Seismic analysis workflow for reservoir characterization in the vicinity of salt

Colin J. Ferguson, Anthony Avu, Nick Schofield and Gaynor S. Paton describe a five step post stack seismic analysis workflow to aid the interpretation of reflectivity data around and under salt layers.

Analyzing reservoirs and trapping geometries in complex geologic environments containing salt can only be successful if an accurate delineation of the salt boundaries and associated faulting can be achieved. Salt is present within the stratigraphy of major hydrocarbon-producing regions such as the central and southern North Sea, the Gulf of Mexico, offshore West Africa, and the Middle East.

The acoustic characteristics of salt present major problems in imaging geological structures below salt. The high velocity of salt (4.5–6.5 km per second compared to 2.0–5.0 km per second for most sandstones and limestones – Kearney et al. 2002) has two major effects in subsurface imaging:

- Seismic energy travels into underlying strata at an increased speed and arrives at a sub-salt stratigraphic boundary early. This produces reduced travel times leading to ‘pull up’ in geological boundaries below salt which can affect both imaging and final depth calculations.
- Major refraction (and scattering) of seismic energy into and through the salt and into surrounding strata produces random noise, which can render the seismic image difficult to interpret.

The development of seismic processing technology has greatly improved viewing and subsequent interpretation of sub-salt strata (Howard et al., 2007). However, imaging and interpreting fine detail within sediments adjacent to salt and immediately below salt is still challenging due to the steeply dipping reflectors at salt margins and adjacent sediments (Platt and Walter, 1995; Hornby et al., 2007), and the scattering of seismic energy which reduces the clarity of structures underlying salt.

The data
The seismic data used here to illustrate the workflow is from the Central North Sea and contains Permian-Cretaceous strata in which the Zechstein Salt (Late Permian) features prominently and provides an excellent analogue for testing the salt workflow. Highly variable salt thickness is observed and has developed due to repeated episodes of basement faulting since the Triassic. Differential sediment deposition on the salt during the Triassic also contributed to diapirism. The dataset is situated on the south side of the mid North Sea – Ringkøbing-Fyn High (MNS-RFH), a structural high which marks the northern side of the Southern North Sea (Figure 1). The workflow itself has been tested on data from other salt regions including the Gulf of Mexico, Angola, and offshore Brazil.

The stratigraphic interpretation in Figure 2 was carried out using information from the nearby Tyne Gas Field (Underhill, 2009). Within this section the deepest and subsequently oldest rock layers observed are Permian (Rotliegend, Zechstein) in age and largely composed of sandstone (Rotliegend) overlain by salt (Zechstein). These layers are in turn overlain by Triassic strata which are divided into the Bacton Group (Early-Mid Triassic) and Haisborough Group (Late Triassic). The Bacton Group

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Figure 1 Location of the data.
more dominant noise present beneath the salt. In this North Sea example an aggressive noise cancellation was applied throughout the data due to the strength of the noise present at all levels (Figure 4). The noise cancelled data show improved continuity along reflectors with minimal distortion of the information content of the data. Faults and fractures have been preserved and a greater level of detail is visible below the Zechstein interval.

Spectral Enhancement. The spectral enhancement process increases the mean frequency and bandwidth of the data whilst simultaneously removing noise. This enables the vertical resolution and spatial localization of the imaged seismic events to be optimized, resulting in differentiation of previously unresolved events. As the process only enhances information that is contained within the original signal the risk of introducing artefacts is minimized. This aspect of the workflow was introduced in the final stages of the project and was therefore not performed on the Southern North Sea data. Application of spectral enhancement on the other data sets studied show an improvement in the interpretational

Salt workflow
Post stack seismic analysis has been shown to be effective at improving image quality and for highlighting and delineating structural and stratigraphic features in many hydrocarbon provinces. However, there has been limited publication of the results of post stack 3D seismic analysis in the vicinity of salt. The tools within ffA’s SVI Pro software were used to analyze seismic data containing salt from different geographic locations, resulting in the development of a salt workflow which features robust algorithms and advanced visualization techniques specially suited for the analysis and delineation of geologic features within salt data sets.

The salt workflow is divided into 5 parts (Figure 3).

