Determining Fault Seal Indicators from 3D Seismic

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1. Introduction

Obtaining accurate and detailed information on the properties of fault systems has a significant impact on the E&P workflow. Assessment of whether a particular fault is sealing can directly affect prospect assessment and recovery estimates and support detailed understanding of a reservoir system during the recovery phase.

There are many facets to understanding the sealing capacity of a particular fault or fault system and gaining a complete understanding of the properties of both individual faults and more complex multiple-fault networks in and around a reservoir or prospect is a significant task.

Some well known techniques for understanding the sealing capacity potential are rooted in seismic interpretation and use interpreted fault and horizon surfaces to clarify the stratigraphic environment in which a fault is embedded.

Techniques such as Fault Slicing (Brown et al, 1987) relative to an interpreted fault plane, to obtain a juxtaposition analysis (Bouvier et al, 1989), draw on structural cues and is one of the key approaches in determining whether a fault is sealing or leaking. When calibrated, such juxtaposition analysis informs the interpreter of the coincidence of the same or similar lithologies across the fault plane itself. Conclusions that a fault is sealing are drawn from understanding, for example, whether or not there is lateral juxtaposition of low permeability beds against high permeability beds (e.g. shale-on-sand lateral contact).

Juxtaposition analysis does not perform well when highly permeable beds are continuous across the fault. In such situations other indicators of fault seal capacity such as Shale Gouge Ratio and Clay Smear Potential (Naruk et al, '02) may come into play, however these indicators are not universally applicable and where faults seal due to cementation, indicators may only be available through pressure studies and/or interpretation of diagenetic processes.

2. Scope

The current work focuses on developing non-calibrated structural indicators of potential fault sealing capacity from 3D seismic data. A workflow has been developed to support analysis of a fault or fault network based on the principles of juxtaposition but applied to volume based analysis of 3D seismic data.

This Fault Sealing Capacity (FSC) workflow derives all measurements directly from seismic data volumes (including Seismic Reflectivity, Acoustic Impedance and Relative Acoustic Impedance data sets).

3. A Volume Based Fault Representation

Faults that are expressed on a seismic scale are rarely isolated neat fractures, however, a planar representation of seismic scale faults is still favoured even though is it typically over smooth and generally encompasses a number of cascaded faults. It is more appropriate geologically to consider both individual faults and networks of faults as regions of damage consisting of many scales of fracturing and stress related distortion (Young-Seog Kim, '04).

In this work we propose that faults are represented by 3D Geobodies that represent the Seismic Fault Damage Zone associated with a fault, derived directly from an attribute driven segmentation of the seismic data volume.

Seismic FDZs serve a dual purpose; firstly they define the region of a seismic data volume which we identify as the expression of a fault and secondly they define by complement the regions of data that are not affected by faulting. Hence, we would expect regions within the Seismic FDZ to include any curvature or flexions associated with the fault as well as any curvature, distortion or dimming at the fault due to the imaging process itself. Conversely, outside of the Seismic FDZ we would expect to see well behaved strata in the seismic reflectivity data, suitably isolated for subsequent juxtaposition analysis.

Capturing the geometry of the seismic fault expression accurately enables subsequent volume based analysis to be applied more appropriately, rejecting data from the juxtaposition analysis that could have been adversely affected by faulting and the imaging process.

4. The FSC Workflow

The workflow can be broken down into four stages (Figure 1).

