Seismic waveform tomography of the North Atlantic litosphere and underlying mantle

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Summary

The enormous volumes of newly available, broadband seismic data and the continuing development of waveform tomography techniques present us with an opportunity to resolve the structure of the North Atlantic at a new level of detail. The evolution of the passive margins on both sides of the ocean, dynamics of the North Atlantic Ridge and the Iceland Hotspot, and the nature of the upper-mantle flow beneath the region can all be understood better using new, more detailed and accurate models of seismic structure and anisotropy within the lithosphere and underlying mantle. We assemble a very large waveform dataset including all publicly available data from Northern and Western Europe, Iceland, Canada, US, Greenland and Russia.

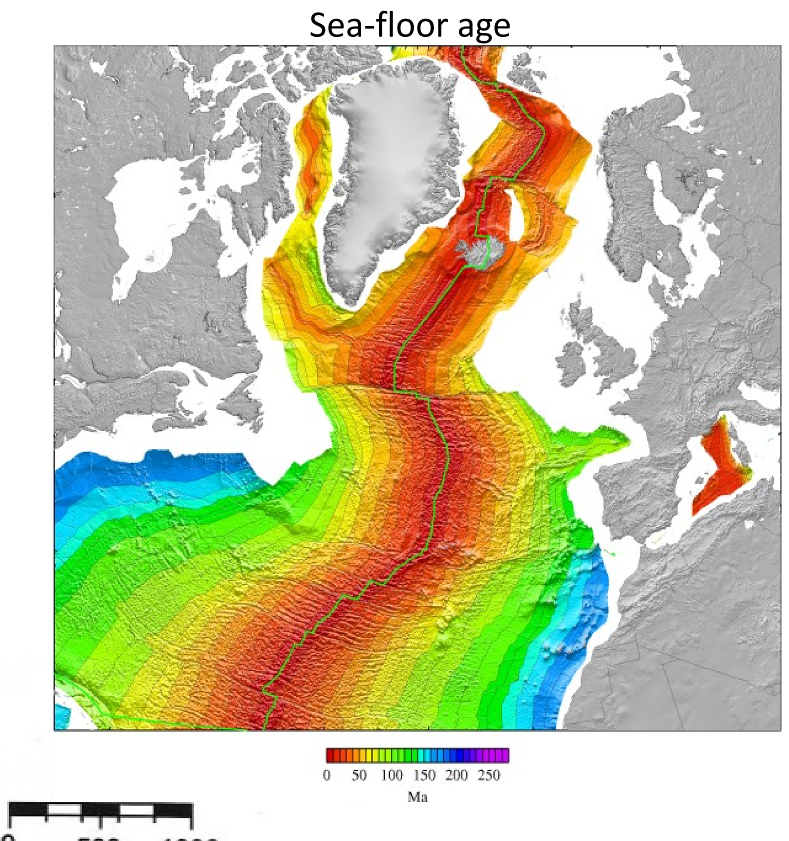
Our tomographic model is constrained by vertical-component waveform fits computed using the Automated Multimode Inversion of surface, S and multiple S waves. The isotropic-average shear speeds reflect the temperature and composition at depth, offering important new information on both regional- and basin-scale lithospheric structure and evolution. Accurate knowledge of the thermal structure of the deep lithosphere will improve our understanding of the thermal structure and evolution of the basins within the region.

