REFINEMENT OF REGIONAL SEISMIC EVENT LOCATION IN NORTHERN EURASIA USING 3-D CRUSTAL AND UPPER MANTLE VELOCITY MODEL

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ABSTRACT

This study was performed within the framework of the United States/Russian Federation (US/RF) Joint Program of Seismic Calibration of the International Monitoring System (IMS) in Northern Eurasia and North America. The Joint Research Program was signed on 18 March 1997 between the Nuclear Treaty Programs Office of the Department of Defense (DoD), USA, and the Special Monitoring Service of the Ministry of Defense (MoD), Russian Federation. To implement the Joint Research Program, a Working Group has been established. This paper summarizes results for calibration of the IMS for Northern Eurasia using a 3-D velocity model developed for the area stretching from the Atlantic Ocean (western border) to the Pacific Ocean (eastern border) and from approximately 40° N to 75° N. Approximately 200 nuclear and large chemical explosions with known location and origin time have been used in this work.

The 3-D crustal and upper mantle velocity model developed for Northern Eurasia is based on previous results of deep seismic studies and is derived by fitting a model to observed travel-time residuals of regional waves from ground-truth (GT) GT0-GT1 nuclear and chemical explosions with known location and origin time. The model was used to generate a set of Source-Specific Station Corrections (SSSCs) for 28 IMS stations and some additional stations needed for relocation experiments for Pn, Pg, and Sn phases. The program "SSSC2" was used to compute SSSCs up to distance 20° for Pn and up to distance 8.5° for Pg. Corrections were derived for Sn by using a relationship between Pn and Sn travel times derived from the Center for Monitoring Research (CMR) GT database and the IASPEI[2]-91 tables. In regions where no information on deep velocity structure was available, tectonic regionalization was used to extrapolate and/or interpolate seismic data from other regions where the velocity structure was known.

To develop the 3-D velocity model we collected and analyzed travel times of regional phases recorded from 35 calibration events with known location and origin time within Northern Eurasia. These events were recorded within different tectonic units of the territory under investigation. Abrupt and unreasonable variations of travel times from reversed, overlapping, or repeated observations were used as criteria to identify outliers. Maps of deviations of the observed travel times from the IASPEI-91 travel-time tables were made for all calibration events. These maps indicate travel-time variations as a function of distance and azimuth within different geological provinces and provide a basis for the derivation of the 3-D velocity model.

To validate the location accuracy improvement achieved by application of the SSSCs, we relocated 167 GT events (nuclear explosions, announced chemical explosions, mine blasts, and earthquakes) with well-known location and origin time from the CMR GT database and from archived data. These relocation events, located within different tectonic provinces, were completely independent from the calibration GT data that were used to derive the 3-D model. Results of the relocation experiments using Pn, Pg, and Sn phases clearly indicate that the event location estimates were substantially improved, and 90% error ellipse areas were decreased when the SSSCs were applied. Although these results indicate significant improvement in the relocations, the model and validation datasets are still quite sparse in the region, especially for Siberia and the Far East, and the network used contains large gaps between seismic stations. Continued efforts are ongoing to collect additional data for model refinement and validation.

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OBJECTIVES

To improve location accuracy of seismic events, the IMS has to be calibrated. Travel times of seismic waves used for event location must take into account the 3-D velocity structure of the Earth, as has been demonstrated previously by Firbas (2000), Ryaboy et al. (2001), and other work. The aim of this study is to improve regional seismic event location within Northern Eurasia using a 3-D crustal and upper mantle velocity model. In comparison with previous IMS calibration studies of Northern Eurasia [Russian Federation (RF)/United States (US), 2001], this work is for a larger area stretching from the Atlantic Ocean to the Pacific Ocean and from approximately 40° N to 75° N, and uses a substantially greater number of ground-truth (GT) nuclear and chemical explosions recorded within Northern Eurasia. In this study, we used approximately 200 events with precisely known location and origin times. Many references to other regionalization studies may be found in the following papers (RF/US, 2001; Ryaboy et al., 2001). The primary objectives of the present study for the area under investigation are the following:

- Inventory and collection of results of deep seismic studies relevant to the IMS calibration.
- Evaluation of Pn travel times for GT0, GT1 nuclear and large chemical explosions and analysis of the travel-time deviations from the IASPEI-91 tables.
- Development of a 3-D crustal and upper mantle velocity model (preliminary version) and SSSC calculations for IMS stations and additional stations needed for relocation experiments.
- Relocation experiments with GT0-GT2 nuclear and chemical explosions, mine blasts, and earthquakes to validate location accuracy improvement using the SSSCs calculated from the 3-D velocity model.