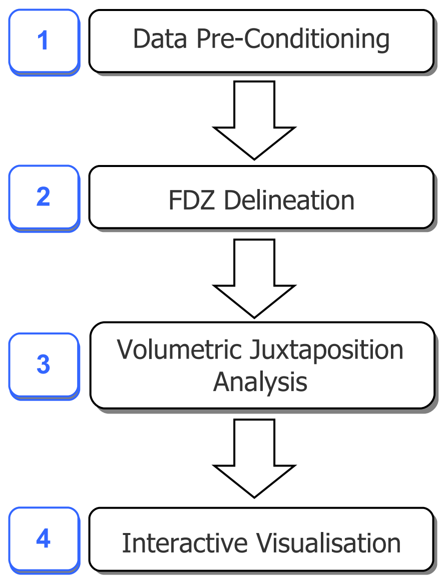

Figure 1 – Key stages in the Fault Seal Capacity Workflow

4.1. Data Pre-Conditioning

Pre-conditioning of the seismic data encompasses noise suppression and in some instances spectral whitening and can have a significant impact on the reliability with which faults can be detected, definition of the fault damage zone and the volumetric juxtaposition analysis. Noise suppression is achieved using structurally oriented edge preserving filters that improve reflector continuity whilst preserving or, in some instances, enhancing discontinuities (Pollak et al, 1999). Determining a suitable level of pre-conditioning is important, as inappropriate changes at this stage can have detrimental effects on the remainder of the workflow. In many cases it will be appropriate to apply a higher degree of pre-conditioning to the reflectivity data used for delineation than the attribute data being investigated.

4.2. FDZ Delineation

Delineation of the Seismic Fault Damage Zones (FDZ) is achieved in two steps:

1. Application of a volume based fault imaging workflow.
2. A statistical region growing process.

Volume based fault imaging results in the extraction of single voxel thick lineations representing the likely position of faults. The FDZ delineation process uses the detected fault lineations to define a set of seed points that are used to initialize the region growing process.

4.3. *Volume based Juxtaposition Analysis*

The first stage of the juxtaposition analysis involves examination of appropriate seismic attribute / impedance values in regions defined relative to the detected FDZ geobodies. The acoustic properties of the region within the FDZ (Bulk Body Analysis) and along the local structure either side of the FDZ are computed. The results of this analysis are mapped onto new fault structure volumes consisting of either the central plane or the 'skin' of the geobody.

In addition to attribute derived statistics it is possible to also measure the geometric properties of the FDZ itself, for example the local thickness.

The second stage is to generate one or more juxtaposition volumes that show the variations in acoustic properties either side and within the FDZ geobody. This is achieved by projecting values from the FDZ skin structures, along the direction normal to the fault's trend, onto the central fault structure.

It should be noted that the seismic attributes being studied can be the result of processes such as seismic inversion), or of direct analysis of seismic amplitudes,

4.4. *Visualisation*

Understanding the spatial variation of values between different faults or fault segments plays an important role in the interpretation of the FSC values, which are uncalibrated. Therefore, visualisation is a key aspect of the Fault Seal Capacity workflow and specific attribute blending tools and non-orthogonal 3D region of interest rendering tools have been developed.

5. Results

The FSC workflow is illustrated by a series of images showing volumes generated at each stage of the processing. The input data were Pre-stack Time-Migrated reflectivity and Relative Acoustic Impedance (RAI) volumes covering an area of approximately 200km^2 in the UK sector of the North Sea. The interval of interest is a 600ms window centred on the Rotliegend group.

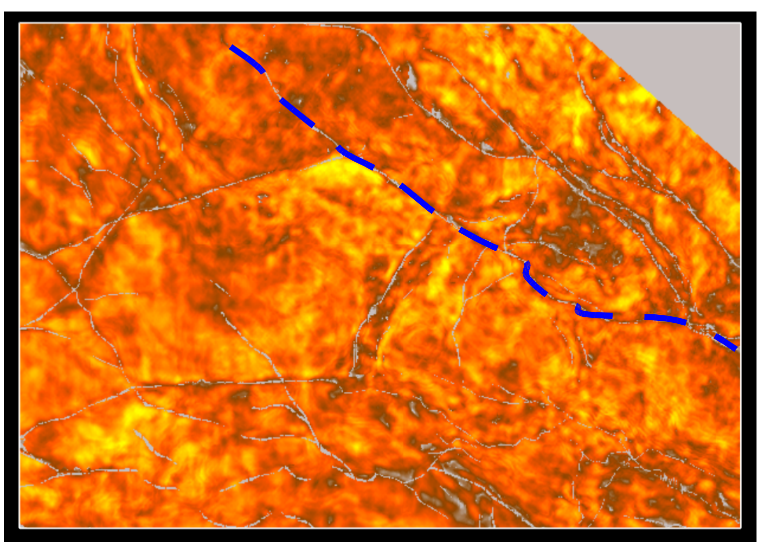

Figure 2 - A reflectivity map of the region of interest showing major interpreted fault structures. The fault section highlighted in blue is shown in isolation in a number of figures.

