Investigating fault sealing potential through fault relative seismic volume analysis

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ABBREVIATED TITLE: **Fault relative seismic volume analysis**

Abstract:

Accurate fault interpretation is key to building a robust and reliable reservoir model, and is essential for further study of fault seal behaviour, and reservoir compartmentalisation. Conventional fault interpretation defines faults as planar features. Although the concept of Fault Damage Zones (FDZ) is well established, manual delineation of Fault Damage Zones from subsurface imaging data is difficult and rarely attempted.

In this work we are using the concept of a Seismic Fault Distortion Zone (SFDZ). The SFDZ differs from the geological Fault Damage Zone and is the 3D extent of the regions where the presence of a fault has perturbed the seismic image. The SFDZ represents an area of significant uncertainty within the seismic volume where the signal is distorted either by changes in geology associated with faulting or by imaging problems due to presence of the fault.

Delineation of the SFDZ is a key step in further analysing 3D seismic data to provide information regarding variations in seismic attributes across a fault that can be used to indicate how Juxtaposition of strata influences a potential sealing fault. The SFDZ is delineated using an adaptive region growing algorithm and produces a set of detailed 3D SFDZ geobodies.

The delineated SFDZ is then used as the input to a set of analysis techniques that examine 3D volumetric juxtaposition of seismic attributes, and properties relative to the fault. The techniques involve automated statistical measurement along seismic structure relative to the fault itself.

The workflow has been applied and its utility assessed on an underground gas storage dataset. Initial results suggest that by taking account of the 3D geometry of the SFDZ and subsequently analysing 3D Frequency and Acoustic Impedance volumes relative to these structures, an improved understanding of the juxtaposition of layers across the fault and the lateral variability that juxtaposition can be determined at seismic resolution, and subsequently used to assess the potential for fault seal and fluid migration.

Key Words: Fault network, Juxtaposition, Inner distortion zones, Outer distortion zone

Introduction

When faults are picked during interpretation of seismic data, they are commonly picked as a single plane running through the centre of a faulted zone. A fault's expression in seismic data is rarely a sharp discontinuity and both manual and automated methods for picking faults must address the problem of precise placement of the fault surface. There is uncertainty in the fault's 'true' position at seismic scale, whichever method is used.

However, both outcrop and well data studies show that complex and often asymmetric zones of disturbance, such as fracturing, grain crushing and bending of rock layers, exist around fault surfaces that can typically range from several cms up to 200m on a single side. The reader is directed to (Berg et al 2005) for an illustration of the disturbance surrounding the Moab Fault, Utah. Although the character of these zones vary to a great degree, they can generally be classified into a fault core and more extensive Fault Damage Zones (FDZ). Typically, the fault core is characterised by fault gouge, internal fault rock, slip surfaces, clay smear and alteration, and will have accommodated the majority of displacement. The FDZ is characterised by subsidiary faults, folds, deformation bands, veins and joints which reduce in frequency away from the fault core. Subsidiary faulting is dominantly parallel to the main fault, but can also occur in vertical or antithetic planes to the main fault (Kim et al, 2004) (Berg et al, 2005). Towards the extents of the FDZ there are often significant regions of drag in the surrounding strata, which may or may not be characterised as damage.

On a seismic scale, the fault core is not resolvable. In standard seismic acquisition, the typical bin spacing of 12.5 to 25m is well above the width of the fault core for the majority of faults on a reservoir scale. Therefore the focus of this research is solely on a wider Seismic Fault Distortion Zone (SFDZ) that is generally resolvable on high quality 3D PSTM or PSDM seismic data. We further classify this into an Inner Seismic Distortion Zone and an Outer Seismic Distortion Zone where these are defined through appropriate use of seismic attributes.

- **The inner zone** is generally expressed by a disruption to the reflectors and reduction in seismic amplitudes (shown schematically in Figure 1b). The inner zone represents the limits to the zone of uncertainty associated with the positioning of the fault core within the seismic volume. The seismic response here is likely to be unreliable, as the fault itself will have introduced distortion during the

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imaging process. Traditional fault attributes such as semblance based measurements are used in characterising the inner zone.

