DEVELOPMENT OF 3-D CRUSTAL AND UPPER MANTLE VELOCITY MODELS OF NORTHERN EURASIA AND NORTH AMERICA TO REFINE LOCATION OF REGIONAL SEISMIC EVENTS

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ABSTRACT

This paper reports research performed by the Russian Federation (RF) / United States (US) Joint Research Program of Seismic Calibration of the International Monitoring System (IMS) in Northern Eurasia and North America. This program was signed between the Nuclear Treaty Programs Office (NTPO), Department of Defense, USA and the Special Monitoring Service (SMS) of the Ministry of Defense, Russian Federation. To date the Joint Program has focused on collection and interpretation of data from large chemical and nuclear explosions with known location and origin time to improve regional seismic event location. A RF/US working group has been established to coordinate the joint research program; the current membership is given below.

Seismic event locations based on regional 1-D velocity-depth sections can be biased by travel-time variations within different tectonic provinces and by ray-paths crossing boundaries between tectonic provinces. Seismic event locations based on 3-D velocity models have the potential to overcome these limitations. This paper summarizes preliminary results for calibration of IMS for North America and Northern Eurasia using 3-D crustal and upper mantle velocity models. Initial 3-D velocity models were tested against maps of Pn travel-time residuals for selected calibration explosions; corrections to the 3-D model were made to fit the observed residuals. The goal was to find 3-D crustal and upper mantle velocity models capable of predicting Pn travel-times with an accuracy of 1.0 - 1.5 seconds (r.m.s.). The 3-D velocity model for North America that gave the best fit to the observed travel-times was used to produce maps of regional distance Source-Specific Station Corrections [SSSCs(3-D)]. These SSSCs(3-D) with their estimated modeling errors, were applied to relocate an independent set of large chemical and nuclear explosions (with known locations and origin times) detonated within various tectonic provinces of North America.

We are testing location accuracy using the SSSCs(3-D) for Pn derived from our 3-D models in comparison both with locations based on the IASPEI-91 travel times and locations based on regionalized travel-time tables. Our test events are GT0 and GT2 events (announced chemical explosions and mine blasts) from the prototype International Data Center (PIDC) Ground Truth database that was not used in the derivation of the 3-D models. Preliminary results indicate that the 3-D model-derived SSSCs improved location accuracy and decreased error ellipse area for some, but not all, tested events. This might indicate that the relocation results may be also influenced by other factors such as phase misidentification, low signal to noise ratios, and underestimated errors of arrival time measurements. This analysis is continuing, and similar experiments are in progress for events in Northern Eurasia.

The RF members of the calibration working group (WG): Colonel Vyacheslav Gordon (chairman); Dr., Prof. Marat Mamsurov, and Dr. Colonel Vladimir Belov.

The US members of the WG: Dr. Anton Dainty (chairman), Dr. Douglas Baumgardt, Mr. John Murphy, Dr. Robert North, and Dr. Vladislav Ryaboy.

Key Words: location, calibration, 3-D modeling, Pn waves.

OBJECTIVE

This paper reports research performed by the Russian Federation (RF) / United States (US) Joint Research Program of Seismic Calibration of the International Monitoring System (IMS) in Northern Eurasia and North America. The International Monitoring System (IMS) is being developed for global monitoring under the Comprehensive Nuclear-Test-Ban Treaty (CTBT). To fulfill this task, seismic events should be located with high accuracy. The globally averaged IASPEI-91 seismological travel-time tables have been used by the prototype International Data Center (PIDC) to locate seismic events. To achieve the CTBT goal of 1000 km^2 location accuracy the IMS has to be calibrated to correct travel times for bias caused by 3-D heterogeneities in the Earth's structure (Firbas, Peshkov, and Ryaboy, 1997). The most precise data that can be used to calibrate the IMS are large chemical and nuclear explosions with known locations and origin times. Deep Seismic Sounding (DSS) data, long-range seismic profile observations, well located mine explosions and earthquakes can also make important contributions to IMS calibration (RF/US, 1997, 1998, 1999). This paper builds upon the methodology of a feasibility study for 3-D modeling presented in (Firbas, 1997a, 1997b, 1999; Firbas, Fuchs, and Mooney, 1998; Ryaboy, Baumgardt, Firbas, and Dainty, 1999). The effort is focused on calibration of IMS stations in North America and Northern Eurasia using 3-D crustal and upper mantle velocity models developed for these regions. The main objectives of this study are the following:

- Analysis of Pn travel-time data collected and exchanged between US and RF;
- Investigation of the feasibility of 3-D modeling for location of regional seismic events in North America and Nortern Eurasia;
- Demonstration for North America of improvements achieved in location accuracy when 3-D models are used.

