (ISC) and to the U.S. Geological Survey's National Earthquake Information Center (NEIC), or made available by other sources, that have been *groomed* using a procedure described by Engdahl et al., (EHB; 1998). The resulting catalog and derived parameters in this database provide a reference data set that can be used in experiments designed to validate three-dimensional (3-D) models of the region of interest. Such a 3-D model has been developed by the University of Colorado (CUB) group and is used in a validation test that compares model-predicted regional path anomalies with empirical path anomalies derived by cluster analysis. As an additional independent validation test, selected events derived by cluster analysis are relocated using only regional data in the 3-D model and compared to similar locations based on the 1-D model AK135 (Kennett et al., 1995).

Methodology

The cluster analysis used in this study is based on the Hypocentroidal Decomposition (HDC) method (Jordan and Sverdrup, 1981) for multiple event relocation. We seek situations where a number of moderate-size earthquakes are clustered (within about 50-100 km of each other) and where at least one of the events has been very well located by a local network. The events in the cluster may be widely distributed in time, as long as arrival-time data are available. This approach is fundamentally a high-resolution cluster analysis for relative event location, forming event clusters that contain one or more candidate reference events. In most cases, reference event data are available from short-term portable seismograph deployments following the initiation of seismic activity. The clusters typically are 50-100 km across and comprise up to 100 events of magnitude 3.5 or greater that have occurred since 1964 and that are well recorded at regional and teleseismic distances. The cluster is located in an absolute sense, as if all the data were from a single event, using the 1-D model AK135. The HDC analyses produce new locations that are defined by "cluster vectors" in space and origin time relative to the hypocentroid, which is then located in the traditional manner to yield absolute locations and origin times. Obviously, this process is subject to bias. To remove the bias, we shift the hypocentroid in space and time to provide an optimal match to one or more reference events that are included in the cluster. This brings all events in the cluster into close alignment with "ground truth". In addition, since the absolute locations and times of all the events in the cluster are now estimated with increased accuracy, many of the events in the cluster may now be "promoted" to reference event status at an appropriate GT level.

The degree of consistency between the relative locations as determined by global arrival-time data and the relative locations specified by the reference event data is one of the tests we use to validate candidate reference events. Shifts in epicenter and origin time (to best match the reference event locations) are typically in the range of 5-15 km and ± 2 seconds, respectively. We validate candidate reference events by requiring that the relative shift patterns of candidate reference events be consistent with the pattern of the corresponding cluster vectors from the HDC analysis. Discrepancies may be resolved by determining that the cluster vector is biased for some reason, or by rejecting the candidate reference event. For this reason, most clusters contributing to the database for this study are calibrated by several reference events.

Engdahl and Bergman (2001) have recently compiled a comprehensive database of well-located earthquakes and explosions that have been validated by cluster analysis. There are currently 23 clusters in this database: 6 explosion clusters, most with source locations known to 2 km or better; 17 earthquake clusters, 12 that are believed to be accurate to 5 km or better; and the remainder 10 km or better. For each event, the database contains associated phase arrival times that were either reported to the ISC or NEIC or contributed by other sources. Hypocentroids for the clusters studied are plotted in Figure 1.

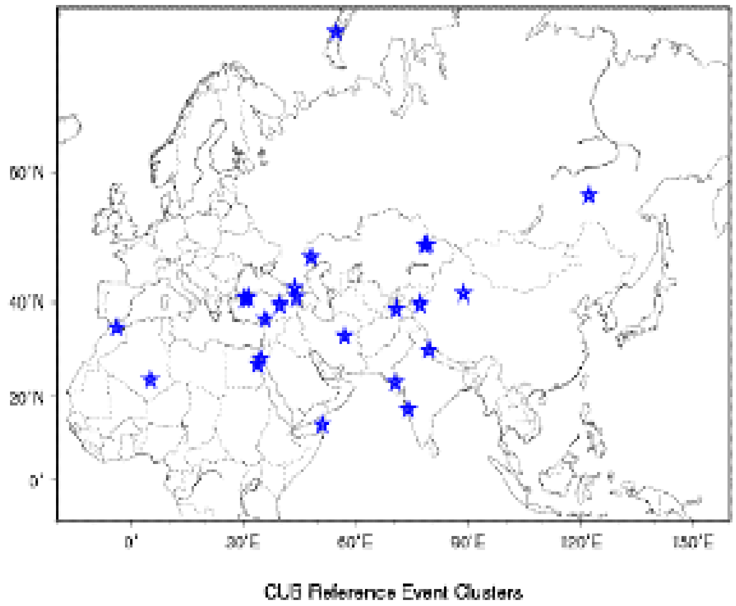


Figure 1. Locations of the explosion and earthquake clusters studied indicated by stars.