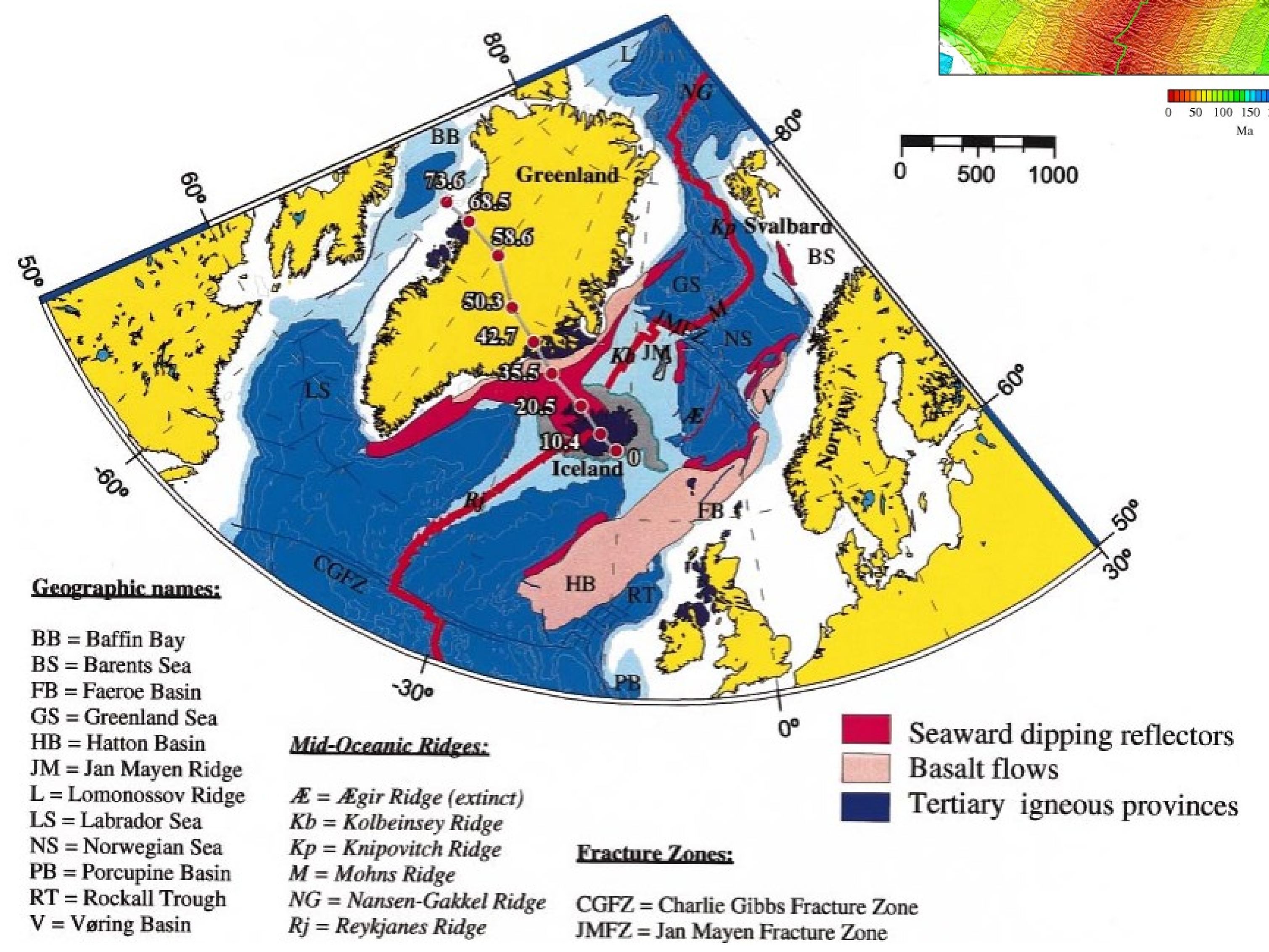
1 North Atlantic

The North Atlantic includes a large variety of geological features. Passive margins enclose a vast portion of spreading oceanic litosphere, which in turn presents various interesting anomalous features. The presence of the Iceland and Azores Hotspot and their nature are topics of major interest, playing a key role in the dynamics of the evolution of the area. The evolution of the underwater continental litosphere presents on the other hand different, more complicated geological settings, which include various igneous provinces and basins and whose deep thermal structure is poorly constrained at the present day (Figs. 1, 2).

Fig. 1 (right): Map of the North Atlantic showing the age of the oceanic crust, from Müller et al. 1997.