Step 1 Data conditioning
The quality of any analysis is dependent on the signal to noise ratio in the data, and the ability to detect events as close to the limit of the seismic resolution as possible. Therefore the first step in the workflow consists of structurally oriented noise cancellation to improve the signal to noise ratio, and spectral enhancement to improve the resolution of thin events.

Noise cancellation. The noise present in the reflectors above and adjacent to the salt can be very different to the

Figure 2 Stratigraphic intervals in the data looking north, from Underhill (2009). Geographical orientation is the same for all figures unless otherwise stated.

Figure 3 Summarized salt workflow diagram.
tion of subtle pinchouts and facies characteristics below the salt pillows.

**Step 2: Screening volumes**

It is often useful to get a rapid overview of the major geological trends and features in the area and we found that a small selection of screening volumes were ideal for this purpose. These volumes include Frequency Decomposition and RGB (red-green-blue) colour blends, the Bedform attribute, and instantaneous Dip, Azimuth and DipAzi combined volumes.

Figure 4 (a) Original data, (b) Noise Cancelled data.

**Figure 5** RGB blend of three frequency magnitude volumes showing structural and stratigraphic variations in the data.

*Frequency Decomposition and RGB blending:* By far the most useful screening volume was the RGB blended combination of three frequency response volumes. Frequency Decomposition generates volumes that show the magnitude response at a range of discrete frequencies. When applied to seismic data sets, they offer a much more sensitive method of analyzing the data than the full frequency amplitude response and can provide information about stratigraphic facies boundaries, structural and stratigraphic geometries, stratigraphic heterogeneity, and bed thickness (Henderson et al., 2007).

With the aid of an RGB blending tool, three magnitude volumes are combined and viewed simultaneously, revealing the geological interplay between the responses at three frequencies. Salt-filled areas in seismic sections usually have a low amplitude appearance and this presents a marked contrast with the surrounding areas which often contain high amplitude strata. Especially interesting is that despite the often large salt zones overlying the areas of interest,
Step 3 Salt and fault attribute generation

This step involves the generation of attribute volumes that help in the delineation of the salt and for delineating faults which could be instrumental in the emplacement of the salt or small scale fractures associated with the salt. Such attributes include Chaos, Deformation Mean, Envelope, and Structurally Oriented Semblance (SO Semblance).

Salt Attributes: Two attributes, Chaos and Deformation, were particularly successful at highlighting salt features, both analyze structural variation but in different ways. The Chaos attribute is a Tensor-based attribute which is generated by solving the gradient structural tensor and analyzing Eigenvalues. It clearly identifies areas of high and low chaos within reflectivity data and was effective at delineating the extent of the salt (Figure 6a). The Chaos attribute has also highlighted areas of disturbance within the Chalk Group which contain chaotic reflector properties, as well as the gas chimney which goes through the Bacton and Haisborough group.

The Deformation attribute analyzes the distribution of the 3D orientation vectors relating to the dip and azimuth values within a neighbourhood surrounding the current point. The vector analysis (Deformation Mean attribute) proved to be effective at highlighting the salt in the data, and was a better indicator of fault lineaments than the Chaos attributes due to the higher resolution of the results (Figure 6b).

Fault attribute: In the vicinity of salt the faults are often numerous, relatively small scale, and often on steeply
dipping reflectors. Several edge detection algorithms were investigated to find the most effective algorithm for this type of fault expression. The SO Semblance attribute is an edge detection algorithm which analyzes semblance variation in a manner conformant with the geology. This attribute highlights faults and fractures in the data whilst being resistant to steeply dipping continuous reflectors which are often picked up in conventional grid-oriented semblance algorithms. This has been very effective in highlighting the faults associated with the Zechstein salt and also sub-salt faults within the Rotliegend which are critical to the emplacement of the salt (Figure 7).

**Step 4 Salt relationships**

This stage of the workflow uses volume combination techniques and advanced colour and opacity blending methods to provide the interpreter with an in-depth view into the relationship of the salt to adjacent strata.