RESEARCH ACCOMPLISHED

The 3-D approach for the IMS calibration includes the following main steps:

- Regionalization based on tectonic data, travel-times, and crustal and upper mantle velocity structures;
- Collection and analysis of Pn travel-times;
- Collection and analysis of 1-D crustal and upper mantle velocity-depth sections;
- Development of a 3-D crustal and upper mantle velocity model;
- Computation of Station-Source Specific Corrections [SSSCs(3-D)] for seismic stations using the derived 3-D crustal and upper mantle velocity model;
- Regional seismic events relocation to demonstrate the improvement in location accuracy.

These steps have been applied to a preliminary study of the continental US, and similar studies are in progress in Northern Eurasia. These steps are briefly described further in this paper.

Tectonic maps of North America (King, 1977) and Northern Eurasia (Belousov, 1989; Zonenshain, Kuzmin, and Natapov, 1990; Pavlenkova, 1996) were taken as starting points for delineating various tectonic provinces. Maps of crustal thickness and Pn velocity compiled for the US and RF territories were digitized by Cornell university and used for this study. These data and a regionalized upper mantle seismic model (Gudmundsson and Sambridge, 1998) provided a preliminary regionalization based on tectonic and seismic data. Several large explosions with known location and origin time were selected to serve as reference events for location calibration. Figures 1 and 2 show maps of location of peaceful nuclear explosions (PNEs) and large chemical explosions within the US and RF territories, respectively, used for the IMS calibration and location experiments (RF/US, 1998; Ryaboy, Baumgardt, Firbas, and Dainty, 1999).

Pn travel-times recorded from the calibration events were collected and carefully evaluated. Data from many seismic stations were used in this study to derive maps of Pn travel-time deviations from the IASPEI-91 travel-times. These maps were used to study Pn travel-time variations as a function of distance and azimuth within different geological provinces of North America and Northern Eurasia. Abrupt and unreasonable variations of travel-times from reversed and overlapping observations were used as criteria to identify outliers. All available Pn travel-time observations along the Fennolora long-range profile in Scandinavia (Hauser and Stangl, 1990) were also used in this work.

Analysis of seismic observations of explosions in North America and Northern Eurasia shows that the Pn travel-time variations are caused by lateral inhomogeneities of the Earth's crust and upper mantle velocity structure, both on large and small scales. Pn travel times for the ancient Pre-Cambrian provinces (North American and East European platforms, including the Canadian, Baltic, and Ukrainian shields) are up to 5 sec early compared to the IASPEI-91 tables for the distance range 1,000 - 2,000 km. The tectonically active regions of the Western US are characterized by substantially slower Pn travel times, up to 5 sec late in comparison with the IASPEI-91 tables. Pn travel time residuals relative to the IASPEI-91 tables for the southern regions of the European part of the RF, including the Alpine tectonic zone, are approximately +/-(1.0-2.0) sec.

The computer program "sssc" (Firbas, 1997b, 1999), was used to compute Source-Specific Station Corrections (SSSCs) for Pn travel-times by utilizing 3-D velocity Earth models. The parametrization of the 3-D model employs an approach that allows combination of the best velocity information available from multiple sources. An advantage of this approach is that the number of parameters varied in an iterative search to improve the base model can be small and these parameters have a clear physical interpretation. The "sssc" algorithm combines the ray-shooting (interval ray-tracing) and linearization approach. In the global background model, each branch of any travel-time curve is represented by a unique code. The ray reaching the station is found by paraxial approximation, bending (morphing) the particular ray by the Fermat principle, and in the last stage, applying linearization to get the best estimate of the travel-time. The IASPEI-91 travel times are also calculated by the program "sssc" and are accurate to at least several hundredths of a second. When the IASPEI-91 travel time is subtracted from the full travel time in the 3-D velocity model, the deviation or SSSC(3-D) is obtained.

The goal of our effort was to define a 3-D crustal and upper mantle velocity model of US territory and the European part of RF capable of predicting Pn travel times with accuracy of approximately 1.0-1.5 sec (r.m.s.). The simplest 3-D velocity models were sought from a family of 3-D models that simultaneously fit the observed Pn travel times for all calibration events used. To develop 3-D models we used in this work eight calibration explosions for US territory and eight calibration explosions for the European part of the RF. The first steps of testing different 3-D velocity models revealed that the crustal model and the Moho depth surface variation had only minor effects on travel times. We fixed the 3-D crustal velocity model (Mooney, Laske, and Masters, 1998) and the Moho depth in further iteration steps and changed the 3-D upper mantle velocity models only.