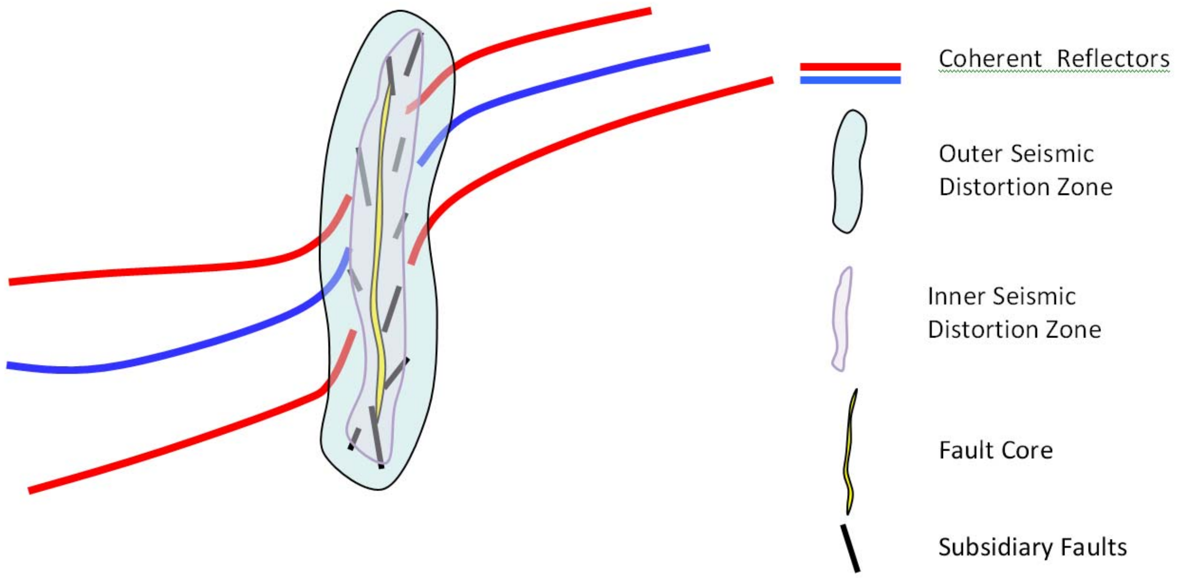

Figure 1 – Schematic demonstrating the Inner and Outer Seismic Distortion zones associated with faulting.

- **The outer zone** is a wider zone within which reflector drag, folding and distortion related to faulting is present and resolvable (shown schematically in Figure 1b). This type of expression can be defined through the use of curvature and flexure type seismic attributes.

Note, this classification is similar to that adopted by (Jones et al, 1996) in their interpretation of "fault damage zones" across a range of scales using seismic attribute maps, although here we work consistently with 3D seismic data based measurements.

Defining the Fault Network

Prior to analysing the fault network, structurally oriented, adaptive and edge preserving noise cancellation algorithms are applied. By increasing the signal to noise ratio whist preserving edges, a clearer definition of fault versus non fault can be obtained.

A 3D seismic processing workflow has been defined and implemented in order to allow fault systems to be analysed by drawing on the information available within noise cancelled 3D seismic reflectivity, derived seismic attribute and inverted seismic property volumes. This workflow builds on existing post stack fault imaging and fault network skeleton extraction methods (Figure 2a & 2b) to provide a starting point for the Fault Relative Seismic Analysis workflow that we discuss here. The process of fault imaging provides us with a number of fault attributes, typically computed through trace-to-trace correlation and/or discontinuity detection algorithms, which are used to extract a skeleton of single voxel thick surfaces across the whole dataset .

This fault skeleton represents potential faults as exhibited in the chosen seismic fault attribute response and is a data driven approach to positioning a 3D fault surface within the zones of uncertainty around faults in the seismic.

Defining the Damage Zone

In order to define the limits of the SFDZ across the volume of interest, an automatic region growing algorithm is utilised. The fault skeleton is used as a starting seed for a region growing process. Used in combination with a selected seismic attribute which highlights the extent of SFDZ in the data, fault structures within the fault skeleton are extended in 3 dimensions so that they cover the corresponding SFDZ regions. The algorithm analyses all adjoining voxels to the seed and those that meet interpreter defined growth criteria are accepted as part of the Seismic Fault Distortion Zone Geobody (SFDZ Geobody) (Figure 2, (c)).

The nature and thickness of the SFDZ Geobodies that are extracted vary according to the attribute used in the calculation. This in turn responds to different SFDZ expressions within the seismic data (i.e. flexures in reflectors, dimming of amplitude, phase change, apparent reflector termination). Seismic expression of the faults can vary significantly within a single seismic dataset. As a result, faults are rarely completely captured by individual attributes across a dataset and optimum results often come from using a number of attributes in combination.