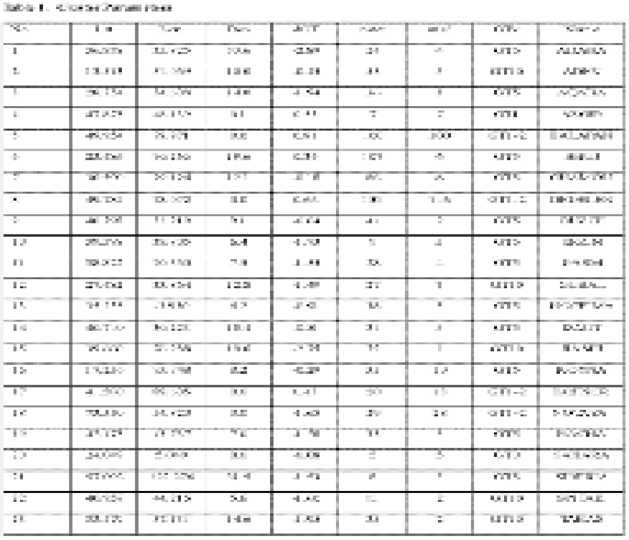
Parameters

Relevant parameters for all clusters studied are listed in Table 1. The location and depth given is for the *shifted* hypocentroid, representing the best fit to reference event locations. The origin time offset is the average difference between the reference event origin times and the origin times obtained by cluster analysis for those same events. Cluster origin times are basically set by the mean of station residuals at all distances. This is perhaps not the best way to make this estimate, as station coverage by distance range can vary (e.g., regional versus teleseismic), and we are considering alternative approaches. Nevertheless, those offsets are indicative of the differences between the crust and upper mantle of the real earth and that of the 1-D model AK135. Relative to AK135, positive offsets would indicate slower velocities and negative offsets faster velocities. On the other hand, the origin time offsets may also indicate errors in the reference event origin times that are normally fitted to within about +/-1 sec. These origin-time offsets can be quite large and, when plotted at their hypocentroid locations, (Figure 2) do seem to show a correlation with tectonic region.

Data

Another feature of our cluster analysis is that we use cluster residuals to estimate station-specific reading errors for each cluster. Use of these derived reading errors, as opposed to assuming standard fixed reading errors (which typically also include the effect of model error) for all arrivals, redistributes the data importance in the inverse problem, which changes the cluster vectors and the hypocentroid. Because of the way in which the HDC method decouples the problems of estimating cluster vectors and the hypocentroid, it is easy to use the derived reading error alone for the cluster vectors, and the reading error plus a separate estimate of model error for the hypocentroid. In the most common case, in which derived reading errors are—on average—smaller than what is usually assumed, the confidence ellipses of the cluster vectors are reduced in size.

Table 1. Cluster Parameters.



In columns left to right are listed: cluster number (No.); latitude, longitude and depth of cluster hypocentroid (Lat, Lon and Dep); origin-time offset (dOT), number of events forming each cluster (nevt); number of reference events used (nref); cluster GT level (GTx); and cluster name (Name).