Fig. 2 (bottom): Simplified Geological map of the North Atlantic area. Present day and palaeogeographic locations of the Iceland Plume (computed with fixed Greenland) are plotted at various ages. Major transform faults are plotted along other main geological features. From Torsvik et al. 2001.





2 Seismic waveform tomography

The tomographic model is constrained by the vertical-component waveform computed using the Automated Multimode Inversion (AMI) of surface, S and multiple S waves. All the equations are combined into a large linear system and inverted jointly for a model of shear- and compressional-wave speeds and azimuthal anisotropy within the lithosphere and underlying mantle. Results from a previous work by Schaeffer and Lebedev 2014 using North American stations only are shown to highlight both the efficiency of the used techniques and the target velocity anomalies whose resolution the presented study will hopefully increase (Fig. 3). Tomographic models of isotropic-average Vs and radial and azimuthal anisotropy can help us to image many large- to medium-scale geological features: the isotropic-average shear speeds reflect the temperature and composition at depth, offering important new information on both regional- and basin-scale lithospheric structure and evolution. Azimuthal anisotropy provides evidence on the past and present deformation in the lithosphere and asthenosphere beneath the region, which can be interpreted together with other evidence from geological and geophysical data.

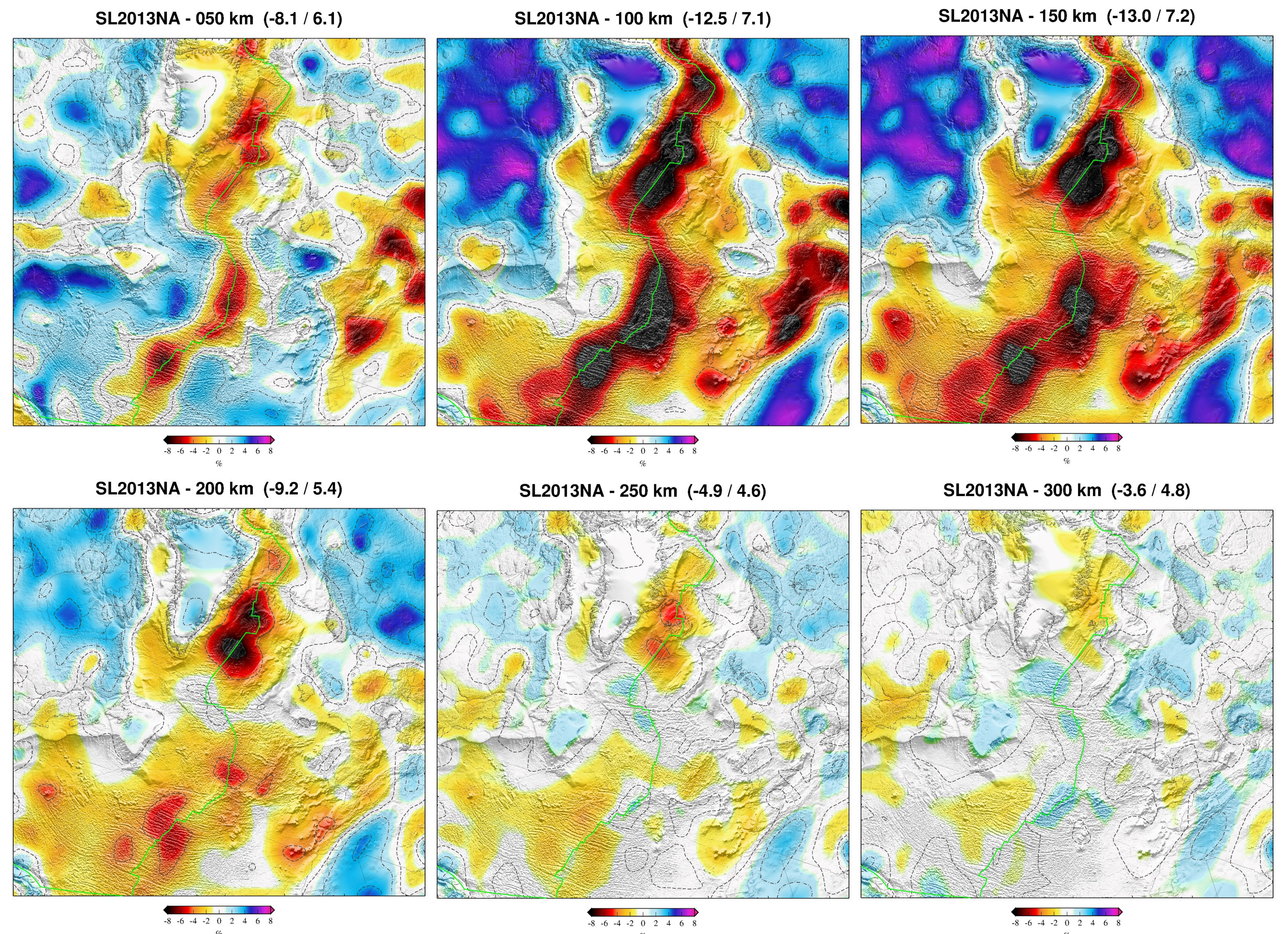


