DEVELOPMENT OF A THREE-DIMENSIONAL VELOCITY MODEL FOR THE CRUST AND UPPER MANTLE IN THE BARENTS SEA, NOVAYA ZEMLYA, KARA SEA AND KOLA-KARELIA REGIONS

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ABSTRACT

The principal objective of the present study is to compile a three-dimensional (3D) seismic velocity model of the crust and upper mantle for the larger Barents Sea region, at a spatial resolution of nominally 50x50 km. The main accomplishments so far have been concerned with compilation, collation and review of primary existing geophysical data, including first of all deep seismic wide-angle profiles (OBS and ESP - two-ship expanded spread profiles), deep multi-channel seismic reflection (MCS) profiles, and shallower 1D velocity profiles. The main source of data has been a database compiled over many years at the University of Oslo (UiO), supplemented by data compiled at the United States Geological Survey (USGS) and from collaboration partners in Norway and in Russia. Subsequently, detailed comparisons of data and models between the UiO and USGS have been performed, and unified criteria for quality assessment have been developed. The result is a full integration of the underlying data, and a common unified model.

The 50x50 km grid tiles in the target region have been defined in an optimum way such that the tiles form a fully equi-distant grid. The filling of the grid tiles so far shows a very good coverage in the western Barents Sea, a reasonable coverage also in the Novaya Zemlya region, but is less-constrained in the northern and northeastern parts of the target region. The results show that the depths to Moho vary from about 10 km in the oceanic crustal domain to more than 40 km in coastal regions of Norway and Russia and in the Kara Sea, while sediment thicknesses are 15-20 km in the southwestern and eastern parts of the Barents Sea. Following the USGS methodology each grid tile is represented with layers for ice, water, soft sediments, hard sediments, and crystalline upper, middle and lower crust. Finally there is a layer describing the seismic velocity and density of the uppermost mantle, which is controlling Pn and Sn travel times.

We have also acquired an upper mantle model (Shapiro and Ritzwoller, 2002) that eventually may be integrated with our new crustal model and tested for a ground truth (GT) database of about 50 events that also has been established as a part of this study. Since some large regional distances also will be used when comparing observed GT travel times with computed travel times through the established model, a mantle velocity model down to about 400 km is needed. To facilitate this travel time testing a number of 2D profiles have been established through the regions that are well covered with initially sampled 1D velocity functions, followed by different smoothing and interpolating techniques, dependent on which modelling method that will be applied. So far 2D ray tracing and finite difference methods have been used here, with preliminary testing also of 3D methods.

Since the grid tiles filled with primary data are unevenly distributed it has been necessary also to develop and to test methodologies for interpolation and extrapolation, in order to have all tiles filled. In regions where the data coverage is not dense, geological provinces are defined which are supposed to hold similar tectonic histories. In this case a method is being tested in which the velocity profiles have been used to calculate the crystalline crustal thickness as a function of sediment thickness. Since the crustal rock velocity distribution for a particular geological province is known, a regional depth-to-basement map can used to calculate representative 1D velocity-depth functions for the entire crust. This technique looks promising as a means for providing an equally sampled crustal model, as is required for seismological purposes.

OBJECTIVE

The principal objective of this study has been to compile a three-dimensional seismic velocity model of the crust and upper mantle for a region including the Barents Sea, Novaya Zemlya, Kara Sea and Kola-Karelia regions, at a spatial resolution of nominally 50x50 kilometers. Using existing seismic profiling data compiled by the University of Oslo, USGS and the Russian institutes, we are in the process of constructing a high resolution, regional lithospheric model based on a comprehensive compilation of all available seismological, geophysical and (where available) drill hole data. The resulting regional lithospheric model will consist of seven crustal layers: (1) ice, (2) water, (3) soft sediments, (4) hard sediments, (5) crystalline upper, (6) middle, and (7) lower crust. An eighth layer describes the seismic velocity and density of the uppermost mantle (with P_n and S_n velocities). Both P- and S-wave velocities and density are specified in each layer.

The purpose of making higher-resolution crust models is to improve seismic event locations and event discrimination for nuclear test monitoring. The goal is to develop a model useful both for further research on the detection, location and identification of small events in the study region and for operational use in locating and characterizing seismic events in the region. Along with the development of the model, a calibration and validation program will be executed, aimed both at quality controlling the model through comparisons between observed and synthetic travel times, and at investigating the potential improvements in terms of event locations.

RESEARCH ACCOMPLISHED

The target area for this study is shown in Figure 1, where a 50x50 km sampling grid has been defined as shown by hexagons. The chosen tiling provides the best conditions for the calculation of transects for subsequent travel time modeling (ray tracing). The grid should also be easy to use as it will be relatively straight forward to assign the nearest tile to whatever coordinates that someone may want to use, and it also optimizes the number of individual 1D models that must be constructed for the model while still maintaining the basic resolution.

The western part of the target region shown in Figure 1 is extensively covered by Norwegian seismic reflection data that largely is available at UiO, where also a large database of 1D velocity profiles has been established. The eastern areas are covered, albeit not so densely, by Russian studies. Most of these studies are, however, too shallow for the purposes of the present study, and what remains of primary interest are the wide-angle profiles shown in Figure 1. The data are mostly based on continuous seismic refraction profiles that are sampled every 25 km (~560 points). These data were achieved by gathering digital profiles (ray-tracing models of newer experiments) and by digitizing published velocity-depth profiles (the complete reference list comprises a large number of entries and will be published elsewhere). The majority of these seismic profiles was acquired with receiver spacings of less than 30 km so that a sampling interval of 25 km seems appropriate. About 120 velocity-depth functions were derived by depth-migration of deep-seismic multi-channel profiles with nearby ESP-information and subsequent gravity modeling (velocity-density conversion). Moreover, about 20 single-location velocity-depth functions complete the database (expanding spread profiles, surface-wave analysis). Approximately 90% of the database constrains the crust-mantle transition based on observed Pn and/or PmP phases.

