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Effective Fault Interpretation using 3-D Software Technology and Fault Displacement Analysis

Peter Bretan,* *Badley Geoscience Limited, UK.*
Amandeep Kaur, *Samit Spectrum EIT Pvt Ltd, India.*

Summary

The traditional aim of interpreting faults in seismic data is to derive a map view of the fault pattern. Faults are interpreted on vertical seismic sections with segments being correlated on a line-by-line basis to build up a map view at a particular horizon. Worst still, faults are often drawn by hand at the mapping stage. The end product is a fault map that is essentially guess work and which has limited Value of Information.

Technology (software) and quantitative workflows exist to enable a more robust geological interpretation of faults to be made. Fault traces picked on vertical sections can be viewed in 3-D perspective view to give an immediate assessment of the plausibility of the interpreted fault geometry. Horizon data can be mapped onto the fault surface to derive horizon cut-offs allowing displacement-related values (e.g. throw heave, separation) to be derived. These displacement data allow the interpreter to quickly examine the veracity of the interpretation and to identify areas in the interpretation that need to be checked again.

Isolated single faults have simple displacement patterns with a maximum near the fault center. Fault arrays show partitioning of displacement between the various splays, with relatively abrupt changes in the displacement at branch-lines. The analysis of fault geometry and displacement patterns enables a more objective assessment of subsurface interpretation to be made.

Keywords: *Fault Interpretation; 3-D Visualization; Fault Throw Patterns; Fault Displacement Analysis;*

Introduction

The traditional aim of interpreting faults in seismic data is to derive a map view of the fault pattern. This aim is typically achieved by picking fault segments on vertical seismic sections and correlating the segments from line to line. Given the currently available technology for interpreting seismic data (e.g. 3-D data, seismic cubes, auto-tracker, 3-D volume displays) the interpretation of faults on 2-D seismic sections and their arbitrary correlation is rather anachronistic often leading to rather spurious fault patterns especially in sparse seismic data sets (Figure 1). Furthermore, the 3-D shape of the fault surface, the linkage of faults with other faults and the distribution of slip on the fault surface is often ignored.

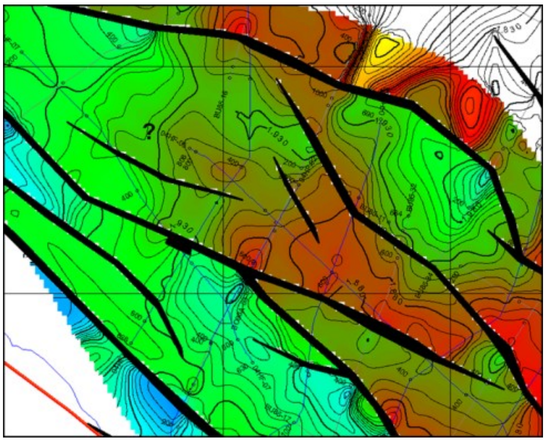

Figure 1: Maps are commonly generated with faults drawn as lines in map view or on a few sections. The fault polygons in this example were made in the mapping stage. They are based on single fault traces and are essentially guess work.

Badley Geoscience Limited, North Beck House, 5 North Beck Lane, Hundleby, Spilsby, Lincolnshire, PE23 5NB, UK
www.badleys.co.uk, email: pete@badleys.co.uk

This presentation illustrates how currently available technology and simple geological methods can be routinely applied by geophysicists and geologists alike at all stages of the interpretation process to derive not only more realistic fault maps but also a geologically robust 3-D portrayal of the faulted subsurface.

Visualization Environment

The use of technology (software) to display seismic data cubes, fault and horizon interpretations and well data in a 3-D volume display is commonplace within the hydrocarbon exploration industry.

At first glance a 3-D display showing different types of data may appear impressive; however, the sheer quantity of data on display can often lead to 'visual overload' which can be a hindrance rather than advantage when interpreting faults. To overcome 'visual overload' simple techniques can be applied to restrict what is actually on view. One technique is to clip the data either to an area of interest or to the geological data object or interest, such as a horizon or fault.

