Z-99 Sub-basalt imaging – integration of surface and ocean bottom seismic data

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Abstract

Potential hydrocarbon-bearing sediment structures in the Faroe-Shetland Basin are often overlain by basaltic sequences of stacked flows up to several kilometers thick. The highly reflective top and base boundaries of these flood basalts and their complex internal structure create strong multiple reflections and severely attenuate seismic energy. To achieve better resolution of the sedimentary formation below these basaltic layers we recorded surface seismic reflection data using a broad-band, low-frequency source. We also recorded seismic data along the same profile with a dense deployment of ocean bottom seismometers (2 km spacing). Integration of these complementary data sets yields increased confidence in the interpretation of sub-basalt features. It reveals complex features between the base of the massive basaltic sequence (~3 km thick) and the basement of presumed Cretaceous age.

Introduction

It is difficult to image structures beneath massive basaltic sequences with conventional seismic acquisition and processing methods. The complex internal basaltic structure strongly scatters and highly attenuates seismic energy. Further, the generally weak sub-basalt signal may be obscured by short-period multiples generated at intra-basalt boundaries. Recent investigations have shown that integrated near-offset and wide-angle acquisition (Fliedner and White, 2001a) combined with a broad-band, low-frequency source (White et al., 2002) have the potential to overcome some of the aforementioned difficulties.

In summer 2002 the iSIMM (integrated Seismic Imaging and Modelling of Margins) project successfully completed a seismic program on the northwest European Atlantic margin with Q-Marine streamer and ocean bottom seismometer (OBS) acquisition. With this comprehensive data set, we will be able to map the base of the basaltic sequence constrained by reflection and refraction data. In this paper we show that use of a broad-band, low-frequency source significantly improves the quality of the final seismic image. Figure 1 shows parts of the seismic reflection profile recorded across the Faroe-Shetland Basin. Furthermore, we demonstrate that recording and processing of densely sampled reflection data combined with information contained in long-offset OBS data enhances confidence in the interpretation of sub-basalt features.

Q-marine and OBS acquisition and processing

Since stacked basalt flows typically exhibit low-pass character to seismic waves, our objective was to design a source wavelet which penetrates through such a sequence without significant loss of its energy. Adapting the approach of Avedik et al. (1996), we designed the airgun array such that the first bubble pulses of the single airguns interfere constructively, which yields a significant amount of low frequency energy in the seismic signal. The unusually large tow depth of the airguns of about 18-20 m further enhances the low-frequency, broad-band character of the seismic signature. Details on the source design and characteristics are published in Lunnon et al. (2003).

The velocity contrast between sediments (~2500 m/s) and the underlying basalt (~4500 m/s) yields large refraction angles and, therefore, reflections from intra-basalt and sub-basalt features are expected to be recorded at large source-receiver offsets. Thus, wide-angle data (in this case to source-receiver offsets of 12,000 m) were acquired along the iSIMM02A profile to ensure that most of the reflected sub-basalt wavefield is recorded. Employing the Q-Marine acquisition system allows such long offsets to be recorded without any restrictions on the spatial source and receiver sampling interval (i.e., 50 m nominal shot spacing, 12.5 m nominal receiver spacing after Q-marine digital group forming of data recorded at closely spaced sensors, where adaptive filtering is applied before data reduction (Ozbek, 2000).

We also deployed 85 four-component OBS (Figure 1), primarily to image the deeper crust and the uppermost mantle and to derive a velocity model for pre-stack depth imaging in the deeper part of the seismic reflection data. However, the first arrival information from these recordings can also be used to estimate the thickness of the basaltic layer. Fliedner and White (2001b) showed that eventually the turning ray (i.e., diving wave) within the basalts hits the base of the basaltic layer and encounters a velocity decrease with depth if it is underlain by sediments. At this point the turning ray terminates and the offset at which this termination occurs is therefore a measure of the thickness of the basalt.