Figure 1 also illustrates the inhomogeneity in data input distribution for the wide-angle and deep seismic reflection data. Whereas the western Barents Sea is well covered with seismic profiles, the eastern part shows larger gaps up to several hundred kilometers in the data coverage (6-8 tiles). Regarding the geological main provinces this disparity gets tempered since the eastern Barents Sea shows broader, more homogeneous extended geological units compared to the western part (Johansen *et al.*, 1992; Grogan *et al.*, 1998).

Model setup and results

The target region is covered by 1,490 tiles as shown in Figure 1, where the average distance between the tiles does not deviate from 50 km by more than about 300 m. For every tile a P-wave velocity (later to be extended with S-wave velocity and density) profile is gathered. The velocity-depth functions of the final model will follow an eight-layer model: water (ice), soft- and hard sediments (with a threshold at 3 km/s), upper-, middle- and lower igneous crust (variable velocity thresholds), and upper mantle.

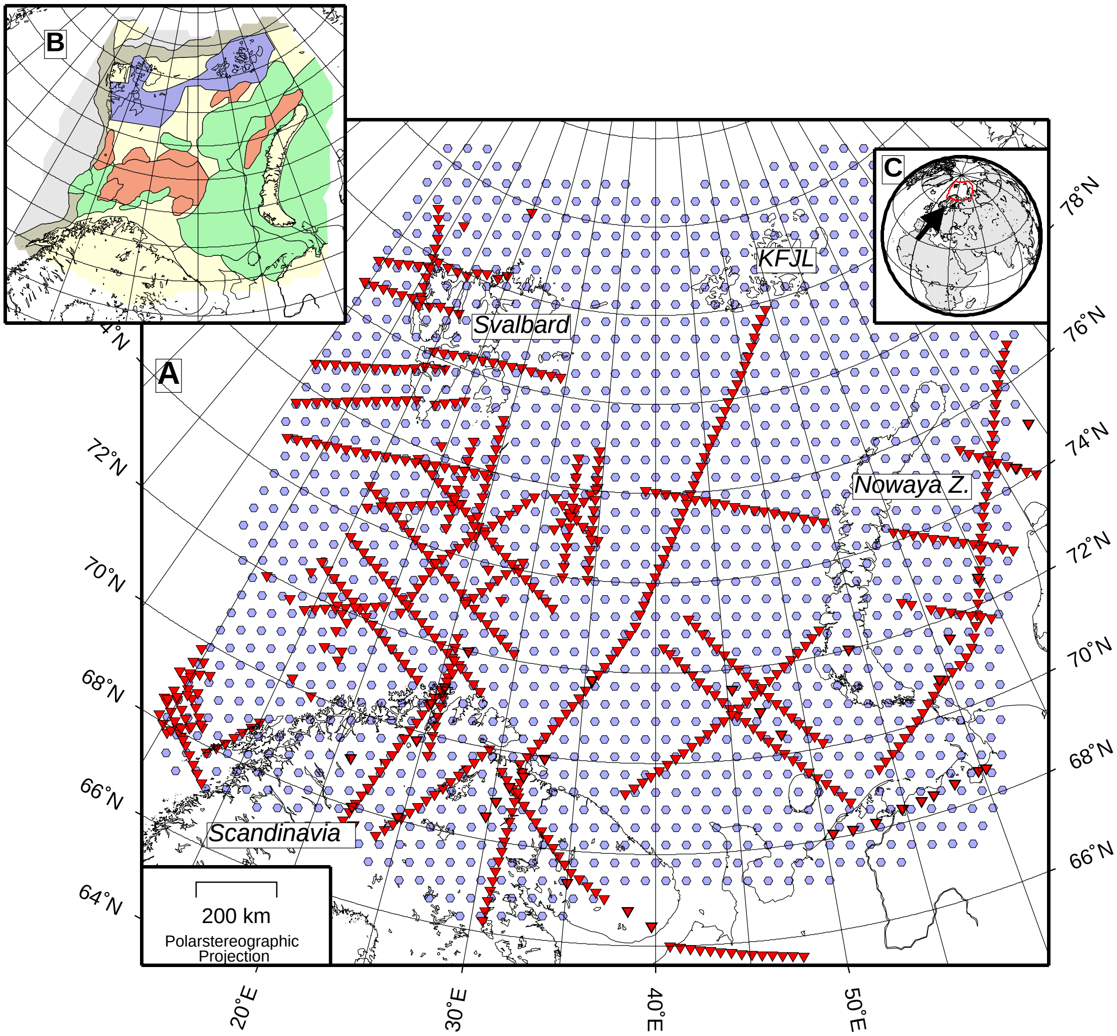

Figure 1. Target area for the present study (A). The sampling grid is shown by blue hexagons, defined so as to satisfy a 50x50 km spacing requirement, disconnected from the latitude-longitude grid. The red inverted triangles show the positions of sampled 1D velocity columns, largely reflecting available wide-angle and deep seismic reflection transects. The insert map (B) is showing the geological provinces within the target region: Onshore regions, platforms (yellow); offshore sedimentary basins (green); offshore basement highs (red); Cretaceous volcanic province (purple); continent-ocean boundary (brown); oceanic crust (grey). The insert map in the upper-right corner (C) shows the general location.

