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A 3D Illumination Study to Investigate Fault Shadow Effects over the Hoop Fault Complex

A.J. Hardwick* (TGS) & L. Rajesh (TGS)

SUMMARY

Fault shadows represent zones of unreliable seismic imaging in the footwall of major extensional faults. They occur due to rapid lateral velocity variations and high velocity overburden which distort raypaths, manifesting themselves as sags on a time image. Whilst interpretation driven techniques in the depth domain have been developed to address this, the problem is fundamentally one of poor illumination which can be a function of the survey design.

In this study fault sags within the Hoop Fault Complex of the Norwegian Barents Sea are investigated to gain understanding of why conventional travel-time tomography fails. Through 3D ray-trace modelling it is demonstrated the fault sags can be traced on illumination maps produced for the originally acquired azimuth. An additional azimuth is modelled, simulating acquisition in the orthogonal direction which demonstrates better illumination in these regions.

Ray attributes allow the generation of synthetic gathers which are time migrated and converted to depth. These demonstrate the sags can be eliminated by the acquisition of an additional azimuth. Whilst the original narrow azimuth 3D survey design is optimal for the shallow targets, if full illumination of the fault complex is a future objective, multi-azimuth or wide azimuth surveys should be considered.

Introduction

Seismic exploration of the Norwegian Barents Sea began over thirty years ago, but the acquisition of 3-D surveys have only commenced in recent years. The design of these surveys is based on the predominant structural grain inferred from the regional underlying 2D datasets. The Hoop Fault Complex (HFC) is one such area that has attracted interest, leading to the first 3D survey in 2009. The HFC itself is a swarm of NE-SW extensional faults with a shallow strike-slip component cutting across the Loppa High and the Bjarneland Platform (Gabrielsen et al, 1990). Its evolution can be traced back to the late Carboniferous with periods of reactivation. Late Cretaceous regional uplift and erosion followed by Palaeogene subsidence and Neogene glaciation uplift and erosion control whether a working hydrocarbon system is in place.

In 2009 TGS acquired 2770 km^2 of narrow azimuth multi-client 3D data over the HFC along strike to the Hoop Graben, orthogonal to the shallow strike slip faulting. This provided a good time image of the prospective shallow Jurassic targets. The Triassic Kobbe formation deposited in a shoreface setting is a deeper prospect with a modelled basin history (TGS internal report), offset by the major extensional faults of the Hoop Graben (Figure 1(a)). Interpretation of the top Kobbe formation is problematic due to ficticious distortions caused by the complexity of the fault geometry and the high velocity lower Cretaceous overburden on a time image within the main Hoop graben and must be addressed by pre-stack depth migration (PSDM).

The causes of fault sags are reasonably well known (e.g. Fagin et al., 1996; Birdus et al., 2007). Sags within the footwalls of the major extensional faults observed in the crossline direction on the original HFC time image could not be addressed in depth with conventional velocity model building using hybrid gridded tomography. Instead an interpretation driven modelling approach (IDM) was applied, imposing constraints on the tomographic inversion by picking a structurally more plausible horizon on an angle limited stacked depth image. The assumed error is incorporated and back propagated in the travel times as described by Rodriguez et al., (2011). This reduced the sags to a large extent (Figures 1(b) and 1(c)), but the failure of tomography to resolve the lateral velocity variations implies an illumination issue.

