

**SEISMIC LOCATION CALIBRATION IN  
THE MEDITERRANEAN, NORTH AFRICA, MIDDLE EAST AND WESTER EURASIA**

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**ABSTRACT**

The objective of the Group 2 Consortium, which comprises the authors of this paper, is to improve seismic event locations and reduce bias and uncertainties in the Mediterranean, Middle East, North Africa and Western Eurasia by providing calibrated travel times for stations in the region. To achieve this goal we follow a model-based approach. High-quality reference events (ground truth or GT 0-5) are collected and validated to facilitate the validation of the global three-dimensional (3-D) models and travel-time correction surfaces.

The project is in its second and final phase. In Phase 1 we demonstrated that significant improvements are achieved by using travel-time correction surfaces generated from global 3-D models. Improved velocity models have reduced *a priori* travel-time variances by 50% while maintaining 90% coverage.

In Phase 2 improved 3D global models, such as the CUB2.0 (Shapiro *et al*, 2002) and the PS362 (Antolik *et al*, 2002) are employed to generate travel-time correction surfaces via ray-tracing. The CUB2.0 model, a global upper mantle model combined with the CRUST2.0 crustal model (Bassin *et al*, 2000), is used to generate correction surfaces for regional phases. For teleseismic travel-time correction surfaces, we employ the PS362 global whole mantle model where the crust is taken into account as a crustal correction derived from CRUST2.0.

A substantially larger set of GT0-5 reference events collected as part of the Consortium effort allows a thorough validation of the models and predicted travel times. Event cluster analysis (Engdahl and Bergman, 2002; Israelsson *et al*, 2002) plays an important role in validating reference events, predicted travel times and error models.

Preliminary results show that further improvements are achieved relative to our Phase 1 results. The comparison of the CUB2.0 travel-time predictions with empirical path corrections obtained from cluster analysis indicates significant improvements in model-based predictions. The potential of using calibrated teleseismic phases in conjunction with calibrated regional travel-times is demonstrated.

## **OBJECTIVES**

The objective of the Group 2 Consortium is to improve seismic event locations and reduce bias and uncertainties in the Mediterranean, North Africa, Middle East and Western Eurasia using calibrated travel-times. We develop, test and validate model-based path-dependent travel-time corrections for stations in the study region.

## **RESEARCH ACCOMPLISHED**

The Group 2 Consortium carries out the location calibration for seismic stations in the Mediterranean, North Africa, Middle East and Western Eurasia. We follow a model-based approach to develop path-dependent travel-time corrections. The project is divided into two phases. In Phase 1, which ended in Spring 2002, we developed preliminary corrections and demonstrated improvements due to calibration. The results are summarized below. Currently we are in the development stage of Phase 2. We spend considerable effort on improving our models and collecting, vetting and validating reference events. Preparations for a comprehensive relocation study are underway.

### **Summary of Phase 1 Results**

McLaughlin *et al* (2002) have demonstrated that seismic event locations in Western Eurasia, the Middle East, Northern Africa, and Europe were improved using calibrated Pn and Sn travel-times at International Monitoring System (IMS) stations (Fig. 1a). Source-Specific Station Corrections (SSSC) were generated via ray-tracing through the CUB1.0 (Shapiro and Ritzwoller, 2002) global upper mantle velocity model. Modeling errors were estimated from residuals using the EHB catalog (Engdahl *et al*, 1998) w.r.t. CUB1.0 (Fig. 1b). Direct comparisons between the model-based corrections and empirical path corrections obtained from cluster analysis indicate that the modeling errors are conservative and capture 44% of the variance of the empirical path corrections.

To validate calibrated travel times, model errors and demonstrate location improvements, 571 GT0-10 reference events were relocated with and without SSSCs. Tests were conducted with calibrated regional phases alone. The results demonstrated statistically significant reduction in both mislocation and uncertainty (McLaughlin *et al*, 2002). The median area of error ellipses was reduced by 50% while the conservative modeling errors assured 90% coverage. The majority of the events were improved, while degradation was less than expected (Fig. 2), accounting for uncertainties in GT data, model and measurement errors. Calibration resulted in reduced Pn and Sn misfits and origin time errors. Finally, a network of IMS and IMS surrogate stations was used to demonstrate expected improvements in the future IMS network. The relocation results with the calibrated regional travel times met or exceeded the metrics recommended by the 1999 Oslo Location Workshop. The SSSCs for IMS stations in the Group 2 region have been approved by the Center for Monitoring Research Configuration Control Board (CCB) for automatic and interactive event location processing.