A total of 45 iterative 3-D velocity models were developed and evaluated for North America. The current model (revision 4.5) fits the observed travel times with an average precision of 1.0 - 1.5 sec r.m.s. Figure 3A shows 1-D velocity models for P-waves derived by this process in comparison with the IASPEI-91 model. Figure 3B shows upper mantle regionalization; numbers on the map of Figure 3B refer the velocity models Figure 3A. Figures 4A and 4B show 1-D velocity models and upper mantle regionalization for Northern Eurasia. Figures 4A and 4B include a 3-D model developed for Europe by P. Firbas (Firbas, 1999). A total of five iterative 3-D velocity models were developed and evaluated for Northern Eurasia. Differences between calculated Pn travel times for the current model (revision 1.4) and observed data for some regions of Northern Eurasia are up to 2-5 sec. The revision 1.4 is a preliminary model for Northern Eurasia which should be improved.

Figures 5 shows as an example a map of the difference between observed and calculated Pn travel times for the Early Rise explosions (Iyer et al., 1969). The differences are mainly within +/- 1 sec, increasing in some relatively small areas to +/- 2.0 sec. Figure 6 compares of observed and calculated Pn travel-time curves for the Fennolora long-range profile (3-D model revision 1.4) for shot point B (southern Baltic shield). Figure 6 shows that observed Pn travel times for southern Baltic shield fit Pn travel times calculated for 3-D model (revision 1.4) rather well. However, similar calculations showed that observed Pn travel times for the northern Baltic shield (Fennolora profile, shot point I) are up to 2-3 sec faster in comparison with the Pn travel times calculated for the 3-D model.

The 3-D velocity model developed for the USA territory (revision 4.5) was used to produce maps of SSSCs for all IMS stations and other stations needed for the relocation experiments. The purpose of the relocation experiments was to evaluate the influence of SSSCs on the accuracy of location of seismic events recorded at regional distances and thus to test the usefulness of the 3-D model. The 3-D model residuals fit the observed residuals in the US to within 1.0-1.5 sec r.m.s. The average r.m.s. value for all calibration explosions is approximately 1.0 sec. The value of 1.0 sec was therefore used as the modeling error in relocation experiments. The calculated SSSCs with the

estimated modeling error (1.0 sec) and the estimated measurement error (0.5 sec) were first applied to locate the eight mentioned calibration events used to derive the 3-D velocity model. This step can be also viewed as a test of the internal consistency of the 3-D model process development. As an independent test, four large chemical explosions with good signal to noise ratio and with known locations and origin times, not used in the model development, were also relocated using derived SSSCs and "surrogate networks" to the IMS network.

As example Figure 7A shows the results of the relocation experiment for the Rockville Dam chemical explosion (LRSM Rockville Dam Report, 1966) using 6 stations placed within the North American platform (2 stations) and the western US (4 stations). The distance between the ground truth epicenter and the estimated location (mislocation) decreased from 20.7 km, in the case using the IASPEI-91 travel times, to 9.0 km using SSSCs(3-D). The calculated error ellipse for the location based on SSSCs(3-D) is substantially smaller than for the IASPEI-91 solution and includes the ground truth epicenter. Mislocation based on the International Seismological Center (ISC) Bulletin solution using 25 stations is 7.1 km. The main results of the relocation experiments are summarized in Figure 7B which shows a boxplot to display the distribution of mislocation values obtained for three methods of location. Locations using SSSCs(3-D) are characterized by the smallest average mislocation and by the smallest width of the mislocation distribution, i.e. they are most accurate and most robust of the three approaches. However, preliminary results of similar relocation experiments for small explosions with low signal to noise ratio (explosions detonated along Deepprobe and Lithoprobe long-range profiles, and mine explosions) showed that using of SSSCs(3D) did not improve location accuracy for all tested events. This might indicate that relocation results may be also influenced by other factors such as phase misidentification, low signal to noise ratio, and underestimated errors of arrival time measurements. This analysis is continuing and similar experiments are in progress.

CONCLUSIONS AND RECOMMENDATIONS

This paper presents the development of 3-D crustal and upper mantle velocity models for the US and RF territories to improve location of regional seismic events carried out within the framework of the RF/US Joint Research Program of Seismic Calibration of IMS in Northern Eurasia and North America. The main results of the study as follows:

1. Preliminary calculations made for Northern Eurasia show that it may be feasible to use for this region a 3-D modeling approach to fit the measured travel-time anomalies of Pn waves and then calculate SSSCs from a 3-D velocity model.

