A revolution in seismic visualisation of fault networks - implications for the drilling and production of resources

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Abstract

Fault and fracture networks can have significant effects on drilling, mining and the safety of resource operations, and can also significantly impact reserve recovery & productivity. Due to this, various automatic fault extraction techniques have been developed for structural volume interpretation purposes in recent years.

This paper presents innovative techniques and workflows that have been developed by the author to integrate high-resolution 3D seismic fault extraction results with the detailed calibration and review of various seismic and well data. From this, groundbreaking insights have been gained into the physical description of 3-dimensional fault networks, and how these, as fluid barriers or fluid conduits, can affect drilling activities and production from resources.

The new techniques have produced faster and more reliable and objective fault interpretations, and a better understanding of structural geometries and fault populations. They have also led to the identification of fault and fracture networks at a much higher resolution than achieved by other current seismic methods. With the increased resolution, higher fault/fracture densities have been found than were previously recognized. Also, many fault penetrations in wells have been identified that were previously not recognized from seismic data or even well data. These seismic fault penetrations have been shown to be often linked with drilling issues (fluid losses, gas kicks, borehole stability/geo-mechanical issues, etc.) and production issues, or opportunities (water/gas channelling, compartmentalisation, access to natural fracture network, etc.).

Examples from compartmentalised, fractured, tight and unconventional Oil & Gas projects around the world, incl. Shale Gas and Basement plays, demonstrate that the new techniques provide a means to better understand drilling and production observations in existing wells. They also, and importantly, allow to optimise drilling activities and increase resource recoveries in future operations. The workflows are proposed as Best Practise tools for resource exploration and development planning & execution.

Introduction

Fault and fracture networks can have significant effects on drilling, mining and the safety of resource operations, and can also significantly impact reserve recovery and productivity.

In Oil & Gas reservoirs, it is often critical to improve the understanding, detection, modelling and prediction of fault and fracture networks and their fluid compartmentalizing effects and storage-transmissivity characteristics. These efforts can help to locate connected hydrocarbon volumes and unswept sections of reservoir, and thereby help to optimize field developments, production rates and ultimate hydrocarbon recoveries (Jolley et al. 2007).

In conventional, matrix-producing reservoirs, faults can offset productive layers and represent zones of reduced porosity and permeability that can compartmentalize the reservoir and provide baffles or barriers to fluid flow in the reservoir (Antonellini and Aydin 1994). In these reservoirs, structural and also stratigraphic compartmentalisation are typically the biggest risks to economic field development, as they directly affect the number of wells that need to be drilled to drain the field reserves.

In fractured reservoirs, where most of the permeability is caused by fracturing, faults can provide efficient conduits for fluid flow (Maerten et al. 2006). Fractured reservoirs contain an important and increasing proportion of the world's hydrocarbon reserves and are generally more complicated than matrix reservoirs (Nelson 2001, Lonergan et al. 2007). Nearly all natural resources are affected by natural fractures, yet the effects of fractures are often poorly understood and largely underestimated (Bratton et al. 2006) or even denied by the hydrocarbon industry at large ('fracture denial'; Nelson 2001).