We recognize that the IMS network is primarily a sparse, teleseismic network. The location error due to a 1-s error in teleseismic travel times is more severe than that caused by a similar error in regional travel times (Fig. 3a). Therefore, the calibration of teleseismic travel times is the next logical step to further improve locations, especially of moderate to large sized events. Antolik *et al* (2001) have shown that spherical harmonic mantle models, such as SP12 (Su *et al*, 1994) can considerably improve teleseismic locations and perform better than high-resolution block models. We further investigate the performance of the SP12 model by relocating 1,700 GT0-10 events. Results show that teleseismic calibration yields statistically significant improvement in event locations and error ellipses while maintaining 90% coverage. Comparisons with empirical path corrections obtained from cluster analysis indicate that a significant part of the 3-D variability in the empirical data is explained by SP12. Fig. 3b shows the relocation of events in the Bhuj, India, aftershock sequence using teleseismic P SSSCs.

Several lessons have been learned from Phase 1, which provide guidance to our effort in Phase 2. A carefully vetted and validated reference event set with a good geographical coverage is essential for model-based location calibration. However, it is extremely difficult to identify and validate candidate ground truth events in regions with poor station coverage. Better estimates of model and measurement errors may further improve location performance. Besides Pn and Sn SSSCs, Pg and Lg corrections are also necessary for regional calibration. This requires an improved model of the crust and sediments. Depth-dependent SSSCs will face challenges in validation testing due to the lack of ground truth. Teleseismic SSSCs can provide the next level of significant improvement.

### **Model development**

In Phase 2 we use improved global 3-D models to calculate travel-time correction surfaces. We employ the CUB2.0 and PS362 models to generate regional and teleseismic SSSCs, respectively.

The 3-D model CUB1.0 and its update CUB2.0 are created on a 2x2 degree grid to a depth of 400 km. Below 400 km both models revert to the Harvard 3-D model S20a (Ekström and Dziewonski, 1998). Both models were 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; Ekström and Dziewonski, 1998).

There are three principal differences between CUB1.0 and CUB2.0. First, the models differ in the crustal reference model used. The crustal reference for CUB1.0 is CRUST5.1 of Mooney *et al* (1998), whereas CUB2.0 uses CRUST2.0 (Bassin *et al*, 2000). Second, the models are based on different surface wave tomography methods. CUB1.0 uses Gaussian tomography, which is based on geometrical ray-theory with intuitive Gaussian smoothing constraints to simulate surface wave sensitivities (Barmin *et al*, 2001). CUB2.0 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. Third, the models differ in the way in which  $V_p$  is computed from  $V_s$ . CUB1.0 uses a simple empirical logarithmic scaling relation  $d\ln(V_p)/d\ln(V_s) \sim 0.5$ , in which perturbations are taken relative to the  $V_s$  and  $V_p$  velocities in ak135 (Kennett *et al*, 1995). CUB2.0 uses 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  $V_s$  model is converted to temperature, which is then converted to  $V_p$ . In CUB2.0 this transformation has not yet 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.

Empirical station-path corrections provide invaluable validation of the travel times predicted from the 3-D models. Fig. 4 shows  $P_n$  and  $P$  travel times predicted by CUB2.0 compared with empirical station-path corrections for an explosion and an earthquake. The general distribution of anomalies is similar. Fig. 5 shows that CUB2.0 fits the empirical station-path corrections better than CUB1.0 in an overall sense. CUB2.0 provides both a lower root-mean-square (rms)-misfit and a better correlation coefficient than CUB1.0. Fig. 6 breaks the misfit into a function of distance. Both CUB1.0 and CUB2.0 provide improved fits to the station-path corrections, but CUB2.0 outperforms CUB1.0 at all distances.

Recently, Antolik *et al* (2002) have developed a joint compressional and shear velocity model of the Earth's mantle. PS362 is a spherical harmonic degree-18 model with a horizontal length scale of 1000 km. Absolute and differential body-wave travel times as well as surface wave dispersion measurements have been used to develop PS362. Using a data set of GT0-10 earthquakes and explosions, Antolik *et al* (2002) have shown that PS362 achieves an improvement of about 10% in rms mislocation for explosions, relative to SP12. PS362 also decreases the origin time error by an average of 0.05 s over model SP12.

Teleseismic P- and S-wave SSSCs are computed with a perturbation theory based ray-tracer in the distance range 25° to 97°, in order to diminish the biasing effects of upper mantle triplications and the core-diffracted phases on the travel times. We estimate that the numerical noise in the SSSCs can be up to 0.15 s. For shear waves we use SV to compute the travel times. This is because teleseismic rays traveling through regions of strong shear wave anisotropy (above 220 km) are primarily sensitive to SV as their ray paths are nearly vertical, and many station operators pick the shear phases on the vertical channel only. We use the International Data Centre (IDC) model error, scaled by 0.5, for our SSSCs, the scaling factor being based on our experience with regional  $P_n$  and  $S_n$  modeling errors. Following an analysis of travel-time corrections for stations in the GSETT-3 network, we note that the average correction for

the P-waves is close to zero suggesting that the radially averaged part of the model may be similar to the IASPEI<sup>1</sup>-91 model. On the contrary, the average S-wave correction is -0.44 s, suggesting that the IASPEI-91 model is slower than the PS362 model. The P-corrections range between  $\pm 2$  s, while the range for the S-corrections is  $\pm 7$  s. We note that the spread of S-wave residuals is about four times larger than that of P. Fig. 7 shows a comparison between the PS362-predicted P travel-time correction surface relative to IASPEI-91 and the empirical path corrections obtained from HDC analysis (Engdahl and Bergman, 2001) for the Bhuj, India, aftershock sequence.