RESEARCH ACCOMPLISHED

Tectonic maps of Northern Eurasia were generalized and digitized to assist interpolation and comparison of seismic data for different tectonic provinces. The generalized tectonic map is also used as a starting point for 3-D model development. The following tectonic provinces exist within Northern Eurasia: East-European and Siberian Pre-Cambrian platforms, including the Baltic, Ukrainian, Aldan, and Anabar ancient shields; West-European, West-Siberian, Skifsko-Turanean, and Timan-Pechora Paleozoic platforms; Kazakh shield; Paleozoic folded belts (Urals, Taimyr, Tien-Shan, Altay, Sayany), and Alpine tectonic systems (Pamirs, Kopet-Dagh, Alps, Kamchatka, Sakhalin, and Kuril regions). There are sedimentary basins within Northern Eurasia with depth to basement up to 10 km and greater (South Barents, Dnieper-Donets, Pre-Caspian, South Caspian, Kopet-Dagh and Ural fore deeps and other sedimentary depressions). These sedimentary basins can also cause anomalies of seismic wave parameters. Figure 1 shows that the primary and auxiliary IMS seismic stations are located in different tectonic provinces of Northern Eurasia and event-station paths intersect major tectonic boundaries.

Detailed seismic studies of the Earth's crust and upper mantle have been carried out in the different regions and published in numerous reports, papers and monographs. Results of these studies show that the Moho depth within Northern Eurasia varies from 55-65 km beneath young mountains (Pamirs, Tien-Shan, Alps) to 30-35 km beneath the West-European platform and North-Caspian sedimentary basin. Pn velocity within Northern Eurasia varies from approximately 7.8-8.0 km/s to 8.3-8.4 km/s and greater. The largest values of the Pn velocity were measured beneath the East-European and Siberian Pre-Cambrian platforms (8.1-8.5 km/s). The smallest values of the Pn velocity (7.7-7.8 km/s) were measured beneath the Baikal rift zone, southern regions of Siberia and the central part of the Paleozoic West-Siberian platform. Comparative analysis of tectonic maps and seismic data showed that major tectonic provinces of Northern Eurasia are characterized by different average values of the Moho depth and seismic velocities of the Earth's crust and upper mantle and different travel times of regional seismic waves.

Analysis of Pn travel-time curves and maps of Pn travel-time deviations from the IASPEI-91 travel-time tables showed that large regional travel-time variations, of the order of 5-10 seconds for Pn waves, were observed at epicentral distances of 1000-2000 km. Pn travel times for the Pre-Cambrian platforms (East-European and Siberian platforms including ancient shields) are the fastest Pn. Tectonically active regions of the southern and eastern areas of Northern Eurasia (Alps, Caucasus, Pamirs, Tien-Shan, Altay, Saiany, Baikal rift zone, Kamchatka and Sakhalin) are characterized by substantially slower travel times. Results of analysis of the observed Pn travel times were used for the upper mantle velocity regionalization.

Our goal was to derive a 3-D crustal and upper mantle velocity model for Northern Eurasia capable of predicting Pn travel times with an accuracy of approximately 1.0-1.5 seconds [root mean square (rms)]. The simplest 3-D velocity models were sought from a family of 3-D models that simultaneously fit the observed Pn travel times for calibration events. The computer program "SSSC2" (Firbas, 2000) was used to compute the SSSCs for Pn and Pg up to distances of 20^o and 8.5^o, respectively, based on 3-D velocity models. The SSSCs for Sn were calculated from the SSSCs for Pn using a relationship between Pn and Sn travel times inferred from the CMR GT database and the IASPEI-91 travel-time tables. To better match the observations we fixed the 3-D crustal velocity model (Laske et al., 2000) and the Moho depth maps inferred from published and archived data of deep seismic studies and changed the 3-D upper mantle velocity model in a series of forward iterations. We applied the iterative process by combining and interpolating regional 1-D velocity-depth sections of the upper mantle. The 3-D velocity model developed for Northern Eurasia can be used to calculate SSSCs for the IMS stations and for other stations needed for relocation experiments.

To develop the 3-D velocity model we selected 35 GT0 and GT1 calibration events with accurate location and origin time. Figure 1 shows the location of these events (stars) and the location of the IMS stations (triangles), respectively. The thin lines are Pn event-station paths. The ray paths connecting the data points and sources provide good coverage for the territory under consideration. Dashed lines designate long-range profiles. One-dimensional upper mantle velocity sections inferred from these profiles were used for development of the 3-D velocity model.

As the first step, the initial 3-D model for P-waves was based on a new global crustal model (Laske et al., 2000) and the 3-D upper mantle velocity model based on results of deep seismic studies. These models have 2^o x 2^o resolution. Moho depth was taken from published and archived maps for Northern Eurasia with a resolution 1^o x 1^o. Comparison of the maps of the observed Pn travel-time deviations from the IASPEI-91 tables revealed that variations in Pn travel times are correlated with tectonic regionalization. Observed and calculated Pn travel times fit better when we use tectonic regionalization and 1-D velocity models developed for different tectonic provinces for constructing the 3-D model. Figure 2 shows an example of evaluation of the 3-D velocity model developed for Northern Eurasia. The top of this figure shows discrete plots of deviations of the observed Pn travel times from the global IASPEI-91 travel-time tables. The shot point is shown as a star. The color coding of these triangles corresponds to the magnitude of travel-time deviations from IASPEI-91. Platform regions on these maps are usually characterized within the distance range from 1000 km to 2000 km by early Pn arrivals (from –3.0 s to –7.0 s in comparison with IASPEI-91 tables). The bottom part of the figure shows the difference between Pn travel times observed and calculated for the 3-D velocity model. These maps of the travel-time difference show that the 3-D model developed fits observed Pn travel times well (rms usually less than 1.0 s – 1.5 s). These maps were plotted for all calibration events. Our studies also showed that Pn travel times measured from peaceful nuclear explosions (PNEs) along the Tiksi-Norilsk / Norilsk-Tiksi long-range profile fit well with the Pn travel times calculated along the long-range profile for the Siberian platform using the 3-D velocity model.