Clipping the 3-D display to a limited depth range focuses the attention to the lateral extent of fault surfaces. As a result, fault segments can be more easily and more robustly correlated into planes (Figure 2).

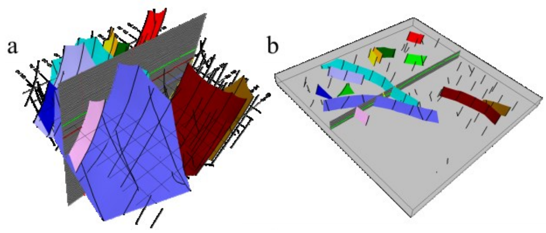

Figure 2: 3-D view of interpretation data (a) clipped to a specific depth range (b). Fault segments (black) and lateral fault correlations become more obvious.

Fault Correlation using 3-D Volume Displays

The correlation of fault segments into planes is a key step in the interpretation of fault structures. However, the correlation of fault segments is often arbitrary, done on a line-by-line basis involving the interpreter's judgment of the 'structural style' of a particular area and his/her geological knowledge and experience. In some cases, interpreters with limited structural geological experience often resort to pieces of paper with line drawings of the interpretation taped to the computer screen to help with the correlation of faults.

A more effective method for correlating fault segments is to use 3-D perspective views. When viewed in 3-D, fault planes containing incorrectly correlated fault segments become immediately obvious (Figure 3).

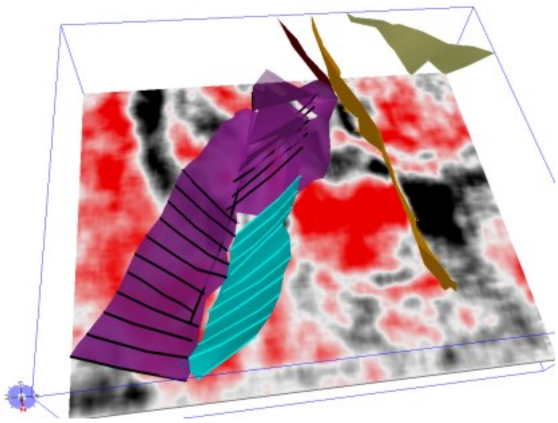

Figure 3: 3-D perspective view makes it easier to see geometrically-incorrect fault picks. In this example, segments (black) of opposing dip have been correlated to the same fault surface.

Fault surfaces displayed in 3-D that exhibit abrupt changes in dip direction and/or have isolated spikes or kinks in the fault surface geometry indicate areas where the fault correlation may be incorrect. Such rapid assessment of the 3-D fault correlation cannot be achieved using 2-D seismic sections alone.

Fault Displacement Patterns – the key to effective fault interpretation

The systematic variation of heave along the length of fault polygons seen in maps is familiar to all seismic interpreters. Single faults often show heaves that increase in width from a fault tip to a maximum and then decreasing again towards the other fault tip. The variation in heave on one horizon is also present on all horizons that are offset by the fault. A systematic variation in the offset across a fault is also evident on seismic sections. Single fault traces often show offsets that increase in size from a resolved upper fault tip to a maximum and then perhaps decreasing again towards the lower fault tip. The significance of these observations is that the systematic

variation in heave (and offset) reflects the underlying systematic nature of displacement on a fault surface.
Fault surfaces are approximately elliptical shaped discontinuities in the rock volume, usually longer than they are tall. Displacement is at a maximum near the centre of the fault surface and diminishes outwards in all directions to the edge of the fault where the displacement is zero (Figure 4).

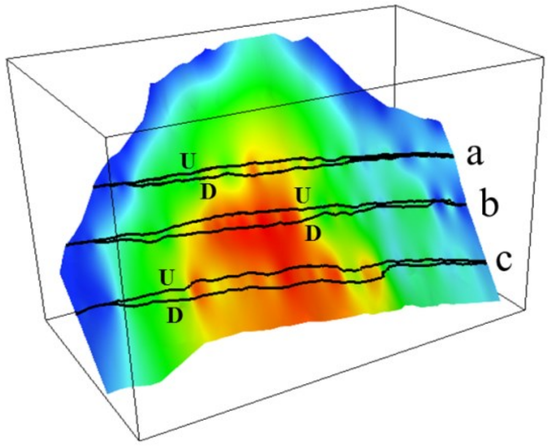

Figure 4: Fault surface showing pattern of displacement from high (red) at the center of the fault to low (blue) at the fault tip. Black lines are horizon cut-offs for three horizons (a,b,c) that intersect the fault. Upthrown and Downthrown cut-offs labelled U and D respectively.

