Diffraction imaging – a tool to reduce exploration and development risk

N.R. Benfield¹, A. Guise² and D. Chase³ show that diffraction imaging gives higher resolution fault definition than either a conventional seismic reflectivity volume or conventional post-stack fault enhancement attributes.

When evaluating exploration prospects, discoveries or a field under development it is essential to build an accurate structural framework at an appropriate scale. Detailed understanding of the fault network enables reservoir compartmentalisation risk to be better quantified at the exploration prospect stage and informs well placement optimisation in the exploration, appraisal and development phase.

This paper presents a method for maximising fault information from depth migrated narrow azimuth seismic data. The faults are imaged in the depth domain by separating the diffracted component from the total migrated wavefield. We show that diffraction imaging gives higher resolution fault definition than either a conventional seismic reflectivity volume or conventional post-stack fault enhancement attributes.

We also show that diffraction volumes can be further processed to generate attribute volumes with fault definition sharp enough to pick with automatic fault detection algorithms, producing a highly-detailed fault network that can augment manual fault interpretation products and be incorporated into the structural framework.

Diffraction imaging is a technique for imaging small scale subsurface geological objects and discontinuities, such as faults, unconformities and karsts using the diffracted component of the total recorded wavefield.

There are two main types of diffraction events, point diffractions and edge diffractions. Point diffractions are transmitted from small discontinuities and isolated objects while edge diffractions are generated by terminations of reflection boundaries such as at fault locations.

In depth domain migrations, all of the components of the recorded wavefield are mapped to the depth imaging point so the total energy for a given imaging point can be considered to be comprised of specular energy and diffraction energy with the proportion of each depending on the geology. Specular (reflection) energy is focused within a narrow range of dips with the energy dissipating from the specular dip (Figure 1). Diffraction energy on the other hand will populate non-specular dips (Figure 2). Specular energy has higher amplitude than the diffraction energy, but the proportion of diffraction energy will increase at geological discontinuities. Therefore, a filter can be designed to attenuate the higher amplitude specular reflections from the migrated pre-stack depth domain data. Attenuation of the specular energy leaves behind diffraction energy that can be stacked to enhance any spatially consistent geological discontinuities.

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Figure 1 Ray path representing Specular Energy.

Figure 2 Ray path representing Diffraction Energy.
Any incoherent events left in the diffraction volume have then to be attenuated before the lineations can be automatically picked as faults. Automatic fault detection algorithms will pick up every lineation, generating more faults than can be practically handled, therefore methods of constraining and editing the picking are required before they can be incorporated into the structural model.

In order to understand the lineations derived from the diffraction volume, it is necessary to co-render them with the reflectivity volume to give confidence that the lineations represent genuine faults rather than noise. Additional confidence can be gained by assessing the nature and orientation of the faults in 3D within the context of the regional stress regime and tectonic setting of the area.

The data example shown was acquired using a narrow azimuth towed streamer acquisition with 10 x 8km cables towed perpendicular to the main fault trends.

The workflow showing the steps from diffraction image processing to structural model generation is shown in figure 3. In this study a map-based approach was taken.

**Diffraction volume generation**

In conventional seismic imaging workflows, the output data is biased to the higher amplitude specular part of the seismic dataset generating clear continuous reflection events for structural interpretation. Faults are then interpreted as breaks in the reflection events. Diffraction imaging workflows aim to achieve the opposite, which is to attenuate the reflectors, leaving behind any focused diffraction events that may be owing to real geological phenomena such as faults, unconformities and depositional discontinuities. Ray-based angle migrations (Koren and Rave 2011) shoot rays from the imaging point upwards in order to select the input data samples to map back to the output image point. This process enables the retention of dip, angle (Figure 4), dip-azimuth and angle-azimuth (Figure 5) information for each data sample; hence each data sample has four dimen-
Various filters are tested in order to achieve the optimum balance between attenuating the specular events and enhancing the diffraction events. In this case, filter 2 was selected and this single filter was applied to all samples of all directional angle gathers.

The result of the specular filter shows clearly that the low angle primary reflection has been attenuated (Figure 10 and 11) and the diffraction event at around 20 degree dip, 120 degree azimuth is enhanced when compared with the input (Figure 7 and 8). Additionally, the low angle reflection data can clearly be seen to be attenuated on the unwrapped depth gathers.

Once the specular filter has been applied, the dip/dip-azimuth gathers are stacked in a conventional way to output a diffraction imaged volume.

**Diffraction volume post processing**

The most geologically meaningful way to review any attribute volume is in 3D and along interpreted horizon slices where applicable. Extractions along a target horizon from the diffraction volume (Figure 12a) show a complex network of lineations that are potential faults. When compared with conventional post-stack attributes; curvature (Figure 12c) and similarity (Figure 12d), more features are visible on the diffraction data but there are similarities in position and trend between all three attributes.

When analysing the diffraction results (Figure 12a), it is clear that there is still considerable noise in the data. This noise is left behind after the application of the specular filter and could be owing to acquisition footprint, random noise or aliasing in the migration step. After the application of the specular filter the events parallel to a fault plane (diffraction energy) will align.

To aid interpretation of the features derived from the diffraction volume, an edge detection filter was used to considerably enhance the faults and reduce the background noise (Figure 12b).
Diffraction volume fault analysis

The post-processed diffraction volume (Figure 12b) has a series of very clear lineations but it is necessary to analyse these results in combination with existing seismic and known structural framework to ascertain whether the lineations can be attributed to faults or are just noise.