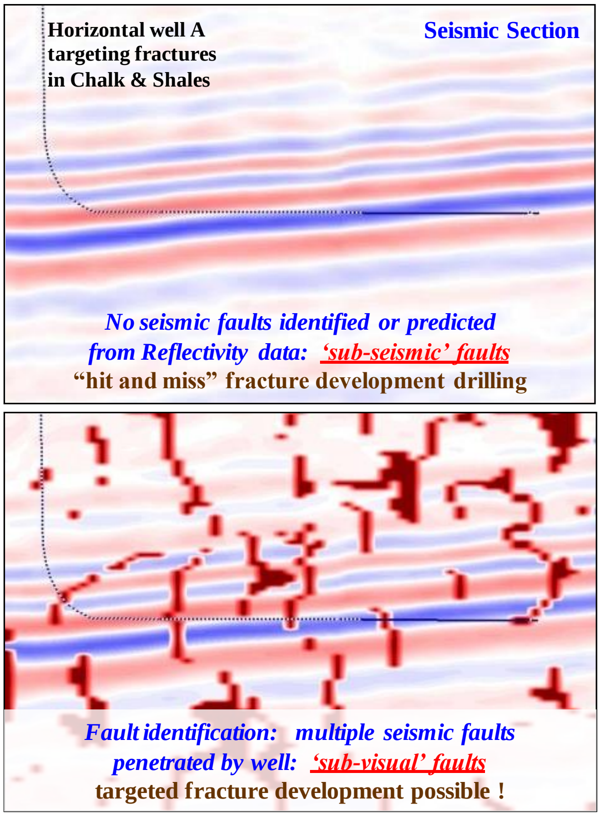


Figure 1: High-resolution fault extraction visualises small-scale spatial changes in amplitude, frequency or phase content of 3D seismic data, and challenges perceptions of what can and can not be identified with seismic data. Comparison and calibration of seismic fault extractions with faults identified in wells (from core, image logs/dipmeter, log correlation) helps to ground-truth extractions and assess the true seismic fault resolution of a particular data set at objective level.

The key problem for the development of fractured reservoirs is the difficulty to define the geometry of the fractures that impact hydrocarbon flow, especially as a large component of the fracture network is (believed to be) beneath the imaging resolution of standard 3-D reflection seismic techniques (Lonergan et al. 2007).

This paper discusses results from the application of novel and proprietary *OPPtimal*™ techniques and workflows in automated fault extraction to a variety of different reservoirs around the world. The results challenge widespread perceptions of what is seismically resolvable from 3D seismic data (Fig. 1), and also offer groundbreaking new insights into the spatial distribution of fault and fracture networks and how they can affect the drilling and production of resources.

Automated Fault Extraction

In recent years, various seismic processing techniques and software packages focused on 3D fault visualization, auto-extraction and also semi-automated fault picking have been developed and are increasingly being applied in the industry. Various attributes are in use to identify and enhance spatial discontinuities that are computed at every data point within a seismic data cube (see Pepper and Bejarano 2005 for a detailed review).

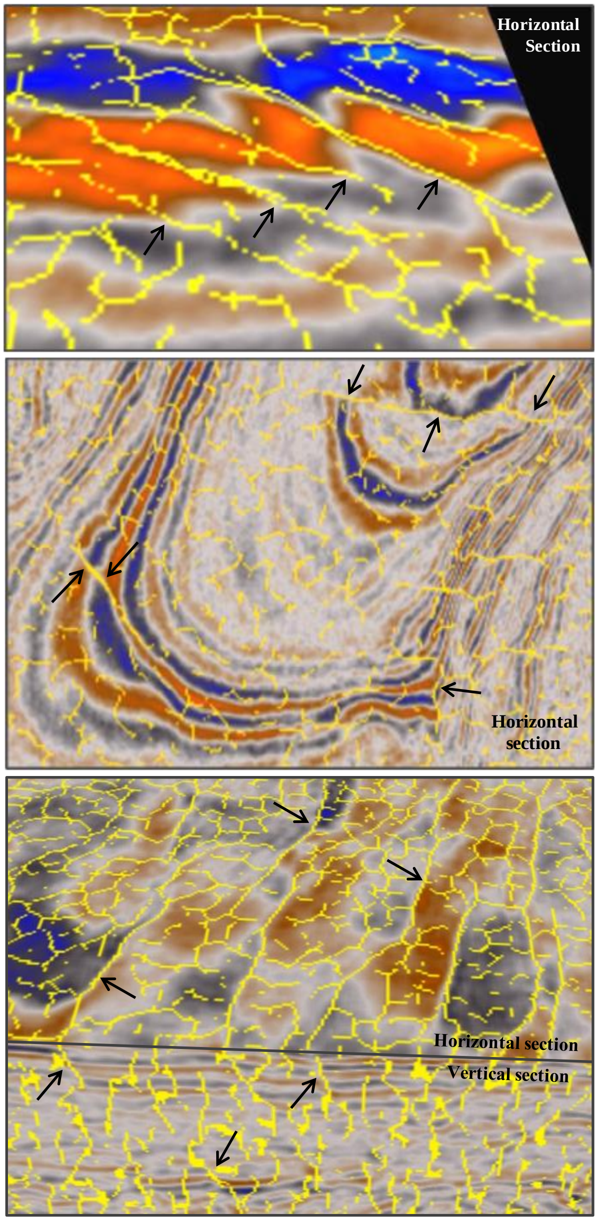
These seismic discontinuities most times represent fault surfaces, but can be also related to other geologic features (channel edges, hydrocarbon contacts etc.) or noise (acquisition/processing artefacts). Noise-contamination of seismic data can be addressed by running spatial filters that remove the noise but retain the geometric detail such as small-scale faults breaks (Chopra and Marfurt 2007). Noise reduction can e.g. be achieved without degradation to the fault expression by data conditioning with structure-oriented smoothing utilising edge preservation (Hoecker and Fehmers 2002).