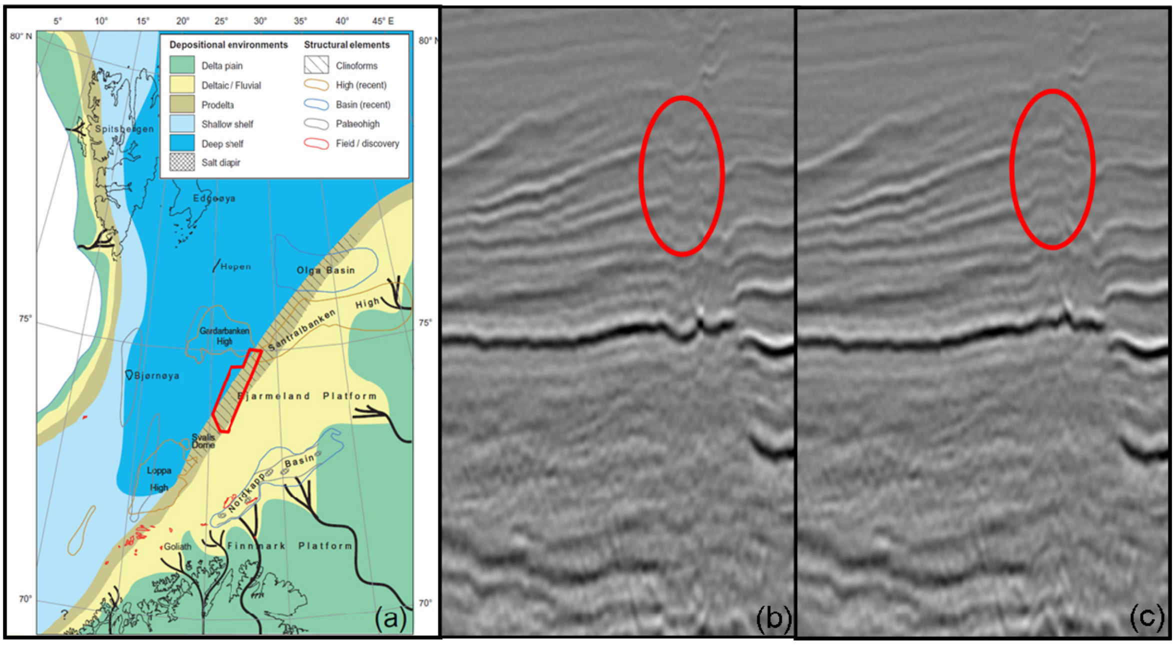

Figure 1 (a) Palaeogeographic map from the Anisian representing the deposition of the Kobbe Formation after Riis et al., (2008) showing the palaeo shoreline situated in the HFC area. (b) PSDM image obtained of the Kobbe foresets from standard hybrid gridded tomography and (c) PSDM image incorporating IDM. The region of the sags is highlighted in red.

In this study TGS apply 3D ray-trace modelling to determine whether irregularities in illumination coverage correlate to the sags observed in the seismic data for the original survey layout. We then simulate illumination as if the survey had been acquired orthogonally. Ray attributes allow synthetics to be generated which are 3D time migrated and stretched to depth for both simulated shooting directions for comparison to the real data. This allows us to consider whether additional azimuths are a requirement to eliminate the distortions if the progradational Top Kobbe foresets become an exploration target.

Modelling approach

The NORSAR 3D software is used for the illumination study which provides numerous ray attributes for any common reflection point gather (CRP) based on a given source-receiver geometry and supplied model. These ray attributes are calculated by an expanding wavefront construction approach. Each time step generates a new wavefront that can propograte differently based on the model rather than a crude single ray with an expanding Fresnel zone. Each 3D horizon is triangulated onto a mesh so that ray attributes can be assigned to a CRP accurately on the target horizon, providing diagnostics for critical assessment. In this study we took the horizons which corresponded to the main velocity and density contrasts. These were Water Bottom, Base Quaternary Unconformity, Base Cretaceous Unconformity (BCU)/Top Jurassic, Top Kobbe, near Top Permian and Imaging Basement.

Interpretation was conducted on the IDM volume which comprised approximately 800km^2 of the central part of the original HFC dataset. Whilst some minor sags still existed on the IDM dataset these where ignored as the modelling requires some smoothing of horizons. The IDM velocity model was converted to density using Gardener's empirical velocity-density relationship. For brevity discussion is limited to the main prospective intervals, Top Jurassic and Top Kobbe. Interpreted depth horizons for the Top Jurassic which demonstrates the imprint of shallow strike slip fault faulting is shown in Figure 2(a) and the Triassic Top Kobbe in Figure 2(b).

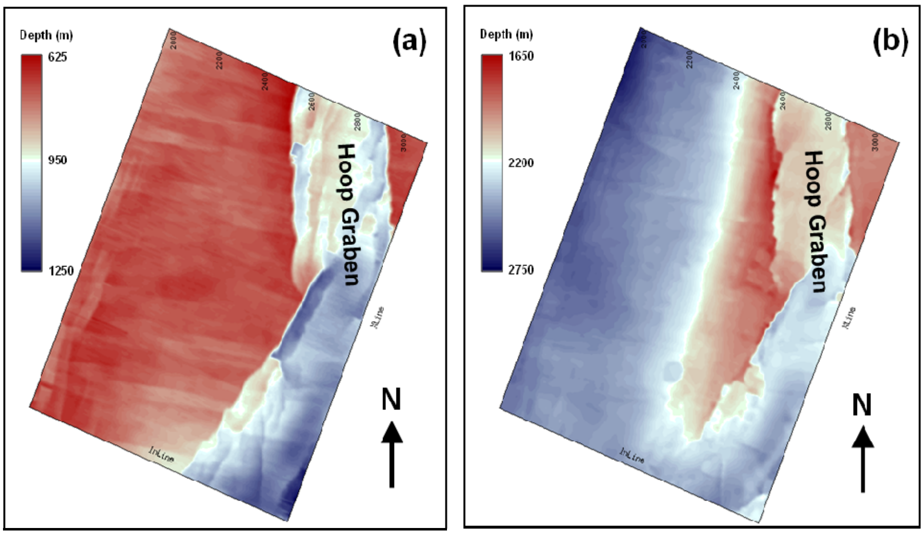

Figure 2 *Modelled targets horizons picked from the IDM depth volume highlighting the Hoop Graben bounded by large scale extensional faulting; (a) interpreted BCU/Top Jurassic horizon showing the imprint of shallow strike faulting, and (b), Top Kobbe (Triassic).*