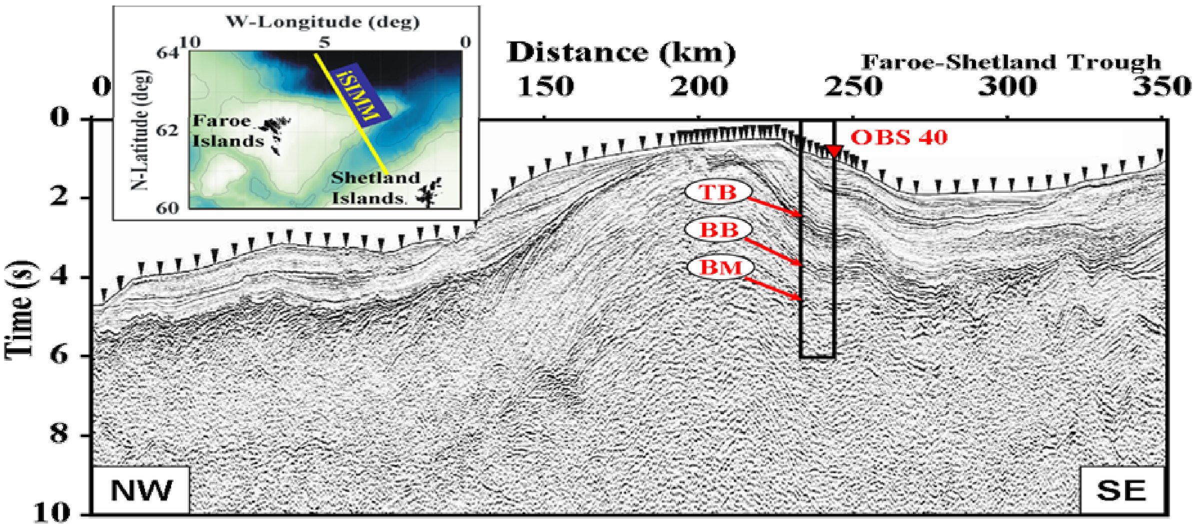

Figure 1. *iSIMM02A seismic reflection profile with location map superimposed. Black triangles at sea floor illustrate locations of OBS stations (2 km and 6 km spacing). Red triangle denotes location of OBS 40 and box marks the location of seismic reflection data, which are both used in this study. TB indicates the top-basalt boundary, BB the interpreted base-basalt reflection, and BM the interpreted basement reflection. Squash plot data courtesy of WesternGeco.*

Results

Applying a processing sequence including shot-by-shot designature, followed by an extensive demultiple sequence (comprising the application of two mute functions in the Radon domain and prediction and subtraction of multiples using wavefield inversion based on the Kirchhoff integral) and Kirchhoff pre-stack time migration yields excellent results. Figure 2a shows an enlarged area of the iSIMM seismic reflection profile (boxed region in Figure 1). Note the detailed image of the internal structure of the massive basaltic sequence from ~3–4 s. The high data quality allows single basalt flows to be identified and, furthermore, features below this sequence can be seen clearly down to 5 s (i.e., interpreted Cretaceous boundary) and below.

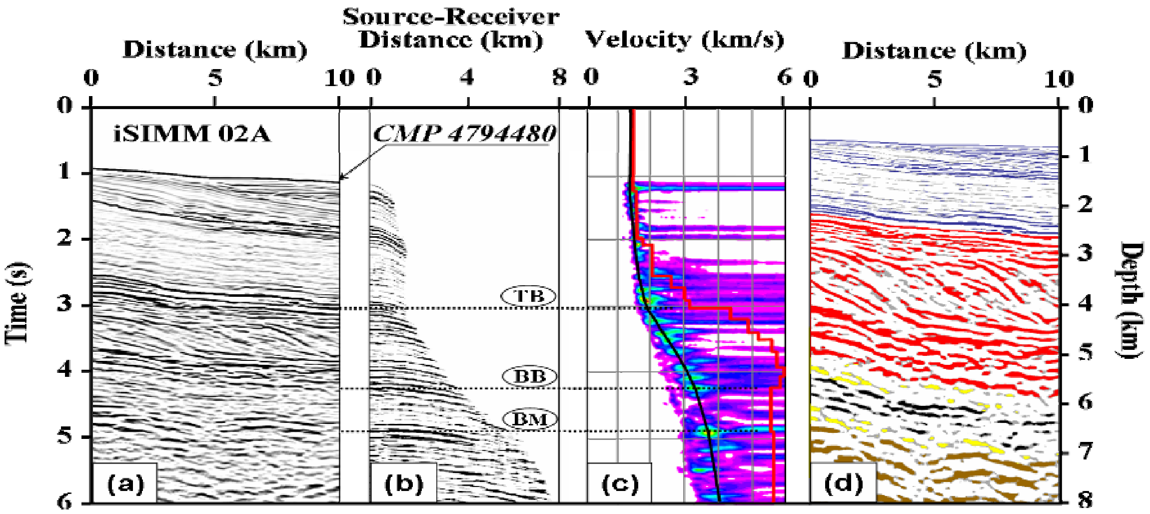

Figure 2. *(a) Enlarged time section of iSIMM02A profile (location indicated by box on Figure 1). (b) CMP supergather (i.e., three adjacent CMP gathers stacked) recorded at position 10 km. (c) Semblance plot derived from CMP supergather in (b) with NMO velocity function (black) and interval velocity function (red). (d) Depth section with interpretation superimposed; time-to-depth conversion performed on data in Figure 3a applying interval velocity function in Figure 3c. Blue – post-basalt sediments, red – stacked basalt flows, yellow – sub-basalt sequence consisting of hyaloclastites and sills (black reflections), and brown – basement of presumed Cretaceous age.*