Figure 2 shows the depth-to-Moho at the locations of the sampled 1D velocity functions (triangles) where depth is color coded by the rainbow palette. The depth range varies between 4.5 km off western Svalbard, within very thin oceanic crust (2 km water depth), and 54 km within the cratonic region of northern Scandinavia. P-wave velocities below the Moho range between 7.4 km/s (serpentinized peridotites at fracture zones along Knipovich Ridge) and 8.35 km/s below Scandinavia. Initially, the work on developing this model was done in parallel at UiO/NORSAR and at USGS, both of which having extensive databases for the target region.

As expected, there was a considerable overlap between the databases employed by UiO and USGS, and the nature and details of this overlap have been fully resolved through a recent workshop in Oslo. The databases have now been completely coordinated and integrated, resulting in a common model, albeit preliminary, based on joint efforts within the project. The final model, with optimal resolution and quality, will be constructed on the basis of original and project reviewed data which are clearly identified and documented, emphasizing transparency.

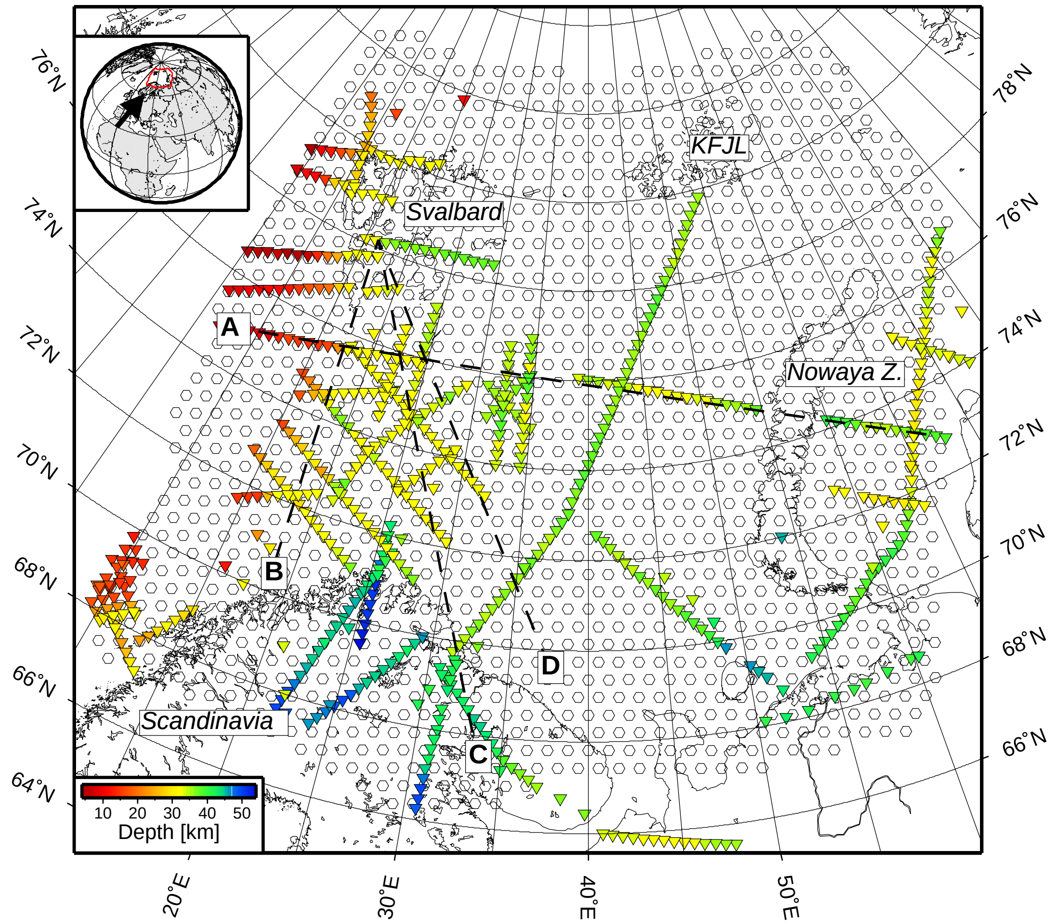

Figure 2. Map showing the depth-to-Moho at all sampling coordinates that directly constrain the crust-mantle boundary (color-coded, inverted triangles). The hexagons show the 50 km-equal spaced grid-construction of the final model. The dashed lines mark the location of the transects A (running W-E in the middle of the map) and B-D (running southwards from Svalbard), to be used in subsequent figures.

In order to illustrate some of the contents of the velocity database (the sampled 1D velocity functions) in Figure 2, we have constructed a transect (A) running west-east between 73 and 75°N (shown in Figure 3). Generally, only sampled velocity functions (see triangles in Figure 2 for location) with a maximum distance of 25 km to the transect line are used for the profile construction.

The seismic velocities in Figure 3 are shown by the color palette in columns, where each column refers to a particular location, depicted by triangles, in Figure 2. In addition the sediment, basement and Moho boundaries are shown. This west-east profile (A) across the entire western Barents Sea identifies clearly the very particular structures in this region, with very thick sediment layers and a strongly varying depth-to-Moho discontinuity.

Since the constraints on the upper-mantle velocity structure are limited throughout the database, a homogeneous upper-mantle model is used initially, below the Moho velocities that are taken from the experiments. This will later, however, be replaced by an upper mantle model derived from Shapiro and Ritzwoller (2002), sampled down to a depth (~400 km) needed for modeling of far-regional P phases (Figure 4). The Moho depths from this model have been demonstrated to be reasonably consistent with the model from the present study. Later, we hope to replace the Shapiro and Ritzwoller (2002) model by an updated model based on new inversions in which more regional surface wave (including higher mode) data are also included, in conjunction with Pn and Sn data.

