Diffraction imaging of Tertiary injectites and basement faults/fractures in the Norwegian North Sea

Introduction

This paper presents diffraction imaging (DI), diffraction modelling (DM) and its associated customization to interpretation (CTI) in the Norwegian North Sea. The targets of interest for this study are injectites and the fractured basement. Diffraction Imaging operates on the same input data as regular pre-stack depth migration (PSDM), but by a modification of the migration kernel it removes specular reflection energy which tends to obscure small, structural details which are important for interpretation. By bringing out the diffraction energy, DI both enhances resolution and illumination of structural targets. The sand injectite reservoir is positioned at a shallow depth range. Here, the interest is imaging from different illumination angles and its impact for well planning. Sand injectite geometries include sills, dikes and feeder systems. These have a rich diffraction response which does not have the same illumination restrictions as reflection (Pelissier et al., 2018 and references there). The basement fracture network is positioned at a deeper level. Here, the interest is the imaging of basement fracture edges, tips, and the roughness of fracture planes. Diffraction imaging provides significant improvement in the definition of the fault system in both the high and low reflectivity/continuity strata (Moser et al., 2020 and references there).

A summary workflow for the DI/CTI consists of the following steps:

1. PSDM conditioning over selected lines to ensure equivalence of non-tapered DI with legacy PSDM, so that the latter can be used as reference for DI at various tapers and for reflector dip extraction.
2. Reflector dip extraction at any location of the legacy PSDM grid.
3. Specularity gather construction/processing, consisting of migration with output sorted into gathers as function of agreement with Snell's reflection law (specularity gathers); these then are tapered against reflectivity and stacked into final diffraction images (Moser and Howard, 2008; Sturzu et al., 2013).
4. Customization to Interpretation all along the DI workflow, starting with a reconnaissance of the geological objectives on the legacy PSDM, providing quality control on the PSDM conditioning and guidance on the specularity taper design, DI stack and post-processing.

Steps 1-3 involve a number of rigorous QC steps to ensure maximal robustness of DI; step 4 ensures maximal interpretation value. The non-tapered DI (or Full specularity Stack, FSS) is equivalent to regular PSDM; however, since it is obtained by parameterizing and stacking over specularity, it typically emphasizes small structural detail in a different way than PSDM. Also, the interpretation objective of PSDM is a reflectivity image with maximal signal-to-noise ratio. Since the objective of DI is to maximize detectability of small structural features, its design often favors resolution against signal-to-noise. Diffraction modelling (DM) is an integral part of CTI, in which target volumes of the DI are selected and used as scattering volume in forward ray-Born modelling (Moser, 2012). The resulting synthetic diffraction data are compared to pre-migration stacked data. The objectives are two-fold: validate DI at target locations and to obtain a better understanding of the diffraction response in relation to interpretation impact (Pelissier et al., 2017, Moser et al., 2020). We present two targets for diffraction modelling, one from the injectite reservoir and another from the basement.

Diffraction Imaging of Injectites

Figure 1 shows the DI response of injectites in section view along with the legacy PSDM and full specularity stack. There is a marked improvement in the definition of the injectites in the full specularity stack as opposed to the legacy PSDM. As noted above, the full specularity stack is obtained by parametrization in terms of specularity instead of offset. This approach helps to preserve the diffraction signal. In addition, we use minimal post-processing to preserve the structural detail. The diffraction tapers progressively attenuate the sub-specular energy. With increasing taper, a greater portion of the Fresnel zone is attenuated. Because of this, the remnant sub-specular reflection images become lower frequency and move upwards. However, diffraction energy remains in place. This property of the Fresnel zone sampling, documented by Pelissier et al. (2017), provides an important interpretation advantage. The interplay between near-specular reflection and diffraction over a range of tapers is especially useful for locating very fine scale features.

Figure 2 compares the full specularity stack to the diffraction image at two depths. Here we can see a clear improvement in definition of the injectite complex. This improved resolution was useful in the interpretation of well results. Since features on the diffraction image necessarily are geologically organized, we derive geobodies. The Thalweg tracker method (Pelissier et. al. 2016) was applied to track an injectite geobody on the DI. This was then forward modelled and compared to the pre-migration stack. The result is show in Figure 3. Here we observe a good character match to the left/right asymmetry of the diffraction response. From this figure, we can also appreciate the efficiency of our model-based DI method, and the challenges of separating out diffraction from reflection energy in data-based DI methods.