Figures 2b and 2c show an example CMP supergather recorded along the profile (position is indicated in Figure 2a) and the calculated semblance plot at this location, respectively. It is straightforward to estimate interval velocities (red line on Figure 2c) within the sediments on top of the basalt (varying from 1.6 km/s to 3.0 km/s) and within the basaltic sequence (varying from 4.5 km/s to 6.0 km/s). A velocity inversion from 6.0 km/s to 5.5 km/s is found in the deeper part of the data, which indicates the base-basalt boundary at ~4.2 s. Finally, applying this interval velocity function for time-to-depth conversion yields the depth section shown in Figure 2d (for details about colored scheme see figure caption). This section together with the interval velocity function in Figure 2c served as a 1-D velocity model for the ray-theoretical traveltime calculation of the termination offset for the diving wave in the OBS record.

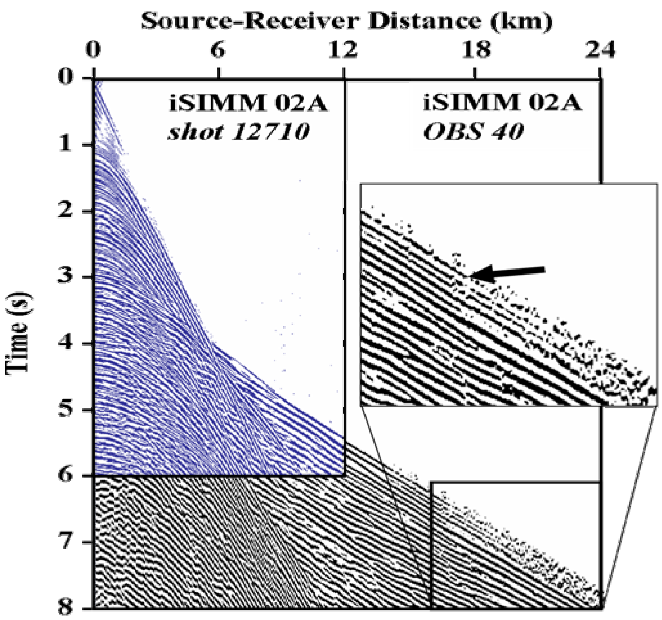

Figure 3. *Shot gather (blue) from iSIMM profile superimposed on traveltime corrected OBS record (black). Both acquired at the same position (Figure 1) with different sources, but similar bubble-tuned wavelets. Trace spacing is 25 m in shot gather, and 100 m in OBS record (i.e., the shot spacing used for the OBS survey). The traveltimes in the OBS record are upward continued to the sea surface to make them comparable with the arrivals in the shot gather. Note the termination of basalt diving wave (i.e., first arrival) at ~17.5 km (indicated by arrow in enlarged area).*

Figure 3 shows an example raw shot gather recorded with the Q-marine system superimposed on an unfiltered OBS record acquired at the same location. Note that the OBS record fits perfectly as an extension of the shot record in both travel time and offset. The OBS record can be used to estimate the thickness of the massive basaltic sequence. Using a velocity gradient of 0.5 /s (calculated from data shown in Figure 2c) within the massive basaltic sequence and a thickness of ~3 km (Figure 2d) yields a ray-theoretical termination offset of ~17.5 km (using equation 2 in Fliedner and White, 2001b), which is consistent with what we observe in the recorded OBS data (Figure 3). Full wavefield synthetic seismogram data (not shown here) further provides confidence in the velocity model shown in Figure 2c and in the interpreted time-to-depth conversion in Figure 2d.

Conclusions

Our ability to image seismically the sub-basalt subsurface at many locations worldwide is limited by the fact that basaltic layers are generally characterized by poor seismic penetration for various reasons, including high reflectivity contrast at the top-basalt boundary, internal scattering and attenuation. To address this issue, we have recorded low-frequency, broad-band Q-marine streamer data that enhance the quality of recordings from sub-basalt regions. In parallel, we also acquired OBS data along the profile. We have shown that these complementary data sets may significantly improve the confidence in the processing and subsequent interpretation of sub-basalt features. The reflection data reveal detailed intra- and sub-basalt structures, whereas the long-offset OBS recordings provide additional information on the velocity structure and thickness of the basalts.

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