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Modelling of seafloor multiples observed in OBS data from the North Atlantic – new seismic tool for oceanography?

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Abstract: In marine seismic wide-angle profiling the recorded wave field is dominated by waves propagating in the water. These strong direct and multiple water waves are generally treated as noise, and considerable processing efforts are employed in order minimize their influences. In this paper we demonstrate how the water arrivals can be used to determine the water velocity beneath the seismic wide-angle profile acquired in the Northern Atlantic. The pattern of water multiples generated by air-guns and recorded by Ocean Bottom Seismometers (OBS) changes with ocean depth and allows determination of 2D model of velocity. Along the profile, the water velocity is found to change from about 1450 to approximately 1490 m/s. In the uppermost 400 m the velocities are in the range of 1455–1475 m/s, corresponding to the oceanic thermocline. In the deep ocean there is a velocity decrease with depth, and a minimum velocity of about 1450 m/s is reached at about 1.5 km depth. Below that, the velocity increases to about 1495 m/s at approximately 2.5 km depth. Our model compares well with estimates from CTD (Conductivity, Temperature, Depth) data collected nearby, suggesting that the modelling of water multiples from OBS data might become an important oceanographic tool.

Key words: Arctic, Atlantic Ocean, controlled source seismology, ocean bottom seismometers, wave propagation, seafloor multiples.

Introduction

Seismic wide-angle profiling with use of air-guns and ocean bottom seismometers (OBS) is one of the most effective techniques in investigations of the crustal

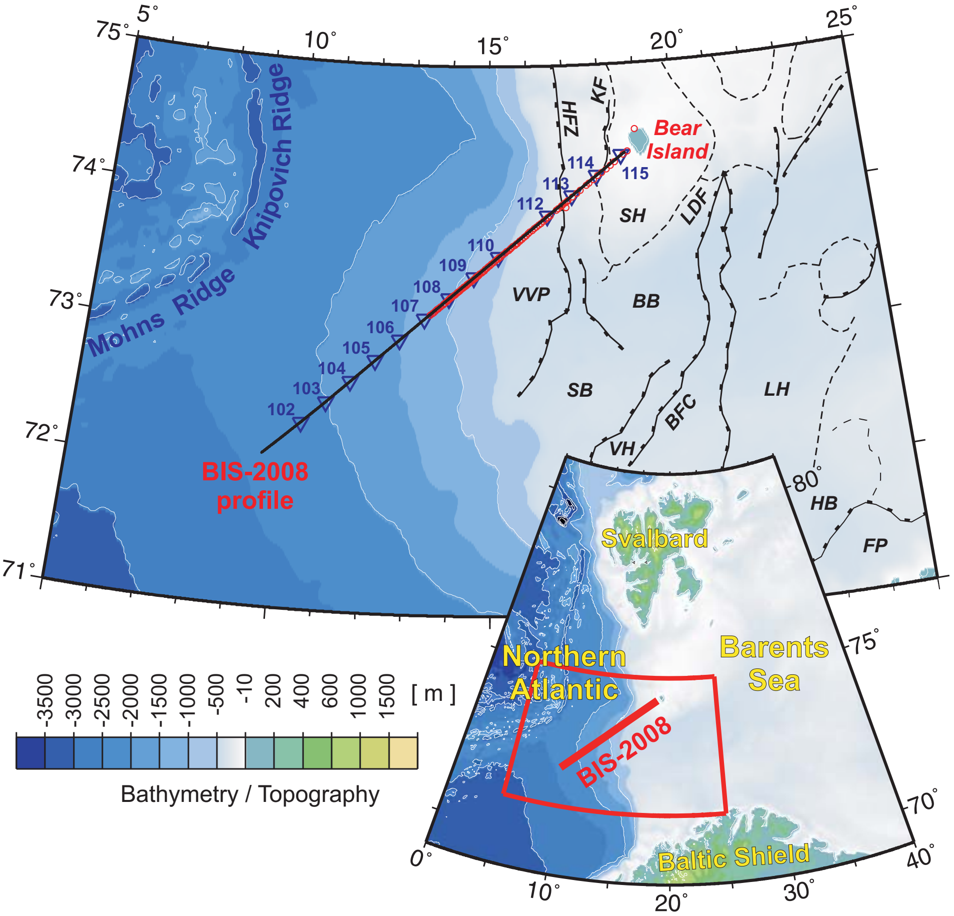

Fig. 1. Location map of the BIS-2008 seismic profile (Mohns Ridge-Bear Island) on the background of a topography/bathymetry map (Jakobsson *et al.* 2000) and simplified tectonic elements of the area (Gabrielsen *et al*. 1990; Faleide *et al*. 2008). Main fault zones and basins: BB, Bjørnøya Basin; BFC, Bjørnøyarenna Fault Complex; FP, Finnmark Platform; HB, Hammerfest Basin; HFZ, Hornsund Fault Zone; KF, Knølegga Fault; LDF, Leirdjupet Fault; LH, Loppa High; SB, Sørvestsnaget Basin; SH, Stappen High; VH, Veslemøy High; VVP, Vestbakken Volcanic Province. Blue open triangles are OBSs with their numbers (102–115). Small red circles show locations of 104 TNT shots with average distance intervals of 2 km, and black line shows 1914 air-gun shots with distance intervals of ~200 m. The red frame in insert is the area for which details are shown in the main map.

structure beneath oceans (*e.g.* Mjelde *et al.* 2008). In August 2008, the seismic refraction profile BIS-2008 (Bear Island – South) was acquired within the 4th International Polar Year (IPY) project "The Dynamic Continental Margin Between the Mid-Atlantic-Ridge (Mohns Ridge, Knipovich Ridge) and the Bear Island Region" (Fig. 1; Schweitzer *et al*. 2008a, b). The 410 km long SW-NE striking profile crosses the boundary between the oceanic crust of the North Atlantic and the continental crust of the Barents Sea platform, and the crustal structure derived from this