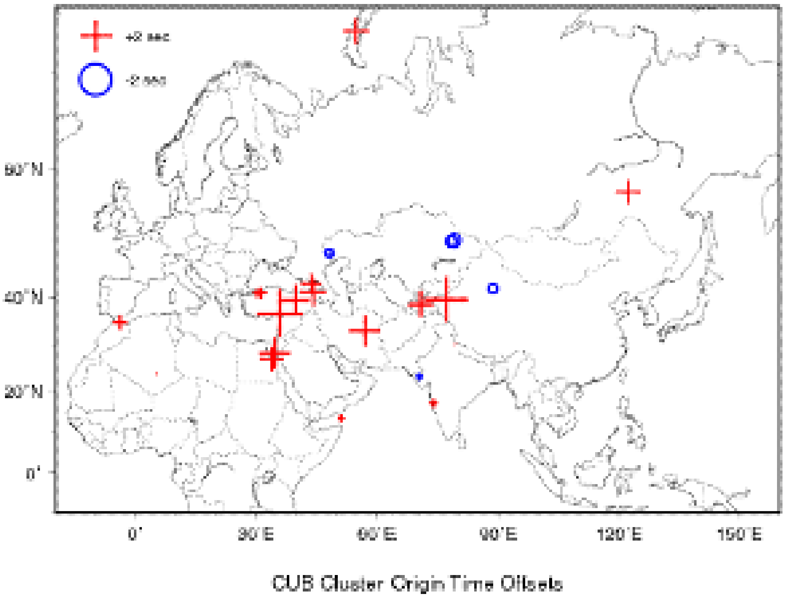


Figure 2. Cluster origin-time offsets. Scaling is given in upper left-hand corner. Earthquake clusters originating in tectonic regions of Eurasia generally have positive offsets, suggesting crust and upper mantle velocities slower than the reference model AK135.

In addition to obtaining more accurate locations, cluster analysis is useful in grooming the arrival-time data to identify and remove outliers. This is possible because cluster analysis estimates the average path anomaly for each seismic station that observes more than one of the events in the cluster. The residuals from this path anomaly are dominated by reading error as described above. Very large cluster residuals can be rejected as spurious readings, even if their absolute travel-time residual is small. Removing outliers in this way improves the resolution of relative locations and reduces the size of confidence ellipses. Figure 3 shows a plot of Pn and P residuals for all arrival times included in the cluster event database with outliers removed and with each cluster adjusted by its origin time offset. The plot is presented in this way so that the effects of anomalous path structure and station reading errors at regional distances are not confused with the effect of the average offset in residuals due to differences in upper mantle structure (relative to AK135). Not unexpectedly, estimates of the residual median and spread over one-degree distance bins show considerable variation over the regional distance range. In particular, residuals for Pn arrivals between about 9 and 17 degrees, corresponding to ray paths bottoming in the lithosphere well below the crust and perhaps encountering low-velocity zones, are more dispersed, with a maximum spread at distances of 12-13 degrees. A contributing factor to this dispersion at larger regional distances also could be the difficulty of phase identification between Pn and P in regions of highly complex structure where the cross-over distance between the first arriving branches of these phases can vary considerably.

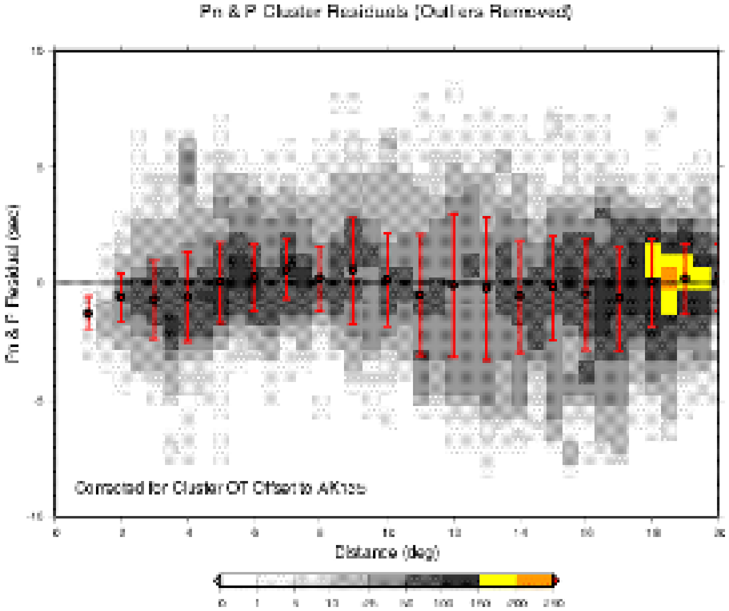


Figure 3. Residual density plot for reported Pn and P phases with outliers removed. Station cluster residuals corrected for cluster origin-time offset are binned at 0.5 degrees in distance and 0.5 sec in time. Bin hit counts are plotted according to the scale for number of hits at the bottom. Estimates of the residual median and spread at one-degree intervals are also over plotted as circles and vertical lines, respectively.