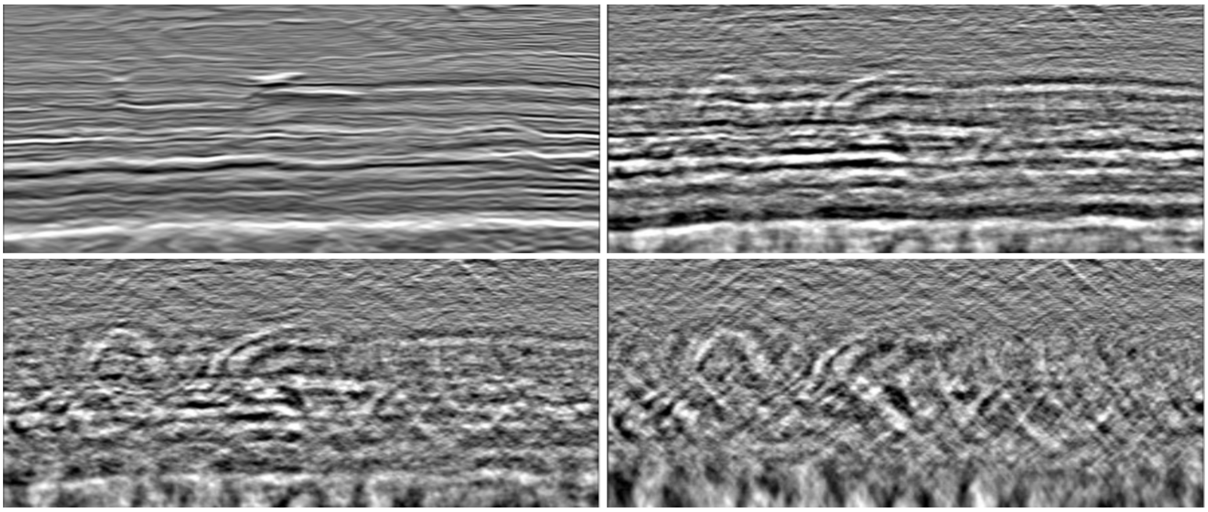

Figure 1 *Section view across injectite of legacy PSDM, FSS (top left/right), DI at 94%, 88% (bottom left/right) (vertical axis denotes depth).*

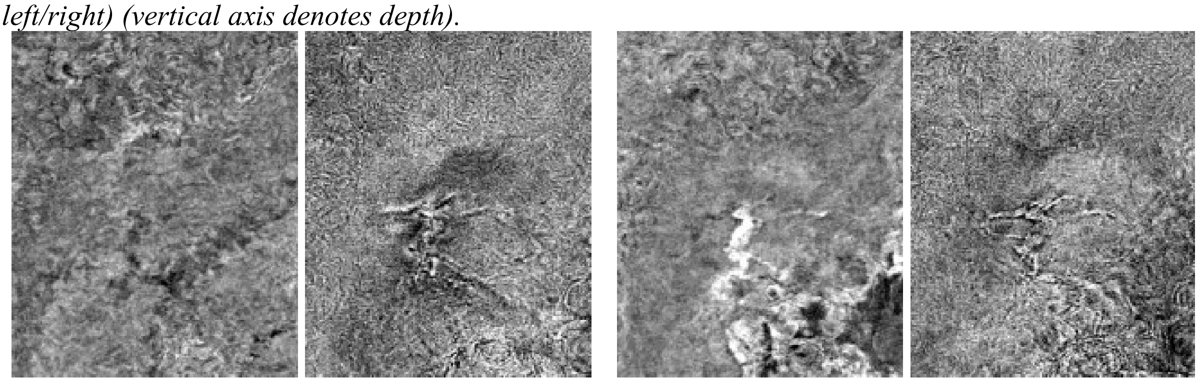

Figure 2 *Depth slice pairs at shallow (left) and deeper (right) level comparing injectite of FSS and DI at 88%.*

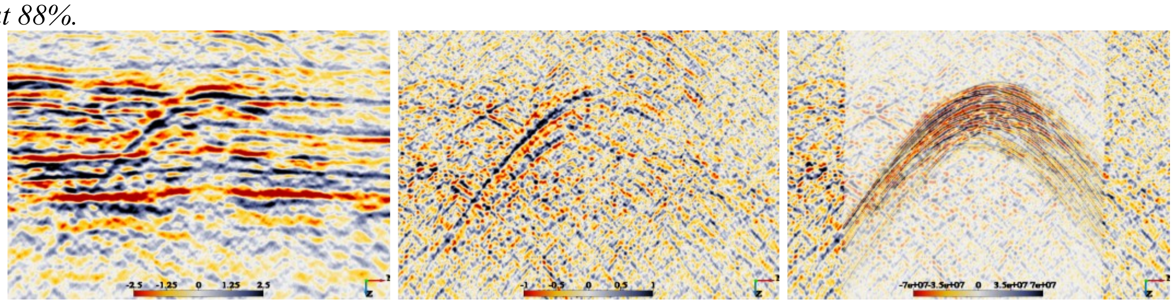

Figure 3 *Section views through injectite of pre-migration stack, gradient, diffraction modelling overlain (left/middle/right) (vertical axis denotes two-way traveltime).*