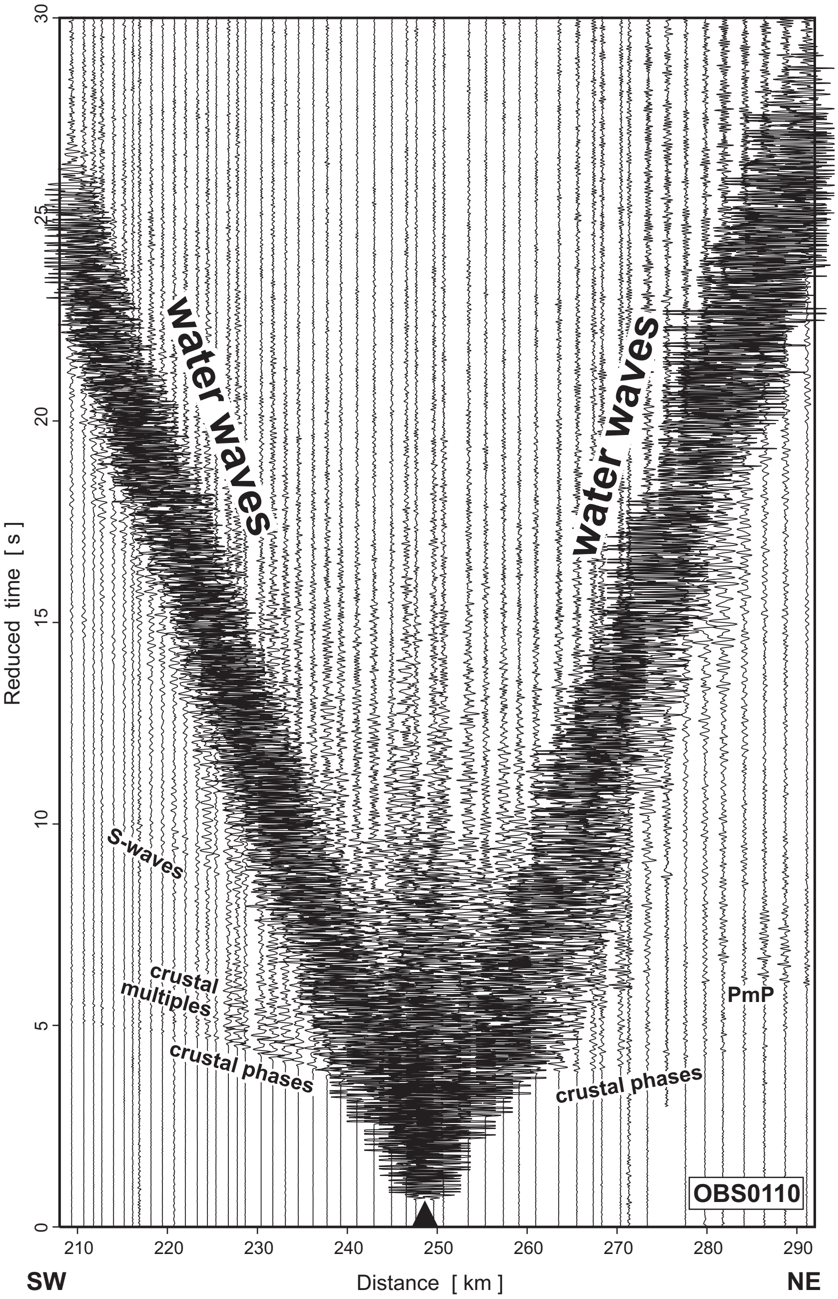

Fig. 2. Example of amplitude-normalized, vertical-component seismic section of TNT shots recorded by OBS110; location of the OBS is shown by black triangle. Note characteristic strong phases recorded in the oceanic part of the profile – water waves (direct and multiples), which contain most of the energy, relatively weak P-waves in the crust and uppermost mantle, multiples and S-phases. Band-pass filtration is 3–17 Hz and reduction velocity is 8 km/s. The amplitude scaling factor (ampl = 6.05) is trace normalized and corresponds to 6.05 km of the distance scale.

profile were presented by Czuba *et al*. (2011). The main task for deep seismic soundings by use of the refraction technique is recognition of the sedimentary cover structure including hydrocarbon reservoirs, crystalline basement and the crust-mantle transition (Moho).

In addition to sedimentary and crustal arrivals, the seismic wave field recorded off-shore contains high-energy waves that have propagated in the water layer only. During processing of multichannel seismic data, much effort is generally used in order to reduce such strong water reverberations. It has been shown, however, that processing of the data aiming at imaging the water layer itself can provide useful oceanographic information (*e.g*. Holbrook *et al.* 2009). The direct down-going wave and seafloor multiples have very high amplitude in OBS data (Fig. 2), but since the crustal arrivals of interest generally arrives earlier, the direct wave is usually not considered in further processing and modelling of the data. In this paper we will show, as a feasibility study, that modelling of the seafloor multiples can provide a detailed estimate of the sound velocity in the water layer. This new approach of handling OBS data might become an important oceanographic tool.

Data acquisition

The seismic refraction experiment along the North Atlantic BIS-2008 profile was performed in August 2008 with use of two ships: Norwegian *R/V Håkon Mosby* and Polish *R/V Horyzont II*. The geographical coordinates of BIS-2008 profile terminations are: ϕ_0 = 72.114°N, λ_0 = 9.600°E (southwesternmost air-gun shot), ϕ_{end} = 74.460°N, λ_{end} = 19.263°E (Bear Island in northeast; Fig. 1). The sources of seismic waves were air-gun and chemical shots performed in the sea. Off-shore air-gun shooting along the whole profile length was done by *R/V Håkon Mosby* with use of a system of four air-guns of volume 1200 in^3 each (total volume of 4800 in^3 or 78.66 l). Altogether 1914 air-gun shots were performed with distance intervals of 200 m (corresponding to about 1 minute time interval), at a water depth of 10–12 m. A total of 104 chemical shots (25 kg of TNT each) were fired in the water by *R/V Horyzont II* along the northeastern part of the profile (distance along profile 176.4–385.5 km), with average distance intervals of 2 km. The firing depth of the chemical explosions was approximately 30 m.

All shots were recorded by 15 short-period, three-component ocean bottom seismometers (OBS; station numbers 102–115) deployed by *R/V Håkon Mosby*. Location determination and synchronization of all shots and seismic receivers were obtained using the GPS satellite system. All OBSs recorded continuously during the experiment with a sampling rate of 4 ms (256 Hz). After resampling to 10 ms (100 Hz) records of 60 s length (with zero time corresponding to original shot time) were tied to the navigation.