Figure 3 shows the final result of our iterative procedure used for 3-D model development. All the territory of Northern Eurasia under investigation was separated into 30 units (top), and each of these units was characterized by one 1-D upper mantle velocity model (bottom) derived by the iterative procedure described above. Numbers on the map (top) refer to numbers on the 1-D velocity models (bottom). This 3-D velocity model developed for Northern Eurasia can be used to calculate maps of SSSCs for IMS stations and additional stations needed for relocation experiments. An updated set of SSSCs was calculated for 28 IMS stations and some additional stations located within Northern Eurasia. To have reasonable resolution and size of the SSSCs files, we calculated time corrections and modeling errors with different latitude/longitude grids for each station. The SSSCs files have grid 0.5^o for the latitude axis. The grid for the longitude axis has a constant value within the range from 0.5^o to 1.2^o for each station depending on the latitude of the station. Modeling error was calculated as the weighted average of the rms deviation for each region between the grid point and the station. Maps of the modeling errors of the Pn, Sn, and Pg waves were used for modeling error calculations. As an example, Figure 4 shows maps of SSSCs and modeling errors calculated for Pn (top) and Sn (bottom) waves for the ARU station.

Relocation experiments were performed to evaluate the influence of the SSSCs for Pn, Pg, and Sn on regional seismic event locations within Northern Eurasia and to estimate the improvement both in terms of location accuracy and in the reduction of the size of the 90% error ellipses. The LocSAT program was used for seismic event location experiments. A total of 167 events in two sets were relocated (Figure 5). These data were independent from the data used to develop the 3-D model. Only Pn, Pg, and Sn phases were used for relocation experiments. Lg travel times were not used because there is no reliable method for Lg arrival-time measurement available. We did not use teleseismic phases because we wanted to demonstrate location capabilities using only regional phases.

Set 1 includes 102 events from the CMR GT0-GT2 database. These event locations are shown on Figure 5 by small stars. The events are mainly located within the European part of Northern Eurasia. Time arrivals of the Pn, Pg, and Sn phases for relocation experiments were used from the Reviewed Event Bulletin (REB). It was found that the median mis-location changed from 15.7 km to 7.2 km, and the median 90% error ellipse decreased from 3,543 km^2 to 652 km^2. Set 2 of relocation events includes 65 historical nuclear explosions. As for set 1, only Pn, Pg, and Sn phases were used for relocation experiments. These event locations are shown on Figure 5 by large stars. The events were relocated using additional stations in the IMS. Additional stations were used to substitute for IMS stations for which data were not available. These stations are up to 200-250 km from the IMS stations and may be used for the IMS network simulation. Averaged results of relocations for set 2 show that the median mis-location changed from 22.5 km to 6.1 km and the median 90% error ellipse decreased from 3,003 km^2 to 665 km^2. For example, Figure 6 shows some results of relocation experiments. One can see that the event location estimates were improved and the 90% error ellipse area was decreased when SSSCs were used.

CONCLUSIONS AND RECOMMENDATIONS

1. An inventory of seismic and tectonic data relevant to the IMS calibration of Northern Eurasia was performed. Travel times of regional phases recorded from 202 GT events were collected and carefully analyzed. Travel-time anomalies were recorded and plotted.
2. A 3-D crustal and upper mantle preliminary velocity model of Northern Eurasia was developed. This model was evaluated by comparison of observed and calculated travel times of regional phases and may be improved by using additional observational data.
3. The 3-D velocity model derived in this study was used to calculate SSSCs for Pn, Pg, and Sn waves for 28 IMS stations and some additional stations in Northern Eurasia.
4. The SSSCs were used to relocate two sets of 167 GT events. These sets of relocation events were independent from the calibration GT data that were used to derive the 3-D velocity model.
5. Results of relocation experiments using Pn, Pg, and Sn phases for events located in different regions of Northern Eurasia clearly indicate that the event location estimates were improved when SSSCs were applied. Efforts are ongoing to collect additional data for model refinement and validation.