Results

The most intuitive ray attribute to analyse is the ray density or hit count for CRPs on the target horizons. Figure 3 shows the hit count per square kilometre for the BCU/Top Jurassic horizon and Top Kobbe for both the simulated original survey design and through rotation orthogonally. The BCU/Top Jurassic illumination maps clearly show an acquisition footprint, irrespective of the shooting direction. This was addressed when extensions to the original HFC survey were acquired in 2011 by reducing the distance to the first receiver group. Whilst some areas of poorer illumination can be traced both in the footwall and hanging wall at the top of the HFC the high velocity Cretaceous overburden has limited impact on the image obtained, irrespective of shooting direction – due to the high velocity gradient and the limited angle range available to stack. However the illumination maps show the original acquisition overall is superior for this interval where the primary exploration focus has been.

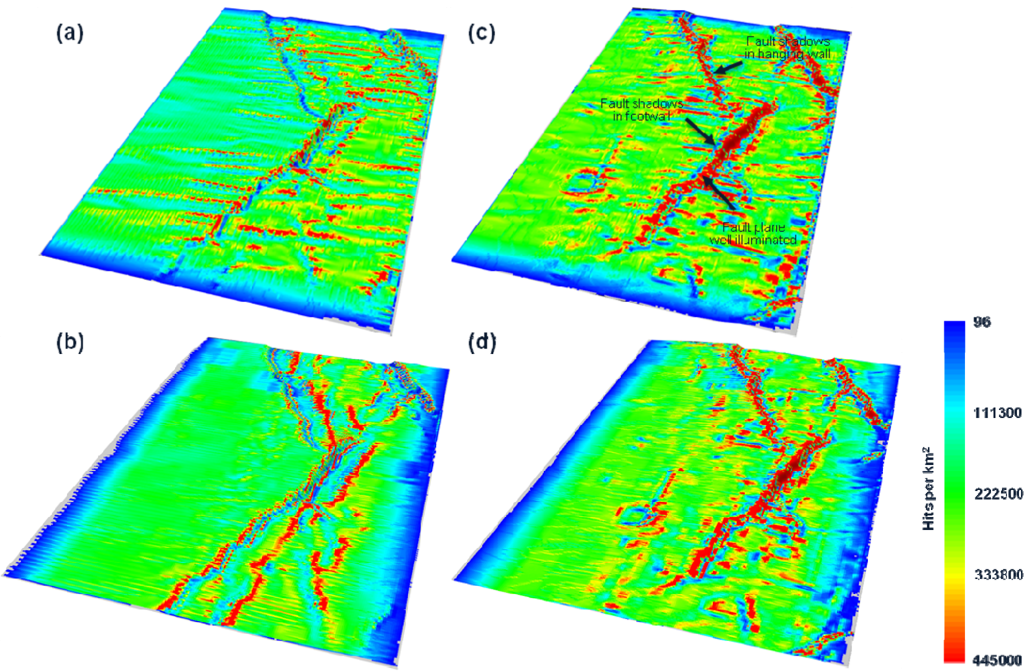

Figure 3 *Illumination hit maps from the NORSAR 3D modelling for the target horizons; (a) BCU/Top Jurassic for the original acquisition azimuth and (b) for a simulated orthogonal azimuth; (c) and (d) show the same respectively for the Top Kobbe horizon.*

The illumination maps obtained for the Top Kobbe show variations which have more of an impact on the sags observed. The main extensional fault planes of the Hoop Graben are well illuminated by both shooting directions; however regions of poor illumination can be traced along the footwall and hanging walls almost without exception for the original survey design. These correlate directly with faults sags and pull ups on the time image and depth image without IDM. Whilst some are present on the simulated orthogonal direction, they are reduced.