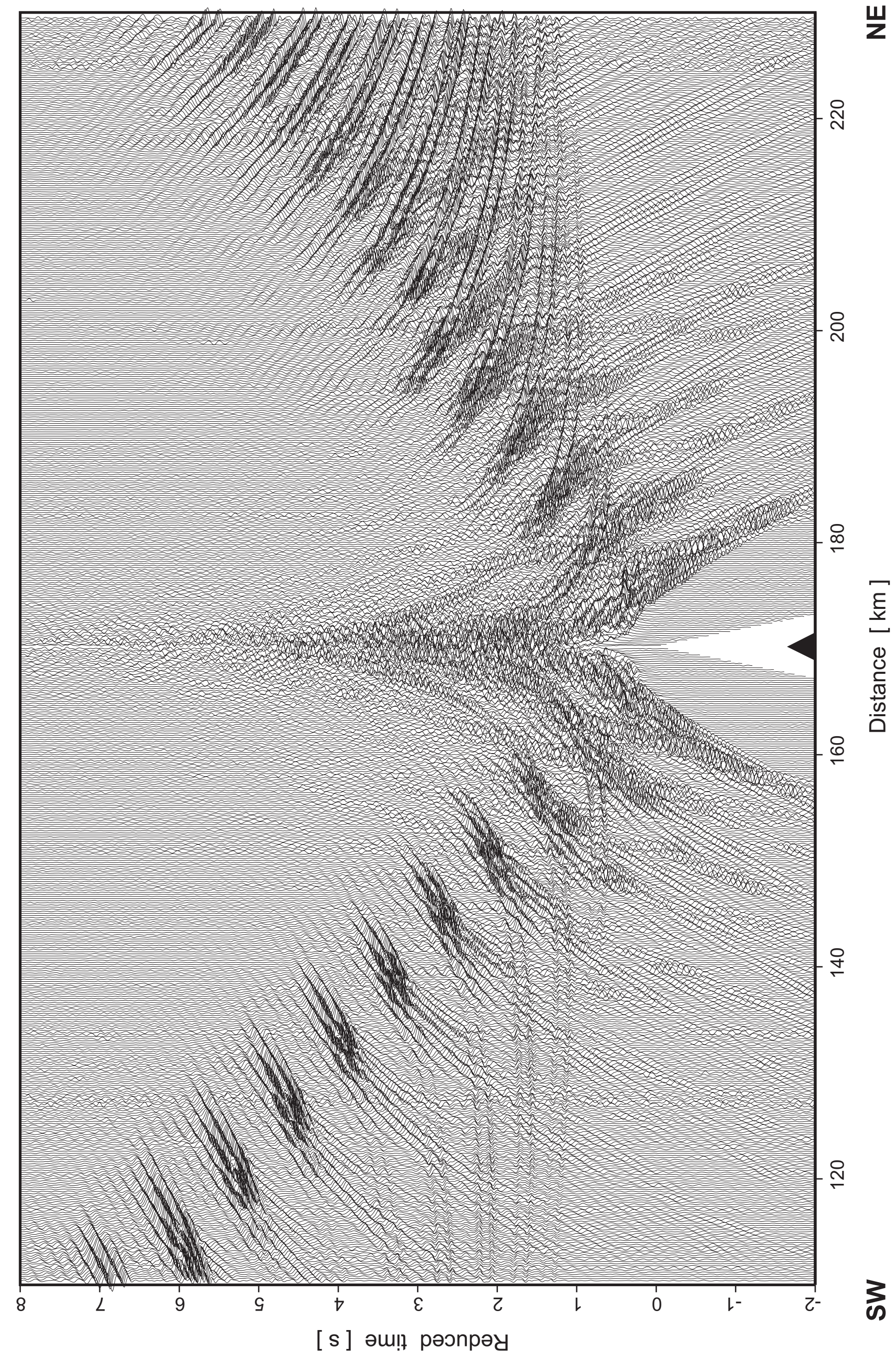

Fig. 3. Example of amplitude-normalized, vertical-component seismic section of air-gun shots recorded by OBS107 located in the middle of the profile. Band-pass filtration is 2–15 Hz and reduction velocity is 1.5 km/s. Note the asymmetry of water multiples between the *ca* 2 km deep ocean (left part of the section) and shallower, *ca* 1 km water depth (right side).

Observed seismic wave field in water

The seismic records obtained along the BIS-2008 profile are of good-quality, which allowed detailed wave field analysis and crustal structure modelling (Czuba *et al.* 2011). In the interpretation process, different bandpass filters, zooms and amplifications were applied to record sections in order to display interesting arrivals as clearly as possible. Seismic wave fields recorded off-shore are usually dominated by waves propagating in the sea: the direct water wave, bubble pulses and multiples. An example for an amplitude-normalized seismic section from TNT shots recorded by OBS110 is shown in Fig. 2. Strong water waves (direct and multiples) recorded in the oceanic part of profile contain most of the seismic energy, while waves from the crust and uppermost mantle are much weaker.

Although records of chemical shots have the best signal-to-noise ratio, air-gun shots have advantages in more stable pulse shape and better spatial sampling. The short distance between shots (in this case 200 m) permits straight forward correlation of phases from trace to trace. An example of air-gun shots recorded by OBS107 located in the middle of the profile is shown in Fig. 3 (plotted as wiggle trace WT). The plot shows all traces spaced every 200 m and plotted as amplitude-normalized seismograms. The reduction velocity is 1.5 km/s and it is easily seen that the strongest water phases propagate with a velocity slightly slower than 1500 m/s. The 2–15 Hz band-pass filtered seismograms are dominated by water multiples, which appear much stronger than crustal arrivals and their multiples (seen with higher velocities recorded closely to the OBS, in the reduced time interval from -2 to 1 s). The asymmetry of the water multiples results from the depth to the seafloor, which changes from *ca* 2 km in the left part of the section to *ca* 1 km depth on the right side.

Fig. 4 demonstrates the large pattern differences of the recorded water waves between an OBS deployed at 2 km depth (OBS104) and 0.5 km depth (OBS110), respectively. Note the much higher resolution for the dense air-gun source in comparison to the coarser TNT shots recorded by the same instrument (OBS110; Fig. 2). Another visualisation has been used for OBS103, OBS109 and OBS114 in Fig. 5. All traces are here plotted as variable area (VA) plot with band-pass filtration 2–15 Hz and reduction velocity 1.5 km/s. The amplitude-normalized, vertical-component seismic sections of the air-gun shots illustrate how the pattern of water multiples changes with ocean depth h and distance x along the profile. In the case of a deep ocean floor, consecutive multiples are clearly separated from each other. For OBS103, located at 2015 m depth, the direct water wave traveling from the surface to the seafloor is recorded in reduced time at about 0.3 s. The first multiple needs to travel back to the surface and then back again to the seafloor in about 0.6 s, and is thus recorded at about 0.9 s. Subsequent multiples are also delayed by about 0.6 s, and hence recorded at 1.5 s, 2.1 s, etc. For OBS109, located at 878 m depth, the time difference between multiples is much shorter, and for OBS114, located at 240 m depth, the individual multiples interfere.