The first step in analysing diffraction data is to co-render with the reflectivity volume (Figure 13). The lineations from the diffraction volume can then be correlated directly with breaks in the reflectivity volume amplitude. Often associated with minimal or, indeed no discernible horizon offset, these amplitude breaks are unlikely to have been conventionally interpreted as faults. Additionally, the overall trend of the lineations in three planes can be visualised to analyse continuity and spatial orientation. The orientations of the co-rendered lineations (Figure 13) are perpendicular to the known direction of regional extension, and parallel to the large-scale faults that are clearly imaged by the reflectivity volume. These QC processes provide a high level of confidence that the majority of the diffraction volume lineations are attributable to fault planes.

It should be noted that the main regional faults are not well discriminated by the diffraction volume, but are clear on the post-stack reflectivity attributes. There are a number of possible explanations for this:-
The major fault planes are reflectors that are attenuated rather than diffraction events particularly where they are less steeply dipping.

- The major faults cover spatial zones rather than discrete edges.
- Imaging uncertainty due to fault shadow effects.

A zoom of the co-rendered diffraction and reflectivity volumes (Fig 14) clearly shows the faults aligning with the seismic amplitude discontinuities. Additionally, there are lineations that are parallel to the clearly imaged faults that do not coincide with amplitude breaks in the reflectivity volume. These are higher resolution faults that the pre-stack diffraction imaging technique is able to resolve.

**Diffraction volume fault interpretation**

The diffraction volume contains many thousands of potential faults/discontinuities, too many to interpret manually. Therefore, an automatic fault picking algorithm is required. Fault picking algorithms do not effectively work on the raw diffraction volume (Figure 12a) due to the amount of noise present. Therefore an attribute volume designed to attenuate and sharpen the faults is required as input (Figure 12b). Even so, the picker will pick any continuous lineation regardless of area, orientation and dip resulting in many tens of thousands of fault segments. Therefore an efficient method of editing the number of faults is required. By using histograms to select the faults patches to filter by one, or a combination of attributes such as; fault dip angle, azimuth, patch area, lateral or vertical extent, or confidence it is possible to significantly reduce the number of patches whilst retaining those of most interest.

In this example the fault dip angle was used firstly to isolate and remove patches which were unlikely to represent genuine fault planes, but which may represent seismic discontinuities caused by primary depositional or erosional processes. Fault azimuth attributes were effective in isolating regional, counter-regional and cross-fault trends; each of which may be viewed differently in terms of sealing capability, dependent on regional stresses. Thirdly, filtering patches by area allowed only the largest, and therefore most structurally significant faults, or everything including the smallest faults, to be retained and taken forward into the structural framework. The fault patch size which is considered significant will clearly vary across the different stages of the exploration-appraisal-development life cycle, and can easily be parameterised accordingly to retain the desired level of detail.

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![Figure 12](image1.png) *Extractions along a target horizon, clockwise from top left, a) raw diffraction volume, b) enhanced diffraction volume, c) positive and negative curvature volume, d) similarity volume.*

![Figure 13](image2.png) *Diffraction volume co-rendered with seismic reflectivity.*

![Figure 14](image3.png) *Diffraction volume co-rendered with seismic reflectivity volume showing diffraction events imaging faults that are visible as terminations on the reflectivity volume and those that are not and therefore of a higher resolution.*
After editing, there were still many hundreds of fault segments that needed to be incorporated into the structural framework for the prospect.

**Incorporating faults into the structural model**

In this particular example, the automatically picked fault set was firstly restricted to the zone of interest for the prospect; both areally and vertically. This reduced the number of fault patches significantly; however the same workflow could also be employed for the full seismic dataset. The fault patches were then imported into the structural modelling software and gridded. The reservoir horizon was then gridded in conjunction with the fault surfaces, and the intersections of these surfaces were outputted as polygons. The unedited polygons were then visualised along with the fault polygons generated from the manual fault interpretation, in order to QC their consistency with regional trends. It was clear that the auto-picked fault patches, after filtering, were dominantly aligned with the fault trends which had been mapped manually, and in many cases duplicated the same faults. This built confidence in the robustness of the auto-picked faults, and therefore in the validity of the higher resolution faults which had emerged internally within individual larger fault blocks.

As can be seen in Figure 15 and 16, the auto-picking process outputs many small fault patches which, when combined, form a single larger fault plane. It is therefore necessary to merge the fault patches in some way to produce laterally and vertically continuous faults. Merging the patches in 3D was considered to be too labour intensive for the exploration prospect, and so the decision was taken to merge the patches after creation of the horizon intersection polygons, as described above. This involved manually editing the polygons to form linked, merged fault polygons. Polygons duplicated by the automated interpretation process were removed. The final step was to re-grid the reservoir horizon using both the manually and automatically-derived fault polygons as constraints. The reservoir structure maps before and after this process are shown in Figure 17.

**Conclusions**

This study demonstrates that depth domain diffraction imaging can be used to generate higher resolution fault definition than conventional reflectivity volumes, or their derivative post-stack attributes.

To fully utilize and understand the diffraction image volume, post-processing and co-rendering with the reflectivity volume are required as well as including regional structural and stress information.

The fault image information has to be incorporated into the structural model of the prospect to have maximum value, and this can be undertaken with automatic fault interpretation in three dimensions and interactive editing. Some of this improvement in detail may have been achievable by very
fine-scale manual fault interpretation. However, as shown in Figure 14, the diffraction volume is capable of imaging higher resolution faults than can be seen on the reflectivity data.

The final results are gridded into the structural framework producing detailed fault information that can be used to improve the assessment of reservoir deliverability, and optimize well placement.

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References