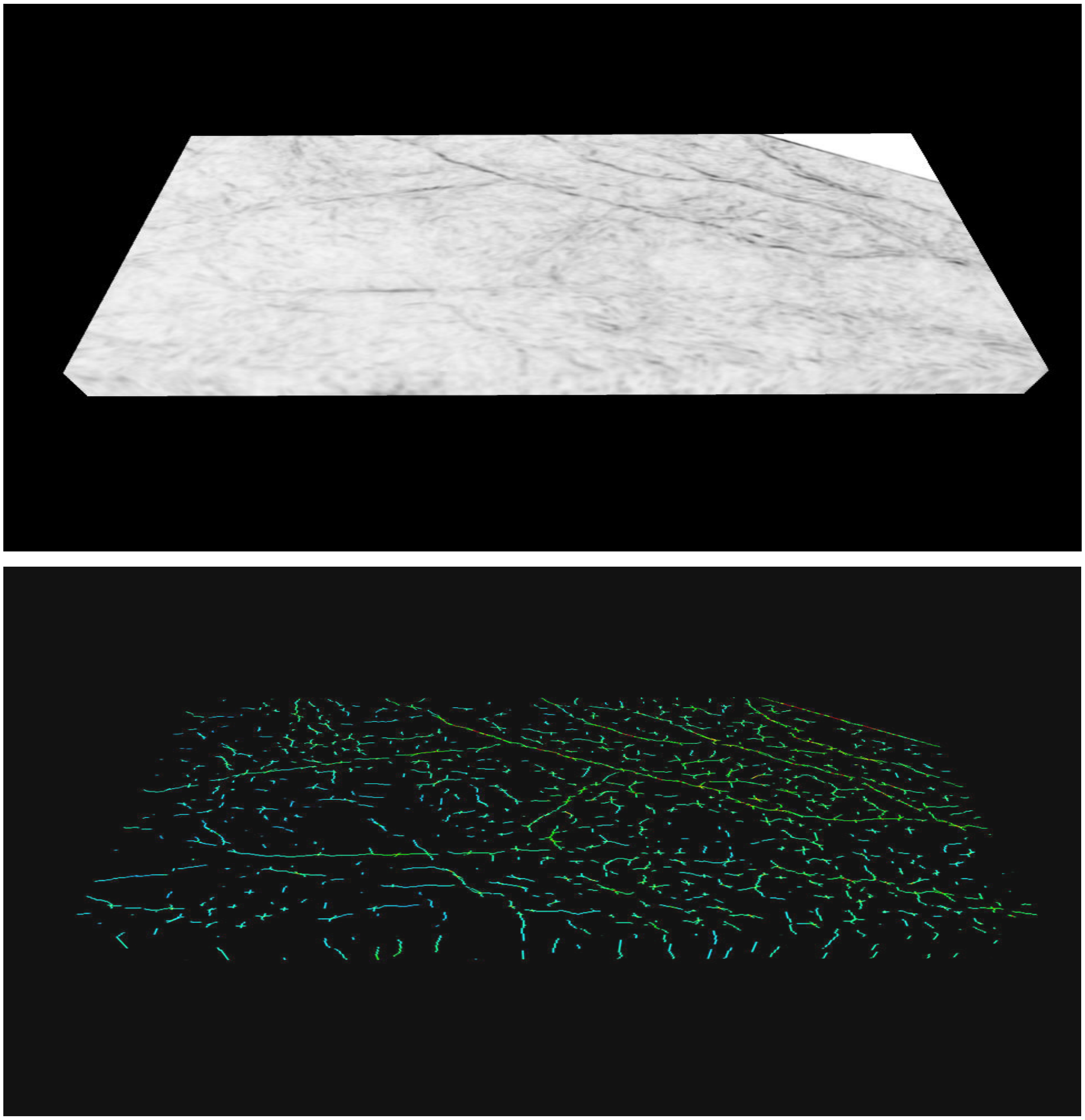

Figure 3 - The Fault Imaging stage involves computation of a Fault Attribute volume *(top)* that represents both the location of potential faults and the regions of deformation associated with these faults. The Fault Detect Volume *(bottom)* shows the most likely fault lineations and is used to define seed points for the FDZ geobody delineation process. The Fault Detect Volume also provides indications of the general behaviour of a fault, for example whether the fault is disrupted and consists of a suite of "en échelon" events, thus giving information on possible fluid flow general directions.