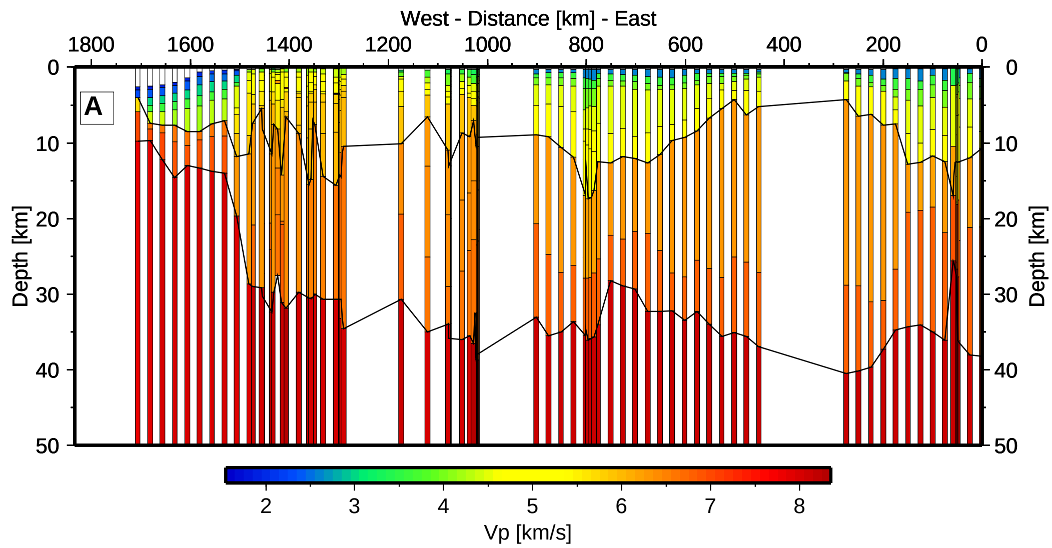

Figure 3. 1D-velocity functions along the EW-oriented transect A in Figure 2. The thick lines crossing the velocity columns mark the top of the crystalline basement and the Moho discontinuity, respectively.

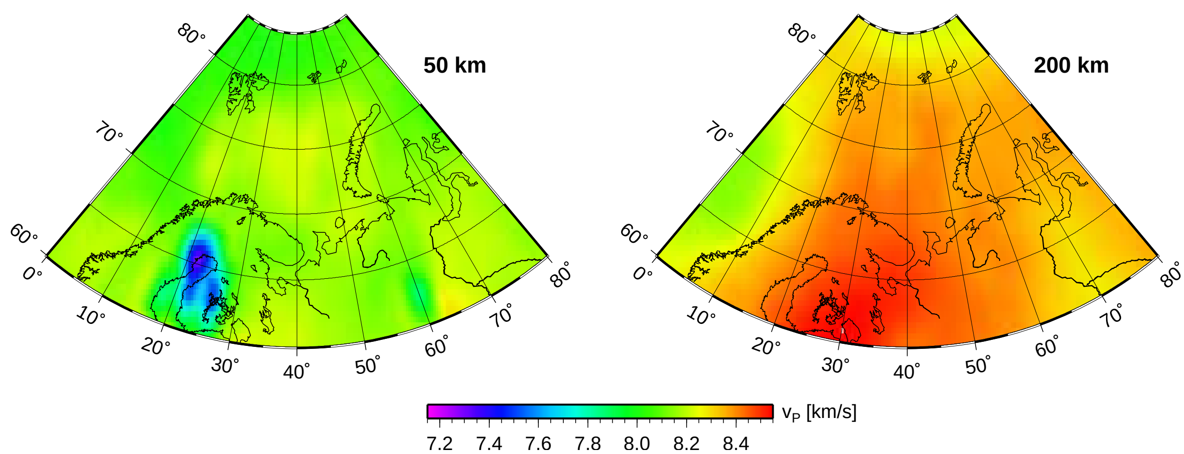

Figure 4. Mantle P-wave velocities at two depths (50 and 200 km), based on the model of Shapiro and Ritzwoller (2002). This model will be used initially in conjunction with the crustal and Pn velocity model established in this project. Courtesy of A. Levshin, Univ. of Colorado-Boulder.

Model interpolation, method and results

More than 40% of the 1,490 model tiles (Figure 1A) are directly constrained by one (or more) sampled velocity-depth function(s). According to the sampled seismic profiles some functions contain more detailed (geological) information than it is required for the suggested final 8-layer structure. To enable a homogeneous construction of constrained and unconstrained tiles of the final 3D model the following ‘interpolation’ method was tested and is now being considered to be used for filling the remaining tiles.

The provinces shown in Figure 1B bear in general a nearly similar geological history, hence a similar basin architecture can be assumed to be present throughout the entire province. It is reasonable to assume that this is due to a common setting in a broader tectonic regime and a common physical behavior of the deeper igneous crust and its isostatic response. An extensional regime would therefore result in increasing sediment thickness with decreasing igneous crustal thickness, while strong compression might lead to crustal thickening and subsequent erosion of sedimentary strata.

This assumption gains substantial support from an observed strong correlation between the sediment thickness and the remaining igneous crustal thickness. Three examples of this are shown in Figure 5a, where data are taken from the sampled velocity functions that appear as inverted triangles in Figure 5b. If we ignore some outlying observations (which should be expected), we find reasonably well constrained linear relations throughout most provinces, and we also find that these relations are significantly different from each other.

