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Sub-Basalt Imaging in the Norwegian Sea Using Common-Offset RTM Tomography and Least Squares Reverse Time Migration

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Summary

Sedimentary basins with prospectivity potential beneath volcanic intrusions are common in many parts of the world. However, the rugosity and high-impedance contrast of the basalt create significant challenges in imaging sub-basalt structures. Two-way wave equation techniques may be employed to address the complex multipathing that occurs during propagation of the wavefield through basalt. This is illustrated by the successful application of common offset RTM (COR) tomography and least squares RTM to a 3D data set from northwest Europe. The use of these techniques has significantly improved the imaging and velocity model within and beneath the basalt.

Introduction

In several basins around the world potential prospectivity exists beneath volcanic intrusions. These basins exist offshore (e.g. India, Angola and Greenland) and onshore (e.g. Argentina and Siberia). In Europe, large areas of northwest European waters are affected by basaltic flows extruded in the Palaeocene during extensional phases related to the break-up of northwest Europe and Greenland.

The difficulty of processing sub-basalt data is well documented (Gallagher & Dromgoole 2008; Spjuth et al. 2012). Challenges are caused by the rugosity and high impedance contrast of the basalt coupled with extreme heterogeneity in its internal structure. High-frequency energy is scattered and the low-frequency energy that penetrates through the basalt is overprinted by high energy peg-leg and interbed multiple trains. While the reflection coefficients of the basalt are high, reflection coefficients of sub-basalt reflectors are small and easily obscured by strong noise or multiples.

The highly variable topography of top-basalt surfaces and their heterogeneous internal structure impart considerable complexity to the wavefield as it propagates. While Kirchhoff methods have often been used to image beneath basalt, the complexity of the wavefield requires wave-equation solutions (Jupp et al. 2005). In this work we demonstrate the successful application of wave-equation based methods, specifically reverse time migration (RTM) methods, to the velocity model building together with more recent least squares RTM (LS RTM) imaging methods.

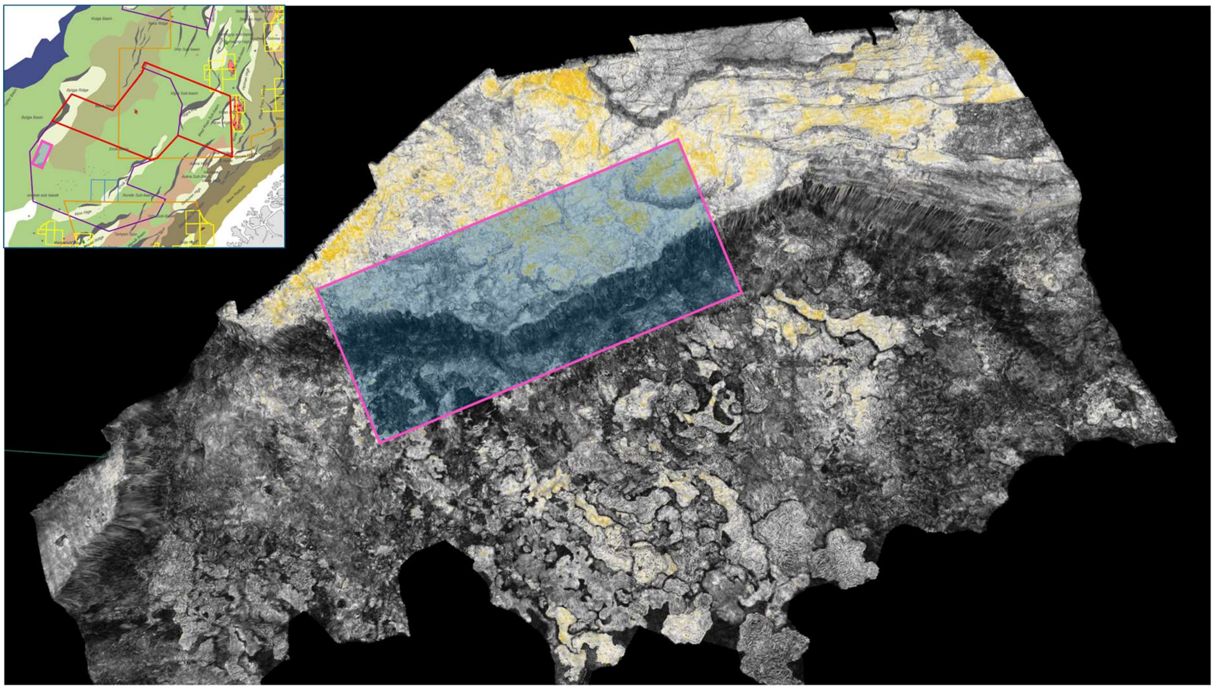

Figure 1 *Location of the survey and test area plotted on an amplitude extraction along top basalt from the fast track Kirchhoff prestack migration (KPSTM) volume.*