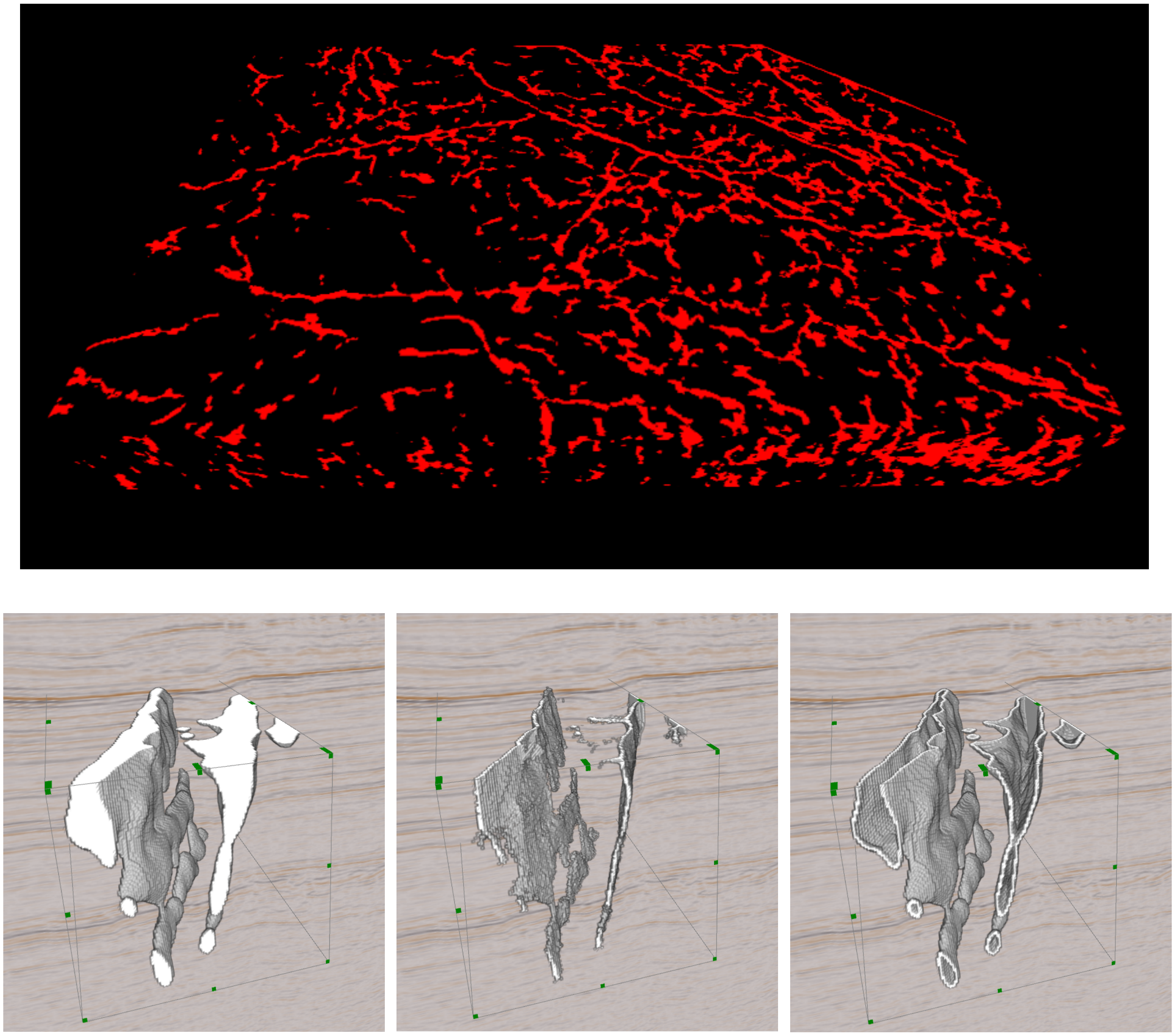

Figure 4 – The FDZ geobody region growing process results in a 3D representation of areas in the seismic reflectivity affected by faulting *(top)* as captured in the fault attribute volume.

Individual fault segments or sets of fault segments can be isolated *(bottom-left)*, along with the associated central planes of the these segments *(bottom-middle)*. The outer geobody skin can be extracted separately *(bottom-right)*. The geometric complexity of the FDZ geobodies is evident.