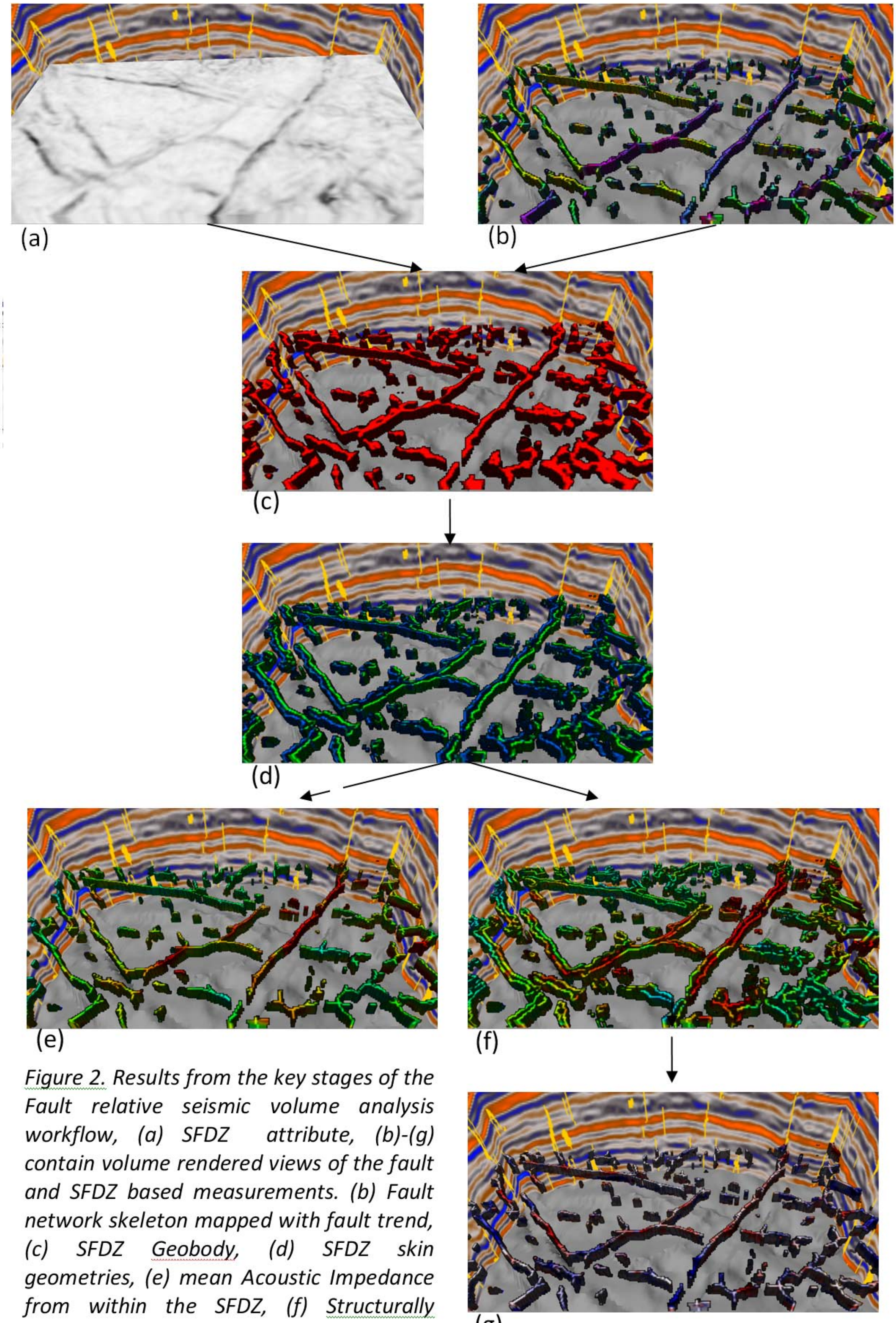

Figure 2. Results from the key stages of the Fault relative seismic volume analysis workflow, (a) SFDZ attribute, (b)-(g) contain volume rendered views of the fault and SFDZ based measurements. (b) Fault network skeleton mapped with fault trend, (c) SFDZ Geobody, (d) SFDZ skin geometries, (e) mean Acoustic Impedance from within the SFDZ, (f) Structurally oriented average of Acoustic Impedance outside of the SFDZ, (g) Acoustic Impedance Juxtaposition Difference.

Figure 3 shows a selection of attributes and how they image the SFDZ's of two faults. The inner zone is well defined by attributes such as Deformation Distance (a vector based measurement of disruption), Semblance, Dip, and Tensor (a measurement of disruption based on eigenvalues of the gradient structural tensor). The outer zone is well defined by measurements of Curvature, including the measure of Structurally Oriented Curvature shown here.