It is of key importance to confirm that the discontinuity extractions represent structural features rather than artefacts. A number of calibration steps help with this validation process (Oppermann 2010):

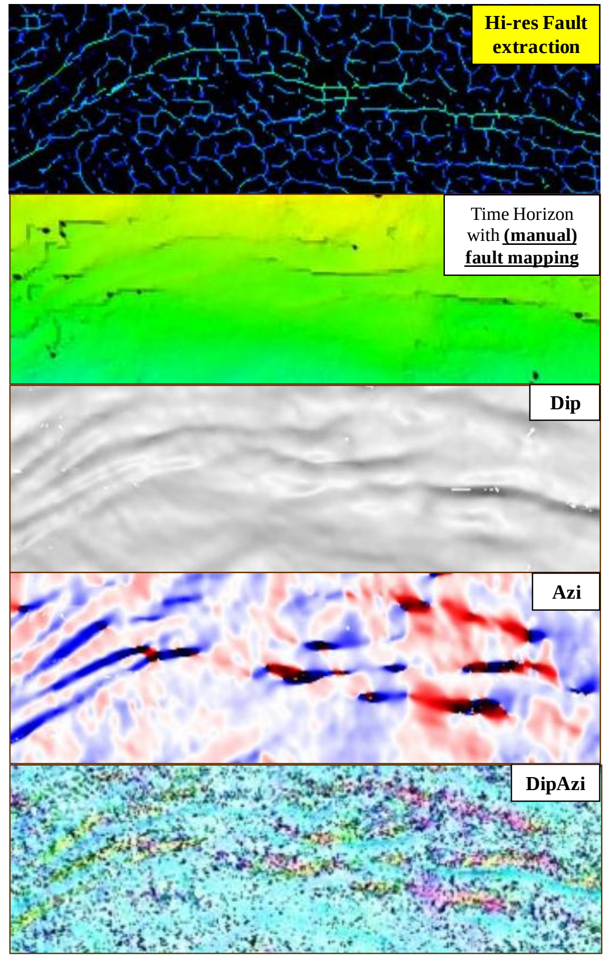
- visual inspection of extraction results on sections, time slices and in volume view (Fig. 2)
- calibration against previous (manual) fault interpretation (Fig. 3)
- calibration against other structural highlighting data (e.g. Dip, Azi, DipAzi, Semblance, etc.; Fig. 3)
- calibration against faults & fractures identified from image logs, dipmeter, log correlation, cores etc.
- generation of discontinuity histograms/rose diagrams, for discontinuity population analysis
- calibration against drilling observations (drill breaks, fluid losses, kicks, HC shows, borehole instabilities, well losses etc.)
- calibration against well test observations (presence of fluid conduits or barriers)
- calibration against production observations (water/gas channelling, baffles/boundaries, compartmentalisation, 4D seismic data, production enhancement through natural fractures etc.)