Method

Starting in early 2017 we acquired over 45,000 km^2 of 3D seismic data as part of the Atlantic Margin survey. The survey area includes the Møre Marginal High, which extends with a north-easterly trend from the UK border north of the Brendan Basin to the Jan Mayen lineament. The Møre Marginal High is defined by a 150-km long row of untested structural highs based on gravimetrical data and now seen in new 3D data. The main reason that the highs are untested is a volcanoclastic delta that sits above them. The volcanoclastic delta consists of brecciated-flow basalts, pillow lavas interfingered with normal near-shore sediments. This is a very heterogenic interval with large, local seismic-velocity differences. Early versions of the processed data show rotated fault blocks, tilted and faulted strata defining sub-basins around the gravity defined high and which are modeled to be within the oil window.

Any source rocks present could then present leads like those in the Northern Viking Graben or the Halten Terrace.

Depth imaging of rotated fault blocks can be a nontrivial imaging challenge at the best of times. Here, however, the difficulty of the challenge is increased several-fold by the intrusion of a rugose, high-impedance volcanic body above the faulted strata. To ensure the sub-basalt sediments are successfully imaged, a portion of the 3D data, consisting of approximately 790 km^2, is selected with the specific intention of evaluating the benefit of RTM-based techniques for sub-basalt velocity model building and imaging. The flow that is derived has four main elements: 1) a standard reflection tomography for the supra-basalt sediments; 2) intra- and sub- basalt tomography using common offset RTM (COR) gathers; 3) post-RTM image enhancement using directional imaging stacks (DIS) and 4) least squares RTM.

To create an initial Kirchhoff prestack depth migration (KPSDM) velocity model, a time, RMS velocity field is used. It is converted to depth, interval velocity and smoothed along several geologic horizons. Tilted transverse isotropic (TTI) parameters are estimated and the sediment velocities down to the top basalt are updated using image-guided high-resolution tomography (Hilburn, et al. 2014).

In conventional tomography updates, KPSDM or beam migration common-image gathers (CIGs) are used. The accuracy of the velocity update depends on the quality of the residual moveout (RMO) picking on the CIG gathers, which in turn depends on their signal-to-noise ratio. If the signal-to-noise ratio of the CIG gathers is good, tomography using KPSDM or beam migration CIGs can produce a high-resolution velocity model. However, below basalt, the signal-to-noise ratio of KPSDM CIGs is very low due to the poor ray coverage below the complex basalt geometry and the small sub-basalt sediment reflectivity. In contrast, common-offset RTM (COR) gathers (Rodriguez, et al. 2016), handle the poor ray-coverage better and, therefore, have a higher signal-to-noise ratio and more coherent events. The benefit of using COR gathers for RMO picking under basalt because of the higher coherent events is clearly visible in the gathers (Figure 2).