Ray attributes from the modelled surveys were used to generate synthetic shot gathers in time for a 200km^2 region of the northern part of the IDM PSDM volume, such that both flanks of the Hoop Graben were imaged. These were 3D time migrated and stacked with the same parameters for the original dataset. The IDM volume is in depth, so all other examples have been stretched using the final IDM velocity model for comparison. The results are quite striking, but confirm the observations from the illumination study. From the synthetics we can infer that the original shooting is optimal for the shallow targets, as the BCU/Top Jurassic is well imaged. This is not the case for the Top Kobbe. Synthetic depth slices at ~ 2 km are shown in Figure 4 and comparisons of the images for an example crossline in Figure 5. Fault sags on simulated original acquisition correspond to those observed on the pre-stack time migrated (PSTM) volume stretched to depth (Figure 5(c)) and also shows an area where IDM has been less successful. Significant wavefronting effects can be seen on the near Top Permian horizon, which was also a feature of the PSTM volume. For the simulated orthogonal shooting, sags in the footwalls of the two large scale extensional faults controlling the Hoop Graben are eliminated (Figure 5(d)).

Conclusions

3D exploration of the Barents has only recently begun. Narrow azimuth surveys are adequate to address the shallow targets, but in the HFC area where two major structural trends are juxtaposed at almost ninety degrees to each other, one is inevitably compromised. The modelling shows this clearly, with areas of poor illumination in the footwall and hanging walls of the faults which correlate to the fictitious sags on the prospective Top Kobbe event for the originally acquired azimuth. IDM represents a means of healing the sags in depth, but ultimately an additional azimuth is required. If reliable imaging of the HFC at all depths is an objective, multi-azimuth or wide azimuth acquisition should be considered.

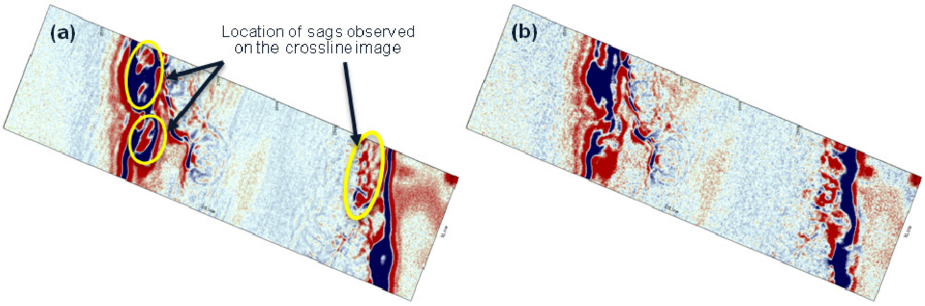

Figure 4 *Synthetic timeslice cutting through the Tob Kobbe target horizon at ~ 2km depth; (a) for the original acquisition azimuth and (b) for the orthogonal azimuth.*

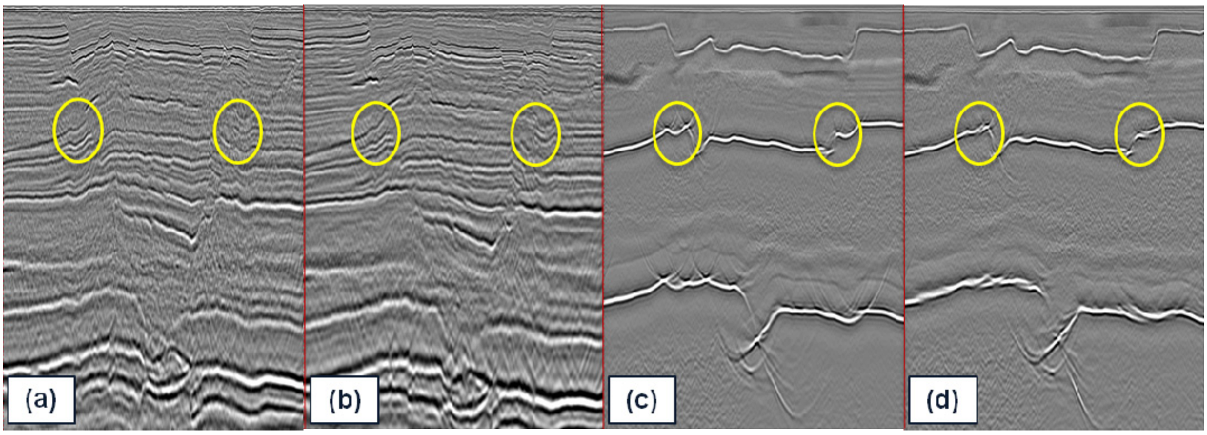

Figure 5 *Crossline examples with regions of distortion along the Top Kobbe event highlighted; (a) PSTM section stretched to depth with the IDM velocity model (sags highlighted in yellow) and (b) the PSDM image obtained from IDM with sags reduced. (c) Synthetic generated from modelled ray attributes for the original acquisition direction and geometry and (d) for the orthogonal direction.*

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