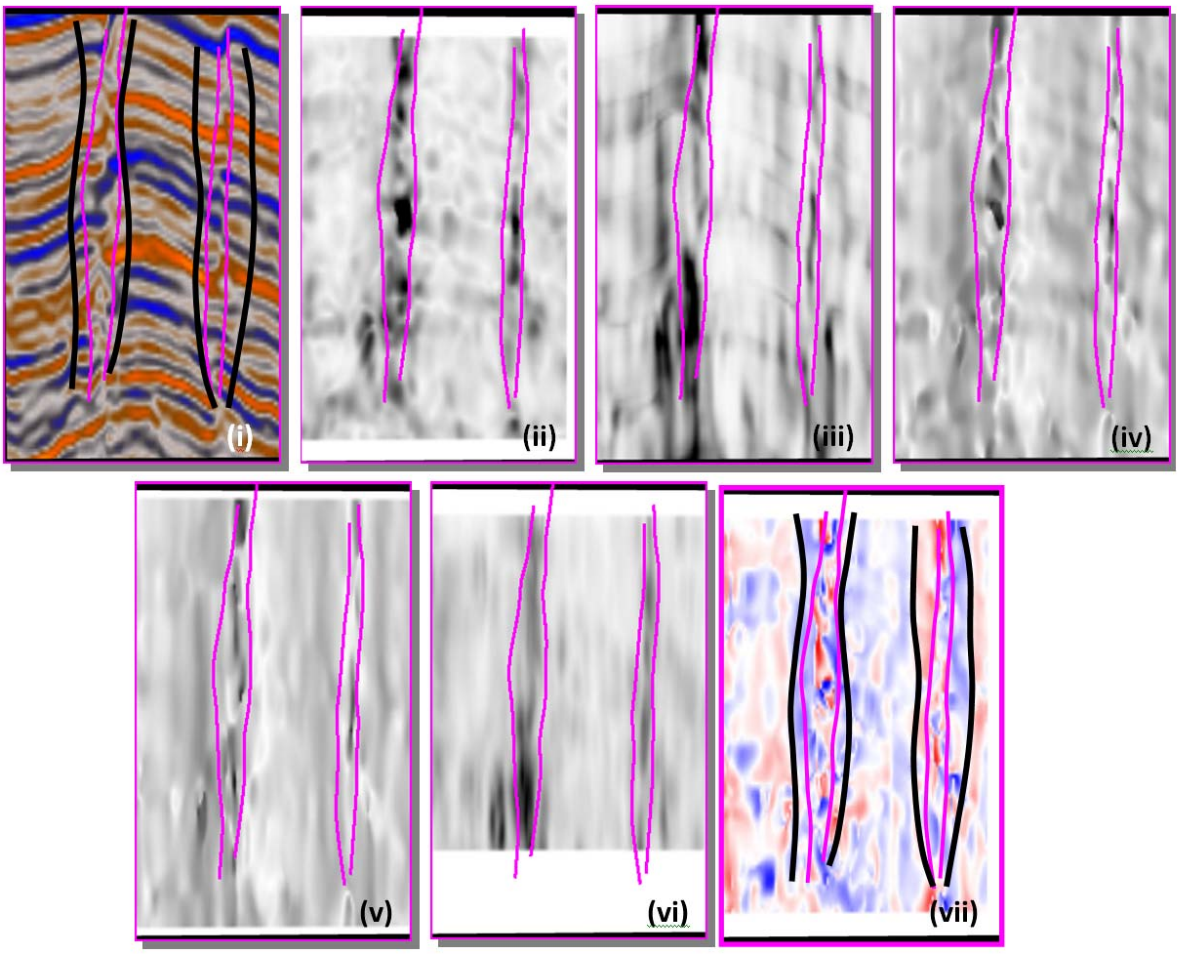

Figure 3: Expressions of the Seismic Fault Distortion Zone. (i)Reflectivity, (ii – vi) volumetric fault attributes; (ii)Deformation, (iii)Semblance, (iv)Dip A, (v)Dip B, (vi)Gradient Structure Tensor. (vii) volumetric local curvature. Pink represents a manual interpretation of the Inner Seismic Distortion Zone and black a manual interpretation of the Outer Seismic Distortion Zone.

Fault Relative Analysis associated with Damage Zones

Once a SFDZ has been defined (either the inner or outer zone depending on user focus), both its lateral thickness and changes in a selected seismic attribute response across the SFDZ can be evaluated. The thickness

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of the damage zone is mapped directly onto the fault network and enables the user to rapidly see variations in the extent of fault related distortion. The outer surface of the SFDZ Geobody is also extracted (Figure 2d) and this 'skin' is used to constrain statistical analysis of seismic attributes. By studying the juxtaposition across the damage zones of the defined SFDZ and calculating the difference in these attribute values on either side of the SFDZ, areas of significant contrast and areas of no contrast are readily highlighted. This is achieved via the application of structurally oriented filters that initially sample then juxtapose data from either side of the damage zone onto the central fault plane. Steering volumes are used to align the structurally oriented filter footprints along dominant reflectors and thus maintain structural variations. By taking the local mean of an attribute a noise free representation of it is provided, whilst the variance gives a measure of its distribution. Results are initially stored on the skin of the damage zone (Figure 2f) then horizontally juxtaposed from both sides onto the central plane in a direction perpendicular to the trend of the central fault. With the variance and mean attribute value on either side of the fault now stored co-incident to the fault plane, a difference volume can be generated and the contrast in properties across the fault visualized in a single volume, which is named the Juxtaposition Difference (Figure 2g). The result of this process is a data derived juxtaposition map being produced, at seismic resolution, on the 3D fault surface representation itself.

Attributes proposed for this workflow include acoustic impedance (AI), porosity or frequency. However juxtaposition difference maps for any seismic attribute or inverted volume could be applied during this process. Through use of appropriate seismic attributes and inversion data, the Juxtaposition Difference can aid in the overall process of assessing fault seal by allowing detailed examination of subsurface properties around faults via seismic resolution attribute map's as opposed to interpretation based juxtaposition diagrams,

In the case of Acoustic Impedance, we see the following behaviour; where there is shale-to-sandstone contact at the SFDZ, the Juxtaposition Difference will yield high values and where there is either a sandstone-to-sandstone or shale-to-shale contact at the damage zone, the FSC Index will yield low values. By restricting the evaluation zone of interest to centre on the reservoir interval and calibrating with known lithologies at well locations, low juxtaposition difference regions corresponding to sandstone-to-sandstone contacts can be identified, and thus potential non-sealing regions are highlighted and spatially defined for further analysis within an overall fault seal analysis workflow.

In the case of a sandstone-to-sandstone contact, a Juxtaposition Difference value of zero implies that the AI on either side of the fault is identical and a small value implies that there are differences in AI of the sandstone on either side of the fault. The 3D nature of the analysis enables the lateral and vertical variation of these contrasts to be viewed along the length of a single fault or cross a fault network.

In the juxtaposition analysis described above, the data derived SFDZ is used to ensure that only data samples outside of the SFDZ are included in the measurement. In an additional step within the workflow, the statistics of the selected seismic property volume can also be assessed within the SFDZ. Within the SFDZ the analysis is performed relative to the seismic sampling grid, as (by definition) there are no conformable reflectors present here, and larger sample neighbourhoods are typically adopted. The calculation of the bulk mean and variance within the SFDZ is used to produce a further attribute map of the fault surface (Figure 2e). This can be used to examine the apparent continuity of seismic properties within the SFDZ.

Case Study

The workflow described above has been applied to approximately 100km^2 of 3D seismic data acquired over an onshore Underground Gas Storage area, (UGS). The data is a merge of 3 different vintages that have been processed to produce a single seismic reflectivity volume. The seismic data is of fair to very good quality with bin spacing of 20m by 20m and elevated noise in some areas as a result of varying fold due to the presence of surface facilities.

The target level contains 3 reservoir intervals, with an approximate total thickness of 70 to 160m. This interval is contaminated by noise, remaining internal multiples and intrinsic complexity (three reservoir levels, themselves divided into 4 levels). However, the current interpretation of the entire sequence has good well control, with more than 100 wells present in the area.