### **Reference Events**

With the recognition that a high-quality set of reference events is crucial for validating models and travel-time correction surfaces, the Group 2 Consortium invests considerable effort in collecting and validating reference events. Due to this effort, the number of reference events has been doubled during Phase 2 (Fig. 8a). However, collecting reference events has proven to be more difficult than anticipated, especially in regions with sparse network coverage. We have established contacts in the Middle East and North Africa and acquired national bulletins that are normally not publicly available (e.g. Yemen, Kuwait, Saudi Arabia). Phases for identified reference events are being picked from the waveforms of existing and future IMS stations that infrequently report to organizations such as the ISC, NEIC or EMSC.

Improved selection criteria for candidate GT5 events at the 95% confidence level have been established and validated using GT0 explosions (Bondár *et al*, 2002a; Bondár *et al*, 2002b). These require that an event be located with

- at least 10 stations within 250 km with an azimuthal gap less than  $110^\circ$  and a secondary azimuthal gap less than  $160^\circ$
- at least one station within 30 km from the epicenter

The latter constraint gives some confidence in depth. For the sake of regional studies we also require that events be recorded beyond 250 km.

To validate candidate reference events we employ multiple event location techniques, such as Joint Hypocenter Determination (JHD) (Douglas, 1967; Dewey, 1991) and Hypocentroidal Decomposition (HDC) (Jordan and Sverdrup, 1981; Engdahl and Bergman, 2001). The two methods were cross-validated (Israelsson *et al*, 2001) to ensure that they can be used interchangeably. Candidate events are accepted if multiple event location results, using phases from regional and teleseismic distance ranges, are consistent with the local network solution. Events, originally not identified as GT5 candidates in the clusters, may be promoted to GT5 level if the semi-major axis of their 90% confidence ellipse is less than 5 km.

Event cluster analysis also provides path-dependent station corrections (Engdahl and Bergman, 2001). These empirical path corrections have been proven to be an invaluable tool in the validation of model-based travel-time predictions and model errors. Fig 8b shows the regional paths of empirical path corrections in the Group 2 region.

### **Novel Approaches for the Validation of Calibrated Travel Times**

In addition to the proven techniques such as comparing model-based SSSCs to empirical path corrections obtained from cluster analysis and relocating reference events with and without SSSCs, we explore new ways of validating travel-time correction surfaces.

Many of the reference events are recorded by several hundreds of stations with excellent azimuthal coverage. These events are located so well, that no matter whether calibrated travel times are applied or not, the locations will not change. Therefore, simply relocating these events has no statistical power to demonstrate improvements. We generate bulletins from the well-recorded events by taking random sparse subsets of stations that satisfy predefined constraints on the number of stations, primary and secondary azimuthal gaps. These bulletins simulate sparse networks and allow better estimations of location bias, mislocation and uncertainties. Fig. 9 shows the relocations of a GT5 earthquake, originally recorded by 195 regional stations, from the Hoceima, Morocco, cluster with unique

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<sup>1</sup> International Association of Seismology and Physics of the Earth's Interior.

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station configurations of 6-10 stations with an azimuthal gap less than 130° and a secondary gap less than 160°. The sparse network simulation indicates that calibrated travel times yield more than 50% reduction in location bias.

Despite the Consortium effort, vast areas are still not covered by reference events. We relocate the entire GSETT-3 bulletin in the study region to test the hypothesis that the scatter in seismicity decreases due to calibrated travel times. We quantify the scatter in seismicity via metrics such as entropy (Nicholson *et al*, 2000) and the ratio of the distance of nearest natural neighbors of calibrated and uncalibrated locations (Bondár *et al*, 2002c). Fig. 10a shows that the entropy decreases; i.e., the seismicity gets tighter, in most regions when regional SSSCs are applied. Fig. 10b shows the locations of mid-Atlantic ridge events without (left) and with (right) SSSCs. Although there is no ground truth available in this region, we may conclude that events align better on the ridge when calibrated travel-times are employed.