Path Anomalies

The expanded set of groomed residuals, relative to *shifted* hypocenters derived by cluster analysis, are now available to calculate source-station path anomalies. These anomalies are estimated relative to the 1-D reference model AK135 for regional seismic phases reported by IMS primary and surrogate seismic stations, and other seismic stations in the region of interest. This is a rather straightforward process by which, for each cluster, all groomed residuals are examined for phases of interest (Pg, Pn, P, Sg, Sn and S) at each of the reporting stations in that cluster. Medians and spreads are calculated for all these phases and the resulting source-station phase path anomalies accepted when minimum requirements of five observations and a spread of less than 1.40 sec and 2.8 sec is met for P-type and S-type phases, respectively. Ordinarily, there are too few Pg phases in the database and the S-type phase residuals are too noisy to obtain any useful results for those phases. For the Pn and P phase path anomalies at all distances, however, there were 848 and 5176 successful estimates of source-station path anomalies, respectively. The results are plotted for the regional distance range in Figure 4. These empirical estimates range from about -7.5

sec to +5.0 sec, with maximum differences occurring at distances of 11 to 18 degrees (similar to Figure 3) where the influence of interfering travel-time branches makes phase identification difficult.

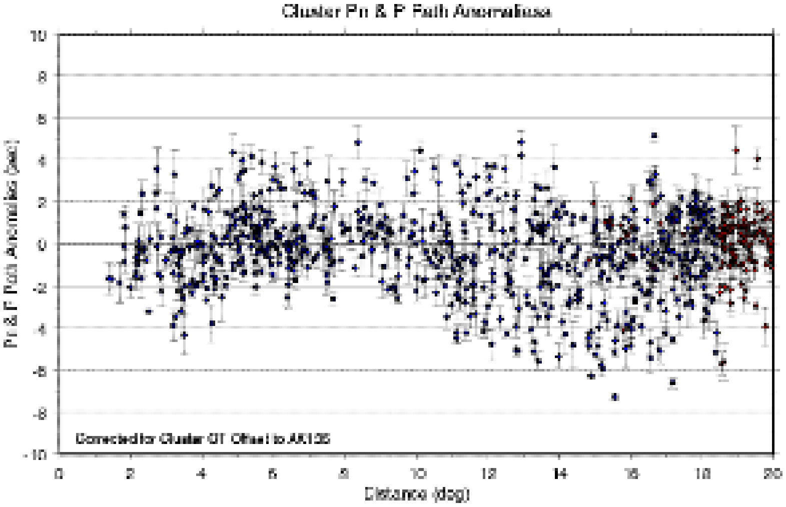


Figure 4. Cluster Pn (blue) and Pn (red) path anomalies (corrected for origin-time offsets) plotted as median and spread estimates with respect to distance.

3-D Model

The CUB 3-D model is created on a 2 deg x 2 deg grid to a depth of 400 km. Below 400 km the model reverts to the Harvard 3-D model S20a (Ekstrom and Dziewonski, 1998). The model is constructed using a Monte-Carlo inversion method (Shapiro and Ritzwoller, 2002a) applied to group (e.g., Ritzwoller and Levshin, 1998) and phase velocity dispersion curves (Trampert and Woodhouse, 1995; Ekstrom and Dziewonski, 1998). The crustal reference model used is CRUST2.0, which is an update of CRUST5.1 (Mooney et al., 1998). The surface wave tomography method used to develop the model is based on diffraction tomography (Ritzwoller et al, 2002), which uses a simplified version of the scattering sensitivity kernels that emerge from the Born or Rytov approximations. Diffraction tomography accounts for path-length dependent sensitivity, wave-front healing and associated diffraction effects, and provides a more accurate assessment of spatially variable resolution than traditional tomographic methods. Velocity vp is computed from vs using a theoretical conversion based on mineralogical partial derivatives for a hypothetical composition of the upper mantle. The method is based on the work of Goes et al. (2000) and is described in detail by Shapiro and Ritzwoller (2002b). In essence, given the mineralogical composition, partial derivatives of the elastic moduli with respect to the independent variables at infinite frequency, a mixing law, and a relation between temperature and shear Q which is the basis for the anelastic correction; the vs model is converted to temperature which is then converted to vp. In CUB2.0 this transformation has not been regionally tuned. Mineralogical composition is homogeneous across the region of study, there has been no account for the possible effects of fluids in the mantle beneath tectonically deformed regions, and shear Q is purely a function of temperature.