Within this data, several faults studies have been performed, focusing at different levels; above the top reservoir, adjacent to top reservoir, and inside the reservoir itself. The decoupling of fault studies into depth ranges is a direct consequence of tectonic decoupling that can be observed on seismic reflectivity.

Initial mapping and manual interpretation of faults provided a good but simple understanding of the faulting present in each of the levels (Figure 4a) but does not provide information about the interplay between faults and fluid movement although different pressure regimes have been discovered between some specific pairs of wells (Well pairs A-B and B-C on (Figure 4a).

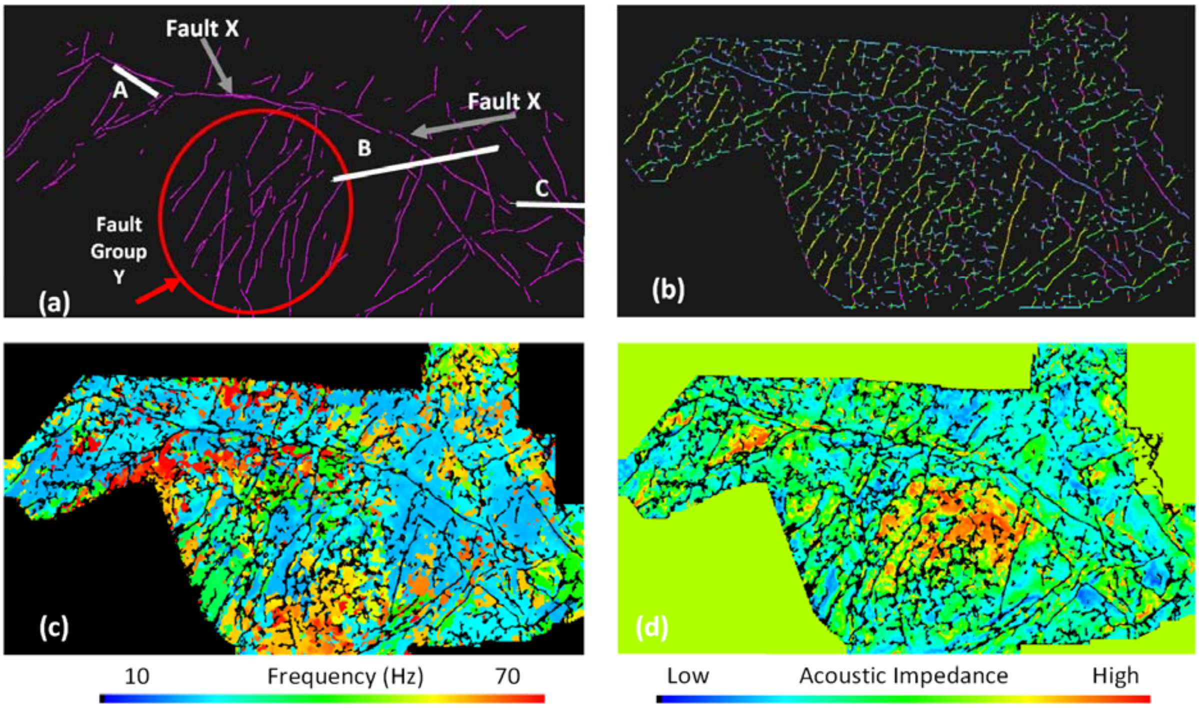
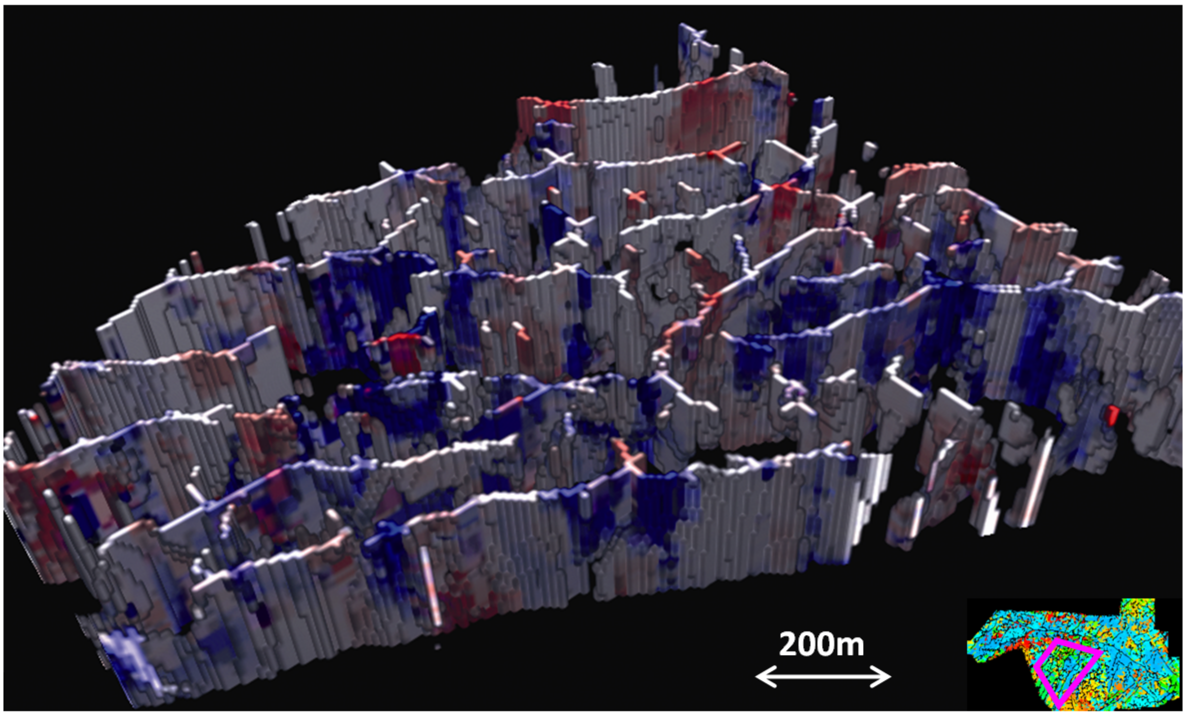