Fig. 3: Horizontal cross-sections through SL2013NA (Schaeffer and Lebedev 2014) at various depths (50, 100, 150, 200, 250, 300 km). Perturbations plotted with respect to AK135 1D reference model. The shallower sections show a very clear negative anomalies below, e.g. the North Atlantic Ridge, Iceland and the western Mediterranean, while deeper cross-sections highlight the strength of the anomalies related to the so-called Iceland Hotspot and below the Azores and Canary Islands. The locations of the stations used for the proposed projects should allow for a better ray-path coverage on this region.

3 Automated Multimode Inversion

The Automated Multimode Inversion technique exploits full automatization to allow the processing of very large datasets (e.g. millions of seismograms), producing high-resolution images of the target region. The input are event-related teleseismic and regional broad-band recordings. AMI computes synthetic seismograms using the JWKB mode summation for each source-receiver pair using a combined set of two 3D global reference models: 1) CRUST2 (*Bassin et al, 2000*) for the crust, 2) 1D Mantle average model (Modified AK135, *Kennett et al. 1995*) for the mantle. Using 3D reference models greatly improves the results of the inversion by avoiding the approximations typically associated with 1D models (Fig. 4). After an accurate pre-processing, real seismograms are fitted to the generated synthetics to derive a set of non-linear equations with uncorrelated uncertainties, describing finite-width sensitivity-volume-averages of S- and P-velocity perturbations along source-receiver paths. The computational efficiency of this technique is based on an accurate selection of time-frequency windows, which isolate fundamental- and higher-mode parts of the wave train from the ones affected by scattered waves (Fig. 5)

