Introduction

Conventional reflection seismic processing images primary reflectors only. When the target depth is shallower than the minimum source-to-detector distance, wide reflection angles can compromise the image. Alternative acquisition techniques can alleviate these issues (usually at higher cost), but, in many cases, existing legacy data sets must be used.

Water-layer multiples are often regarded as noise, but they contain very valuable information as they provide additional reflection points recorded at near angles and with different subsurface illumination. Methods have been developed to image the multiples by injecting a downgoing wavefield as a secondary source, especially in multi-measurement streamer data (Lu et al., 2015). More recent methods rely on separating the multiples by type and order, and imaging them independently (Kristiansen et al., 2018). Separation and independent migration of source- and receiver-side multiples prevents crosstalk that would otherwise happen between different types of multiples during migration. In addition, we can compensate for the different raypaths between source- and receiver-side multiples in the amplitude regularization step. A recent innovation in multiple imaging technology uses Kirchhoff ray-signature depth migration, where the ray tracing is performed to accurately account for the reflections and transmissions of a specific multiple type (Kristiansen et al., 2018).

We present a case study of imaging the source-side water-layer multiple in the Alvheim field, North Sea, using ray-signature Kirchhoff prestack depth migration. This approach delivered a complementary and higher-resolution image relative to the migration of primary reflectors. We also show how the enhanced resolution benefits shallow hazard analysis.

The Alvheim field and survey description

The Alvheim field is located in the central part of the North Sea, west of the Heimdal field and near the border with the UK sector. It includes the three discoveries Kameleon, Boa, and Kneler. The water depth in the area is 120-130 m. The reservoir is of Paleocene age and located at a depth of 2,200 m. A 4D monitor multi-sensor marine streamer seismic survey was acquired over the Alvheim area in 2017, using a 2013 survey as baseline. In 2019, the monitor survey was reprocessed to provide a high-resolution 3D cube suitable for shallow hazard analysis. Imaging using multiples was tested to improve the shallow section where the primary reflections are affected by normal moveout stretch.

Source-side water-layer multiple and ray-signature Kirchhoff migration

The raypath of a water-layer-related multiple will have at least one upward reflection point on the water bottom. An illustration of the source and receiver sides of a water layer multiple is shown in Figure 1.

Figure 1 Primary reflection, source- and receiver-side of a water-layer multiple. Note that, in a source-side multiple, the reflection point moves towards the receiver.
We executed an imaging with multiple workflow to create an image using the source-side multiple. We separated the source-side multiple using a generalized deterministic water-layer demultiple approach (Xavier de Melo et al., 2016). The Kirchhoff algorithm employed in this work was described by Kristiansen et al. (2018). It uses ray signatures in the ray tracing to accurately calculate traveltimes for a given multiple. The Green’s function is then customized for the same set of reflections and transmissions that form the multiple being imaged. The method does not rely on having separate upgoing and downgoing wavefields available, but does assume that no ghost effects are present.

Kirchhoff migrations are sensitive to irregular coverage. Voronoi weighting (Jaramillo, 2005) is one way of reducing this sensitivity by weighting the input traces based on spatial regularity. We used a Voronoi scheme to condition the source-side multiple model prior to migration. Figure 2 shows the results of the regularization testing, demonstrating that the skewed Voronoi provides the best balance between image sharpness, definition, and reduced footprint.

![Figure 2](image)

*Figure 2* Near-offset Kirchhoff migrations of the source-side raw multiple model using different prior regularization schemes: (a) unregularized, (b) 4D interpolation, (c) Voronoi weighting.

**Comparisons to standard primary image**

Figure 3 compares the migrated image of the source-side multiple model to the primary migration from the high-resolution processing. The multiple image provides improved resolution and sharper delineation of the shallow features. Acquisition footprint is reduced due to the improved coverage given by the multiples. The migration of the multiple provides improved focusing of the events and enhances details in the structural image.
Figure 3 Stack time slices at 190 ms (upper row) and inline sections (bottom row) of: (a, c) Primary Kirchhoff depth migration (KDM) after post-migration processing; (b, d) KDM of the source-side multiple model after post-migration processing. Note the footprint reduction and sharper definition of geological features.

Shallow hazard analysis

Modern towed-streamer exploration seismic acquisition is increasingly used for shallow hazard analysis prior to drilling, as the high quality and availability of exploration seismic data can preclude the requirement for dedicated shallow hazard surveys. Guidelines regarding data quality are in place to govern fit-for-purpose use of seismic data for shallow hazard workflows. These criteria are led by the International Association of Oil and Gas Producers (IOGP), who advise globally on oilfield best practices, including drilling site assessments. These guidelines are increasingly followed internationally and include footprint removal, frequency content, signal-to-noise ratio, and binning increment requirements. The geophysical difficulties inherent in shallow-water areas that were highlighted previously create challenges for addressing the IOGP shallow hazard seismic criteria.

After determining that the high-resolution processing volume met the IOGP criteria, we conducted a shallow hazard assessment to validate the use case for the data set. The distribution of seafloor, subsurface, and man-made hazards were mapped through a traffic-light system indicating relative locations of subsurface stability for future drilling locations. Neogene-Quaternary clastics of the Nordland Group cap the Alvheim area. Unconsolidated marine clays are present with a fluvio-glacial cap (Figure 4). The sediment transport system includes rafted blocks that form the primary drilling hazard in the shallow subsurface.
Figure 4 RGB blended amplitude extractions at 250 ms with seismic transects highlighting improvements in intra-channel resolution. Original 2017 acquisition (top), high resolution primary migration (centre), and multiple migration (bottom). Identification of discrete rafted blocks within channel matrix can be achieved when interpreting on multiple imaged 2-ms seismic data.

Conclusions

Migration of the predicted source-side multiple model delivered an image with sharper delineation and higher resolution of the shallow structures, compared to the primary high-resolution migration. It provides additional coverage and less evidence of acquisition footprint. This complementary information enables more-accurate structural interpretation of the shallow targets in this field. Based on industry accepted standards for shallow hazard identification on seismic data, we demonstrated that imaging the source-side water-layer multiple is applicable for accurate shallow hazard assessment. Analysis of subsurface hazards provided greater confidence in modelling shallow Quaternary channels, both their extent and intra-channel definition. Relatively shallow risk maps can be established for future well planning without the requirement for additional focused data sets.

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References