Figure 4. Fault Imaging; (a) Manual interpretation of fault network with key wells marked (A – C), (b) Automatically detected fault network mapped with 2D trend (c) Seismic Fault Distortion Zones (Black) mapped on to Frequency and (d) Seismic Fault Distortion Zones (Black) mapped on to Acoustic Impedance. This analysis can be seen on time-slices or in a horizon-consistent manner.

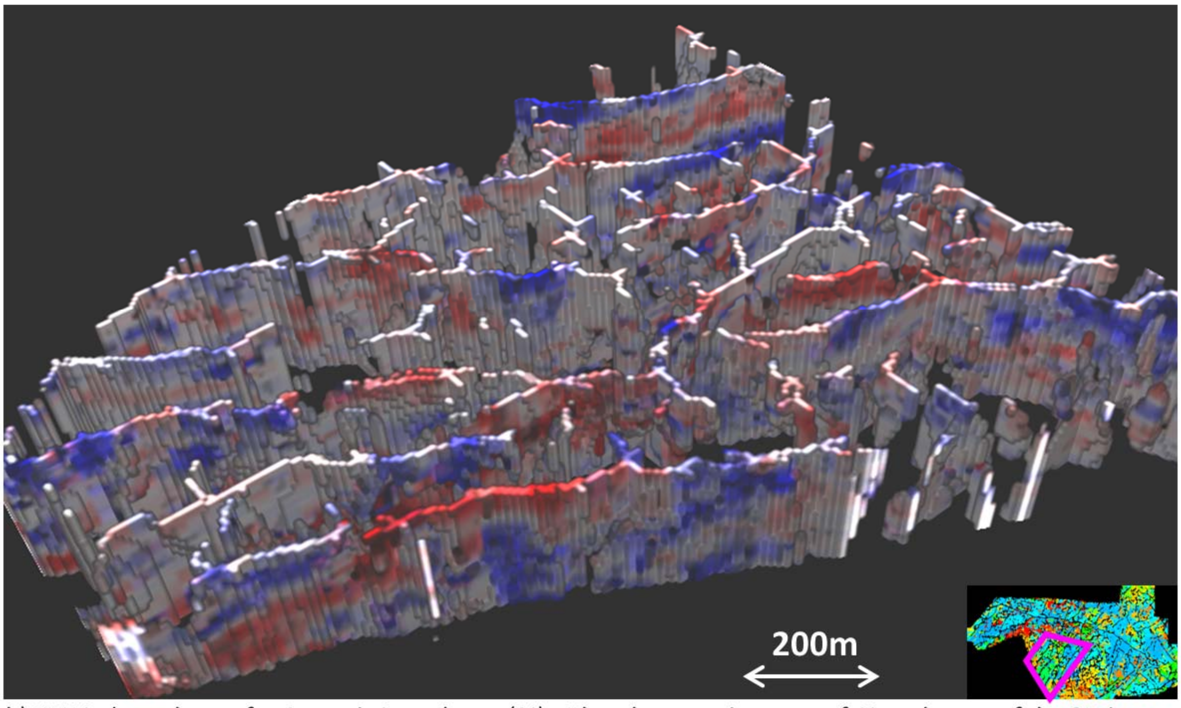
In order to optimise results, structurally oriented edge preserving and adaptive noise cancellation filters were applied to remove the coherent and random noise within the seismic reflectivity data whilst maintaining the structure of subtle faults and discontinuities. By utilising automated fault detection and extraction workflows a more detailed map of faulting than previously interpreted has been defined (Figure 4b) enabling interpreters to distinguish and study internal fractured zones in addition to major and en-echelon faults seen in the area. By mapping the volumetrically calculated SFDZ onto a horizon of interest or viewing simply along a time slice we can see the variation in thickness between and along faults (Figure 3b). Varying damage zone thickness can relate to different fault mechanisms as well as the lithology in which faulting has occurred and is of interest as it can influence fluid flow across a fault. Damage zones along both fault X and fault group Y have similar widths, which range from 80 to 120m.

SFDZ Analysis has been applied to both frequency and acoustic impedance volumes. Seismic frequency can be affected and attenuated by depth, lithology, bed thickness, porosity and fluid fill. In particular, the presence of gas is often seen to reduce frequency. It can be clearly seen in (Figure 4c) that dominant faults (such as those in fault group Y) and their associated damage zones are often sharply bounding areas of high and low frequency.