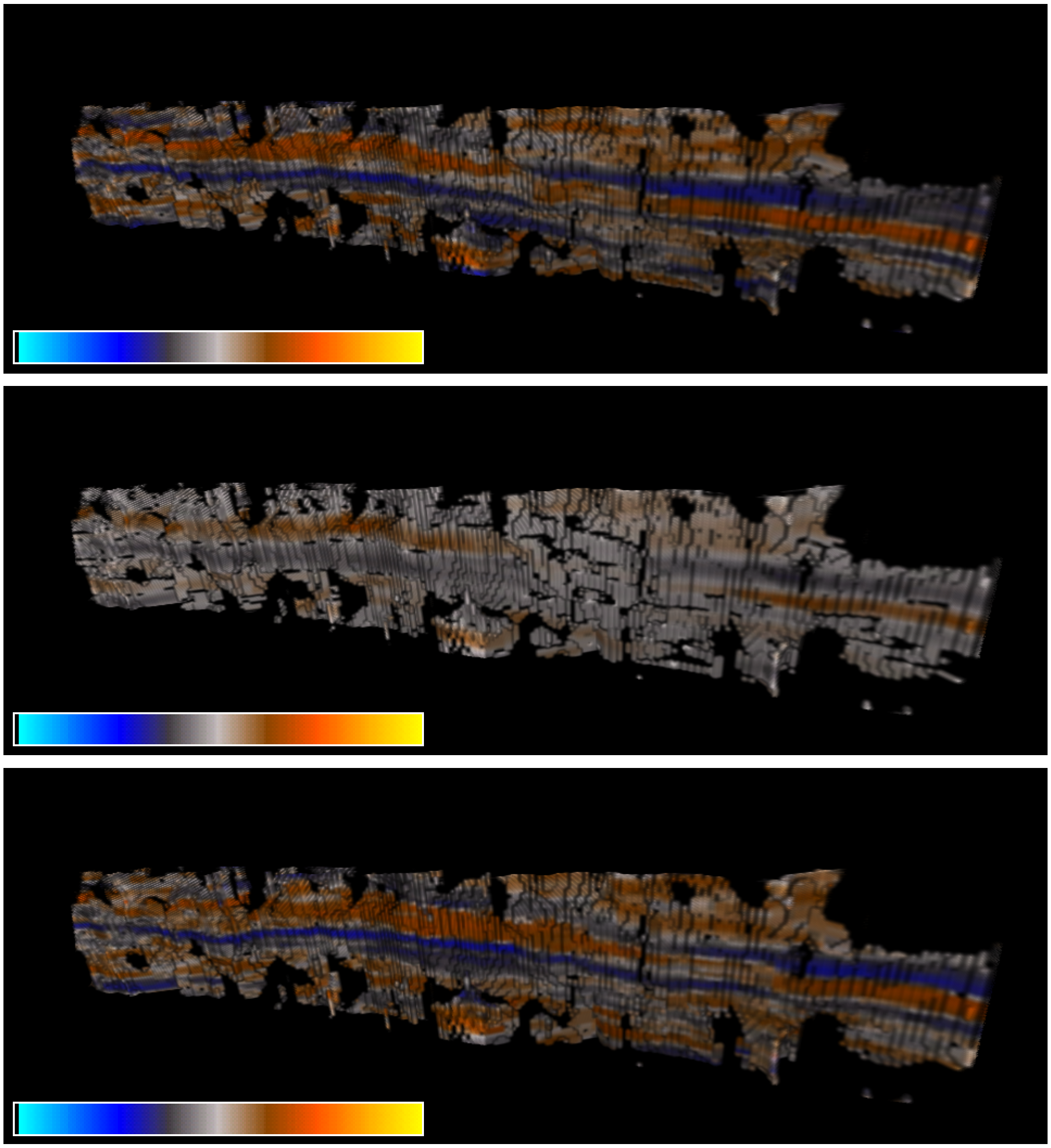

Figure 5 – As a result of the juxtaposition analysis, the local statistics of a user selected attribute are computed over the region within and the regions either side of the FDZ geobody. These statistical values are then projected across the FDZ, juxtaposing relevant values based solely on the geometry of the FDZ.

These juxtaposed values are pasted onto the central fault plane of the Fault. (*top "trailing side", Middle "inside", bottom "leading side")*. In this instance, the values represent average relative acoustic impedance (RAI).

The validity of seismic attributes within the FDZ has to be investigated. Accepting that this area is hampered