ACKNOWLEDGEMENT

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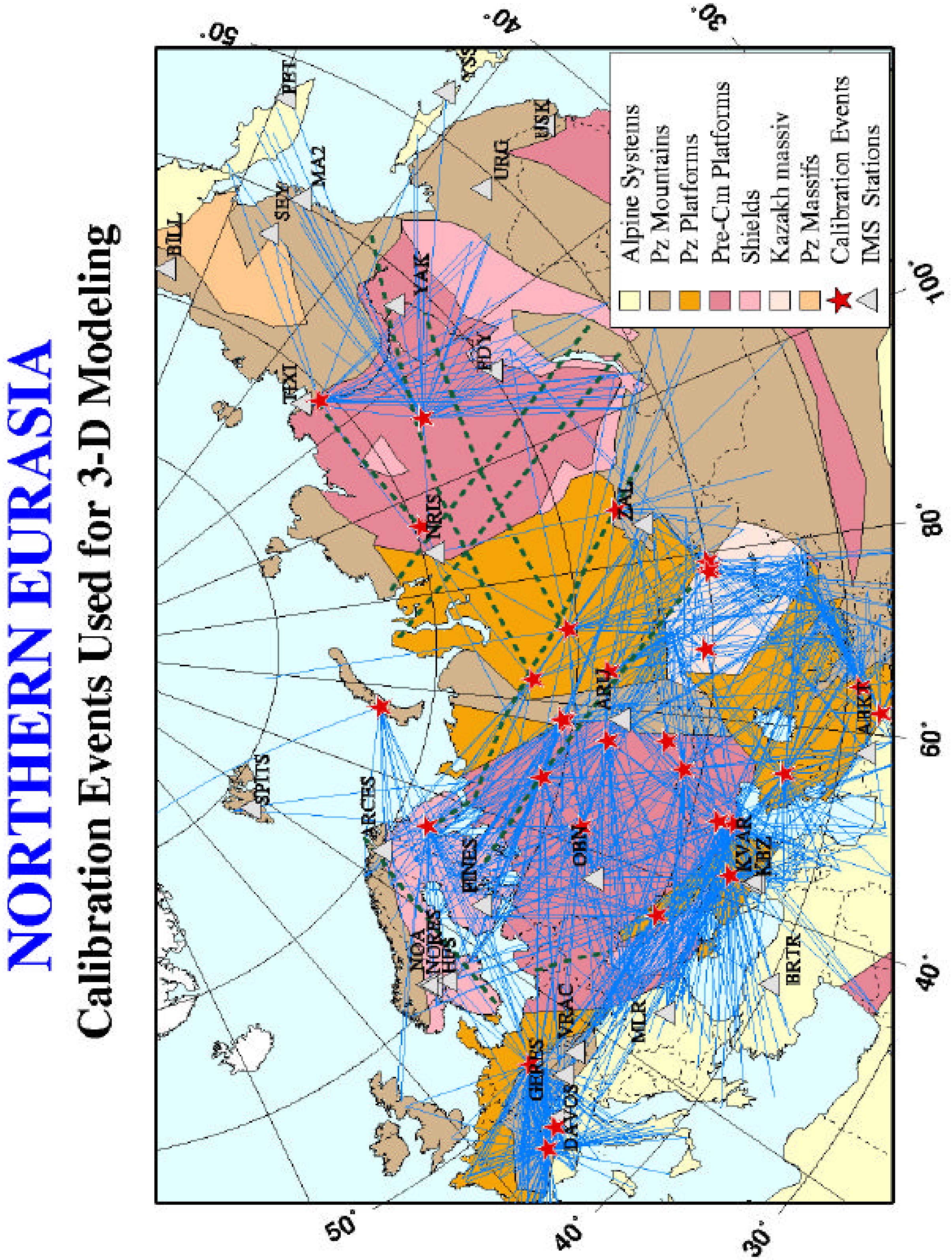
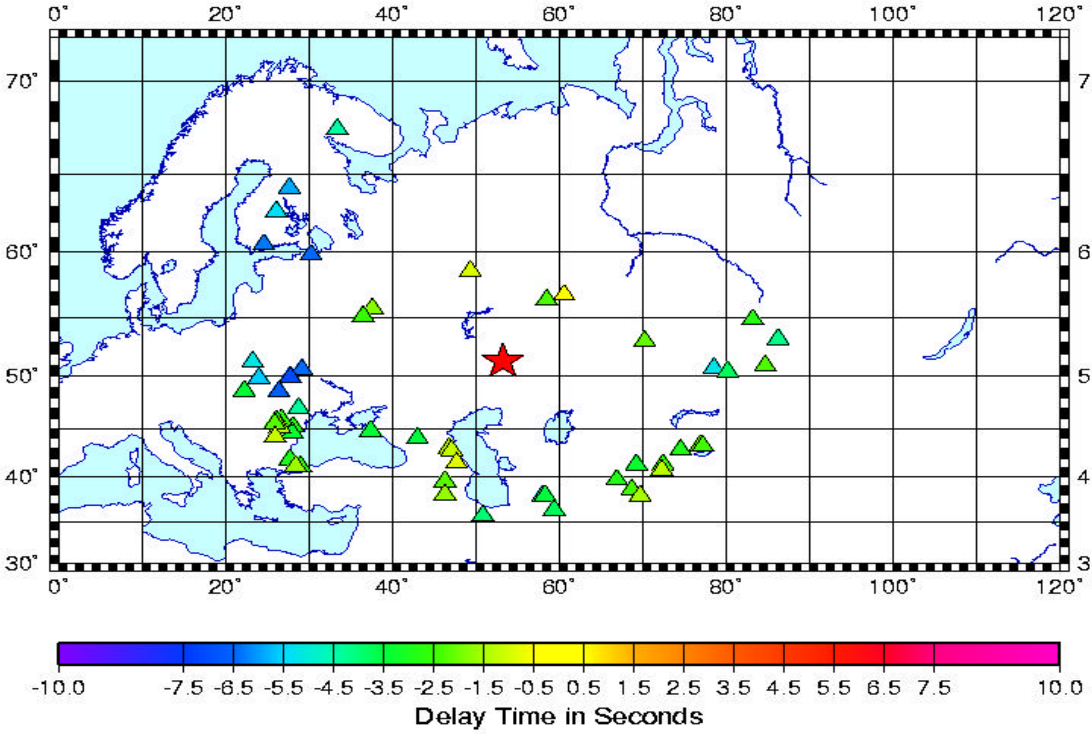