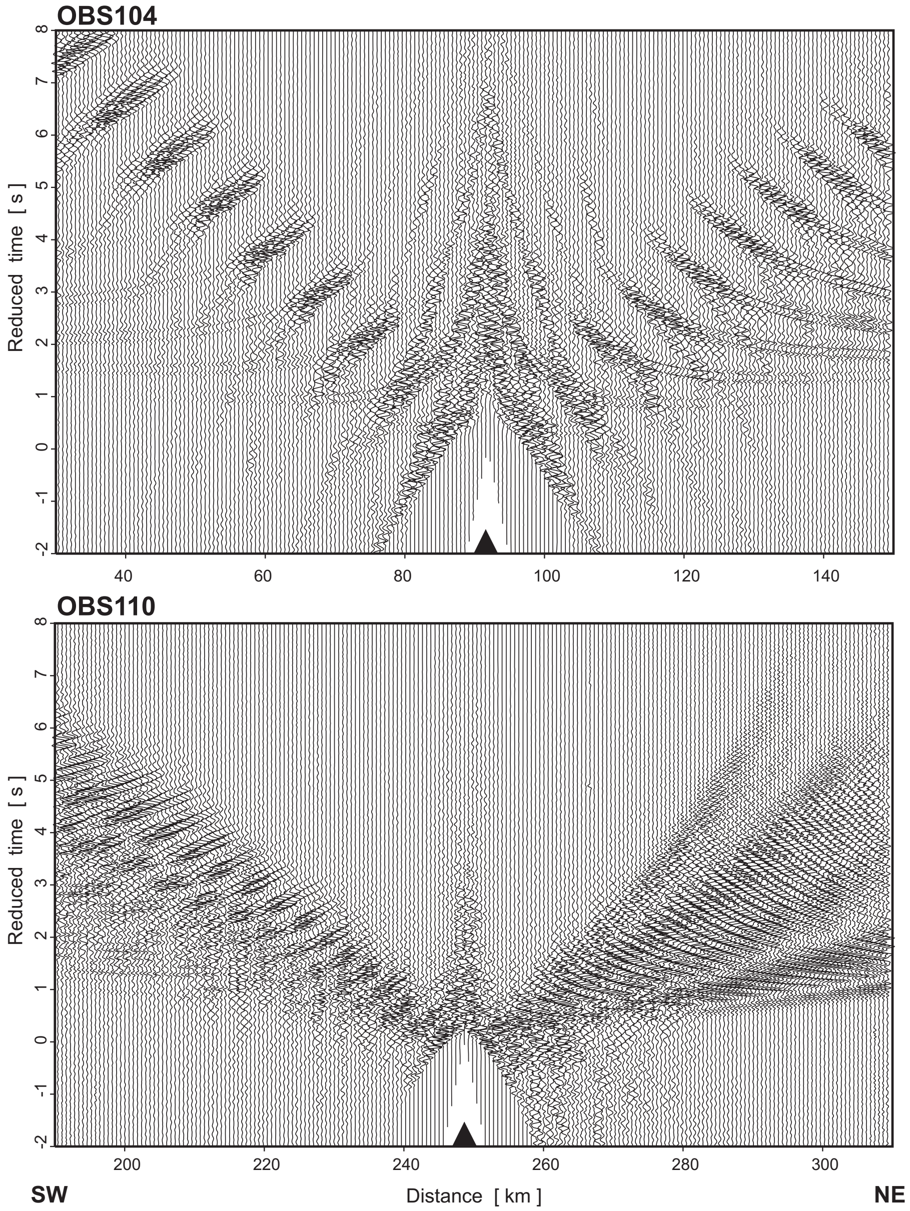

Fig. 4. Example of amplitude-normalized, vertical-component seismic sections of air-gun shots recorded by OBS104 and OBS110 (compare with Fig. 2). Each third trace is plotted, band-pass filtration is 2–15 Hz and reduction velocity is 1.5 km/s.

Variable area plots are adequate for demonstrating correlation of phases and are thus preferred for visiual correlation and kinematic modelling. On the other hand, a wiggle trace (WT) plot express the true relative amplitudes and is hence preferred in dynamic modelling, when observed and calculated amplitudes are compared.

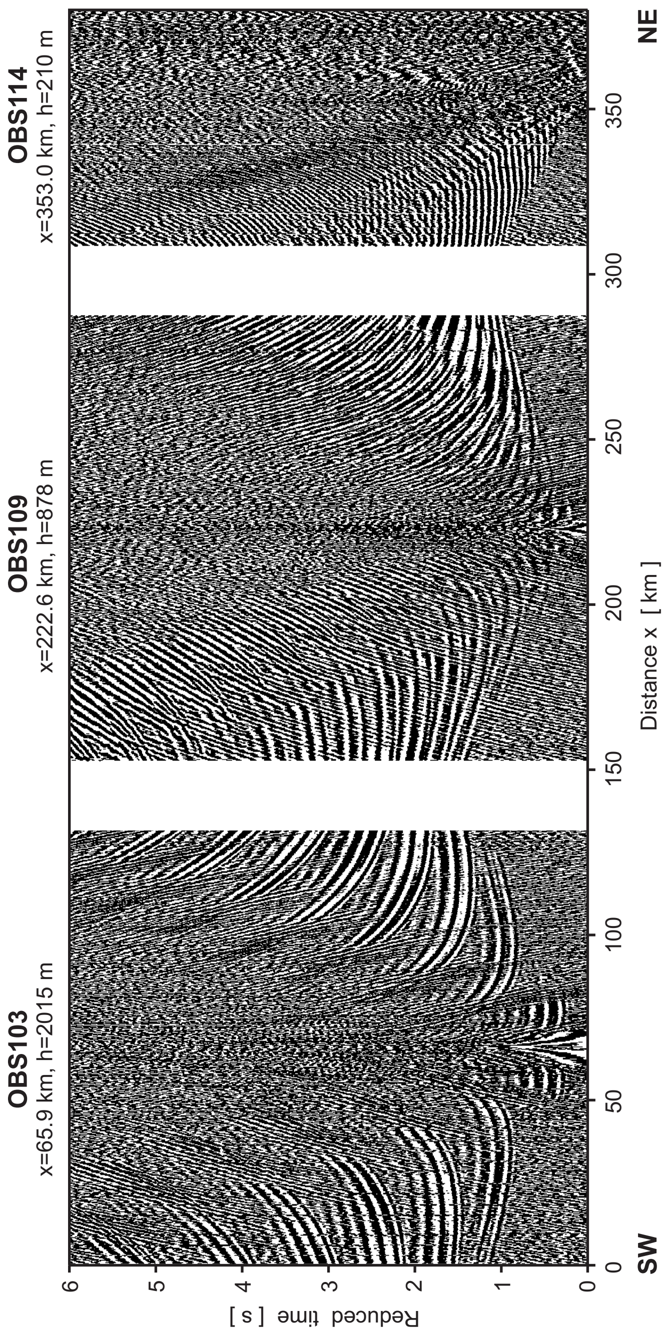

Fig. 5. Example of amplitude-normalized, vertical-component seismic sections of air-gun shots illustrating the changing pattern of multiples with ocean depth, recorded by OBS103, OBS109 and OBS114, respectively. X and h are distances along the profile and depths of the OBSs, respectively. All traces are plotted as variable area (VA) plot, band-pass filtration is 2–15 Hz and reduction velocity is 1.5 km/s.

Modelling method

The 2D modelling of water waves recorded along the BIS-2008 profile was performed using a state-of-the-art ray tracing technique. Computation of travel-times for direct and water multiple phases, as well as ray paths and synthetic seismograms were performed using the SEIS83 software (Červený and Pšenčík 1983). The modelling can be performed with constant velocity, or it can include vertical and horizontal velocity gradients.

Travel-times for the direct wave and the consecutive multiples were successively altered by trial and error and recalculated until congruence was obtained between observed and model-derived travel-times. A misfit of the order of 0.05 s was typical. The modelling was based on the 2D velocity model for sediments, consolidated crust and crust-mantle transition presented by Czuba *et al.* (2011).

Derivation of 2D sound velocity model in water

In the modelling of ocean sound velocity distribution along the BIS-2008 profile we used record sections plotted with a reduction velocity of 1.5 km/s. The reduced time interval from -2 to 8 s is dominated by water waves, with exception of crustal waves with higher velocities recorded in the vicinity of the OBSs. All record sections with water waves are of high quality, but due to their increased spatial resolution, most of the modelling was based on the recordings from the air-gun shooting.