Validation - Station Path Anomalies

Pn and P rays were traced through the 3-D CUB model described to determine predicted travel times. These times were used to construct travel-time correction surfaces for the two phases. Empirically determined station path anomalies are plotted on these surfaces in Figure 5 for the Lop Nor and Racha clusters. In general, the more robust features of the predicted correction surface match the empirical anomalies. However, in detail there are some differences that may be the result of fine scale deviations of the real earth from the CUB model (i.e., at the edges of its resolution) and/or shallow crustal structures.

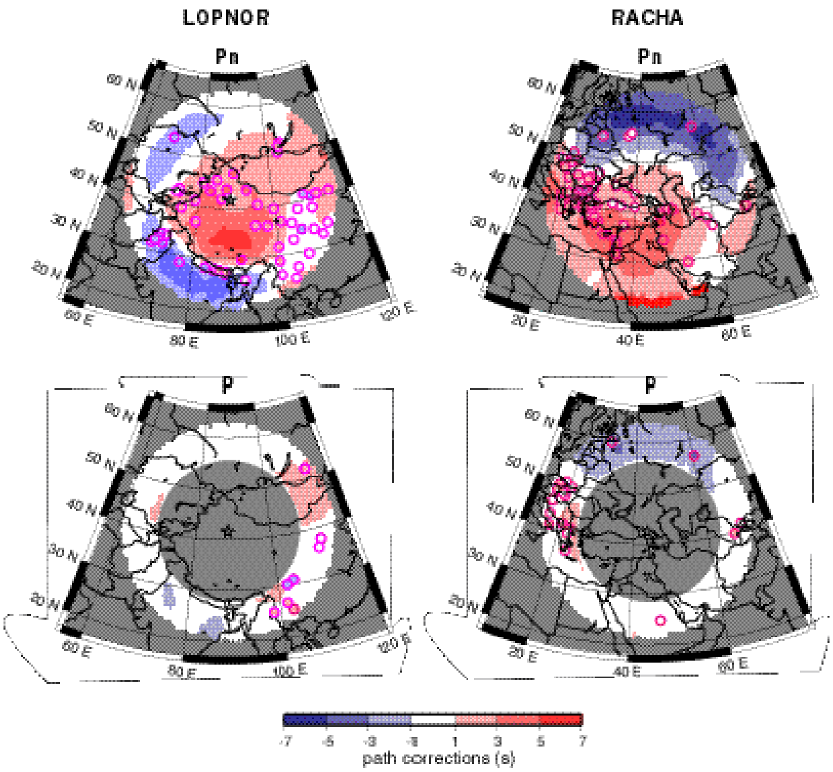


Figure 5. Event-centered Pn and P phase travel-time correction surfaces (relative to AK135) for the Lop Nor and Racha clusters compared with the empirical station path anomalies. The colored contours are the predictions from the CUB model referenced to the travel time from the 1-D model AK135.

An overall comparison between the P and Pn travel times predicted by the CUB model and the empirical station path anomalies for all GT5 or better clusters listed in Table 1 are plotted in Figure 6a. The correlation (0.84) is quite good, largely the result of using an improved model, but also a result of implementing an automated phase re-identification procedure. Basically, the phase identification (Pn or P), which provides the best fit in travel time to an empirically determined path anomaly, is adopted. A summary of the RMS-misfit with respect to the 1-D model AK135 shown in Figure 6b suggests significant improvement by using the 3-D CUB model to re-identify phases at distances where the first arriving Pn and P branches are predicted by the CUB model to cross. Proper phase identifications would not otherwise have been possible using a 1-D model alone and a fixed cross-over distance.

