Introduction

In a conventional seismic imaging workflow, specular reflection energy is favoured over the rest of the seismic wavefield (Grasmueck, et al., 2012). While this is convenient for continuous geological horizons, real-world geologies are rarely continuous and are instead complex, full of structures at a range of scales which form breaks in the horizons. Where these discontinuities are small in comparison to the wavelength, a diffraction will form, scattering the seismic wavefield in all directions (Klem-Musatov, et al., 2016). By separating these diffractions and imaging them independently, a diffraction image can be created which highlights discontinuities and which provides valuable information on the subsurface. However, separating the diffractions from the reflections is a complex task due to the low amplitudes of diffractions and the overlap of diffraction and reflection energy (Grasmueck, et al., 2012).

Existing methods for reflection-diffraction separation can be categorized as pre-migration, such as plane-wave destruction (Fomel, 2002), coherent subtraction (Schwarz & Gajewski, 2017), anti-stationary phase filtering (Moser & Howard, 2008), and common-reflection-surface based diffraction imaging (Dell & Gajewski, 2006), or post-migration. Post-migration separation is commonly applied on dip-angle gathers and includes apex destruction (Klokov, et al., 2010a) and Radon filtering (Klokov & Fomel, 2012). Here, a combination of pre- and post-migration separation techniques have been applied to a dataset from offshore Gabon. This combination, or dual approach aims to better separate diffractions from reflections and noise.

Method

Plane-wave destruction is a common pre-stack diffraction imaging technique which is applied locally in the common-offset domain (Fomel, 2002). First, the slope $s$ of the plane-wave is estimated using the equation:

$$\frac{\partial P}{\partial x} + s \frac{\partial P}{\partial t} = 0 \tag{Equation 1}$$

where $P(t, x)$ is the wavefield (Clairbou, 1992). For stability, some smoothing is required, and must be carefully applied as a dip field calculated with too coarse resolution can fail to remove reflection energy (Decker, et al., 2013). Plane-wave destruction also requires a continuous variable dip. In areas where this assumption is not met, i.e. at synclines, reflection energy is left which creates artefacts in the diffraction image. Finally, it can be difficult to estimate the slope in areas with steep dips, complex fault zones and high lateral variable dips; therefore, remnant reflection energy in these zones is common.

Dip-angle gathers are a post-migration data domain transform created during migration. Traces are obtained by integrating across all scattering angles during migration for each common-image gather. By contrast, conventional migration integrates across both migration dip and scattering angles (Audebert, et al., 2002). Dip-angle gathers show the range of migration dips during migration for each common-depth point. In this domain, reflections appear concave, with the apex of the reflection event focussed on the dip of the reflector, while diffractions appear flat at the depth of the diffractor (JafarGandomi, et al., 2018). This kinematic difference between reflection and diffraction events allows for their separation in the dip-angle gather domain.

By removing the apex of the reflections, where reflection energy is focussed in the dip-angle gather domain, and by stacking the gather, a diffraction image can be created (Klokov, et al., 2010a). As the apex of the concave reflection event on a dip-angle gather is concurrent with the dip of the reflector, a dip field can be calculated on the conventionally migrated data and used to guide a dip-filter in the dip-angle gather domain (Klokov, et al., 2010b). Here, care must be taken into selecting the width of the filter. A filter that is too wide removes too much diffraction energy and a filter that is too narrow leaves remnant reflection energy (Decker, et al., 2013). While this method works well to remove reflection energy, it always removes some diffraction energy as the diffraction is flat across all dips and hence may overlap with reflections at the reflection apexes.
Hybrid Radon filtering is another method for diffraction separation in dip-angle gathers. As diffractions are flat in dip-angle gathers, whilst reflections are concave, the Radon transform provides a convenient way to separate these shapes as the events focus to different parts of Radon space (Klokov & Fomel, 2012). For this study, we suggest using the τ-p domain, a variant of the Radon transform which separates the curved reflection events from the flat diffractions. While the Hybrid Radon is effective, the τ-p transform is more computationally efficient while providing a similar function of separation. By filtering the parts of the τ-p space, which pertain to reflection energy, reflections can effectively be removed from the dip-angle gathers; however, the apex of the reflection events is also flat and will therefore map to the same τ-p space as the diffraction energy. Klokov & Fomel (2012) suggested preliminary plane-wave destruction in order to remove the reflection energy before migration but apexes from remnant reflection energy still map to the same Radon space as diffraction energy. Klokov et al. (2010b) proposed apex destruction followed by Radon filtering in order to remove the flat reflection energy prior to the Radon filtering; however, Klokov did not apply preliminary plane-wave destruction.