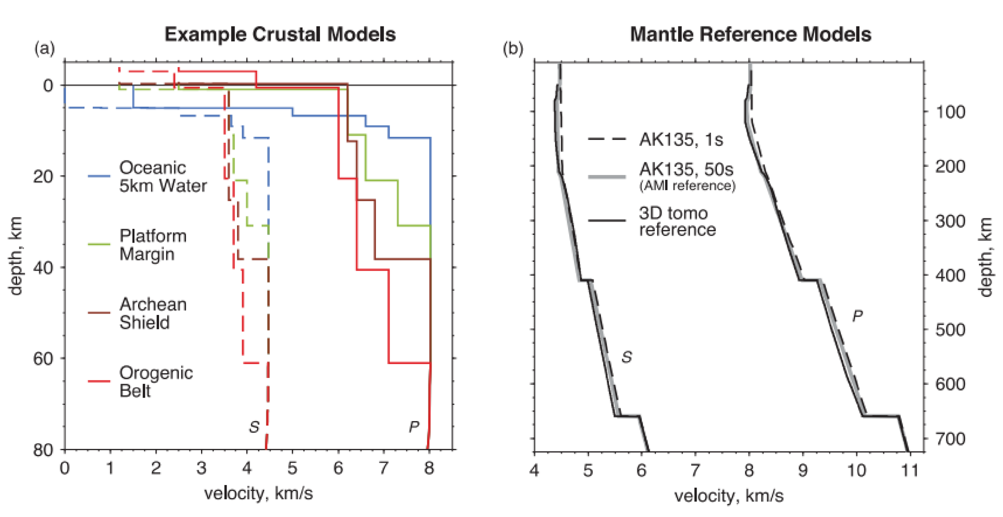


Fig. 4 (top): Reference velocity models used for AMI and 3D Tomography. Panel a) shows four different models based on CRUST2. Crustal models converge below the Moho to the same reference model for the mantle (modified AK135), shown on panel b). From Schaeffer and Lebedev 2013.

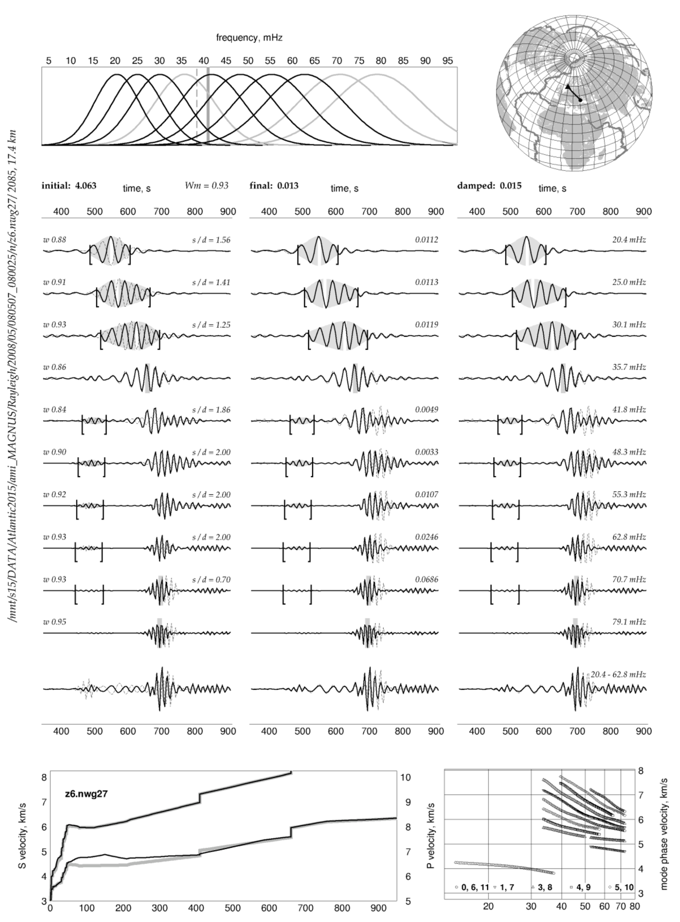


Fig. 5 (right): Example of Automated Multimode Inversion for an earthquake occurred 07-05-2008 08:00:25 north of the black sea and recorded by one of the temporary stations of the MAGNUS experiment (S. Norway, path shown on top right corner map). Filters used for frequency-time windows generation are shown on the top left corner. Waveform matching to synthetic seismograms (solid and dashed lines, respectively) in the different windows are shown as initial fits, final fits (after the non-linear inversion for sensitivity-volume average perturbation) and after the damping. Bottom two plots show P and S velocity profiles compared to 3D reference models and dispersion curves (left and right, respectively).

4 Data

To increase the model's resolution for the North Atlantic region, recordings from all the available stations around the region of interest have been collected from both large datacenters and smaller data repositories, including ORFEUS, IRIS, GEOFON, RESIF, NNSN, POLARIS, CNSN and KIT. The selection of stations includes both permanent networks and temporary deployments (Fig. 6).