*Combination volumes:* The salt delineation attributes target specific properties in the seismic data and are generally used as standalone interpretation volumes. In order to gain a more detailed insight into their relationship with other properties, it is useful to combine volumes in such a way that the individual properties can be assessed in a more meaningful context. The salt workflow incorporates two methods for doing this. The first involves combining an attribute that contains structural information such as Dip or SO Semblance with an attribute that contains stratigraphic information, such as Envelope (instantaneous amplitude), Chaos, or Deformation. The combination is done by binning the information contained in both volumes so that colour change and colour saturation will denote a change in the different attributes. One example (Figure 8) is to combine the Dip and Envelope volumes so that colour change signifies the change in amplitude while colour saturation signifies change in the degree of dip. In the sub-salt Rotliegend group this combination shows clearly the zones of high amplitude and their relationship with the darker lineaments of the faulting.

The second method involves a technique called ‘cookie cutting’ where one volume is taken as a mask, and values from a second volume are used to populate areas defined by the mask. An example of this combination is in the Bedform-Chaos volume (Figure 9). The Bedform attribute extracts thin lineations which represent the apex of the wavelet peaks and troughs, the Chaos attribute was then cookie cut between these lineations. Pinchouts, onlaps, and other reflector terminations are now visible within an attribute defining the extent of the salt.

**CMY colour blend:** The CMY (cyan-magenta-yellow) Blend is based on the same principles as RGB Blending but provides another visual scheme for displaying three
attribute volumes. Mapping the Envelope volume in the cyan channel, the SO Semblance volume (with inverted values) in the magenta channel and the Chaos in the yellow channel results in a 3D blended volume that highlights the geological interplay between the responses of the three inputs (Figure 10). The major horizons are clearly visible in the volume (deep cyan) and additional horizons are seen throughout the Triassic strata. The low SO Semblance and Chaos values illustrate the structural stability associated with these zones. Regions of high SO Semblance and Chaos (red = magenta + yellow) are seen in the salt, underlying fault zones, gas chimney, and Chalk layers, and illustrate the importance of faulting in forming the salt diapirs. Major faults are observed individually in the Rotliegend (magenta) but most faults occur within strongly chaotic regions (yellow-red) illustrating the strong relationship between faulting and structural variability.

**Step 5: Extraction of salt geobodies**

Salt diapirs are complex 3D entities and, whilst attributes can give an indication of their location, the salt bodies need to be extracted as 3D geobodies to get a full understanding of their detailed geometries.

**Geobody extraction**: Body labelling the salt attribute volume (usually Chaos) created 3D geobodies of the salt and colour coded them according to their connectivity (Figure 11a). Varying thresholds were defined which limit the range of the attribute values extracted enabling different interpretations to be investigated whilst maintaining the ‘data driven’ ethos of seismic analysis.

We also investigated the use of the Bedform attribute, cookie cut with the instantaneous frequency volume (Bedform Frequency), to create an attribute that can be used as a template for the extraction of geobodies that correspond to high frequency layers and potential pinch outs in the data. This was computed by running a structurally oriented smoothing filter on the Bedform Frequency volume. This in effect concentrates high frequency zones and makes them more connected and continuous. This attribute helped highlight the pinch out features within the Bacton group which thin from the basin centres (overlying thin salt) towards thick salt, highlighting differential sediment loading on the salt during the Triassic as salt movement progressed. This attribute has also highlighted pinch out features below the salt in the Rotliegend. These pinch out zones were body labelled and combined with the salt geobody, providing a useful volume for the investigation of stratigraphic traps below and around the salt (Figure 11b).

**SkinIn volume**: Creating a SkinIn volume by extracting the outer skin of the salt geobody and embedding this into the noise cancelled reflectivity data served as a visual corre-
Interactive facies classification: An alternative method of extracting the facies geobodies is to use the Interactive Facies Classification Tool. This is an interpreter driven seismic classification module which allows the user to input a number of attributes and define classes by selecting individual seed points or polygons over particular regions. The Chaos and Envelope attribute volumes were used as an input into this tool and picks were made to delineate the salt body and the major reflectors. In Figure 13, the salt zone is shown as a red class with a central turquoise class corresponding with the most disturbed reflections. The grey class represents zones of high amplitude stable reflectors and has not only delineated the major horizons but also events within the Zechstein and Bacton groups with similar seismic expressions.

Conclusions

3D seismic analysis tools provide powerful but simple-to-apply workflows for delineation of salt, and prospect identification around and below complex salt terrains. In particular advanced multi-volume visualization techniques improve the understanding of the relationships between fault systems, salt diapirism, and trapping mechanisms. This can be achieved not only at a regional scale but also at a more detailed prospect level scale.

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References