Here, we propose combining plane-wave destruction, apex destruction, and τ-p filtering. By using these three methods together, we aim to better image diffractions with less remnant reflection energy and noise, alleviating the issues associated with each method individually, whilst retaining their advantages.

**Application and Discussion**

We have applied the new approach to a real dataset from offshore Gabon. This dataset is characterised by a series of large and complex faults, oriented NW-SE and NE-SW in clastic and carbonate sedimentary layers. A large salt layer adds more complexity to the data, causing further faulting counter to the dominant geological bedding, as well as folding and reactivation of previous faults. The structural and stratigraphic complexity creates an ideal dataset for diffraction imaging.

Firstly, plane-wave destruction was applied to the data. Due to the steep reflection dips of the salt body, plane-wave destruction is not able to remove all reflection energy. Additionally, complex fault zones in the data cause a high lateral variable dip which the plane-wave destruction algorithm can fail to find because of the dip smoothing (or regularisation). Despite this, plane-wave destruction produces a reasonable diffraction image albeit with obvious remnant reflection energy and noise.

Having removed a large amount of the reflection energy, we migrate the plane-wave destruction data into the dip-angle gather domain and apply apex destruction. A relatively small filtering window is used in order to preserve diffractions. Following this, the data is transformed into the τ-p domain. Here, the flat diffractions map to linear events while the residual reflections map to points due to their curved shape. A filter is applied to remove these points while retaining the linear diffraction energy. This final step also helps to denoise the data and helps to boost the diffraction energy due to the τ-p transformation spreading energy back into the area removed by apex destruction.

This combined method has been compared to plane-wave destruction and apex destruction methods applied individually (Figure 1). While both methods work well individually, difficulties and drawbacks associated with each method cause artefacts in the final image. These artefacts mostly relate to difficulties with estimating the dip, especially steep dips such as those seen in the salt flanks. By combining pre-migration and post-migration methods, many of these artefacts can be significantly reduced, producing a clearer diffraction image for interpretation.

This diffraction image can be compared with conventional discontinuity imaging methods such as the coherency attribute (Figure 2). While coherency works well to identify shallow faults, there are some areas of missed energy, especially for faults in complex fault zones and in areas where the fault orientation may be counter to the conventional fault orientation. The diffraction image locates these faults and manages to identify other diffraction forming discontinuities in the image. Conversely, there are areas in which the diffraction image can fail to find energy, due to poor illumination and weak diffractions, which may be imaged using the coherency volume. By using the diffraction and coherency image together, a clearer interpretation of the subsurface can be created.
Figure 1 Conventional image (top left), plane-wave destruction image (top right), apex destruction $\tau$-$p$ filtered image (bottom left), and combined pre- and post-migration separation image (bottom right). Note while the diffractions are highlighted in each of the diffraction images, the residual reflection energy and noise is reduced in the combined method compared to either of the other methods.

Conclusions and Future Work

We have demonstrated the benefit of a combined pre- and post-migration diffraction separation approach. By combining three methods, one pre-migration and two post-migration, a more reliable diffraction image has been created which contains less remnant reflection energy and noise than any of the methods applied individually. We find that diffraction imaging can highlight areas missed in the conventional coherency volume. However, some areas with weak diffraction energy or poor illumination are better imaged by the coherency volume than the diffraction image. As these images complement one another, using them in conjunction allows for the clearest interpretation of the subsurface.

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References


Figure 2 Conventional image (top left), combined pre- and post-migration separation diffraction image (top right), diffraction image overlaid on conventional image (bottom left), and coherency overlaid on conventional image (bottom right). Green arrows show faults which are better highlighted by the diffraction image while blue arrows show faults which are better highlighted by coherency. The green box shows a complex fault zone well imaged with the diffractions but not seen in coherency.