For all the selected stations, event-related waveforms were downloaded for most of the events listed in the Harvard Centroid Moment Tensor solutions catalog since 1994. This data selection allows for the creation of a global model which will have higher path-coverage in the North Atlantic area. For this specific project, event selection criteria have been relaxed to allow for analysis of the short-distance events from e.g. the North Atlantic Ridge (Figs. 7,8).

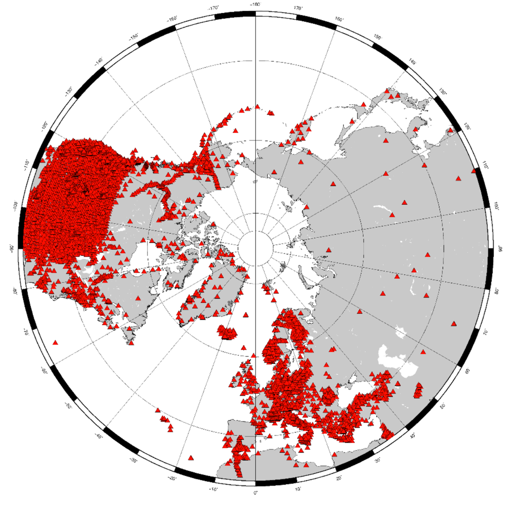


Fig. 6: Station map. Stations include deployments active between 1994 and 2015. Earlier recordings are skipped because of low seismogram quality. For poorly-covered regions, the time range has been extended to 1990 to get the most ray paths.

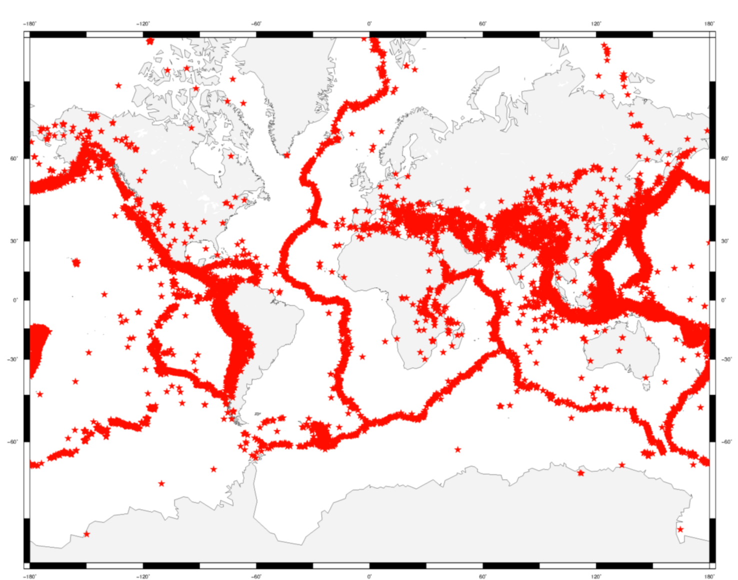


Fig. 7: Map of the events used for the imaging of the North Atlantic area. Events are selected from the Harvard CMT solutions catalog following source-receiver distance criteria.

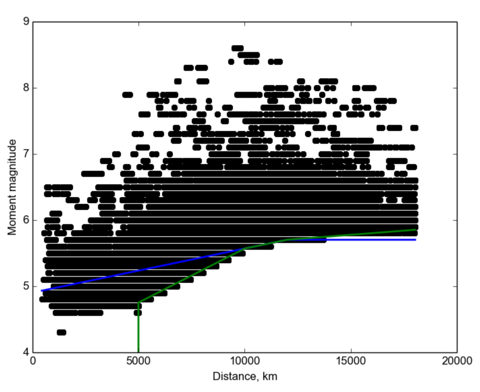


Fig. 8: old and new event selection criteria (blue and green lines, respectively). Black dots are event-station pairs for temporary Leicester Uni. Deployments, which were active between 2006 and 2008. Previously discarded short distance events can be seen between the two lines.

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