Figure 1. Map of the calibration events and IMS stations. Thin lines are Pn event-station paths. Dashed lines are long-range profiles used for the 3-D model development.

PNE, July 21, 1984 (Lira 2-1)

Pn Time Deviations from IASPEI-91



Difference between Observed and 3-D Model Pn Travel Times (Rev. 3.4)

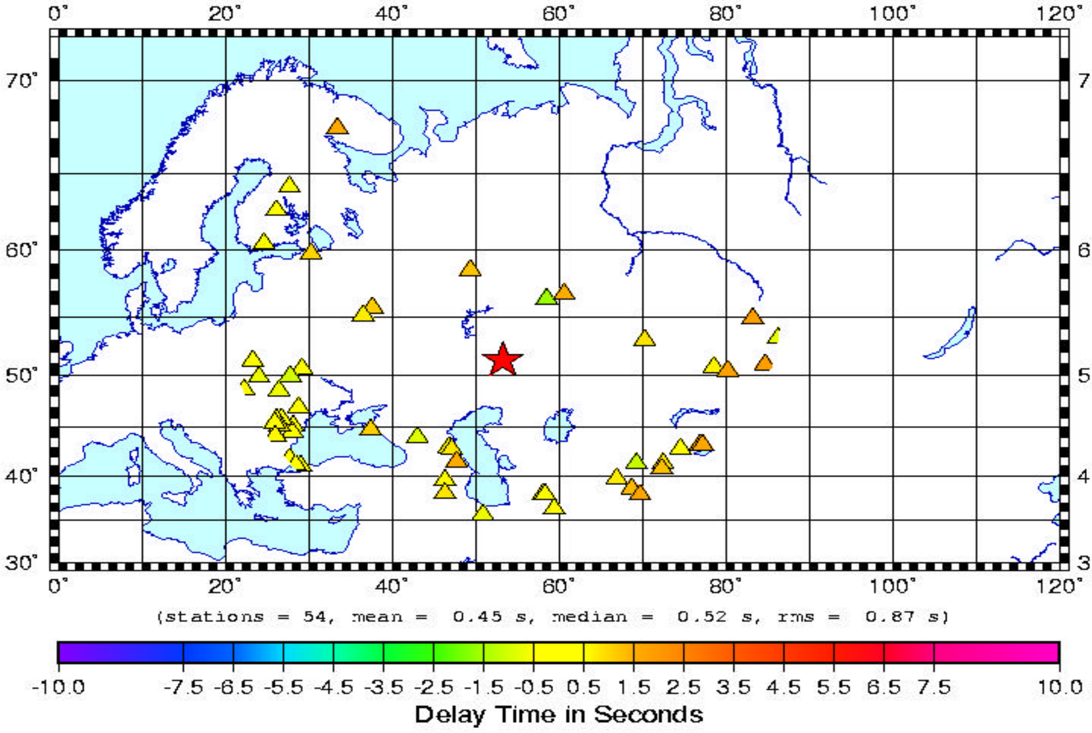
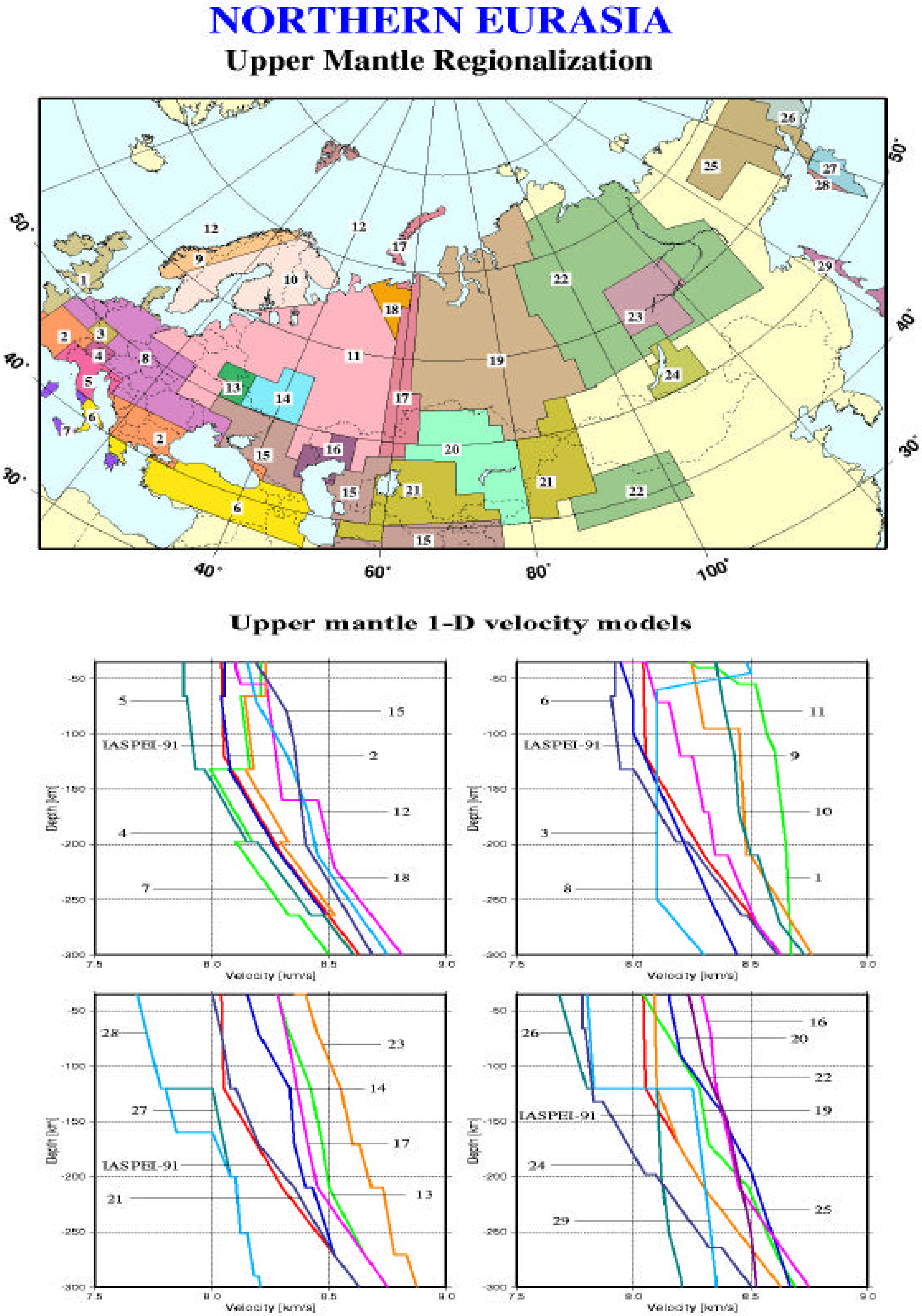
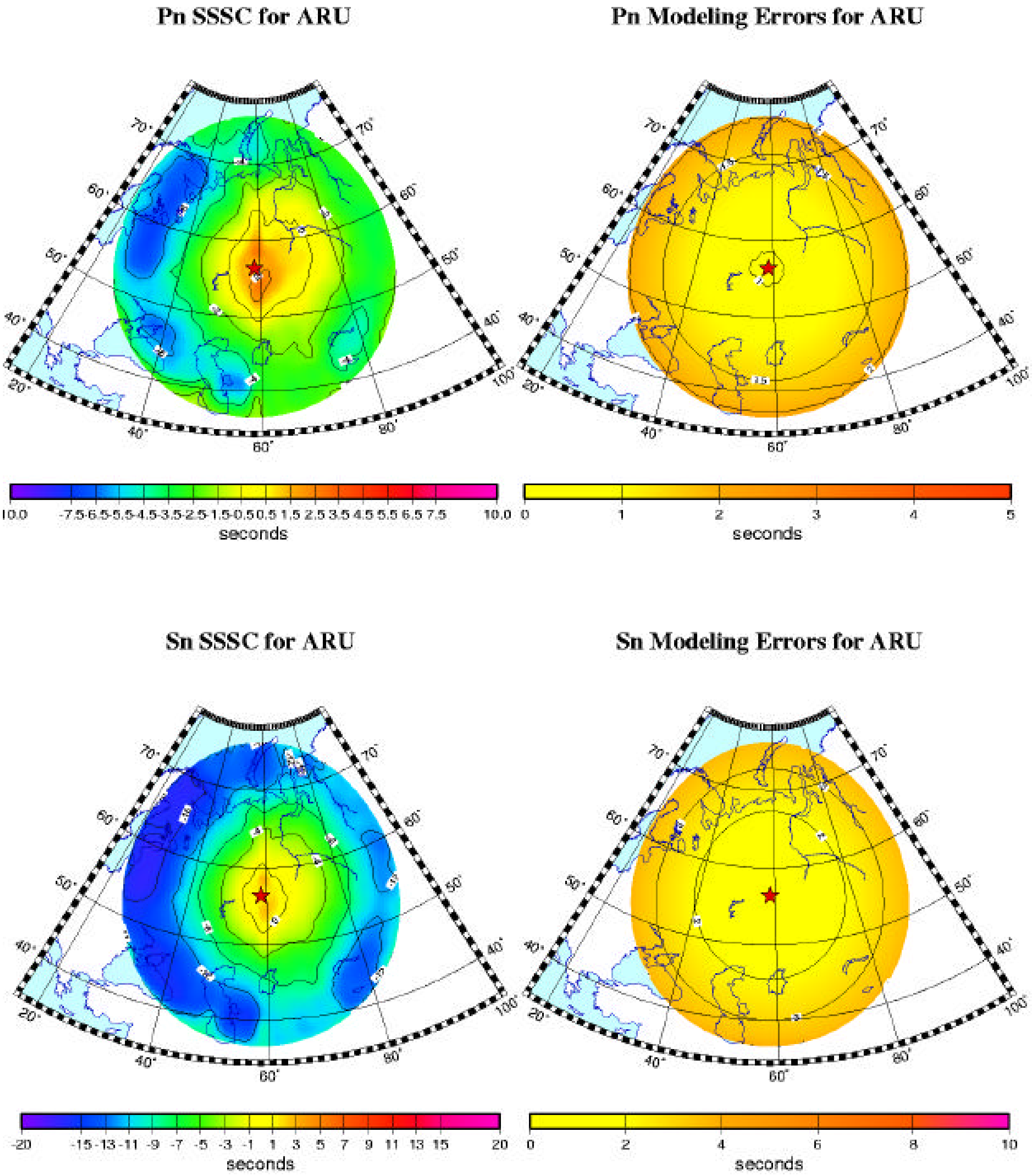