Although other, more complex patterns of displacement occur where faults interact, the overall fault displacement pattern varies in a systematic manner.

Fault displacement can be assessed by posting the upthrown and downthrown cut-offs of all the faulted horizons onto the fault surface (black lines in Figure 4). Using the horizons projected on to the fault surface gives the most accurate representation of the horizon traces. The raw data provided by the horizon separations can then be gridded to produce a map of throw on the fault surface.

Any variation in the cut-off geometry should be attributable to real geological cause. Figure 5 shows the throw variation on two faults (Faults A and B) that overlap at a relay zone. The throw distribution is shown in colour on the fault surface and also in graphical form. Note how the throw of Fault A (blue) decreases to the right whilst throw on Fault B (red) increases. The complementary transfer of fault throw is a characteristic feature of relay zones and is an invaluable aid when interpreting such structures.

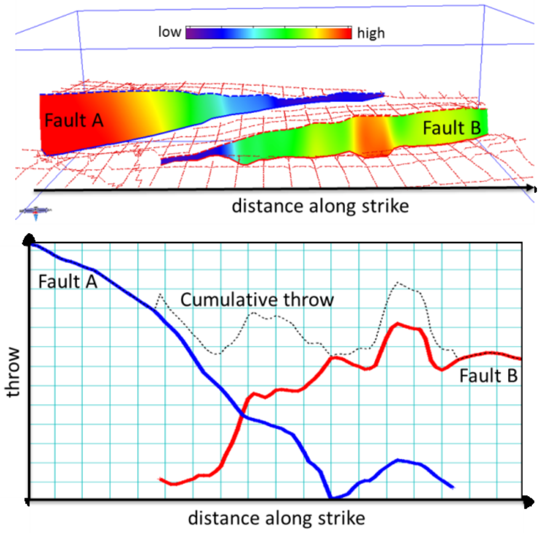

Figure 5: 3-D view of fault throw on two overlapping faults in a relay zone (upper diagram) and shown in graphical format (lower diagram). The decreasing throw on Fault A is complimented by an increase in throw on Fault B. When throw from both faults is added together (cumulative throw – black dotted line) the overall distribtuion of throw is similar to that seen on a single fault. Dashed line on faults is upthrown cut-off line; solid line is downthrown cut-off line. Horizon shown as red grid.

If non-systematic variations exist, which cannot be explained geologically, there is the possibility that the mapped fault surfaces may not be, in fact, built from correctly correlated fault picks or that there are mistakes in the horizon interpretation close to the fault.

Analysis of the fault displacement patterns, together with the 3-D representation of the fault surface, is **the most important method** for quality checking interpretations and for testing fault correlations. It allows for a more objective assessment of the subsurface interpretation to be made. Note that displacement analysis is not model-driven nor based on any mode of deformation or fault geometry. It is based on the simple observation that displacement on a fault varies in a systematic manner.

Conclusions

The habitual interpretation and correlation of faults using vertical seismic sections alone leads to poor fault maps and unrealistic 3-D fault frameworks.

The application of 3-D visualization technology, together with simple geological concepts such as fault displacement analysis enables geologically robust 3-D fault models to be derived in a more time efficient manner and with added Value of Information.

The ‘mapping’ of horizon cut-offs onto fault surfaces dramatically improves the accuracy of mapped fault polygons.

Analysis of fault displacement patterns allows an interpreter to objectively assess: i) the reliability of horizon & fault interpretation, ii) the correlation of fault sticks into 3-D planes especially in sparse datasets, iii) the 3-D interaction and transfer of displacement on fault surfaces.

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