- comparison of extraction results derived from different seismic vintages, e.g. time lapse seismic data, to test the repeatability of results.

The aim of calibration is to turn discontinuity volumes into calibrated fault & fracture network volumes, which can then be further utilised to optimise drilling and production results in future operations, e.g. to build detailed fracture network models incl. sensitivities, or to identify well work-over opportunities, or to predict and ensure (or avoid) fault & fracture intersections in future wells.



<u>Figure 2:</u> Visual inspection of fault extraction results confirms that faults with larger offsets (arrows) have been successfully delineated. In addition, also smaller scale faults without obvious offsets are identified, most of which an Interpreter could not pick confidently and reliably by visual means only. [Perspective views on to horiz./vertical sections]



<u>Figure 3:</u> Comparison of high resolution fault extraction results with manual fault mapping results, and other structural highlighting data. Fault extraction usually delivers a much higher resolution than e.g. visual fault mapping, Dip, Azi or DipAzi volumes.

Benefits of Fault Extraction

Automated fault detection techniques have been primarily developed to support or (partially) replace manual fault mapping efforts, which are labour-intensive and time-consuming (Admasu et al. 2006), but also largely subjective, and with this imprecise and often biased. The application of fault extraction workflows in Oil & Gas projects around the world has shown that properly calibrated fault & fracture network volumes typically deliver faster, more reliable and fully objective fault evaluations (Oppermann 2010).

Automated fault extraction is based on the physical measurement of spatial variation in amplitude, phase and/or frequency content of 3D seismic data, and is as such free of bias and interpretation. Fault extraction therefore allows to separate measurement (i.e. fault identification by using algorithms) from the interpretation of a measurement (i.e. fault mapping by traditional manual/visual reflector offset interpretation). Extraction furthermore has the advantage of being performed in true 3-dimensional space.

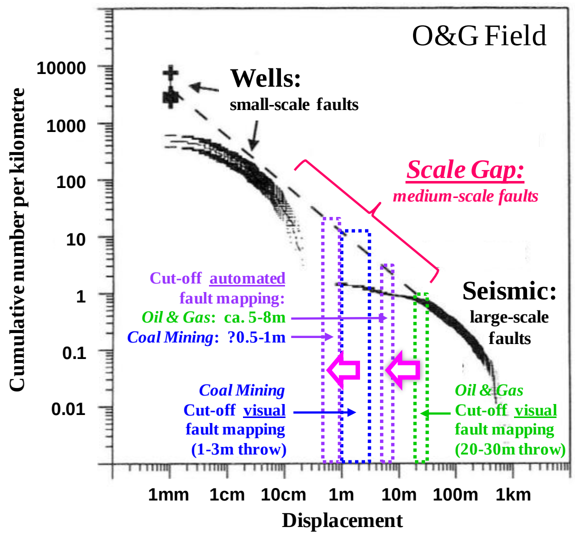


Figure 4: Comparison of visually mapped seismic fault throw data with well displacement data (modified from Needham et al. 1996). Displayed are also the cut-off ranges for visual fault mapping of faults from Oil & Gas and Coal Mining 3D surveys. These cut-offs can be lowered by automated fault extraction.

Fault extraction also leads to a better understanding of structural geometries and more comprehensive sampling of fault populations, due to a marked increase in fault resolution, and a resultant dramatic increase in the number of (medium-sized) faults that are identified from seismic (Fig. 4). With the increased structural resolution, much higher fault & fracture densities are found than previously mappable or recognised. The very latest fault imaging technology pushes fault resolution down to the true fault resolution of a particular seismic data set, not the perceived fault resolution that is typically established by visual (Interpreter) mapping only. Most 3D surveys in the resource industries are therefore currently underutilized, as an entire medium-sized, 'sub-visual' (but not sub-seismic) fault population can be extracted from already existing data with relatively little effort.