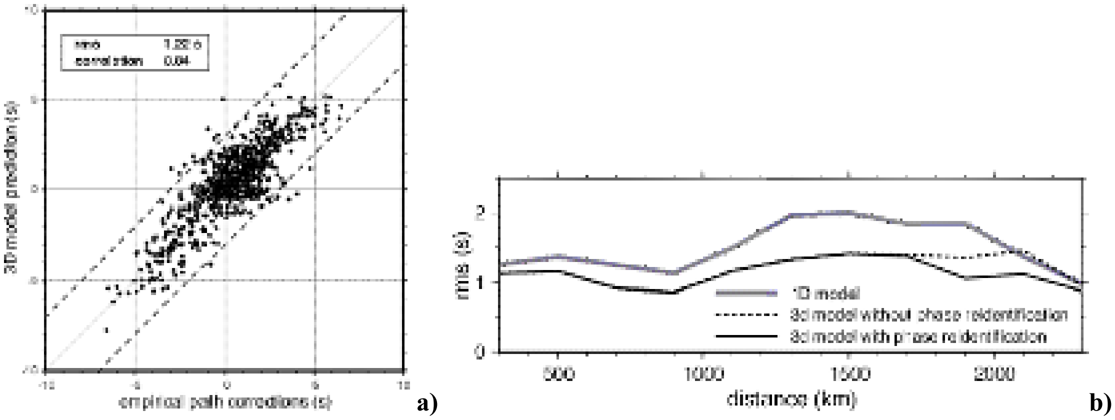


Figure 6. Overall comparison between the P and Pn travel times predicted by the CUB model and the empirical station path anomalies for all GT5 or better clusters listed in Table 1. Results are presented only for regional phase data (epicentral distance less than 20 degrees). (a) The empirical station path anomalies are on the horizontal axis and the 3-D model predictions on the vertical axis. (b) RMS-misfit between the empirical station path anomalies and the travel times predicted from three models plotted versus epicentral distance computed in a 200-km moving window (thick solid blue - AK135, solid black - CUB model with phase re-identification, and dashed black - CUB model without phase re-identification).

Validation - Relocation

The location procedure is based on a grid search, in which the rms misfit of predicted-to-observed travel times is the functional minimized (Levshin and Ritzwoller, 2002). Epicentral latitude and longitude are the two unknowns searched across a spatial grid. The third unknown, origin time, is found for each trial location by minimizing the rms residual. Event depth is fixed to the ground truth value because it trades off strongly with origin time and to first-order is independent of the epicentral location for shallow crustal events. Fixing event depth, therefore, has little effect on the error in the epicentral location in most cases. The grid is centered at a starting location (usually the teleseismic PDE location). Only first arriving mantle P phases at epicentral distances less than 20 degrees are used. The spatial grid is usually 1 x 1 km and covers 2500 square km. For each grid point, the difference between the observed and predicted time for each observation is found. Observations with residuals having absolute values above a certain threshold (3 s) relative to the starting location are discarded. The distance between the best spatial node (with minimal rms) and the ground truth location for a given event is considered as the relocation error. Examples of the rms misfit grid for a nuclear test at Lop Nor on 5/15/1995 using different models are shown in Figure 7.

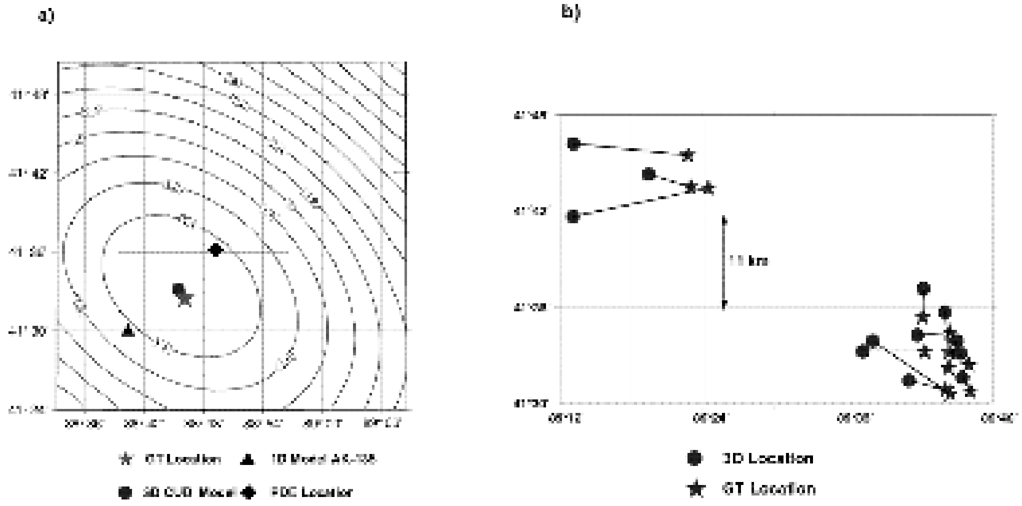


Figure 7. Grid-search method and location results for Lop Nor. (a) Misfit contours for one event at Lop Nor using the CUB 3-D model. The PDE location, the regional locations from the CUB 3-D model and from the 1-D model AK135 are also shown. (b) Mislocation vectors for locations based on the CUB 3-D model with respect to ground truth locations. This example is for events at the Lop Nor test site.