2. The application of SSSCs(3-D) with an estimated modeling error of 1.0 second derived from a preliminary 3-D velocity model led to a clear improvement in seismic event location accuracy and substantial decrease in error ellipse area compared to locations based on the IASPEI-91 travel times and locations based on two regional travel-time curves (1-D velocity models).

The next steps to be made should include: (1) development and evaluation of the 3-D velocity model for Northern Eurasia including relocation experiments using SSSCs(3-D) for events with known location and origin time, (2) continued collection and exchange between RF and US travel times major regional phases recorded from calibration events, (3) extension of the 3-D model developed for US territory to cover the areas north of latitude 55 degrees N, (4) calculations of SSSCs(3-D) for other major regional phases (Pg, Sn, and Lg) for the IMS stations located in North America, and (5) continuation of relocation experiments for calibration events.

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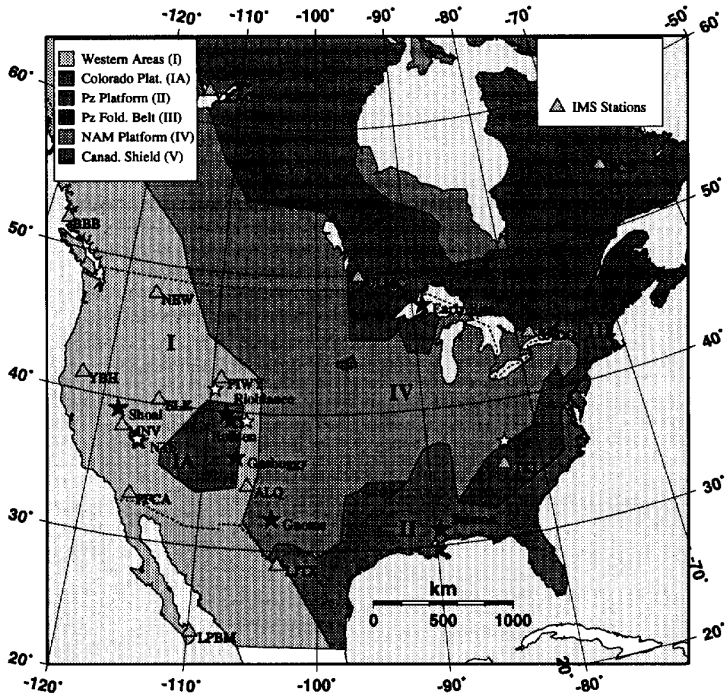

Figure 1. Location of large explosions used for the IMS calibration and location experiment in US. Solid stars are calibration explosions used for the IMS calibration and relocation experiments, and open stars are explosions used only for relocation experiments. In the background the simplified tectonic map is shown.

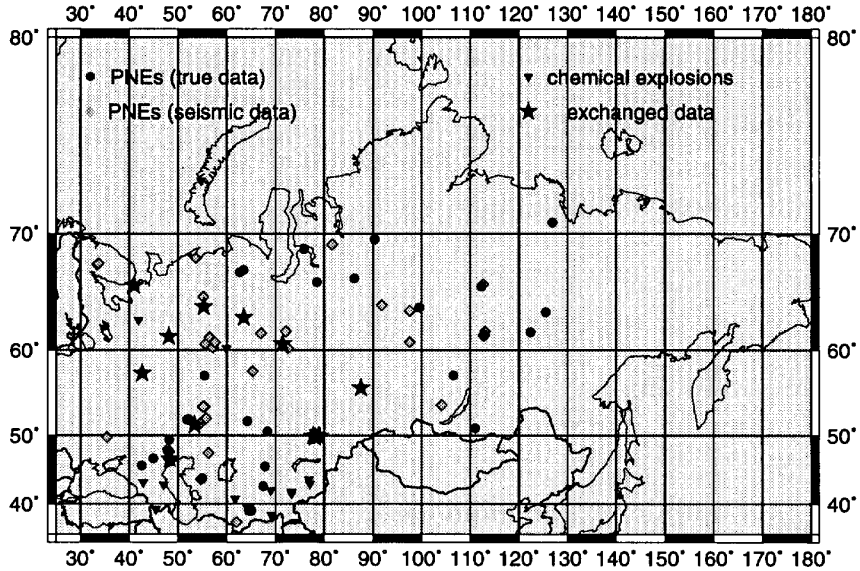

Figure 2. Location of nuclear and large chemical explosions within RF.
PNEs - Peaceful Nuclear Explosions located using seismic data and true data.