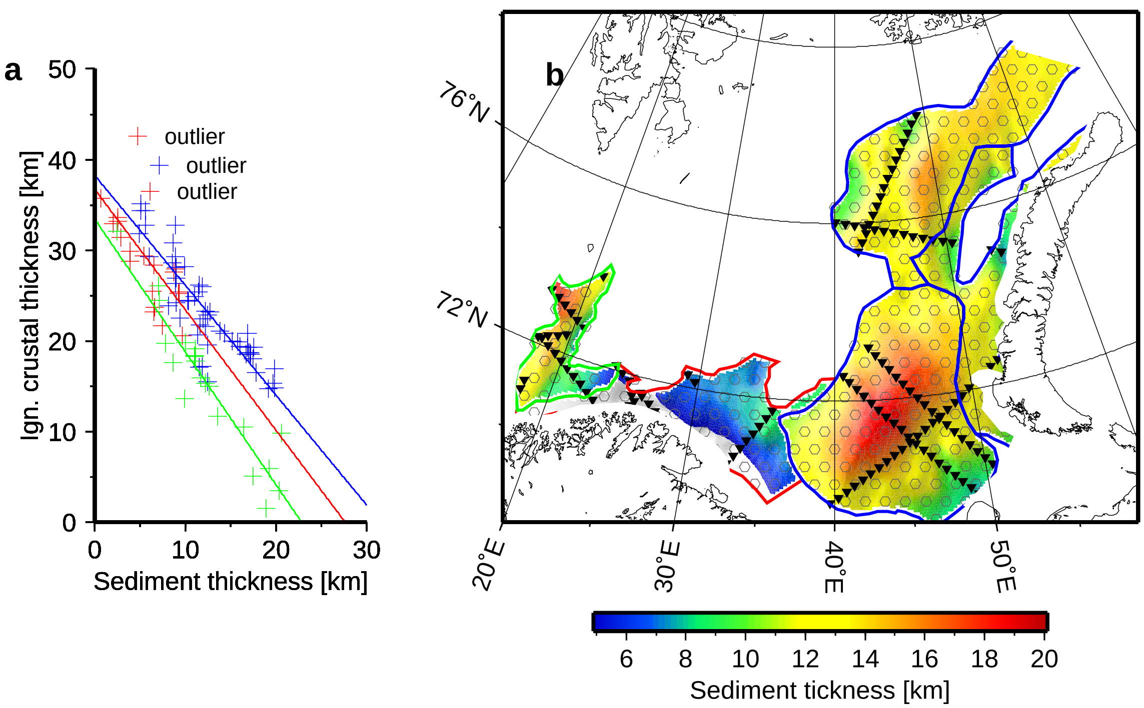

Figure 5. A. Relations between sediment thickness (abscissa) and igneous crustal thickness (ordinate) in three example regions: SW Sedimentary Basins (green); Finnmark Platform (red); and E-Barents Sea Basin (blue). For location see enclosed regions on map B. Relationships are taken from the sampled velocity functions, locations are marked by inverted black triangles in B. Green, red and blue thick lines in A are linear regressions that can be used for calculation of the igneous crustal thickness where only sedimentary thickness is known (Myklebust, 1994).

On this basis, area-wide sediment thickness data as taken from the so-called Magnetic Mapping of the Barents Sea (MMBS) project (Myklebust, 1994), based on potential field, seismic reflection/refraction, and borehole data, can potentially be used to calculate the igneous crustal thickness for those provinces that hold sufficient sampled profiles to manifest a relationship, as demonstrated in Figure 6. Tiles that are constrained by sampled profiles are equipped with the exact measured depth-to-basement and depth-to-Moho (hexagons in the vicinity of black inverted triangles). Unconstrained tiles are in this setup assigned a sediment thickness taken from area-wide data and an igneous crustal thickness inferred from manifested relationships. Mean seismic velocities for all six crustal and mantle layers are calculated from the sampled velocity-depth functions and are used for the entire province.

For the spread of the sediment thickness data of the MMBS-project (Myklebust, 1994) we calculated the respective total crustal thickness using 15 different regression lines, based on the methodology described above. Figure 6 illustrates well that occasionally, at province boundaries, the different regression parameters result in unintended stepping (e.g. 35°E, 72.5°N). Further it appears that prominent high and lows are aligned along sampled profiles (e.g. 40°E, 74°N). The latter effect is due to systematic deviations in the sedimentary thickness along these sampled profiles from the sediment thickness database (MMBS). In order to avoid these artefacts future steps will probably incorporate: (i) Initial adjustment of the sediment thickness data to the velocity database gathered within this project (merging), (ii) a final filtering/smoothing within and across geological provinces, (iii) adjustments of the province boundaries.