by many artefacts, (e.g. diffractions), it is still likely that statistically it bears information on the geological behaviour of this distorted zone.

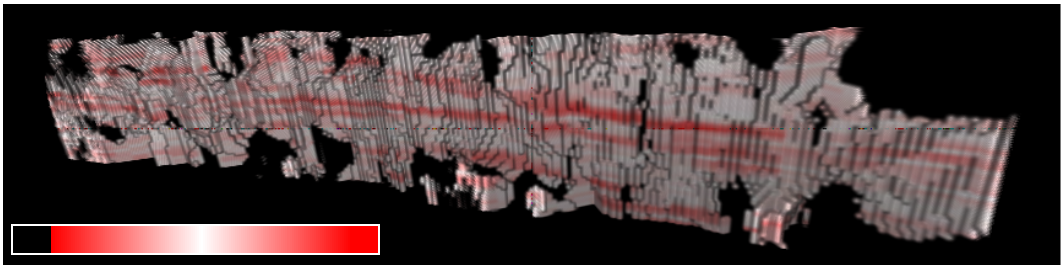

Figure 6 – A FSC indicator is computed from the difference of juxtaposed attribute statistics from the trailing and leading sides of the FDZ. Here, white bands indicate a small or no difference between the RAI values either side of the fault. Red values indicate a large difference between RAI values. Alternatively, a multi-channel rendering technique such as RGB blending (Henderson, 2007), enables the juxtaposition of RAI data from either side and from within the FDZ to be visually interpreted.