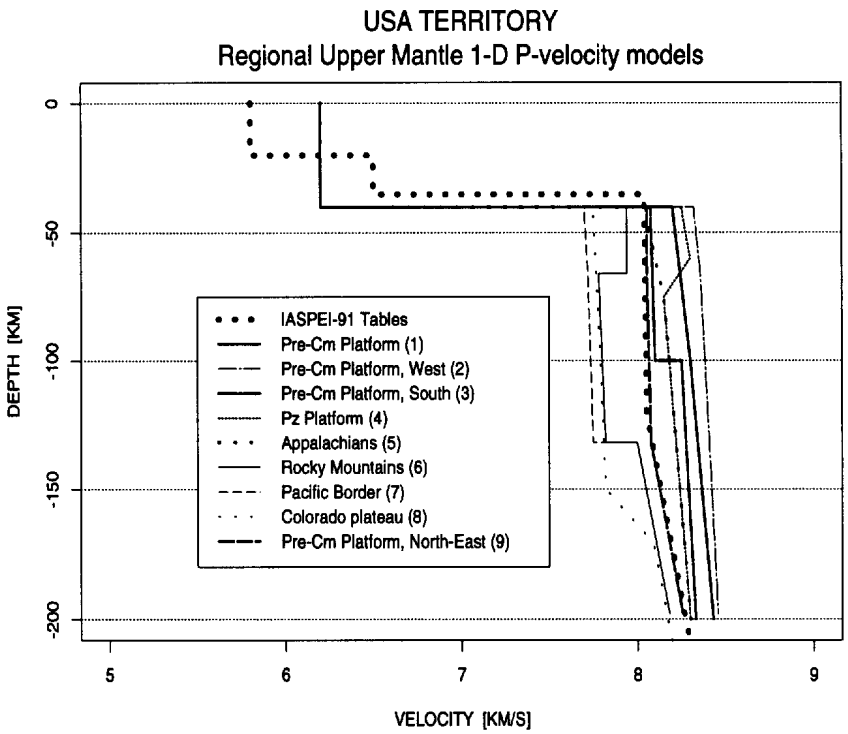

Figure 3A. Regional upper mantle 1-D P-velocity models of the USA territory and neighboring regions of Canada.

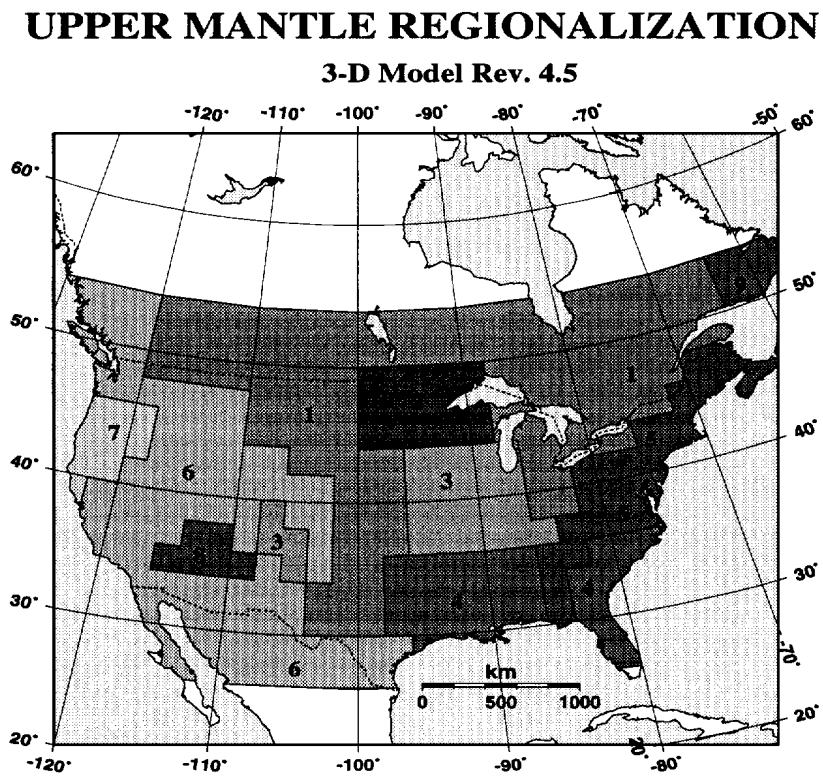

Figure 3B. Upper mantle P-velocity regionalization of the USA territory and neighboring regions of Canada (3-D model, revision 4.5).