Figure 2. Pn travel-time deviations from IASPEI-91 (top), and difference between observed and calculated Pn travel times for 3-D model developed (bottom).


NORTHERN EURASIA
Upper Mantle Regionalization

Upper mantle 1-D velocity models

Figure 3. Final for this work an upper mantle P-velocity regionalization map (top), and 1-D upper mantle velocity models (bottom) were used for the 3-D model development.



Pn SSSC for ARU

Pn Modeling Errors for ARU

Sn SSSC for ARU

Sn Modeling Errors for ARU

Figure 4. ARU station. SSSCs and modeling errors calculated for Pn (top) and Sn (bottom) phases.

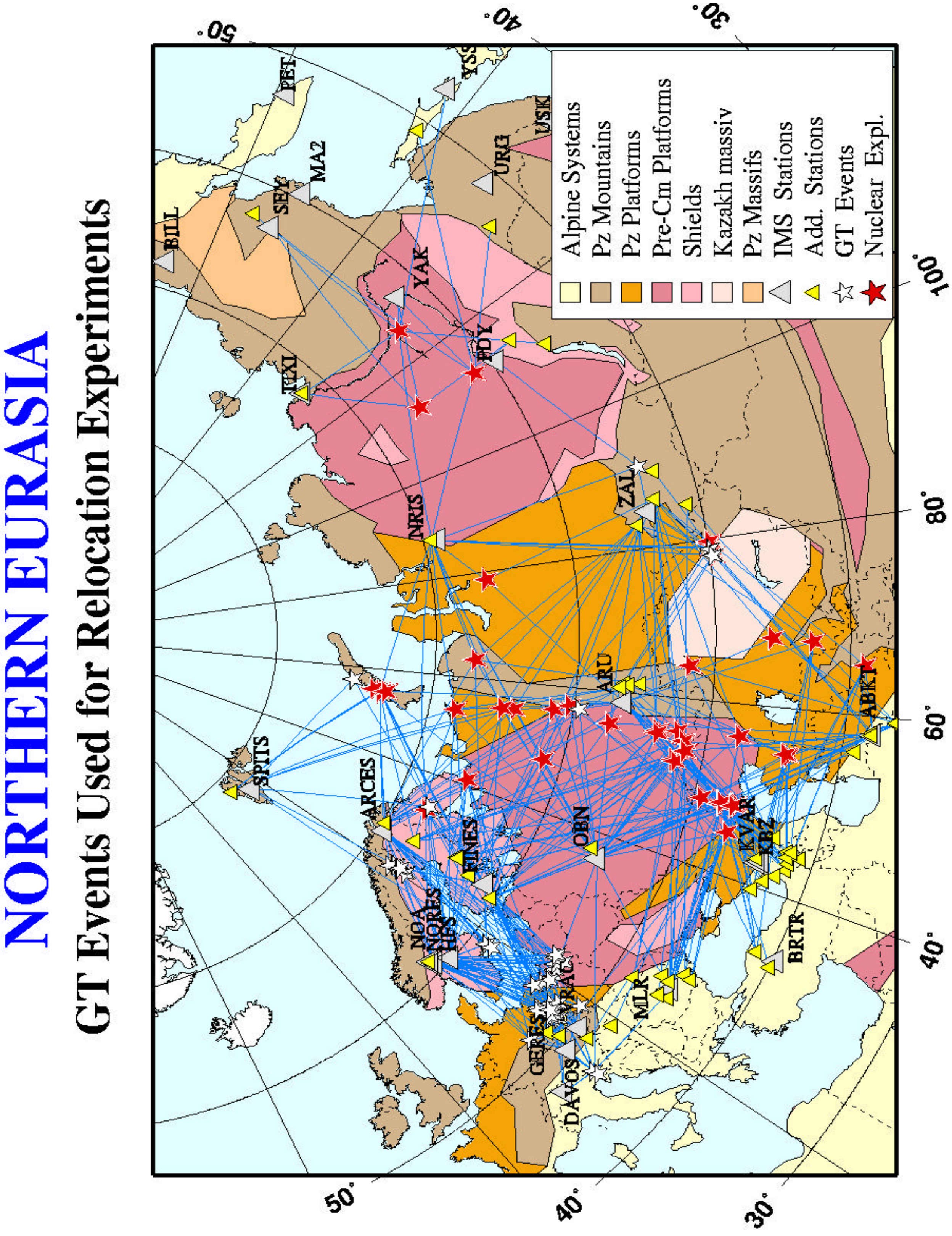
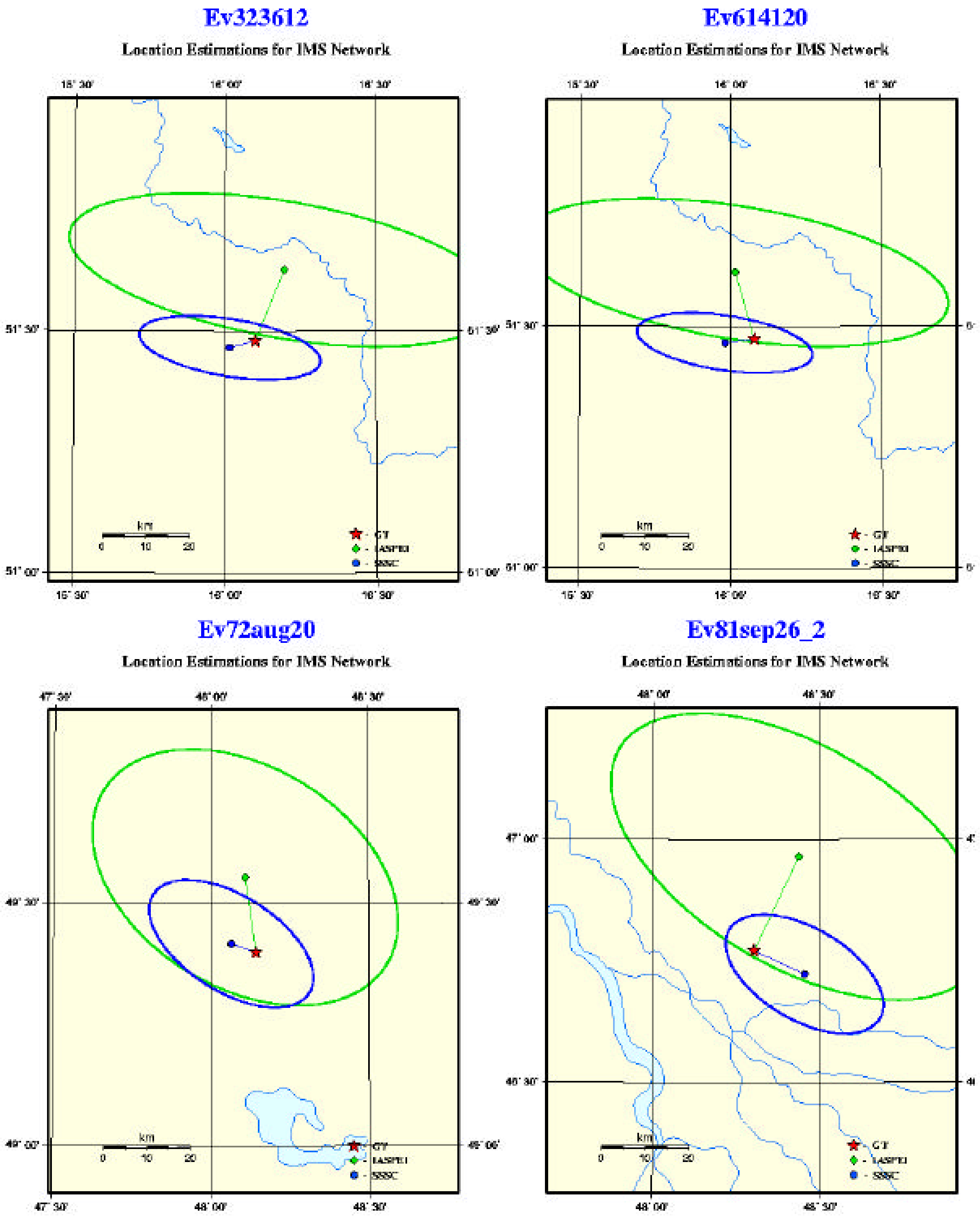


Figure 5. Map of two sets of GT events used for relocation experiments. Thin lines connect the GT events with seismic stations at regional distances used for relocation experiments.



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Location Estimations for IMS Network

Ev614120

Location Estimations for IMS Network

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Location Estimations for IMS Network

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Location Estimations for IMS Network

Figure 6. Examples of location maps of GT events.