High-resolution fault extraction also typically identifies many fault penetrations in wells that were previously not recognised from seismic data, or even well data. As such, the technology helps to reduce the scale gap between seismic and well data (Fig. 4). Vertical wells (with Total Depths of ca. 10,000 ft) penetrate between 5 and 25 seismically resolvable faults, in horizontal wells this number can increase to 50 seismic faults. Typically, very few of these faults were identified before high-resolution fault extraction had been performed, particularly if no image logs were acquired.

Overall, much improved and multiple 3-dimensional fault & fracture network models can be generated through high-resolution fault extraction, and can subsequently be compared and calibrated with drilling and production results (Fig. 5). Calibration may result in the selection of a preferred (Base Case) extraction method. The significance of faults and the confidence in fault presence can be objectively and semi-quantitatively evaluated by performing extractions with different parameterisations and by comparing the differences in results.

With this new information, drilling and production observations in existing wells or mines can be better understood, and future drilling and production outcomes can be optimised. Detailed fault imaging can reduce operational risks and costs, and can deliver increased recoveries from resources. Faults linked to drilling, mining and/or production risks or hazards can be avoided.

Safer, cheaper and more successful wells can be drilled by designing future wells (especially deviated/horizontal wells) to stay clear of faulted or fractured zones previously not predictable on seismic, or by predicting zones in the well where fluid losses, potential kicks and borehole instabilities could occur.

Future hydrocarbon wells can be optimally placed with respect to fluid boundaries or fluid conduits, which is particularly important for the development of compartmentalised, tight, fractured, unconventional and structurally complex reservoirs. Fault intersections can be planned to drain different fault compartments (in matrix-producing fields), or to access the productive natural fault & fracture network.

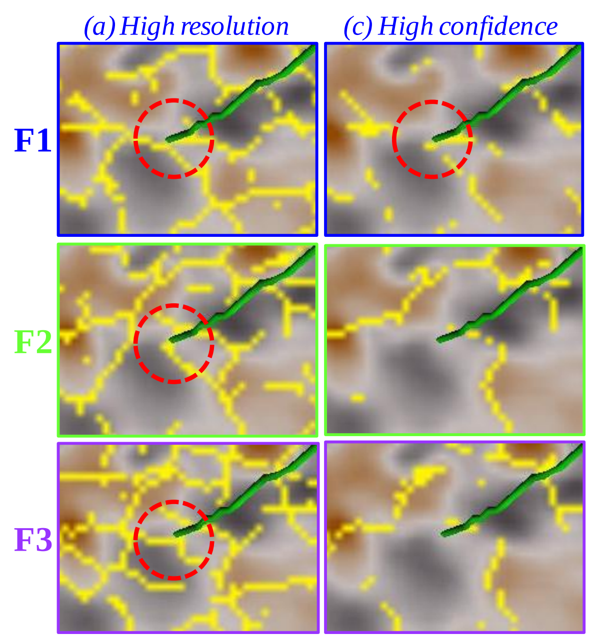


Figure 5: Three different high resolution fault extraction methods show a seismic fault that is directly associated with productivity in a Basement well. Method F1 picks up this fault in both high resolution and high confidence extraction volumes. [Red circle=well intersection point with time slice.]

Conclusions

Novel techniques and workflows in automated, high-resolution fault identification open up a new dimension in the visualization and understanding of compartmentalised, tight, fractured and unconventional reservoirs by pushing fault resolution into the 'sub-visual' fault domain. 'Sub-visual' imaging provides exciting opportunities to increase resource recoveries and reduce operational risks and costs, and is proposed to be established industry-wide as a Best Practise tool for resource development planning and execution.

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