In the first step of modelling we used models with constant water velocity. The water depth was taken from the echo sounder, which recorded continuously along the profile. The sea bottom depth changes from about 2400 m in the SW end of the profile, to about 1200 m near the continental-ocean boundary at about 250 km along the profile, and to zero at the Bear Island coast in the NE end of profile (see bathymetry in Fig. 1). Examples of modeled water multiples for the homogeneous water model are shown for OBS102 in Fig. 6. The figure shows the recorded section for OBS102, and sections with calculated travel-times for constant velocities in the water of V = 1460, 1470 and 1480 m/s, respectively. In all three cases the travel-time of the direct water wave fits the recorded arrivals well (see distance interval 25–55 km along the profile). However, for the water multiples the fit is not satisfactory for the 1460 and 1480 m/s cases; note late arrivals for 1460 m/s and early arrivals for 1480 m/s. For velocity V = 1470 m/s the fit is very good, which means that the average velocity of sound in this part of profile is very close to 1470 m/s. This comparison shows that the average sound velocity in the water can be estimated to ±3 m/s.

A different wave field is observed in the case of shallow water. The amplitude-normalized, vertical-component seismic section recorded by OBS115 in very shallow water (36 m) is shown in Fig. 7. No water arrivals can be observed in the air-gun section (Fig. 7a), while in the TNT section (Fig. 7b), clear water arrivals

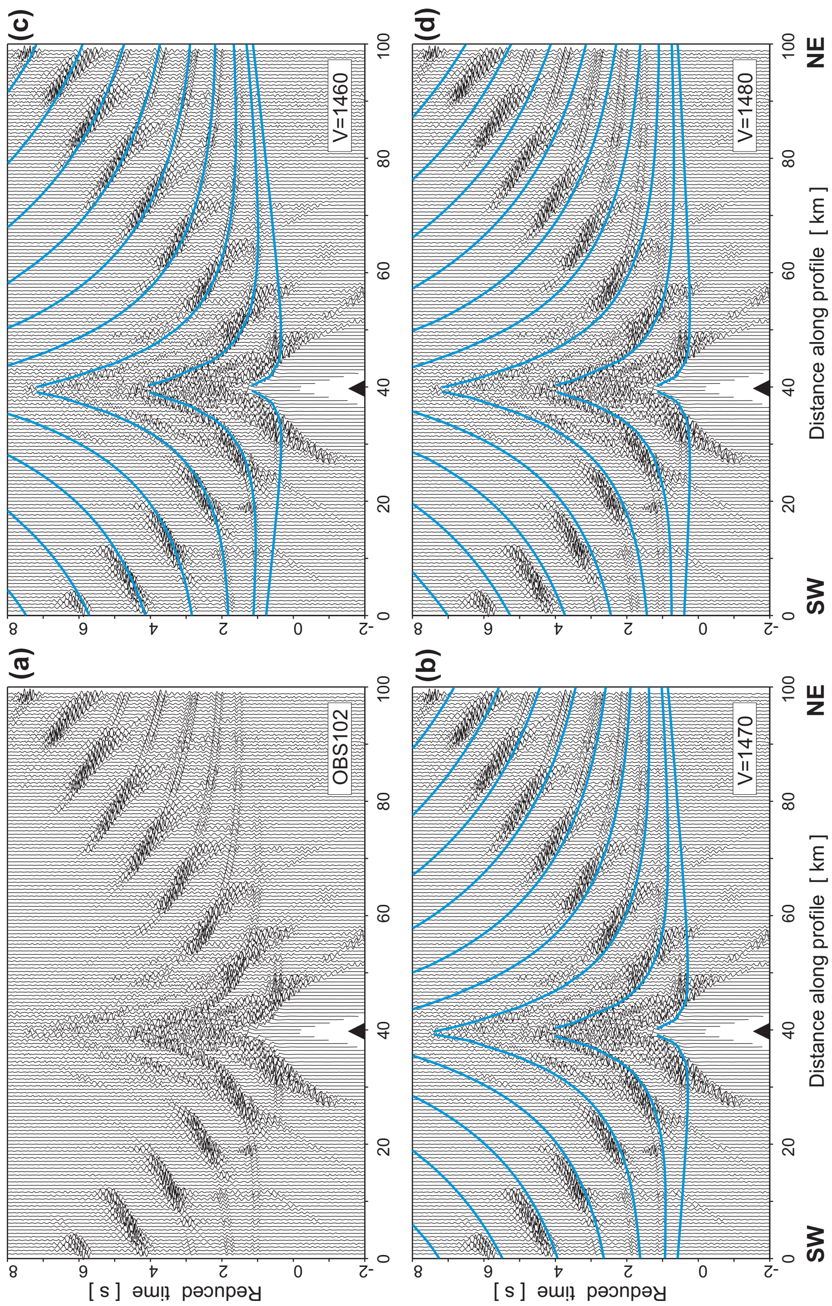

Fig. 6. Examples of modelled water multiples for the homogeneous water model. Labeled are the recorded section for OBS102 and sections with calculated travel-times (blue lines) for constant velocities in water: V = 1460, 1470 and 1480 m/s, respectively. Note the late arrivals for 1460 m/s and early arrivals for 1480 m/s. For V = 1470 m/s fitting is very good. This example shows that the average velocity in the water layer can be determined to ±3 m/s. The observed cut-off of the direct wave at about 40 km offset shows the necessity of including a vertical velocity gradient in the water.

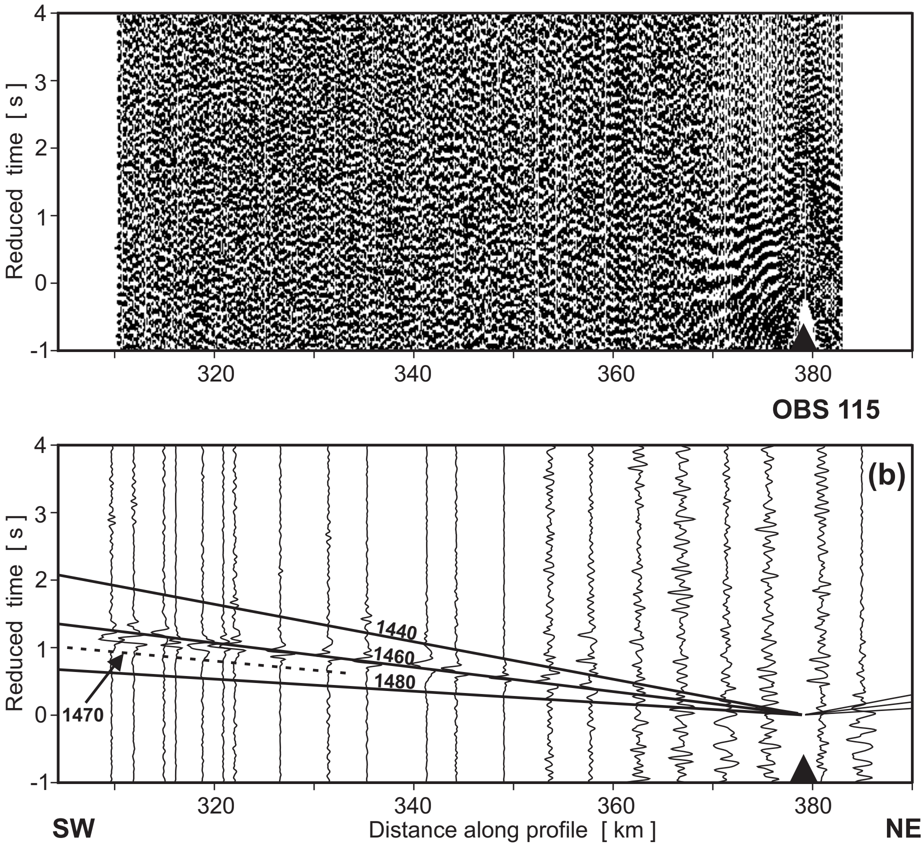

Fig. 7. Example of amplitude-normalized, vertical-component seismic sections of air-gun shots (a) and TNT shots (b) recorded by OBS115 in very shallow water (36 m). No water arrivals can be observed in the air-gun section (upper), while clear water arrivals are seen in the TNT section (lower). Solid lines are travel-times of the water wave with constant velocities of 1440, 1460 and 1480 m/s, respectively. A constant sound velocity of about 1460 m/s seems to represent a good envelope for water phases close to the OBS, while slightly higher speeds are required at 310–330 km distance (dashed line for 1470 m/s).