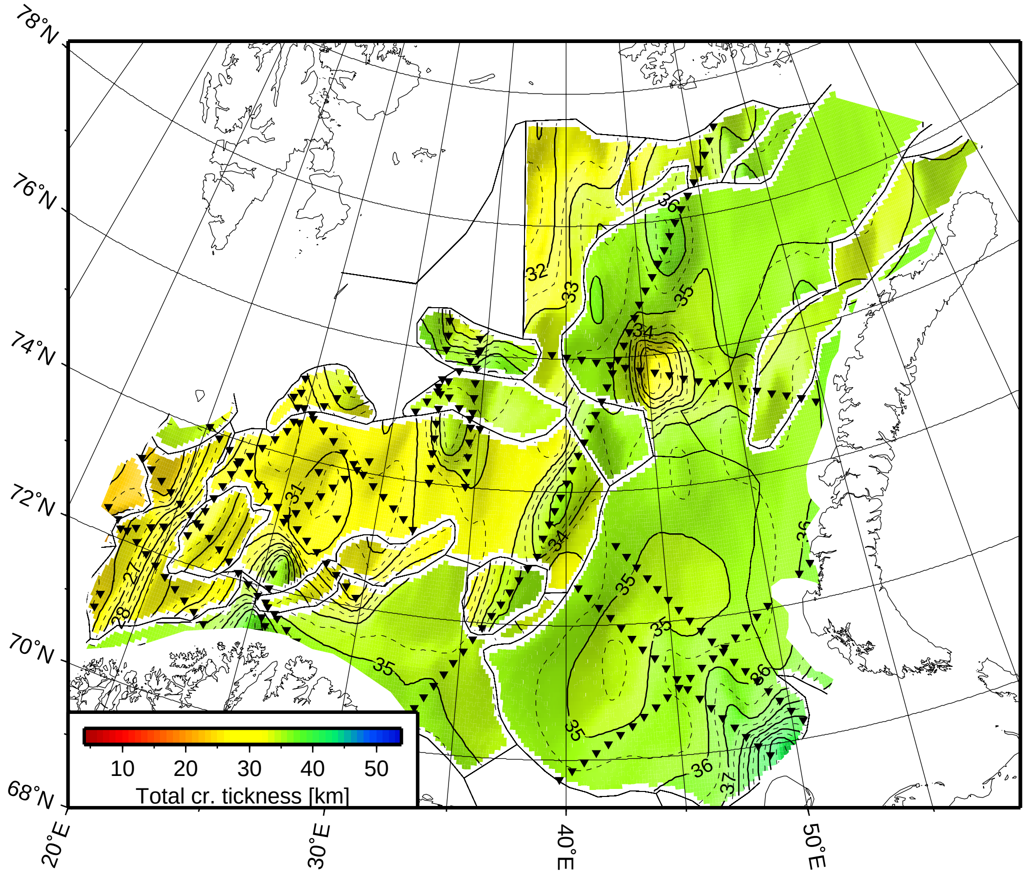

Figure 6. Map showing the inferred (interpolated) total crustal thickness for 15 geologic provinces within the target region, covering most of our target area. Black inverted triangles mark the position of sampled velocity functions. Solid isolines at 1 km, dashed lines at 0.5 km. The total crustal thickness is nearly similar to the Moho depth, since the water depths are not higher than 400 m within the displayed region.

The thickness of the igneous oceanic crust is independent from sediment thickness, rather it is a function of other factors such as spreading rate or asthenospheric temperatures. Therefore the method described above is not applicable for this domain. The sedimentary thickness data are used to constrain the thickness of the sedimentary layers of the velocity models. The igneous crustal thickness within the oceanic provinces therefore have to be derived basically by lateral interpolation, since regional seismic profiles show no indications for broad thickness undulations, i.e. basement ridges or extensive fractures.

Ground truth data; validation

A database of around 50 potential ground truth (GT) events has been established for this project, to a large extent based on work done under earlier Defense Threat Reduction Agency (DTRA) and Department of Energy (DOE) contracts. The events are all relocated based on the available travel time data, and initial GT levels have been assigned based on the formal uncertainties. These GT assignments will be re-evaluated at a later time.

Figure 7 shows the travel paths for these GT events. Seismic stations are indicated by blue triangles while the events are plotted as open circles, color coded based on formal location uncertainties. For all of these travel paths, seismic data are archived and available at NORSAR, constituting an excellent basis for subsequent model validation and refinement, based on ray tracing through 2D and 3D models. It is seen from Figure 7 that large parts of the target region, notably the eastern Barents Sea and even more so the Kara Sea and the areas southeast of Kaiser-Franz-Josef Land, are not well covered in terms of travel paths, related to low seismicity and poor station coverage. The aims of this study are to determine what is available and compile it into a working database, which we believe we have done, and it seems there is no information available for this region of our study area.