### **CONCLUSIONS AND RECOMMENDATIONS**

In the first phase of the Consortium effort we have achieved statistically significant improvements in location and reduction of bias and uncertainties with respect to IASPEI-91 when using calibrated regional travel times calculated from the CUB1.0 model. We demonstrated that the next significant step to improve locations can be obtained by integrating calibrated regional and teleseismic travel times; that is, the calibration of travel times over the entire distance range.

In Phase 2 we employ improved 3-D models, such as the CUB2.0 and PS362, to calculate travel-time correction surfaces for regional and teleseismic phases. Both models show improvements relative to their predecessors, CUB1.0 and SP12; therefore, we anticipate that Phase 2 relocation results will be superior to those of Phase 1. In order to increase the statistical power of the relocation tests, we explore new approaches to validate calibrated travel times.

We continue our effort in collecting, validating and vetting reference events. Multiple event location of event clusters plays an important role in the validation of reference events as well as in the validation of model predictions through the empirical path corrections. The reference event list can be browsed at the Consortium's web site, <http://g2calibration.cmr.gov>, where each reference event is documented with metadata.

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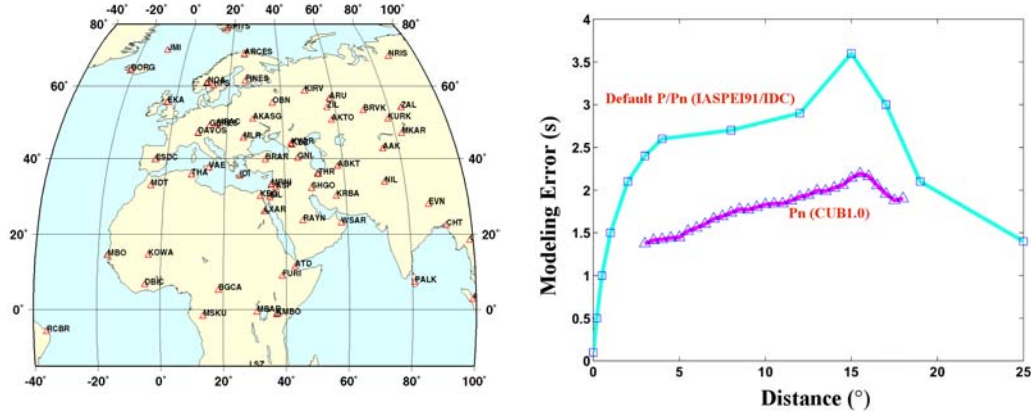


Figure 1. (a) IMS stations in the Group 2 region. (b) Distance-dependent Pn modeling errors used for CUB1.0 as compared to the IDC model errors.

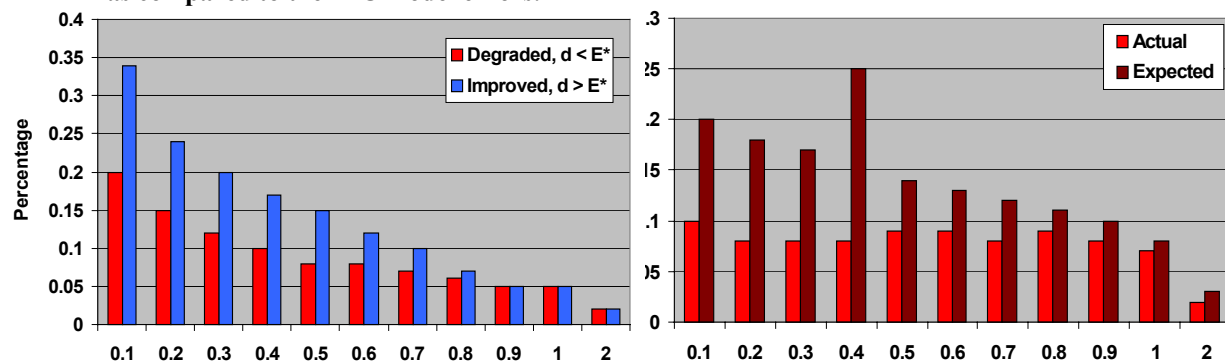


Figure 2. Normalized location improvement of 571 GT0-GT10 events using all Pn & Sn. (a) Improvement is larger than degradation for all values of the coverage test statistic,  $E^*$ . (b) Degradation is less than predicted by random chance for all  $E^*$  values.