are seen. The solid lines show calculated travel-times of the water wave with constant velocity V = 1440, 1460 and 1480 m/s, respectively. A constant sound velocity of about 1460 m/s seems to represent a good envelope for water phases close to the OBS, while slightly higher speeds are required at 310–330 km distance (see the dotted line for 1470 m/s).

The calculation with constant velocity gives travel-time branches extending to maximum offset. The observed sections however, demonstrate termination of arrivals at certain offsets. For OBS102 (Fig. 6) the direct water wave is terminated at about 20 km distance towards SW, and at about 60 km towards NE. The first water multiple arrival is terminated at about 80 km distance towards NE. The long travel-time branches of the direct wave and multiples in the homogeneous model show the necessity of including a vertical velocity gradient in the water layer.

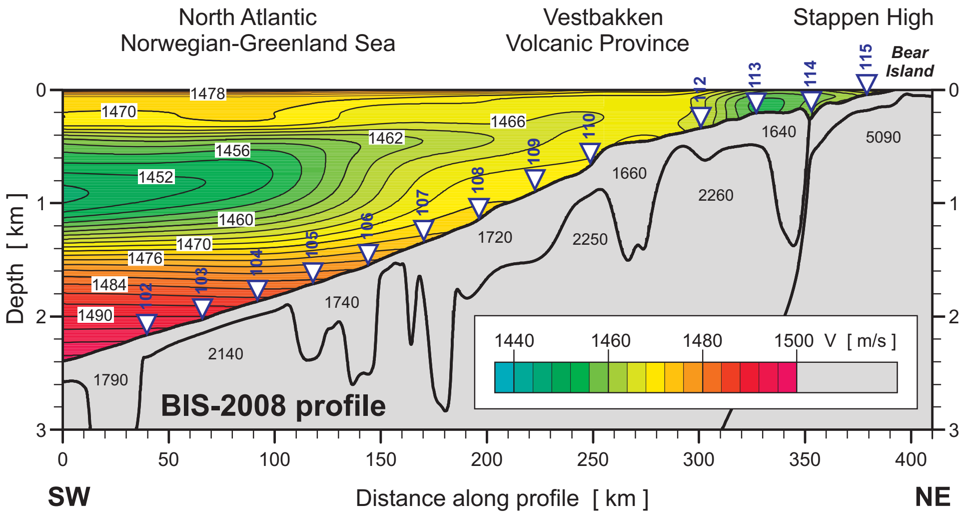

Fig. 8. Water velocity model obtained by trial and error fitting using the SEIS83 package (Červený and Pšenčík 1983). Isolines of velocities in the water are plotted each 2 m/s. The sedimentary velocities (gray area) are from Czuba *et al.* (2011). The blue and white triangles show the location of the OBSs (102–115).

The initial P-wave velocity for the water layer was assumed to be 1470 m/s, which was slightly changed during the modelling process. The final velocity values, shown in Fig. 8, were in the range of 1450–1490 m/s and represent typical sound velocities for the Arctic waters (Walczowski 2009). Examples of the kinematic modelling are shown for OBS103 and OBS108 in Fig. 9. Here, theoretical travel-times calculated for the final water velocity model are plotted on the observed record sections. In addition to kinematic modelling, synthetic seismograms were calculated in order to control the velocity gradients within the water layer, the velocity contrast between water and the seafloor, the Vp/Vs ratio in the shallowest sedimentary layer, as well as the quality factor (Qp) for P-wave attenuation. The modelling of the elastic parameters for the uppermost sediments is presented by Grad *et al.* (2012). Fig. 10, showing the synthetic seismogram for OBS105, demonstrates good qualitative agreement between calculated and observed amplitudes for the water arrivals, as well as refracted and reflected crustal waves.

Sound velocity model

The model of sound velocity along the BIS-2008 profile shown in Fig. 8 demonstrates that the water velocity varies over a relatively wide range from about 1450 m/s to 1490 m/s. In the oceanic crustal part of the model (distance 0–250 km along the profile), the velocities in the uppermost 400 m are in the range 1465–1475 m/s. In the coastal area of Bear Island, velocities from 1455 to 1460 m/s were found in the