The Juxtaposition Difference (Figure 5a) for this volume provides increased detail of how the contrast in frequency changes spatially along the length of faults within fault group Y. Reds and Blues both indicate zones of high frequency contrast (up to 60Hz). Blue shows an increase in frequency across the fault towards the top of the 3D image, red shows a decrease in frequency across the fault towards the top of the 3D image and white shows no contrast in frequency. The Juxtaposition Difference volume implies that the sealing potential based on frequency juxtaposition alone is much more variable along the length of these faults than the horizon slice initially suggests. Analysing the Acoustic Impedance (AI) yields similar results. By embedding the SFDZ into the AI volume, zones where faults are bounding large contrasts in AI can easily be seen (Figure 4d). FSC Index volumes for both frequency and AI reveal high contrasts and thus high potential for juxtaposition based sealing at many locations such as that marked A on (Figures 5a & 5b). However, it is apparent that these regions of potential sealing are all localised and there are many (white) regions of no contrast that have the potential to provide pathways for fluid migration.



a) FDZ Index volumes for Frequency. Blue shows an increase of frequency to the top of the 3D image, red shows a decrease in frequency to the top of the 3D image and white shows no contrast in frequency. The small base map in the right hand corner shows the position of the sub volume on the images seen in Figure 4.



b) FDZ Index volumes for Acoustic Impedance (AI). Blue shows an increase of AI to the top of the 3D image, red shows a decrease in AI to the top of the 3D image and white shows no contrast in AI. The small base map in the right hand corner shows the position of the sub volume on the images seen in Figure 4.

Figure 5. a) Frequency and b) Acoustic Impedance volume rendered view of the fault network skeleton mapped with the Juxtaposition Difference values.

Focusing on a particular fault at the reservoir zone enables detailed Juxtaposition Difference and thickness variations (Figure 6a) to be mapped. Rapid lateral and vertical changes in thickness as well as Juxtaposition Difference suggest possible areas of fluid transmissibility are localised.

Visualisation and correlation of well logs as displayed in (Figure 6b), demonstrates the information borne by Fault analysis (local sample mean of inverted AI within the damage zone) is supported by existing well data. The incorporation of additional and more advanced well information could thus be used for further extrapolation and calibration.

Caveats & Discussion

- The analysis of seismic scale fault damage zones and contrast in attributes/properties across them, can provide additional information and a greater degree of detail regarding the juxtaposition based sealing potential of a fault, or fault network. It must be noted that this is just one of several mechanisms for sealing as a result of faulting.
- The technique relies on seismic reflectivity data and seismic attributes with a high lateral resolution and yields more accurate results when data has been acquired with a small bin spacing (i.e. 12.5 m).
- The fault imaging and fault network skeleton can be used to highlight significantly more detail at and around existing fault interpretations as well as highlighting new unconsidered candidate faults that may positively impact on the overall understanding of reservoir sealing behaviour.
- Although the seismic data under observation is highly perturbed (faulted and even acting as wave propagation barriers), much information can be directly inferred from fault and SFDZ studies. Nevertheless, it is believed that seismic data is statistically sufficient to derive accurate information on sealing/non sealing capacities (varying within one fault), provided some calibrating additional data (pressure from wells) is given.

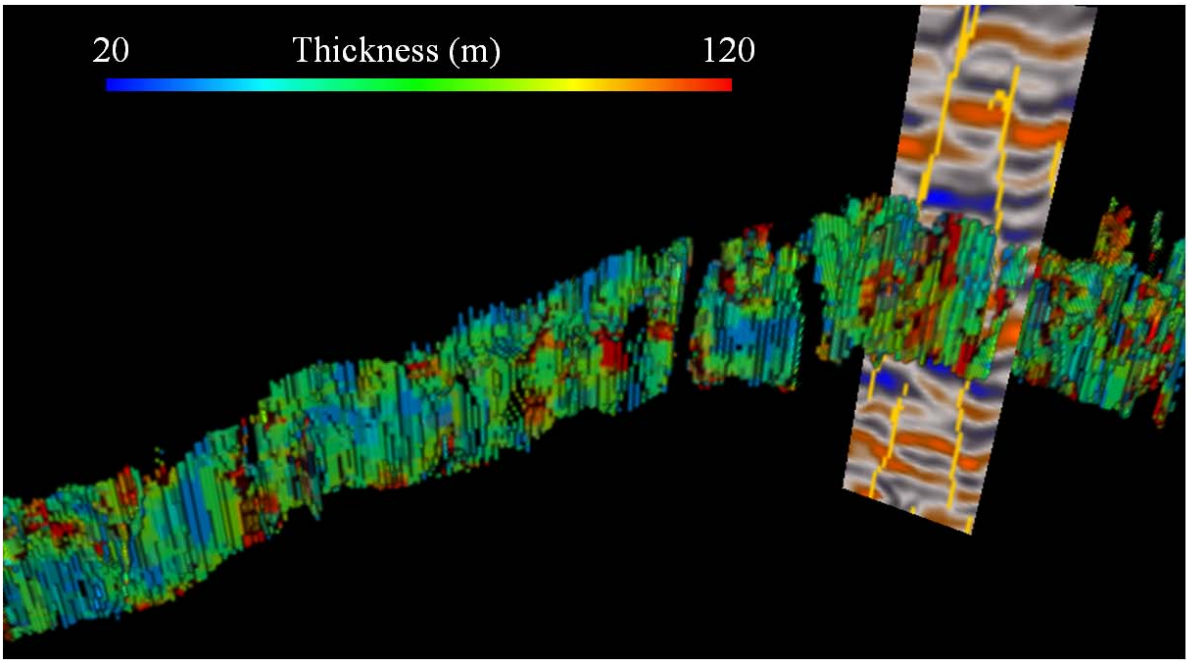


Figure 6(a). Volume render of a single fault cropped to the reservoir level alone and mapped with SFDZ thickness. Variations from low (blue) to high (red) thickness can be observed. Rapid lateral and vertical changes suggest possible areas of fluid transmissibility are localised.