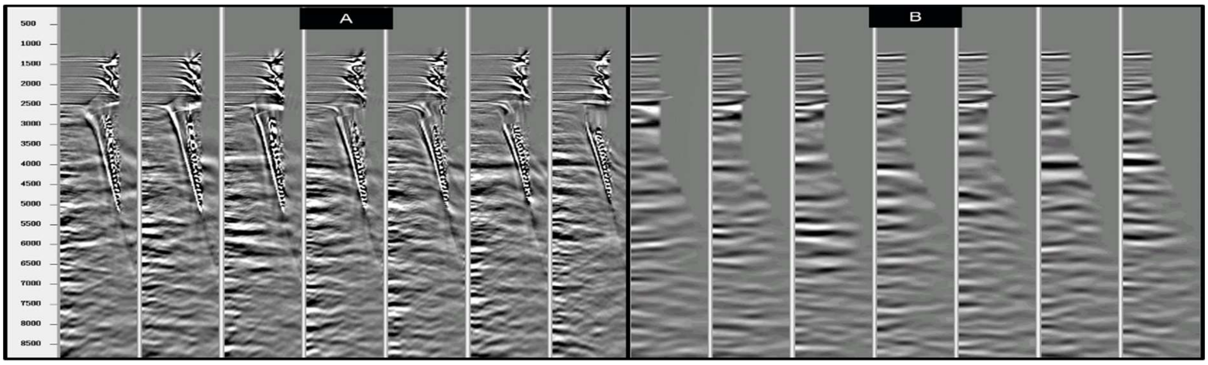

Figure 2 *Depth migrated gathers: a) KPSDM gathers; b) Common offset RTM gathers.*

Further image enhancement was is achieved using RTM directional imaging stacks (Whiteside et al. 2012). This weighted method of stacking the RTM image takes into account source direction, survey geometry and other stacking criteria which allow better separation of signal from noise achieving a more accurate final image.

The last step is to run least squares RTM. A data domain solution was implemented using adaptive least squares RTM (Zeng et al. 2015). Least squares RTM improves signal-to-noise by suppressing migration artefacts and broadens the bandwidth of the data.

Results

The results of the imaging are shown in Figure 3. Figure 3a shows the result of the Kirchhoff prestack time migration (KPSTM) stretched to depth, while some sub-basalt reflectors can be identified where the basalt is thick, the reflectors are noisy and overprinted with swing noise. Further to the right as the basalt thins the KPSTM image breaks down (highlighted with an arrow). Figure 3b shows the results using Kirchhoff prestack depth migration (KPSDM). In general, since the velocity in the basalt varies laterally, it is not surprising that PSDM gives better images than PSTM. We see that event continuity is improved beneath the basalt with clear improvement visible beneath the thinner basalts. Figure 3c shows the results from DIS. Event continuity beneath basalt is improved with no smearing of faults or loss of detail. Figure 3d shows the results from the LS RTM. The LS RTM reduces the amount of migration artefacts and further improves continuity.

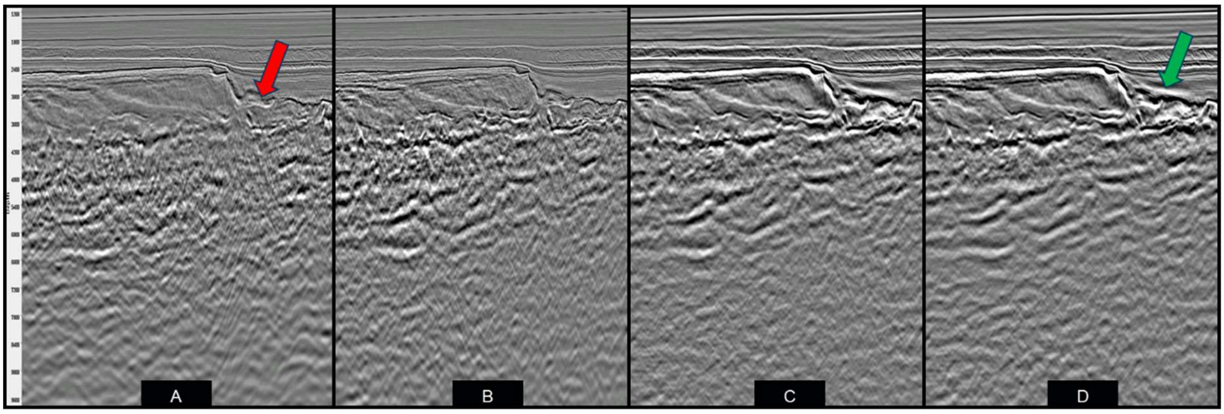

Figure 3 *Imaging and model building results: a) KPSTM converted to depth; b) KPSDM using the velocity model derived from COR tomography; c) LS RTM using the same model as b).*

Figure 4a the final velocity model overlaid on the final LS RTM. The heterogenous velocity structure is well described and velocity variation beneath the basalt related to fault blocks is picked out by the COR tomography. Figure 4b shows a 3D cut out view of the velocity model velocities, values expected for sedimentary rocks occur in several locations beneath the basalt, indicating the possibility of Palaeocene sand pods, these are indicated with arrows in the figure.