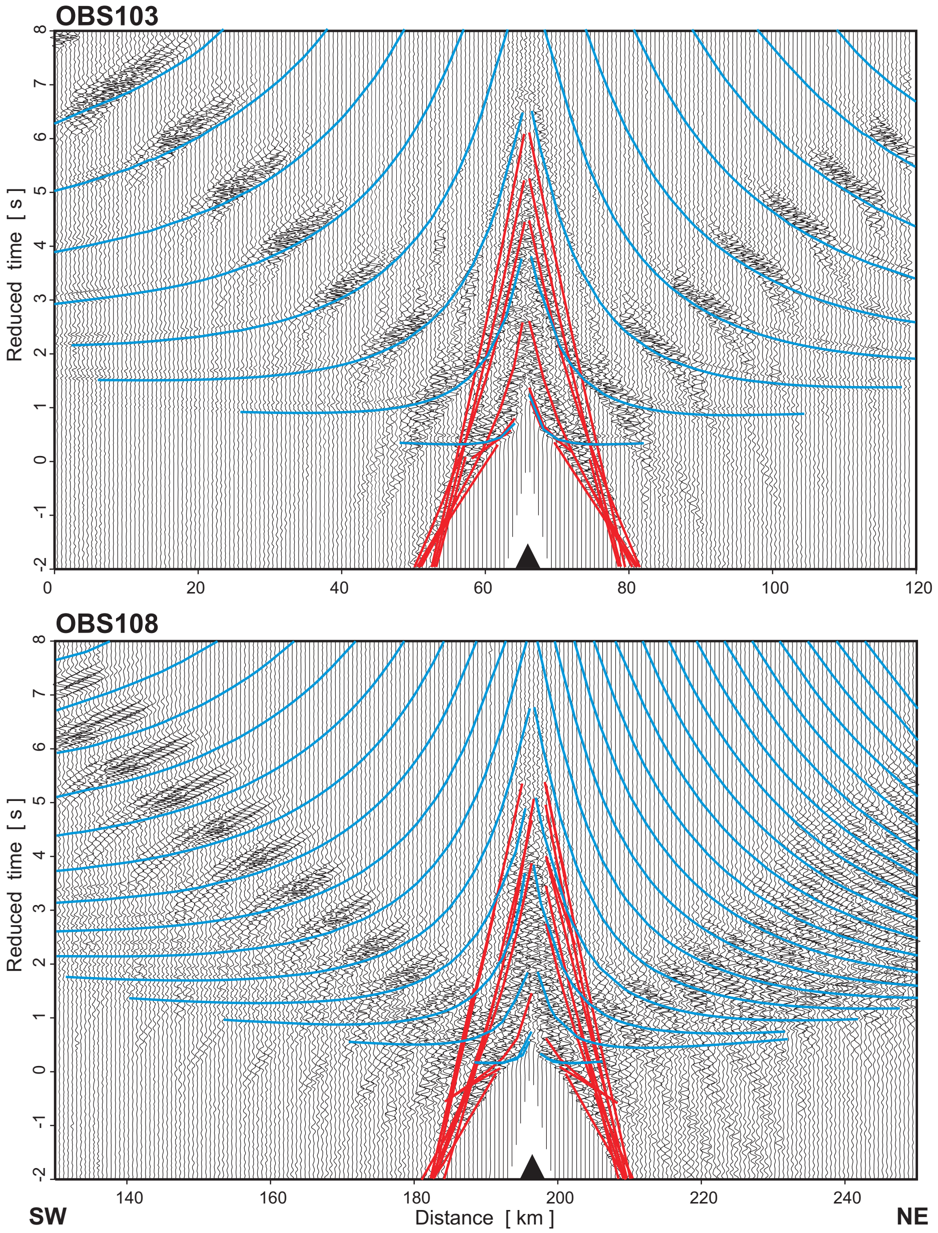

Fig. 9. Examples of travel-time fit for the final model for OBS103 and OBS108. Blue lines are calculated travel-times of water multiples and red lines calculated travel-times of crustal phases.

depth range 0–200 m. This is significantly slower than velocities derived for the same depth range in the open ocean. In the deep ocean, the lowest velocities of about 1450–1455 m/s are found in the depth range 0.6–1.2 km (SOFAR channel). At the depth of about 1.5 km the sound velocity reaches a value of about 1475 m/s, and it

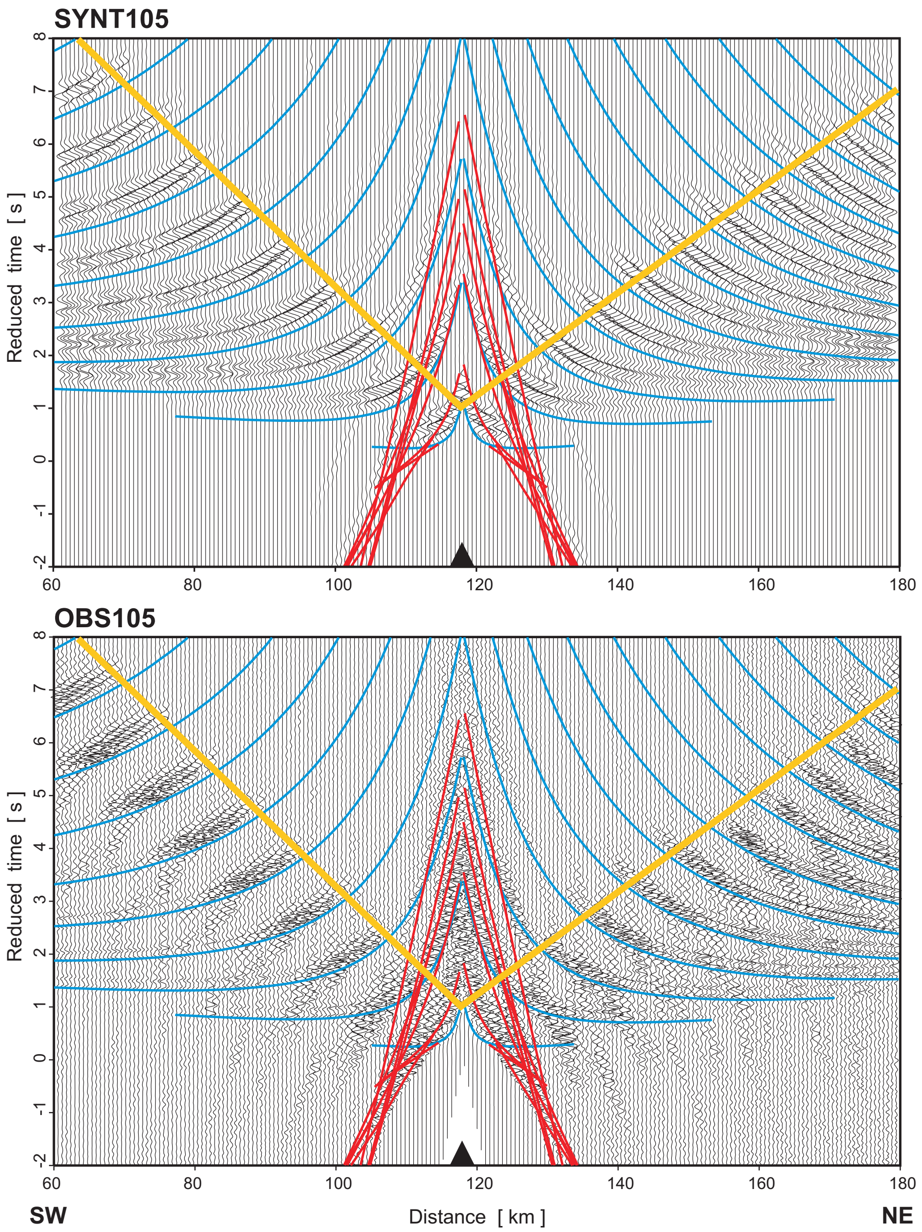

Fig. 10. Example of travel-time fit for the final model for OBS105. Blue lines are calculated travel-times of water multiples and red lines calculated travel-times of crustal phases. Above: the synthetic seismograms for the same OBS. The thick orange lines show the envelope of strong amplitudes related to the water multiples.

increases to about 1495 m/s at approximately 2.5 km depth. The modelling thus reveals high velocities near the ocean surface, lower velocities at about 1 km depth, and increasing velocities towards the deeper ocean. Vertical velocity gradients are needed in order to terminate the travel-time branches at the observed offsets, and lateral velocity variations are also observed.

The P-wave velocities in the seafloor sediments were found along the whole profile length west of the Bear Island (Grad *et al.* 2012). The modeled velocity of 1.7–1.8 km/s is only slightly larger then the velocity in water, due to high porosity. The testing of constant velocity models for the water arrivals showed that the accuracy of the average velocity could be estimated as ±3 m/s, or better. Similar accuracy was obtained by trial and error modelling by use of the ray tracing technique.