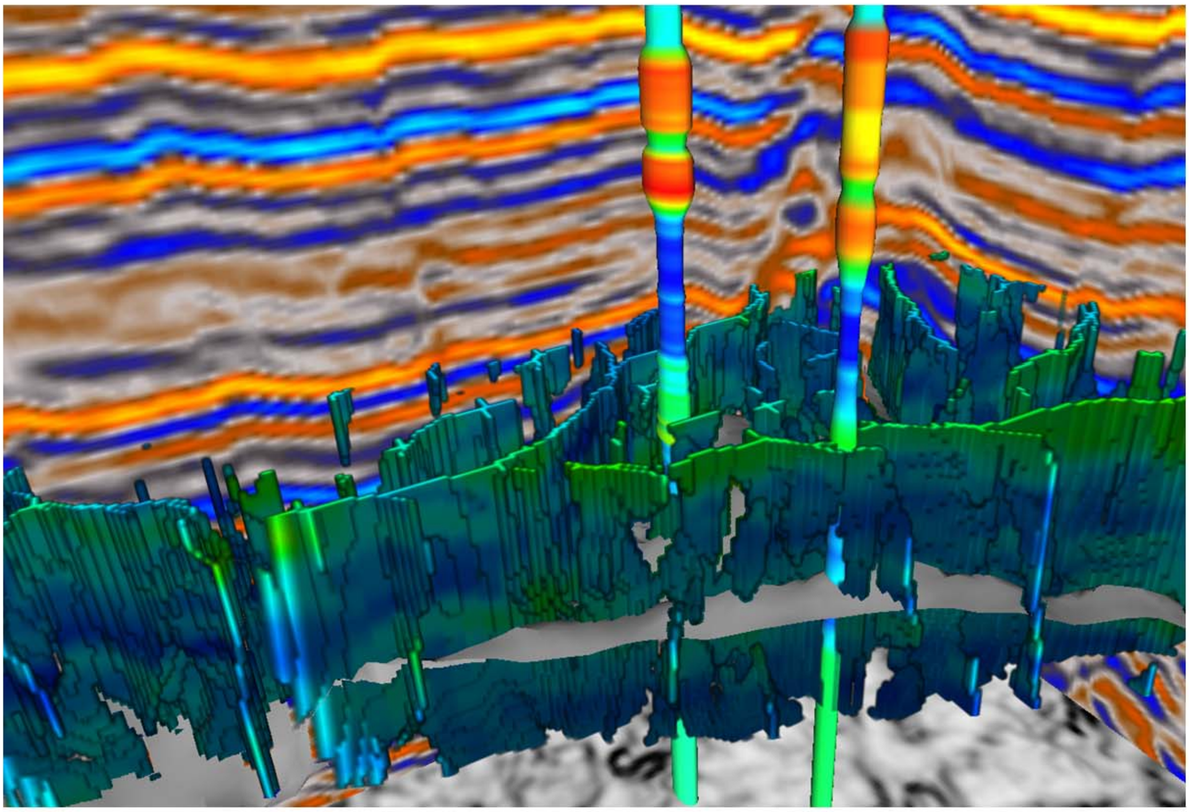


Figure 6(b). Well information. The acoustic impedance within the inner damage zone (mapped onto fault network) is seen to correlate with P wave velocity (Vp) logs, bringing thus the first step in the well calibration procedure (using the porosity logs and pressure measurements).

- Future work includes applying this new workflow to other datasets, particularly those with interpreted fault, Fault Damage Zone geometries and that include parallel fault sealing studies.

- As a data driven workflow to examine subsurface properties around faults, it is highly dependent upon use of robust attributes and inverted data, and upon the availability of well data in order to calibrate the results.

- As far as Underground Gas Storage projects are concerned, a dynamic/historic view of the fault sealing behaviour should also be sought, as there are likely to be significant variation in seismic response with time.

Conclusions:

We have an established workflow that has been applied to a number of case studies. The techniques for extracting a damage zone around the fault are well defined. More work is required in order to understand the best combination of information, from both seismic and wells, needed to demonstrate the behaviour of fluid across an identified damage zone.

For the UGS study presented here, damage zone thickness and symmetry measures, contrast in AI response across the damaged zone, AI variability and spectral decomposition techniques have been used in combination to produce indicators of potential fault sealing behaviour.

Prior to this study, the structural system was simplified in order to fit with current models but the detailed interpretation of the complete fault network, including small faults subsets, and the behaviour provided by FDZ analysis, is delivering a better understanding of the fault network and will have an impact on the forecast of production profiles.

One may highlight that the varying behaviour vertically and horizontally of what were previously considered to be simple single faults brings a clear call for more integration between reservoir models and detailed geological (horizons and faults behaviour included) models derived from seismic data.

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References

Kim, Young-Seog. Peacock, David CP. Sanderson, David J. *"Fault Damage Zones".* Journal of Structural Geology, **26**, pp503-517, 2004.

Berg, Silje S. Skar, Tore. *"Controls on damage zone asymmetry of a normal fault zone: outcrop analyses of a segment of the Moab fault, SE Utah".* Journal of Structural Geology, **27**, pp1803-1822, 2005.

Jones, G. Knipe, RJ. *"Seismic attribute maps; application to structural interpretation and fault seal analysis in the North Sea Basin"*. First Break, **14**, No. 12, December 1996.