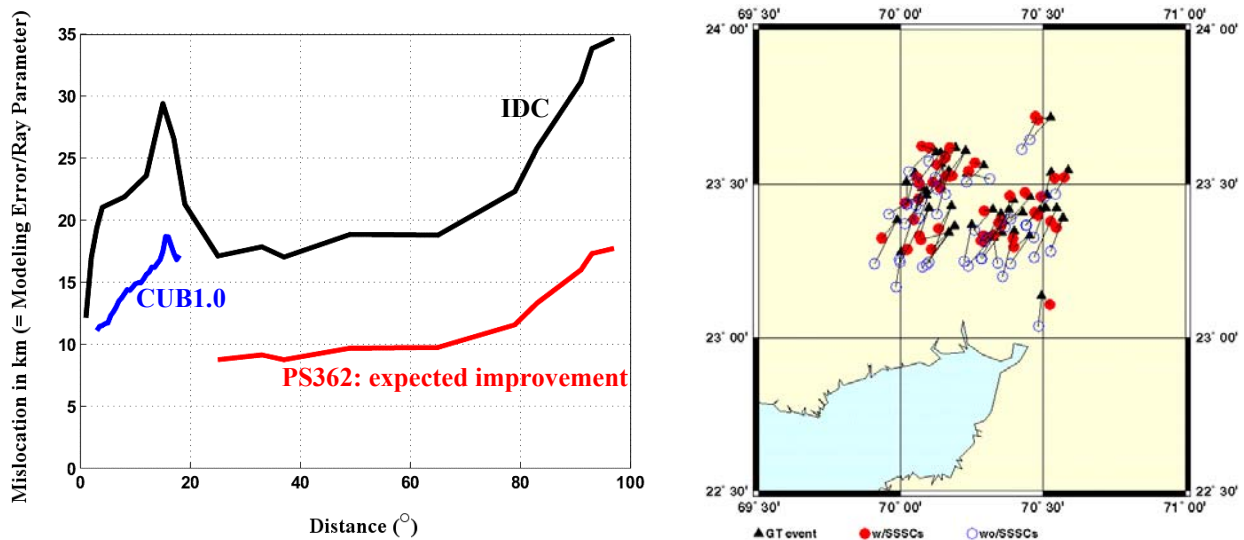


Figure 3. (a) Location error caused by 1-s error. The CUB1.0 model has significantly reduced Pn modeling errors. We expect similar reduction for teleseismic phases using the PS362 model. (b) Event relocation of 45 Bhuj, India, GT5 events using teleseismic P arrivals. The median mislocation is 12.8 km without SSSCs and 4.2 km with SSSCs.

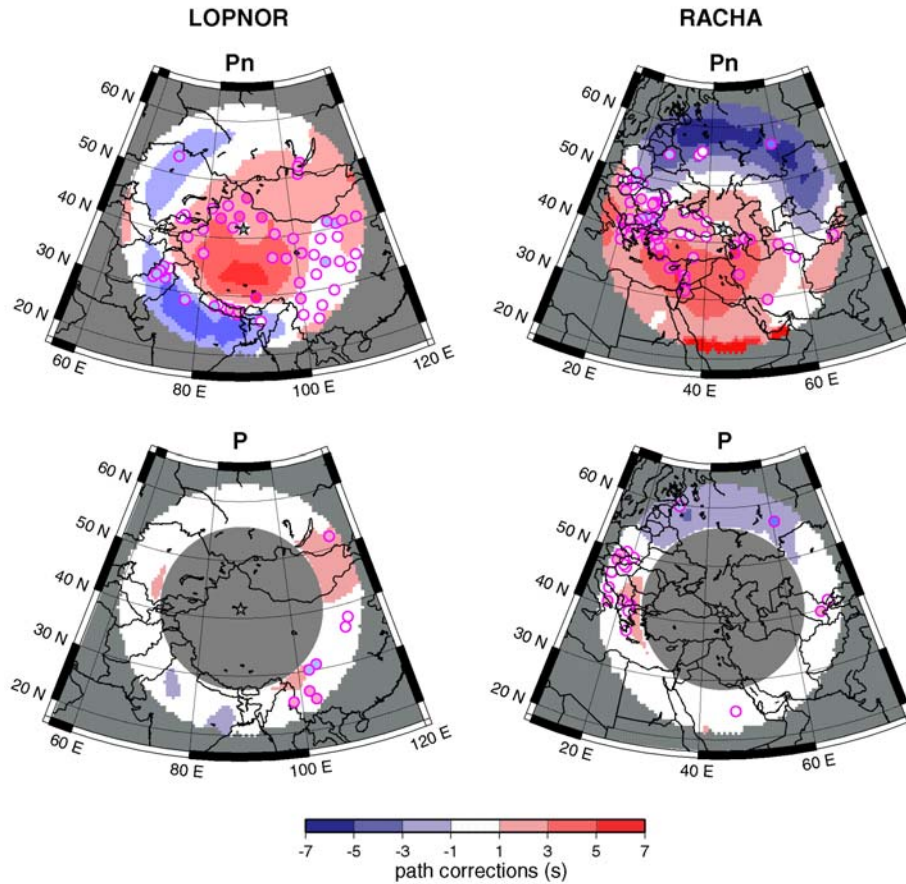


Figure 4. Comparison of empirical station-path corrections to the CUB2.0 predictions for two event clusters. The colored contours are the predictions from the model referenced to the travel time from the 1-D model ak135. The symbols are the empirical station-path corrections, color-coded similarly to the model predictions. Results are shown for two cluster regions: explosions at Lop Nor Test Site and earthquakes at Racha, Georgia.

