Combining logging-while-drilling techniques in the interpretation of a reservoir fault

Introduction

The Askeladd field is part of the greater Snøhvit area (Snøhvit, Albatross and Askeladd) and situated in the Hammerfest basin in the SW area of the Norwegian Barents Sea. The Askeladd structures are located within the N-S trending normal fault system of the Ringvassøy-Loppa Fault Complex. In contrast, the Snøhvit and Albatross structures are fault-bounded horsts following the dominant E-W oriented fault pattern which characterize the main parts of the Hammerfest Basin. The field’s rotated fault block structure consists of Middle-Jurassic sandstone reservoirs and is overlain by claystones of the Adventdalen Group.

The Askeladd drilling campaign consists of three horizontal producers, which were drilled in the North, South and Gamma segments of the 7120/8 block. This study centers on the horizontal producer, 7120/8-L-4 H, where interesting features were identified in the seismic-while-drilling (SWD) vertical seismic profiling (VSP) raw stacked data across the horizontal section of the wellbore. These features pointed to a structural event crossing the wellbore at around 4060-4070 m MD and points to a possible fault zone.

In this study, we propose that a fault exists in this well section which is not visible in the surface seismic volume and has the potential to provide better understanding of the reservoir in the Gamma segment of the Askeladd field. This is also a unique opportunity to bring together VSP and Ultra Deep Azimuthal Resistivity (UDAR), and multiple borehole images.

Recording Methods

Data acquisition occurred during drilling operations of the 8 ½” section of the 7120/8-L-4 H producer well. The bottom hole assembly (BHA) for this section included several logging-while-drilling (LWD) tools, those of which are relevant to this study are described below:

**SWD VSP tool** – the downhole recording tool consists of 8 components -- two sets of downhole hydrophones, and two sets of 3-component geophones -- and an internal battery reserve, which is supported by an external battery sub (SBS2). VSP data were recorded to memory during pull-out-of-hole operations (POOH), i.e. at pipe joint disconnections; first at ~20 m intervals over the horizontal section of the wellbore up to the 14 x 13 5/8” intermediate casing shoe, and then at ~40 m intervals within the multiple-casing section up to the 20” casing shoe. Highly accurate clocks are located within the surface recording system and the downhole tool, and uphold the necessary time synchronicity for later processing of the memory-recorded data.

**UDAR tool** – The tool consists of three antennas separated into two subs -- one sub contains a single transmitter and the second sub contains two receivers. The UDAR tool uses 20 and 50 KHz phase and attenuation resistivity and azimuthal resistivity measurements to detect remote boundaries up to 46 m radially around the tool axis. At the time of the survey, the tool data were recorded and analysed in real-time for the purposes of geosteering and reservoir navigation.

**LWD imaging tools** – LWD acoustic borehole images are sensitive to borehole distance and acoustic impedance changes, whilst the azimuthal gamma ray measures formation gamma ray changes. While 8 sector gamma ray images were available in real-time, the 256 sector acoustic images were stored to the tool memory.

Data Processing & Observations

**SWD VSP data** – The VSP memory data is made available once the tool is back on the drill floor after the POOH survey. Standard and combined wavefield separation processing techniques (H. Mathiszik et al, 2011) were applied to the memory downhole hydrophone and the rotated true vertical component geophone data to produce a deconvolved upgoing P-wavefield (Figure 1).
With particular focus on the horizontal section, a 2D image was generated along the ~191 degree well azimuth near to the TD of the wellbore. An event discontinuity is observed in the processed data between 4000-4100 m MD close to the time/depth curve. Further assessment of the raw stacked data and 3-component geophone data after rotations (Figure 1), notably the horizontal geophone components, reveals steep events (in time) either side of the interval of interest. One proposed explanation is that these are P-wave reflections from a steep fault boundary. The proposed fault reflection events were picked on the horizontal component data after rotating to a common (N-E) geophone coordinate system and assessed at 10-degree increments. The horizontal transverse/horizontal radial RMS amplitude ratios over the interval of interest trend towards a polarisation orientation of approximately 160-170 and 340-350 degrees.

**Figure 1** going clockwise, starting from the left: SWD VSP enhanced deconvolved upgoing P wavefield at recorded time below datum (arrow highlights the ‘fault’ position). Raw SWD VSP data, including stacked downhole hydrophone, and 3-component rotated geophones, z $\rightarrow$ vz, hy $\rightarrow$ ht, hx $\rightarrow$ hr.

**UDAR data** – a Multi-Component While Drilling (MCWD) inversion algorithm was used to process standard resistivity and azimuthal measurements in addition to the ultra-deep azimuthal resistivities. The ultra-deep electromagnetic induction measurements can be influenced by several bed boundaries within the depth of detection of the UDAR tool, so that a visual check on resistivity values and trends does not reveal much information. A much more complete picture of the surrounding formation can be derived by applying inversion techniques. The inversion algorithm is a flexible hybrid scheme which combines deterministic and stochastic elements. The inversion results return thickness and resistivity of the zone being drilled, the thickness and resistivity of multiple adjacent zones within the tool sensitivity range, and the relative dip between the tool and the formation from which an apparent dip can be derived (Tilsley-Baker et al, 2016).

The inversion results on this well (Figure 2) places the wellbore 7-10 m below the roof of a 35-40 m thick sand in a large heterolithic reservoir with high resistivity, ideal for UDAR measurements. In the interval of interest, UDAR data also showed some ambiguity over the same section, with low signal strength due to being close to the electrical midpoint of the reservoir. Many inversion results, from alternative inversion ‘expected’ models, all position a fault-like structure around 4070 m MD.
LWD imaging data – LWD real-time curves showed little or no changes in resistivity and neutron density. Only the gamma ray curve was seen to change over the horizontal well section at ~4068 m MD (Figure 3). This change in gamma ray can be seen as a dip picked as a high angle feature on the 8-sector real-time image. The general bedding dip for the wider interval is well established to be about 5 degrees to the east based on dip picks from both gamma ray and acoustic amplitude images (Morris et al., 2020). This makes the 40 degrees high angle feature in the gamma ray image consistent with the interpretation of a fault plane, with a dip azimuth of 160 degrees.

Conclusions

The acquisition of multiple LWD data in the Askeladd Gamma well has proved to be a special opportunity to image the reservoir section in various modes and resolutions (Figure 4). SWD VSP data...
has been used to initially select an interval of interest, by the presence of curious seismic features that warranted further investigation. Taken in combination with UDAR results, and high-resolution borehole images, the depth of the proposed sub-surface seismic resolution fault event has been narrowed down to ~4068 m MD, and may be part of a more complex fault system in the surrounding geology.

When taking the different sources of data in isolation an interpreter would be hard pressed to be able to definitively confirm the fault’s existence let alone analyze its configuration, however by combining the available information the fault’s existence can clearly be determined.

![Figure 4 Stø 6 reservoir navigation composite display showing VSP, UDAR, borehole images and various logs.](image)

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**References**


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