Table 2 summarizes the relocation results for all clusters studied. Typically, when only regional arrival-time data are used, the CUB 3-D model reduces location errors to about half the values obtained with the AK135 1-D model.

Table 2. Comparison of Relocations Using 3-D Model (CUB) and 1-D Model (AK135)

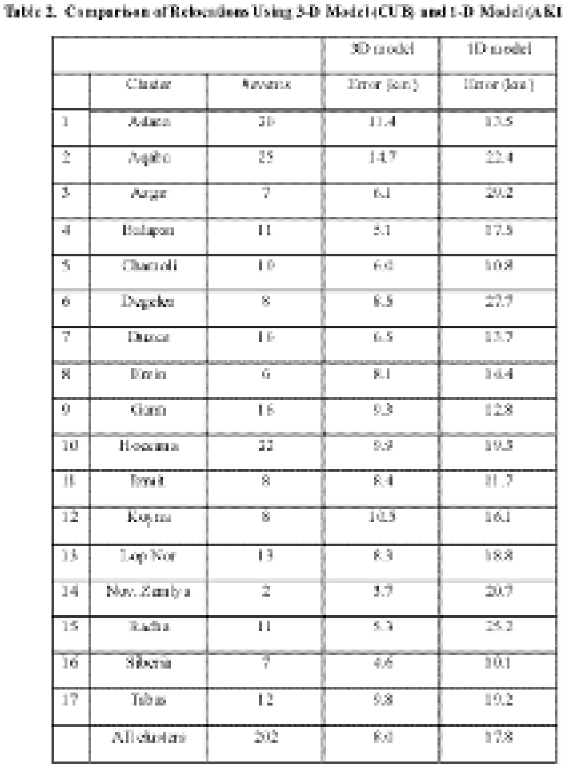


Table 2. Comparison of Relocations Using 3-D Model (CUB) and 1-D Model (AK135)

			3D model	1D model
	Cluster	#events	Error (km)	Error (km)
1	Adana	20	11.4	13.5
2	Aqaba	25	14.7	22.4
3	Argr	7	6.1	20.2
4	Bulapan	11	5.1	17.5
5	Chamoli	10	6.0	10.8
6	Dogeku	8	6.5	27.7
7	Duzce	16	6.5	13.7
8	Erzin	6	8.1	14.4
9	Garm	16	9.3	12.8
10	Hoceima	22	9.9	19.5
11	Izmit	8	8.4	11.7
12	Koyna	8	10.5	16.1
13	Lop Nor	13	8.3	18.8
14	Nov. Zemlya	2	3.7	20.7
15	Racha	11	5.3	25.2
16	Siberia	7	4.6	10.1
17	Tabas	12	9.8	19.2
	All clusters	202	8.0	17.8

CONCLUSIONS AND RECOMMENDATIONS

The Hypocentroidal Decomposition method of cluster analysis has proven to be very well suited to the requirements of ground truth validation exercises. Cluster analysis has been applied to 23 earthquake and explosion sequences in Asia and north Africa for which one or more of the associated reference events is known to an accuracy of 10 km or better (GT10). After removing bias in the relative locations by shifting the hypcentroid to best match reference event locations, these analyses produce new absolute origin times and locations for all the events in each cluster that can be used to determine source-station phase path anomalies across the region.

Estimates of empirical station path anomalies derived by cluster analysis provide a valuable independent validation tool for assessing 3-D models of the region of interest. Moreover, cluster hypocenters that have had systematic bias removed can also be used as a validation tool by demonstrating that locations based only on regional arrival times using a 3-D model can significantly improve locations using a 1-D model. The CUB 3-D model appears to perform quite well under these evaluation metrics.

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