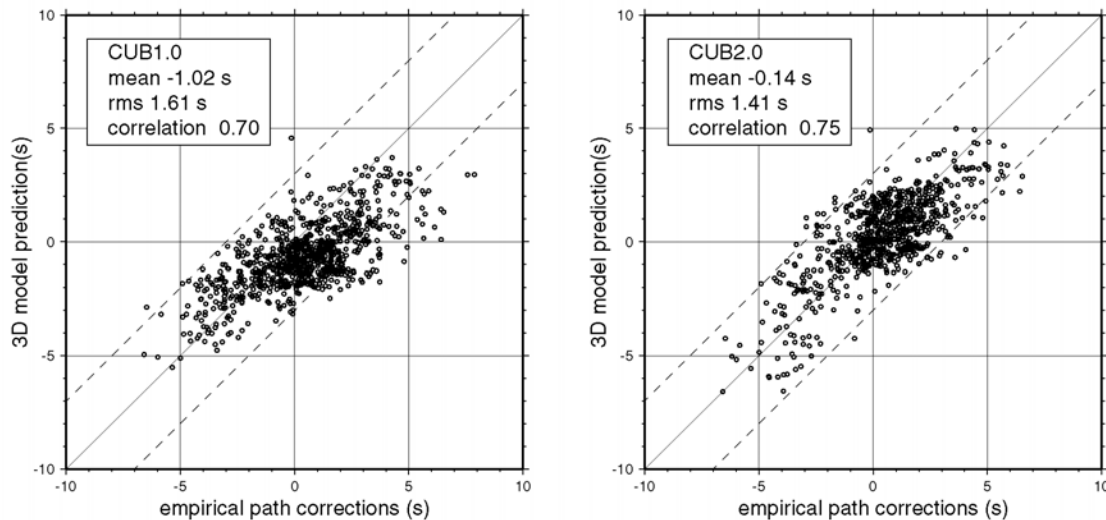


Figure 5. Fit of CUB1.0 and CUB2.0 predicted P and Pn travel times to the empirical station-path corrections. Results are presented only for regional phase data (epicentral distance less than 20 degrees). (a) The CUB1.0 travel times for P and Pn plotted versus the empirical station-path corrections. (b) Same as (a), but for CUB2.0.



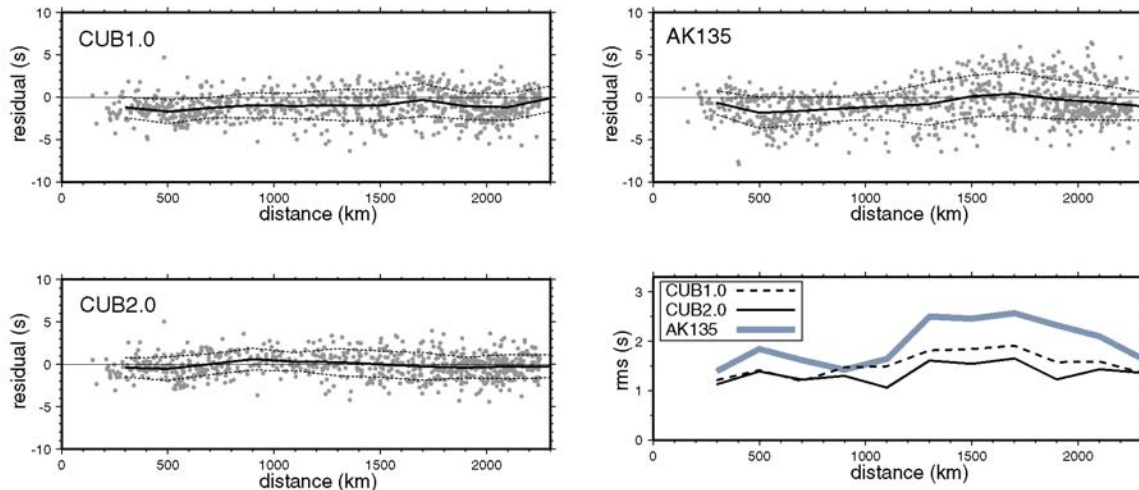


Figure 6. Residual between the travel times predicted from three models (CUB1.0, CUB2.0, ak135) and the empirical station-path corrections plotted versus epicentral distance. Distance dependent rms relative to the local mean is shown. Lower right: rms plotted versus distance for the three models.