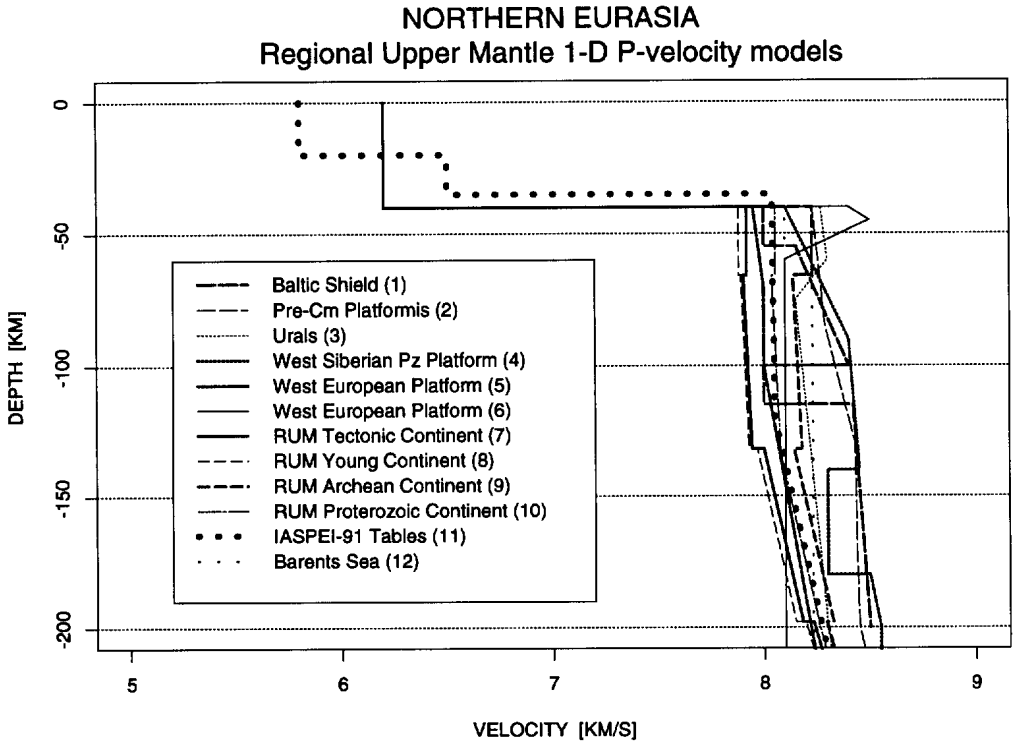

Figure 4A. Regional upper mantle 1-D P-velocity models of Northern Eurasia.

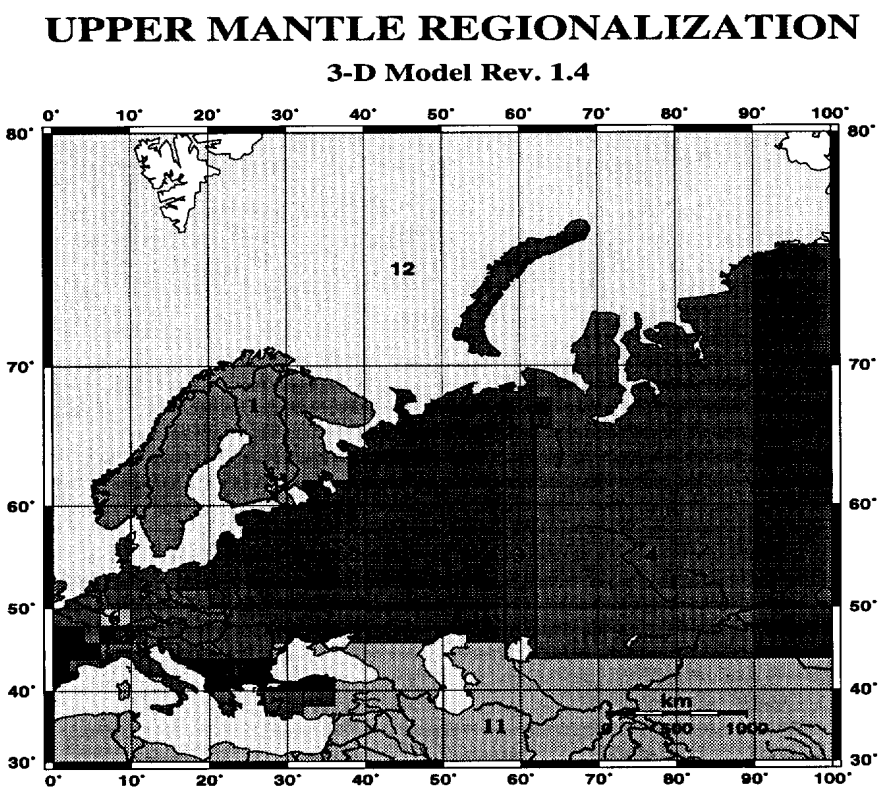

Figure 4B. Upper mantle P-velocity regionalization of Northern Eurasia (3-D model, revision 1.4).