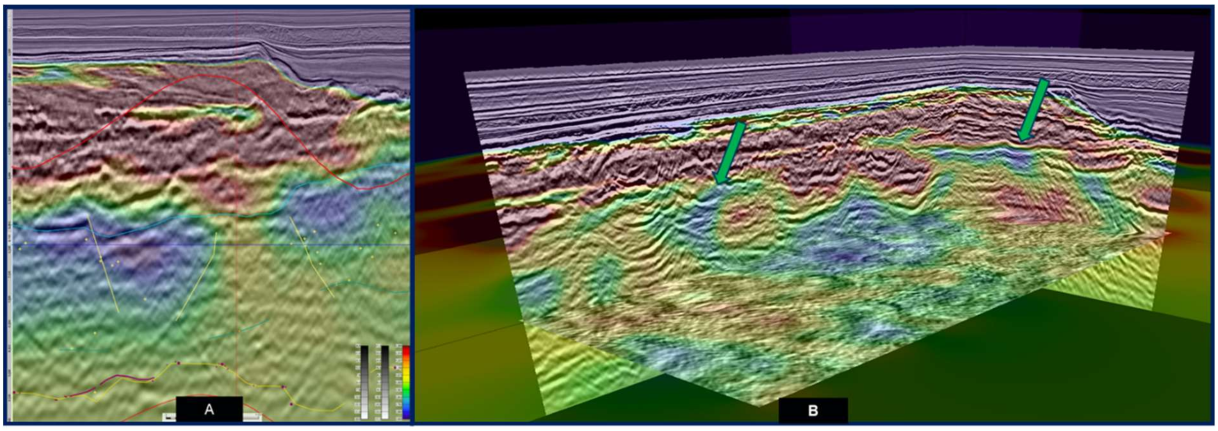

Figure 4 *Final velocity models: a) Inline view of final velocity model overlaid on the LS RTM image; b) 3D image of the same.*

One of the criteria for success on this project is the imaging of mappable horizons beneath the basalt. Several mappable horizons are identified on the imaging results. Figure 5 shows some of these horizons. In Figure 5a the horizon is plotted together with the gravity data, showing good correlation of the horizon structure with a gravity high, providing independent variation of the seismic structure in a spatial sense. Figure 5b shows 3D views of the two of the horizons.

Conclusions

We demonstrate that the application of RTM based technology has improved sub-basalt imaging and the velocity attribute. The seismic data shows recognizable sub-basalt events that can be picked across faults. The faults themselves can be picked with acceptable confidence. Sub-basalt velocities from COR tomography provide valuable interpretation support.

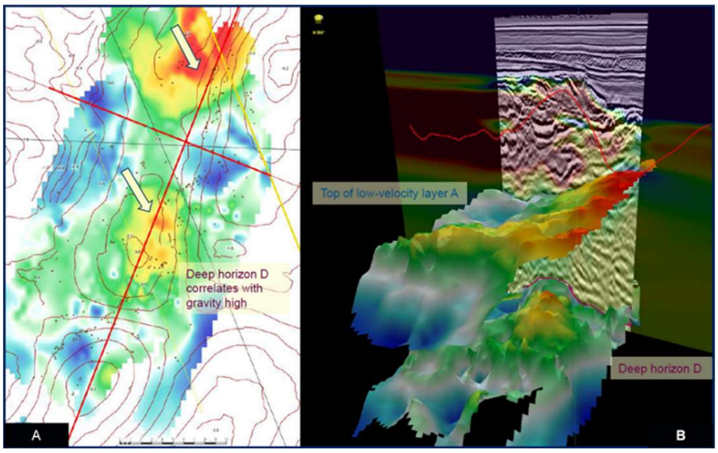

Figure 5 *a) depth map of deep sub-basalt horizon (colour) plotted together gravity (contours); b) 3D view of the picked horizons.*

Although the project was successful, we believe that there is much more that can be done to improve the image. For example, interbed multiples, which are a significant source of noise contaminating sub-basalt reflectors, were not explicitly addressed in the preprocessing. Additionally, techniques such as full waveform inversion (FWI) are expected to provide further uplift to the supra-basalt section, as well as perhaps the intra-basalt reflectors. These techniques will form the basis of further work in the future.

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