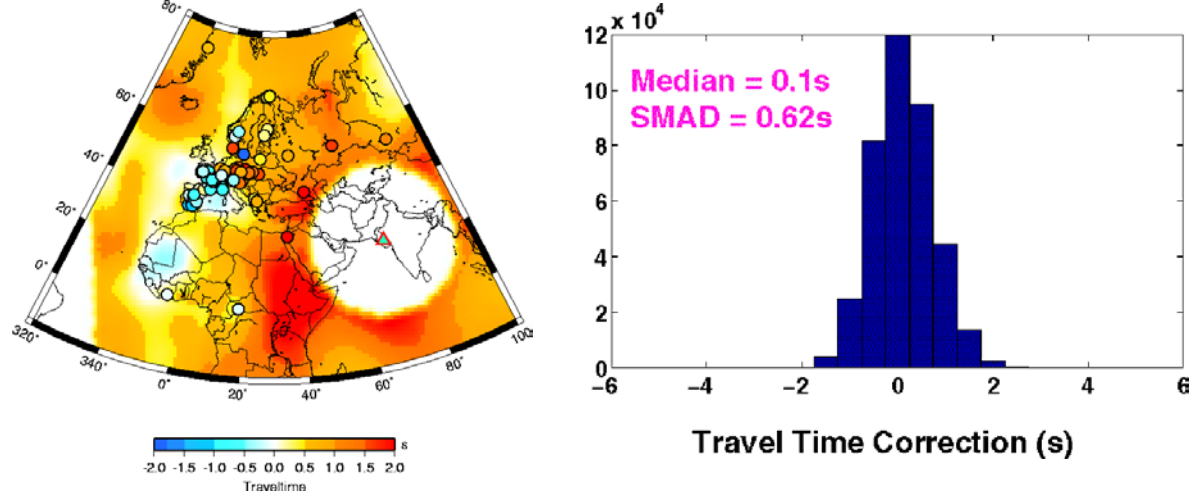


Figure 7. (a) Comparison of P empirical path corrections to the PS362 predictions for the Bhuj, India, cluster. Color contours are the model predictions, symbols, following the same color scale, are the empirical path corrections. (b) Distribution of P travel-time corrections for GSETT-3 stations using PS362.

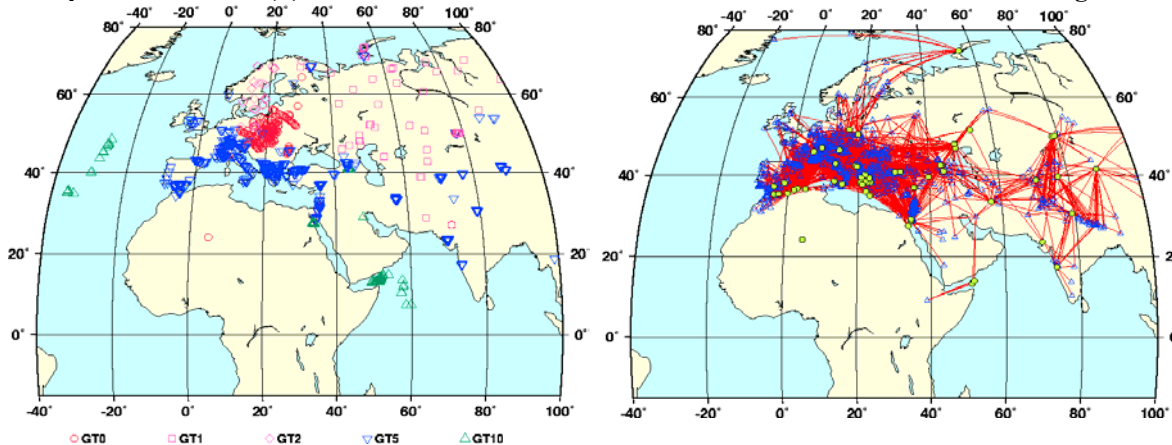


Figure 8. (a) 1,860 validated GT0-10 events in the Consortium's Reference Event List 2.0. (b) Event-station paths for which regional empirical path corrections, obtained from event cluster analysis, are available.