Comparison to CTD data

CTD (Conductivity, Temperature, Depth) profiling represent the state-of-the-art technique in oceanographic investigations of the physical parameters of oceanic water. The CTD acquisition results in 2D profiles along which the electric conductivity, temperature and pressure have been measured with depth at a certain interval. The CTD tool is generally retrieved vertically with a velocity 1 m/s velocity. A typical sampling frequency of 24 Hz thus provides one measurement for each 4 cm, which results in a much higher resolution than provided by the OBS technique. A typical low-frequency source used for OBS surveys has a vertical resolution of about 30 m for the water arrivals.

From measured electric conductivity the salinity can be determined. Using salinity (S; in PSU) and temperature (T; in °C), the sound velocity in water (c; in m/s) with depth (z; in m) can be calculated using the simple formula (Clay and Medwin 1997):

$$c = 1449.2 + 4.6\,T - 0.055\,T^2 + (1.34 - 0.01\,T)\,(S - 35) + 0.016\,z \qquad (1)$$

To compare our sound velocity determination with CTD data we used measurements of salinity and temperature made with depth in the Northern Atlantic (Walczowski 2009). In the summer of 2001, they measured salinity and temperature down to 2 km depth along a profile at 75°N (about 200 km north of the central part of the BIS-208 profile). Typical values of S and T are shown in Fig. 11 (solid lines). The most significant changes are observed in the upper 600 m of the ocean (see also Leroy *et al*. 2008). For larger depths the changes of both S and T are small, and the velocity is found to increase close to linearly with depth.

The velocity values along our 2D model of the BIS-2008 profile are shown by the grey area in Fig. 11 (minimum to maximum values). Down to 1.5 km depth the CTD and BIS-2008 values coincide, but for larger depths the seismic velocities are 5–10 m/s larger than those derived from the CTD data. We consider the similarity between the measurements satisfactory, taking into account the differences related to location and time of acquisition. This shows that the water arrivals in OBS data can be used to obtain a continuous “snapshot” of first order oceanographic properties along 2D profiles.

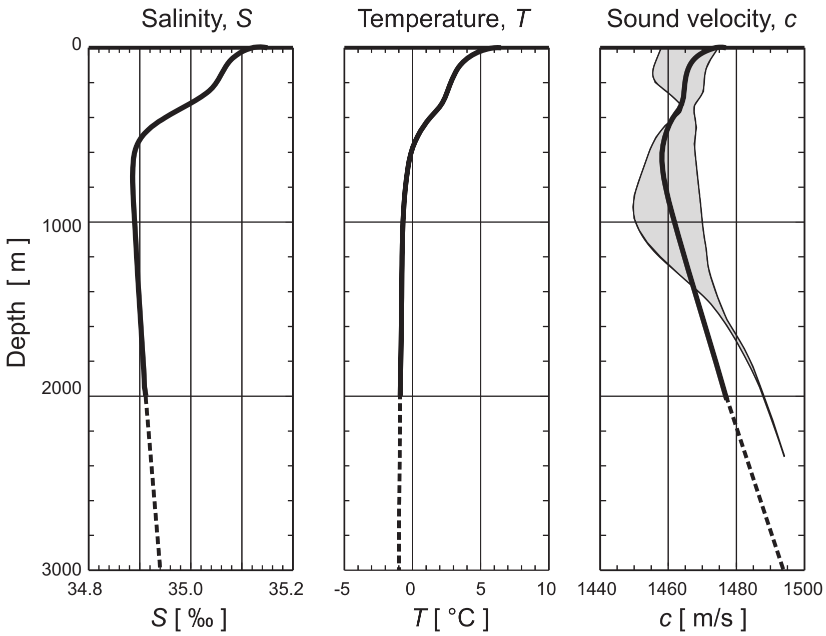

Fig. 11. Salinity (*S*) and temperature (*T*) distributions (solid lines) in the Northern Atlantic at 75°N, measured in the summer of 2001 down to 2 km depth (Walczowski 2009), with extrapolation down to 3 km depth (broken lines). The sound velocity (*c*) was calculated using formula (1), see Clay and Medwin (1997). The data from our 2D water model beneath the BIS-2008 profile are shown for comparison by the grey area (range from minimum to maximum value with depth). See text for details.

Conclusions

Seismic wide-angle profiling by use of OBSs represents a widely used technique for crustal and uppermost mantle investigations. When using air-guns or chemical sources, the recorded seismic wave field is dominated by waves propagating in the water, while "useful" crustal waves are significantly weaker. Strong direct water waves and water multiples are generally treated as noise, and large efforts are used during seismic processing in order to minimize their effects.

On the other hand, well recorded water waves may contain information about sound propagation in the ocean. We show examples of seismic sections from the Northern Atlantic recorded along profile BIS-2008. The acquisition geometry, using a dense system of air-gun shots recorded by OBSs, permits precise correlation of the recorded phases. The short pulse emitted by the source allows clear discrimination between arrivals of consecutive multiples. The pattern of the recorded wave field shows significant changes of multiples with ocean depth. Consecutive travel-time branches of water multiples are very sensitive for the sound velocity distribution, much more sensitive than the direct water wave alone. For the same geometry of source and receiver each additional multiple reverberation can be used to determine the mean velocity more precisely because of the longer ray-path.

Terminations of water arrivals at certain offsets demonstrate the need to include vertical gradients and horizontal inhomogeneities in the modelling. The 2D sound velocity distribution in the water along the BIS-2008 profile is modeled to vary from about 1450 m/s to about 1490 m/s. The velocities in the uppermost 400 m range from 1455 to 1475 m/s, corresponding to the oceanic thermocline (*e.g.* Walczowski 2009). The velocity reaches a minimum of about 1450 m/s at approximately 1.5 km depth (SOFAR channel). For larger depths the velocity increases close to linearly to about 1495 m/s at 2.5 km depth. In the shelf area of the Bear Island, the velocities of 1455–1460 m/s in depth range 0–200 m are smaller than for the same depths in the open ocean (1465–1475 m/s).

We estimate the uncertainty in the average velocity determined from the 2D modelling at ±3 m/s or better. The modelling provides estimates of both vertical gradients and horizontal inhomogeneities. The derived model fits both observed travel-times and amplitudes.

Direct and multiple waves recorded in seismic experiments provide direct information about the time of phases propagating in water. Measured time can be directly transferred to sound velocity in water. On the other hand, oceanographers calculate sound speed from CTD data. Our sound speed determination compares well with the speed calculated from CTD data in the Northern Atlantic (Walczowski 2009). However, for a more precise comparison the location and time of measurements should coincide.

The new method presented in this paper provides velocity measurements in the water layer on a regional scale; much larger than the local scale provided by CTD measurements and smaller than the global scale inherent in oceanic sound speed tomography (Clay and Medwin 1997). We suggest that the seafloor multiples observed in OBS data provide significant oceanographic information, which could be "regained" from many profilings done over the world ocean in last decades. We speculate that the modelling of multiples from OBS data might become an important tool for monitoring oceanic currents and heat transport on regional scale (Piechura and Walczowski 2009; Walczowski *et al.* 2005), as well as in past. For the future, we encourage geophysicists to include the water arrivals in state-of-the-art modelling, and suggest that CTD measurements should be collected above each OBS location in future surveys. Simultaneous use of the two methods needs further exploitation.

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