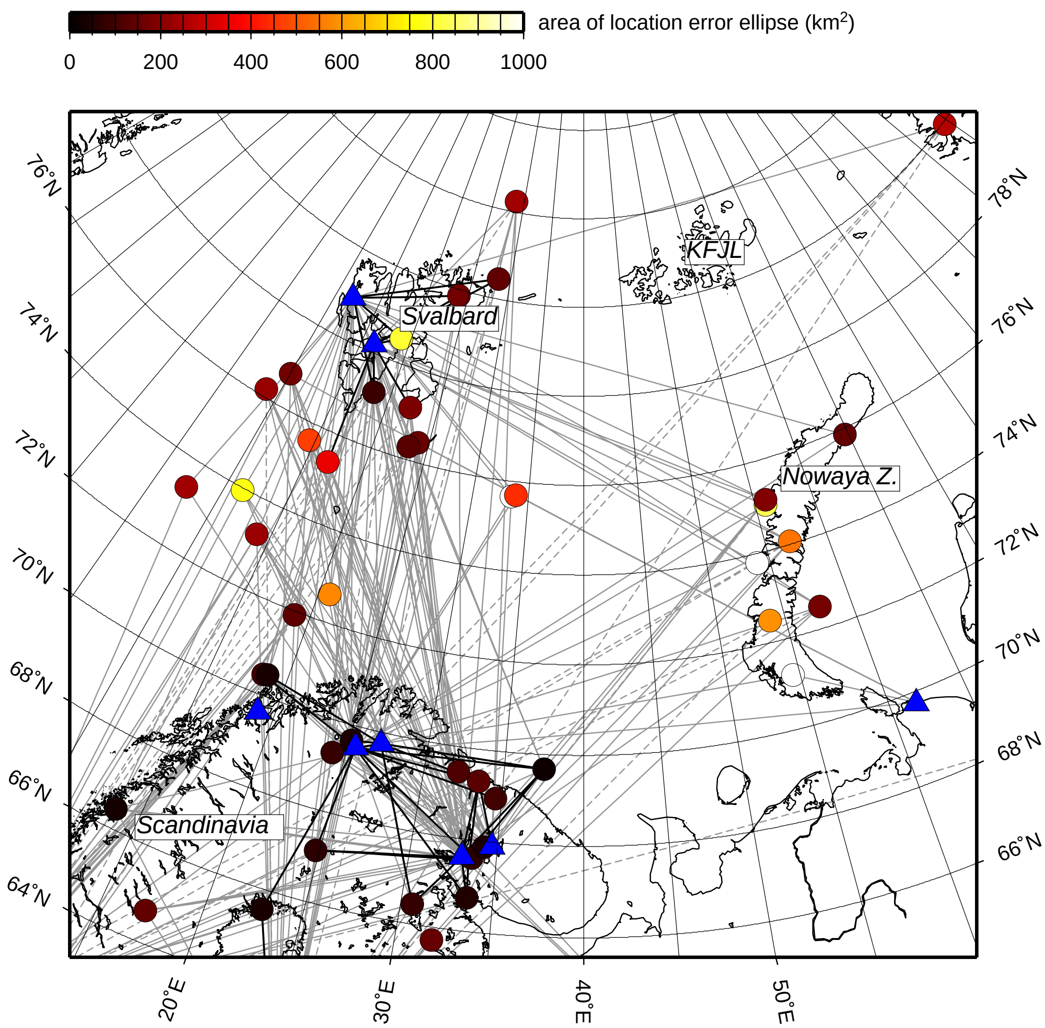

Figure 7. Ground truth travel paths in the target region, where the lines indicate Pn and the dashed lines longer-distance P phases. For most of the Pn data there are also Sn data. The events are color coded with respect to the formal uncertainty (area in km^2).

Figure 2 also shows the location of three additional crustal transects (B, C, D) in the western Barents Sea between northern Fennoscandia and Svalbard (the SPITS array). Transect C stretches from the Kola peninsula to SPITS, and transect D from the location of the Kursk accident to SPITS. Whereas these two transects are in a region of a rather simple, layered crustal structure, the westernmost transect B crosses deep sedimentary basins.

For these three profiles, 2D models comparable to the one in Figure 3 (for transect A) have been established. To calculate synthetic travel times, gaps in the velocity structure have to be filled by interpolation, the model has to be extended downwards, and the model parameterization must be adapted to the specific modelling algorithm used. Figure 8 (bottom panels) shows the 2D velocity structure along the three transects B, C, and D on a regular grid. Crustal and uppermost mantle velocities are taken from the 1D velocity-depth functions, and gaps were filled by Delauney triangulation between 1D functions. Here, the model is extended downward by the 1D BAREY model for the Barents Sea (Schweitzer and Kennett, 2002).

Wave fronts and synthetic travel times were then calculated using a 2-D finite-difference (FD) scheme with a grid node spacing of 0.5 km in both directions. Since the FD scheme assumes a Cartesian grid, an Earth-flattening transformation has been applied to each of the velocity models to account for the spherical Earth. Wave fronts are shown every 5 seconds (dashed lines) and 10 seconds (solid lines). Corresponding ray paths reach depths of about 100 km, depending on the velocity gradient and maximum profile distance. Synthetic first arrival travel times for the three transects are shown in the top panel of Fig. 8. Although corresponding rays travel mostly in the upper mantle, the laterally variable crust significantly affects the resulting travel time curves.

The three transects shown here will be updated continuously and used as test cases for various model parameterizations and modelling algorithms.