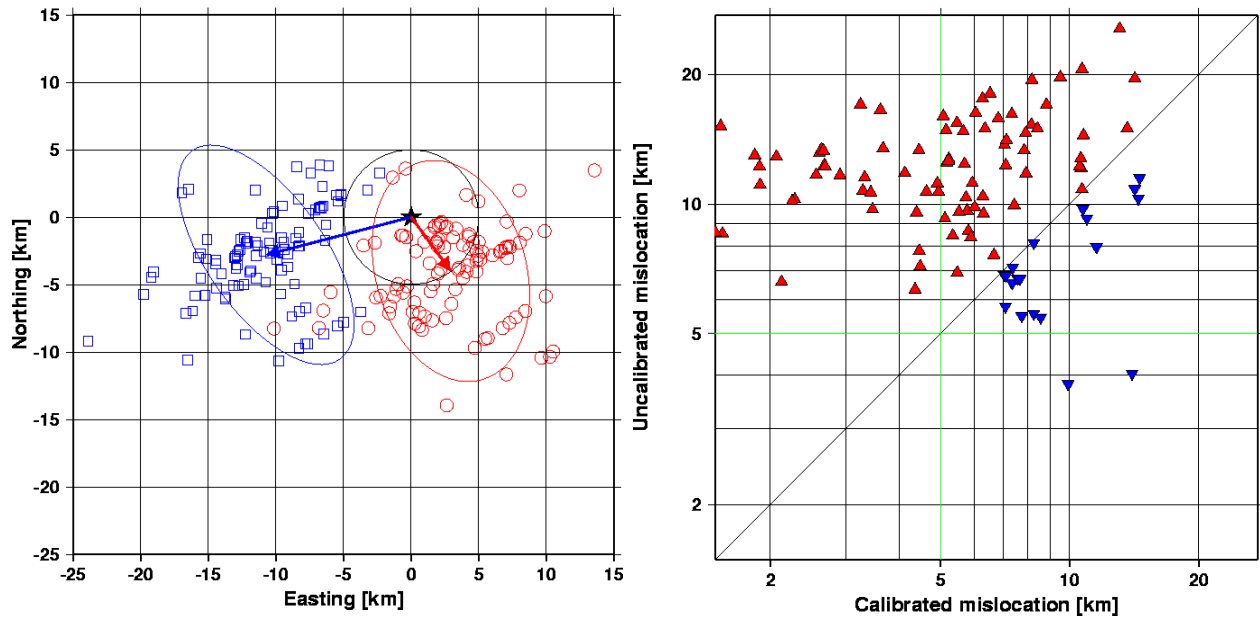


Figure 9. Relocation study of a GT5 event from the Hoceima, Morocco, cluster with sparse, random subsets of stations. Each random subnetwork is unique and has 6-10 stations with an azimuthal gap less than  $130^\circ$  and a secondary gap less than  $160^\circ$ . (a) Calibrated (circles) and uncalibrated (squares) locations relative to GT. The mean bias vectors together with their error ellipse are also shown. (b) Scatter plot of mislocations, points above the diagonal indicate improvements. Eighty per cent of the events were improved due to calibrated travel times, resulting in a 55% reduction in bias.

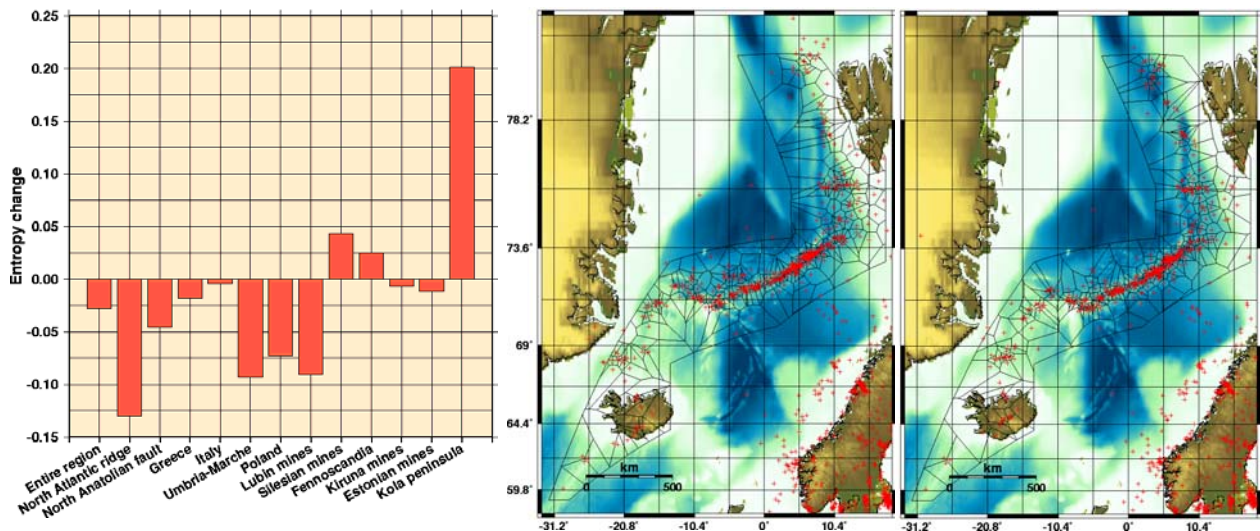


Figure 10. (a) Change in entropy in selected regions due to SSSCs when relocating the entire GSETT-3 Reviewed Event Bulletin using Pn and Sn phases only. Decreasing entropy indicates tighter seismicity. (b) mid-Atlantic ridge events located without (left) and with (right) calibrated regional travel times.