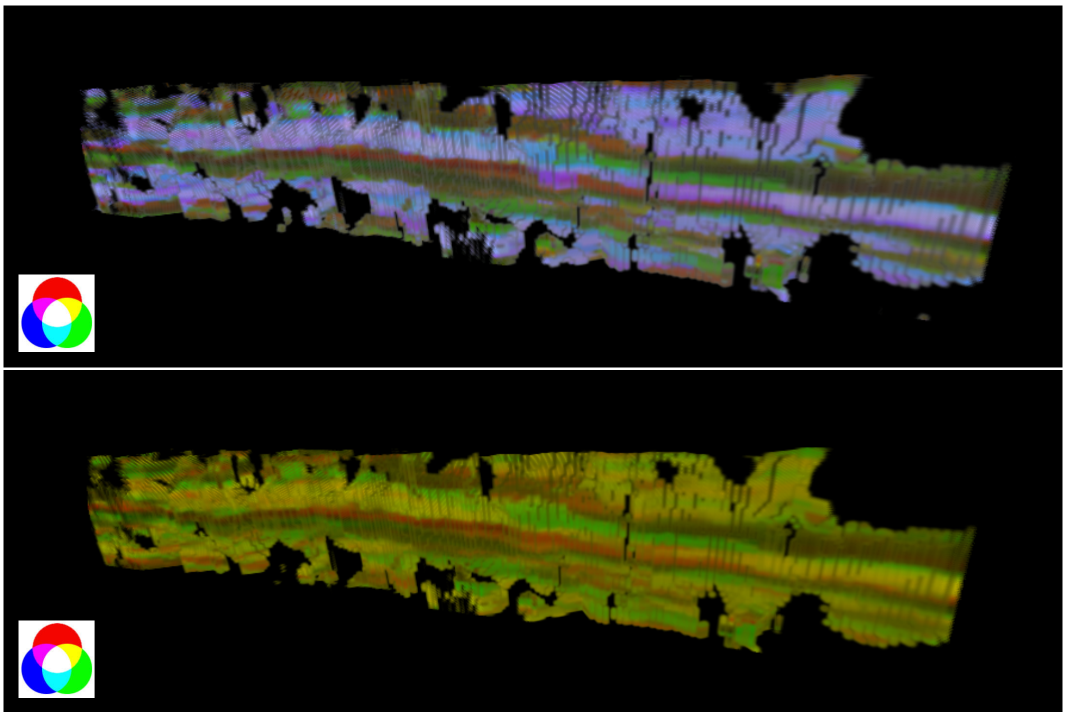

Figure 7 – By RGB blending the juxtaposed values, the fault can be interpreted based on colour *(top)*, where juxtaposed values are used in the red (leading), green (trailing) and blue (central) channels.

In this case, reds and greens indicate a strong contrast in average RAI across the fault, the likelihood of seal is therefore high. Conversely, yellows indicate a low contrast in average RAI and the likelihood of sealing is low. Magentas and cyans also indicate a strong cross FDZ contrast but also indicate strong response from within the FDZ similar to that on the leading or trailing side respectively. As with yellows, blues indicate a low contrast in average RAI across the fault but a relatively high average RAI within the FDZ. White, grey or black indicate that there is no variation in the average RAI through the fault, so no expression of faulting in the attribute.

If the information from within the FDZ is to be disregarded the blue channel can be switched off, leaving only the leading and trailing juxtaposition to be interpreted *(bottom)*.

6. Conclusions

This paper presents a novel workflow aimed at recovering uncalibrated indicators of fault sealing capacity directly from seismic data. The workflow is based on volume processing and attempts to make information available to the interpreter that is not readily apparent from directly viewing the source data.

By representing fault structures as 3D Seismic FDZ bodies the aim is to more accurately reflect areas within the data that are affected by faulting. The FDZ data presented shows the complexity, both structural and organisational, of the Fault Damage Zones. These structures are derived directly from the data and the contrast with the traditional planar representation of faults is clear.

Definition of 3D FDZ geobodies enables data that is affected by the presence of faults to be separated and handled appropriately in the volume based juxtaposition analysis.

Validation of the Fault Seal Capacity is at an early stage. However, the initial results show that the workflow allows appropriate selection of input data for the juxtaposition analysis and enables a clear and detailed understanding of the variations in acoustic response across sets of faults. Further strudy is required in order to determine whether the properties of the FDZ itself can be used to provide additional indicators of the degree of sealing capacity along the fault and through the damaged zone.

7. References

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8. Acknowledgements

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