Diffraction Imaging of Basement

Wells in the survey areas encountered a weathered zone that marks the transition between the over-burden and a very complex crystalline basement composed of granitic gneiss, granitoid, pegmatites and foliated mylonite. The wells indicate that basement is strongly faulted, fractured, and brecciated.

On the FSS (Figure 4), there are chaotic sub-horizontal events which we interpret as reflection from the heterogeneous basement and some weak dipping events indicative of faulting. The diffraction image attenuates the sub-horizontal events to reveal the highly faulted basement. The image can then be enhanced using an edge preserving smoothing (EPS) filter. This filter is based on a method pioneered by Hale (2008). A typical depth slice of the basement is shown in Figure 5. On the full specularity stack, some faint linear features can be seen, especially in the bottom half of the image. The specularity taper provides a marked uplift in definition, which is then further enhanced by application of the edge preserving smoother. A fault attribute based on thin fault likelihood attribute developed by Hale (2008) is shown in Figure 5. Since there is no stratal reflectivity, the method simply uses the DI amplitude as input instead of semblance. The attribute is computed independently on peak and then on troughs and then summed. Figure 6 shows forward diffraction modelling from a selected key target in the basement DI. Progressing time slices show the typical effect of diffraction from a curved edge (caustic and triplication, Pelissier et al., 2012).

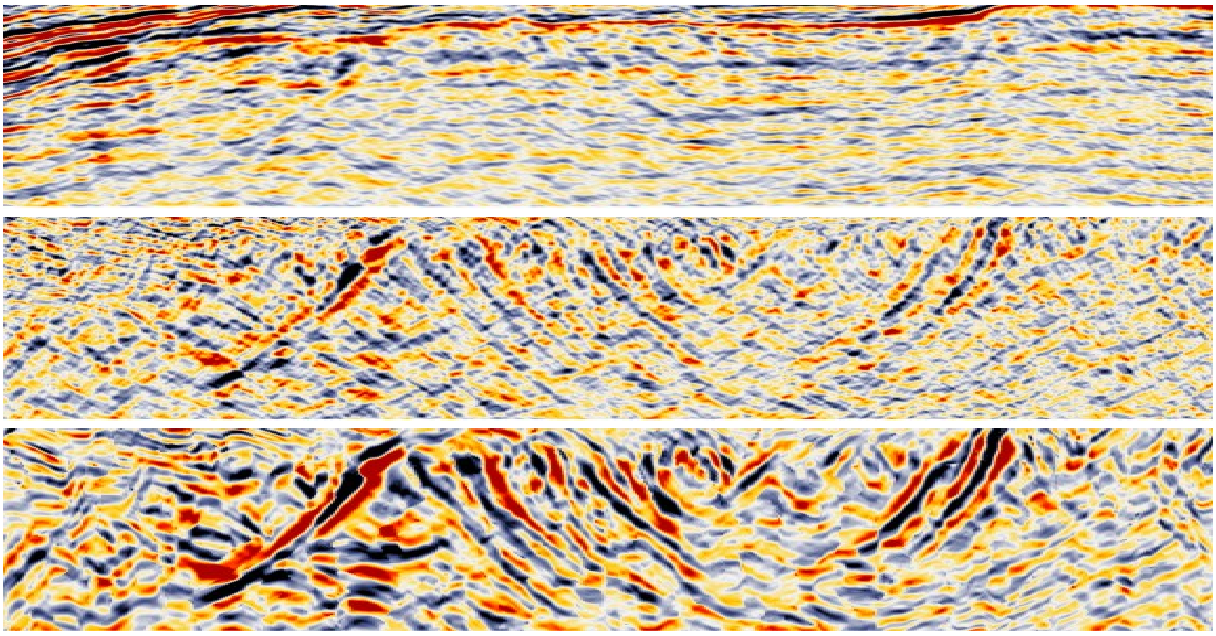

Figure 4 *Section views at basement of FSS, DI at 88% and DI at 88% with EPS (top to bottom, vertical axis denotes depth).*