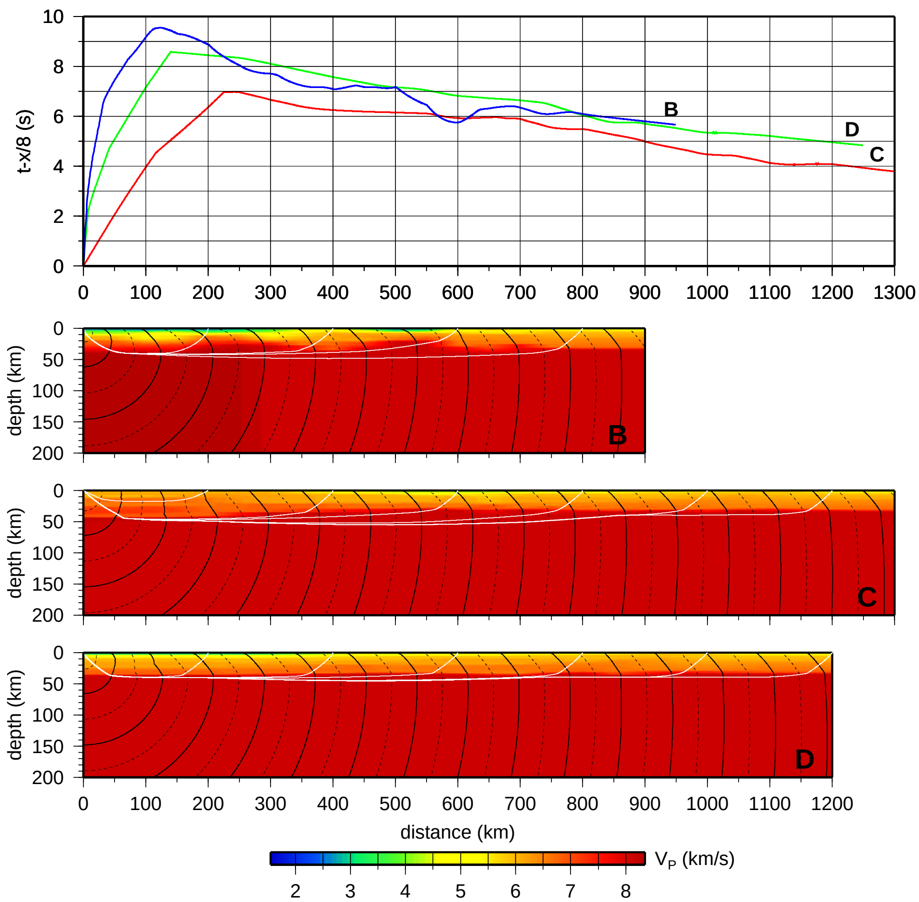

Figure 8. Wave fronts, ray paths and first arrival travel times for the transects in Figure 2, based on a FD algorithm (Cohen and Stockwell, 2003). A reduction velocity of 8 km/s has been applied. The ray paths reflect the small gradient in the upper mantle velocities down to about 200 km. For distances up to 2500 km the rays will penetrate down to about 400 km.

CONCLUSIONS AND RECOMMENDATIONS

After the first year of this two-year study we have come a long way in that the UiO and USGS databases have been fully integrated, done in part in two Oslo workshops, followed by the filling of all of the tiles that can be tied directly to primary observed data. The amount of data that have been collected and reviewed is extensive, with emphasis given to unification, quality assessment and transparency. So far only P-wave velocities have been filled in, but this will be extended with S-wave velocities and densities later. The results show that the depths to Moho vary from about 10 km in the oceanic crustal domain to more than 40 km in coastal regions of Norway and Russia and in the Kara Sea, while sediment thicknesses are 15-20 km in the southwestern and eastern parts of the Barents Sea.

The data coverage is quite good in the western Barents Sea, but weaker in other parts of the target region. Because of this it has been necessary to develop a methodology for filling in the rest of the tiles. The approach which is being tested now and which appears to be quite promising, is based on separating each tile into a geologic province or unit, supposed to hold similar tectonic histories. The key here is the fact that we find a strong correlation between the sediment thickness and the remaining igneous crustal thickness, calculated from the available velocity profiles. Since the crustal rock velocity distribution for a particular geological province is known, a regional depth-to-basement map can therefore be used to calculate representative 1D velocity-depth functions. Using this methodology we have been able to fill most of the tiles in the continental crust not covered by primary data. For the oceanic crust we expect to use a procedure based essentially on lateral interpolation.

The work will continue into the second year with the acquisition of primary data in parallel with the continued filling of the 1,490 grid points (tiles), including S-velocities and densities. A close cooperation with Russian institutions are essential to this end, including Sevmorgeo and VNIIOkeangeologia of the Russian Academy of Science. Both of these have contributed to updates on Russian data/results in our regional compilation. There are also plans for acquisition of new deep seismic data as part of a current Norwegian-Russian research program.

The primary wide-angle data used in the present study provides only Moho (Pn) velocities, while some of the distances to be used in the travel time testing will have rays traversing down to 400 km. Because of this we have initially replaced a homogeneous upper mantle model with the one of Shapiro and Ritzwoller (2001). In cooperation with Dr. Anatoli Levshin, we are planning to combine the data behind this model with more regional surface wave, and Pn and Sn data (e.g., Levshin *et al.*, 2001), thereby developing an updated model also for the upper mantle.

A soon as the first version of a complete model has been established, the validation work will be intensified, essentially based on comparisons between observed and calculated travel times. The GT database already established will have to be further refined, tested and classified in terms of GT levels, and possibly also extended with more events and phase readings. For travel time modelling along transects we use 2D ray tracing in Cartesian and spherical coordinates as well as FD eikonal solvers. Case studies in 3D will follow during the second year of this study.

REFERENCES

Grogan, P., K. Nyberg, B. Fotland, R. Myklebust, S. Dahlgren, and F. Riis (1998), Cretaceous magmatism south and east of Svalbard: evidence from seismic reflections and magnetic data, International Conference on Arctic Margins III, Polarforschung 68, 25-34.

Cohen, J. K. and J.W. Stockwell (2003), CWP/SU: Seismic Unix Release 37: a free package for seismic research and processing, Center for Wave Phenomena, Colorado School of Mines.

Johansen, S.E., B.K. Ostisty, Ø. Birkeland, Y.F. Fedorovsky, V.N. Martirosjan, O. Bruun Christensen, S.I. Cheredeev, A.A. Ignatenko, and L.S. Margulis (1992), Hydrocarbon potential in the Barents Sea region: play distribution and potential, in: Vorren, T.O., E. Bergsaker, Ø.A. Dahl-Stamnes, E. Holter, B. Johansen, E. Lie, and T.N. Lund, Arctic geology and petroleum potential, NPF Special Publication 2, 273-320.

Levshin, A.L., M.H. Ritzwoller, M.P. Barmin, A. Villaseñor, and C.A. Padgett (2001), New constraints on the arctic crust and uppermost mantle: surface wave group velocities, P_n, and S_n, *Phys. Earth Planet. Int.*, 123, 185-204.

Myklebust, R. (1994), Magnetic mapping of the Barents Sea (MMBS) Interpretation report, Amarok A.S., Oslo, Norway.

Schweitzer, J. and B.L.N. Kennett, (2002), Comparison of Location Procedures - the Kara sea Event 16 August 1997, Semiannual Technical Summary, NORSAR Sci. Rep. 2-2001/2002, Kjeller, Norway.

Shapiro, N. M., and M. H. Ritzwoller (2002), Monte-Carlo inversion for a global shear velocity model of the crust and upper mantle, *Geophys. J. Int*., 151, 88-105.