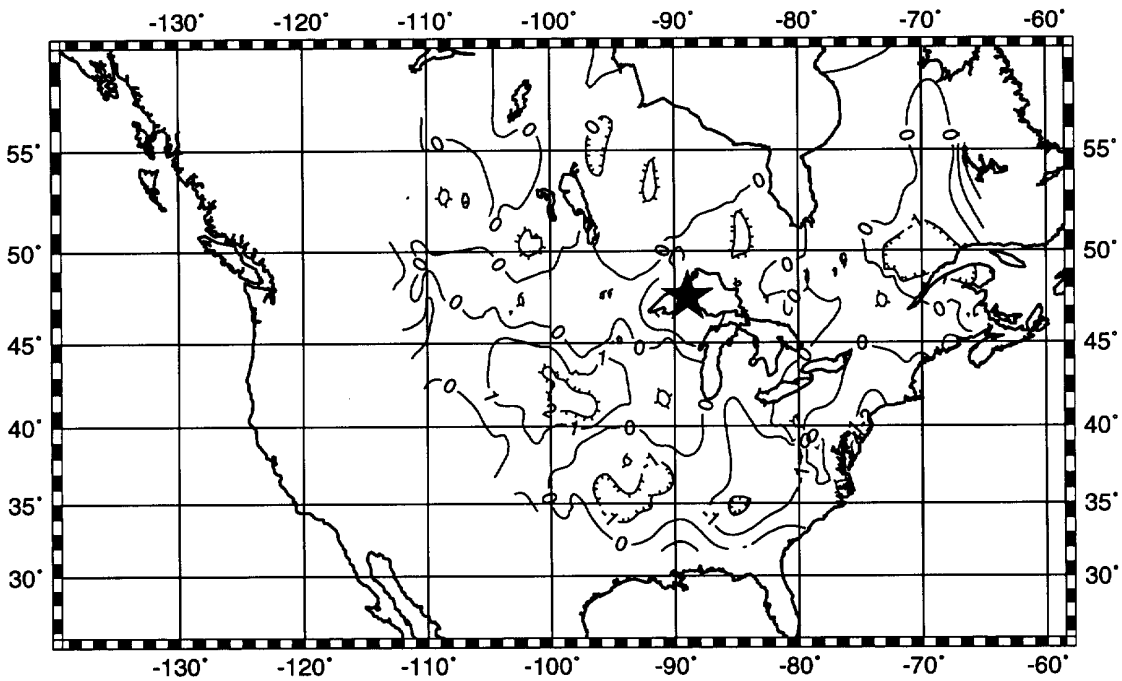

Figure 5. Early Rise experiment (solid star is a shot point). Map of difference between observed and calculated Pn travel-times (in sec) for 3-D model, revision 4.5.

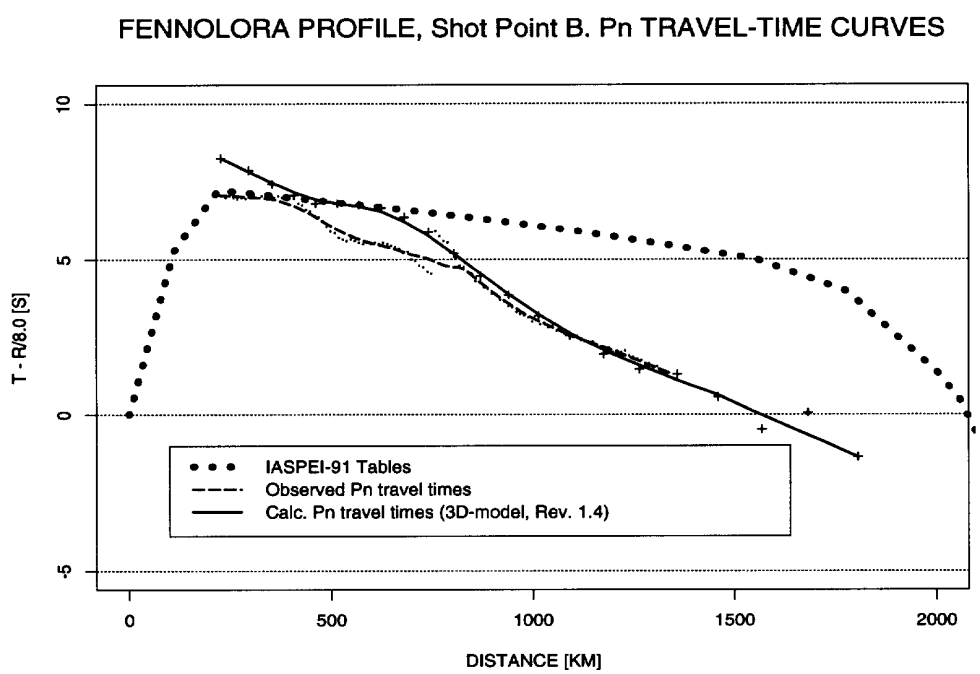

Figure 6. FENNOLORA profile. Comparison of Pn travel-time curves observed (shot point B), calculated (3-D model, revision 1.4), and IASPEI-91.