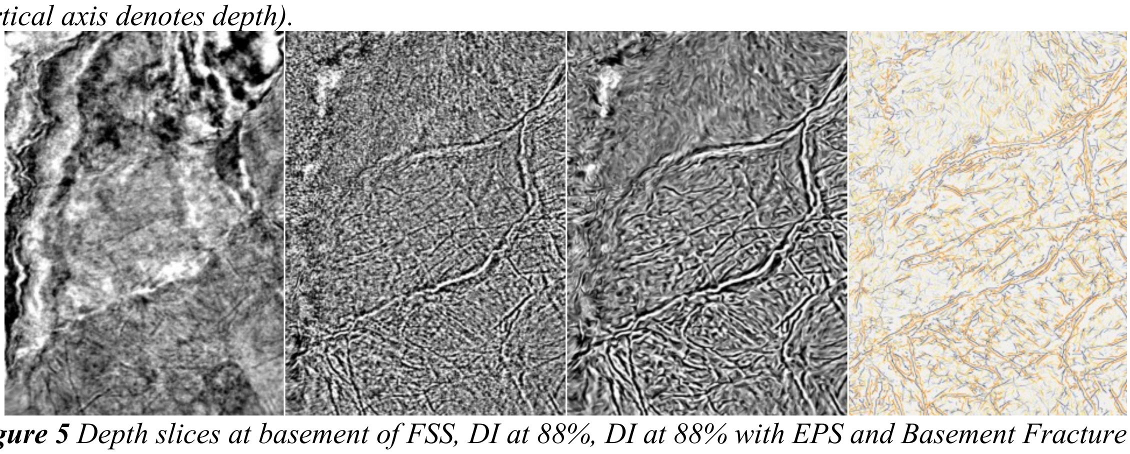

Figure 5 *Depth slices at basement of FSS, DI at 88%, DI at 88% with EPS and Basement Fracture Likelihood (dual polarity) (left to right).*

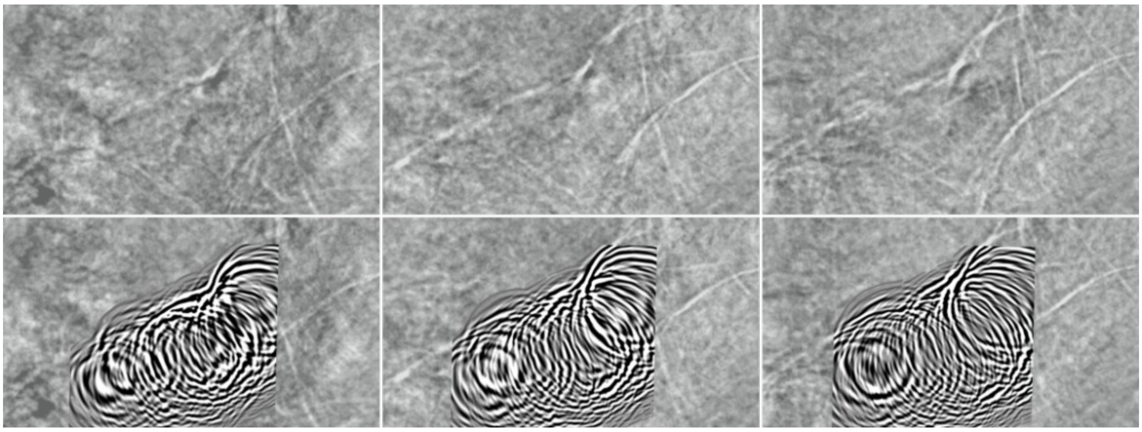

Figure 6 *Time slices through basement (progressing times from left to right) of pre-migration and diffraction modelling overlain (top/bottom).*

Conclusions

A workflow of combined diffraction imaging (DI) and customization to interpretation (CTI) provides significant interpretation value for both the injectite and fractured basement targets. The calibration of the suite of specularity tapered DI volumes is central to our approach. For the injectites the illumination benefit of DI ensures that energy from steeply dipping localized structures is well imaged. For the geologically complex basement the DI provides a clear uplift both in terms of resolution and illumination of the fault system.

DI/CTI is accompanied by forward diffraction modelling (DM) on selected target pieces of the DI and compared to the corresponding portions of the pre-migration stacked data. This allows to serve as a validation for the DI and to obtain a better understanding of the interaction between diffraction data and structural diffractors.

References

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