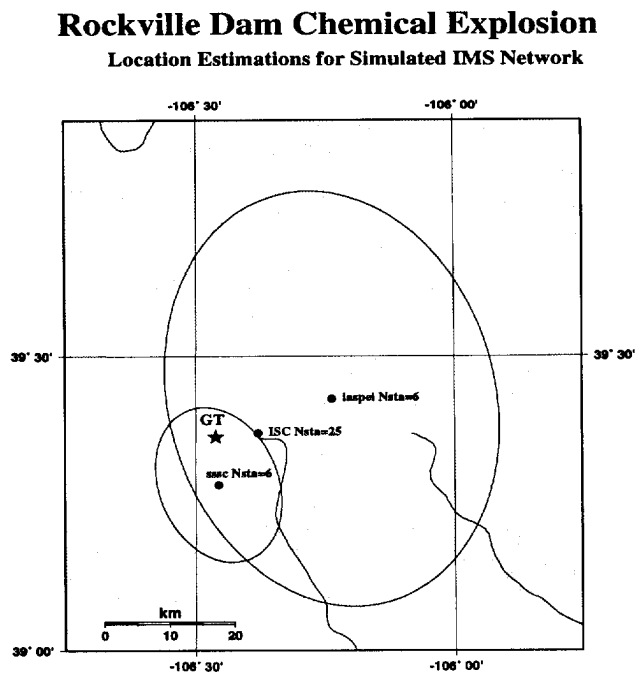

Figure 7A. Locations of the Rockville Dam Chemical Explosion using 6 stations (Nsta=6). Locations: ground truth (GT), iaspei (IASPEI-91 tables, sssc (SSSCs(3-D)).

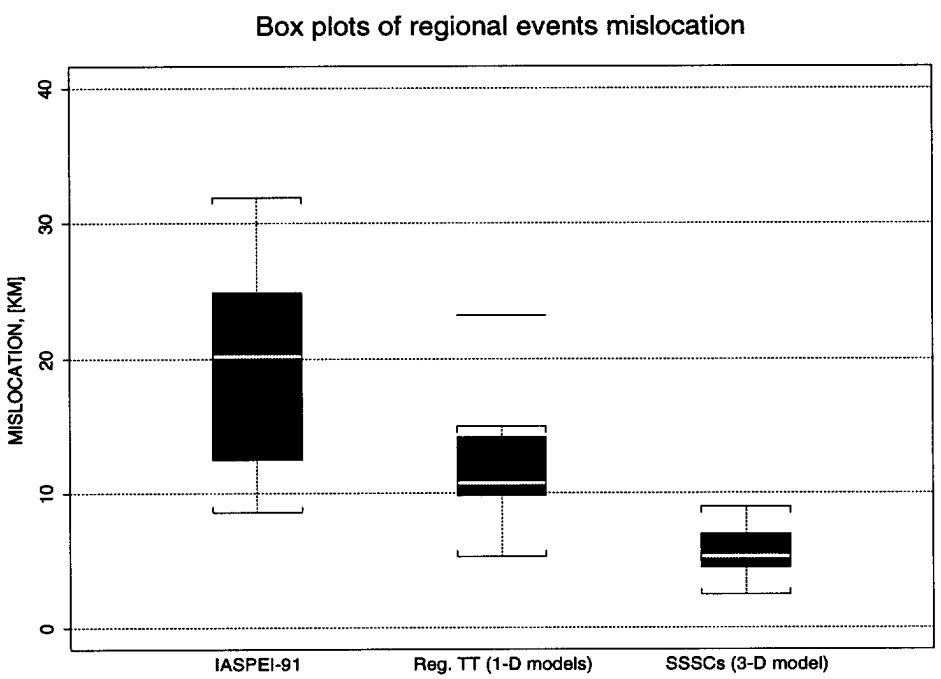

Figure 7B. Box plots of mislocation of large explosions detonated within US. Locations using: IASPEI-91 tables (IASPEI-91) (12 events), two 1-D regional models (Reg. TT) (1-D models) (5 events), SSSCs(3-D) (Source-Specific Station Corrections inferred from the 3-D velocity model of the Earth crust and upper mantle) (12 events).