A new method for high-resolution fault imaging delivers groundbreaking insights into drilling and production of resources

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SUMMARY

Novel techniques and workflows in automated fault extraction have been developed to visualise faults at extremely high resolution from 3-D seismic data, and to subsequently evaluate how these faults can impact resource activities (drilling, mining), resource recoveries (e.g. oil & gas, coal) and the safety of operations (e.g. gas kicks, outbursts).
Examples from resource projects around the world demonstrate that new methods in fault imaging can deliver groundbreaking insights into the drilling and production of resources.
These insights often challenge current perceptions:
- Presently, most 3D surveys in the resource industries are underutilized with respect to the detailed delineation of faults in the subsurface.
- The increased fault resolution results in a dramatic increase in the number of faults that are identified from seismic.
- There are a lot more faults penetrated in wells than realised industry-wide, and these faults can cause a number of drilling and production problems, or production opportunities.
A focused application of the new technology workflows can deliver increased recoveries from resources. And it can result in safer, cheaper and more successful drilling and mining operations. As such, the techniques are viewed as Best Practise tools for resource development planning and execution.

Key words: seismic, fault, fracture, detection, resolution.

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 & productivity. Detailed fault mapping, at highest possible resolution, is therefore important for most resource development projects.

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 underground coal mines, fault and fracture networks can result in significant geotechnical, production and/or safety hazards. Through coal seam offsets, faults can cause major interruptions to production and can affect the economic viability of a coal mine (Cocker et al., 1997; Driml et al., 2001; Kecojevic et al., 2005). Faults can also affect floor and roof stability and cause roof failures, resulting in lost time incidents, or with possibly even lethal consequences. Faults can also act as trap zones for gas, which can result in gas kicks or outbursts during mining, again posing significant risks to production and the safety of mining personnel.

FAULT DETECTION

Given the important role that fault and fracture networks play in hydrocarbon reservoirs, various seismic processing techniques and software packages focused on 3D fault visualisation, auto-extraction and also semi-automated fault picking have been developed in recent years. These automated fault detection techniques aim to support or (partially) replace manual fault mapping efforts, which are labour-intensive and time-consuming (Admasu et al., 2006), and also subjective.
Various attributes are in use for imaging discontinuities in seismic data, e.g. coherence, semblance, dip/azimuth, curvature, similarity, frequency variability, seismic texture etc. These attributes typically identify and enhance spatial discontinuities that are computed at every data point within a seismic data cube. For a description of attributes and a detailed account of the advances made in the automation of seismic fault interpretation, reference is made to the publication by Pepper and Bejarano (2005).
Seismic discontinuities do not necessarily represent fault surfaces, but can be also related to other geologic features (channel edges, dykes, 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).
Most discontinuity processing workflows follow a similar approach - volume conditioning with noise cancellation, followed by automatic discontinuity delineation, conversion into 3D objects and calibration and analysis of these objects.

CALIBRATION

Seismic discontinuities can represent both noise and geology. It is of key importance to confirm that the discontinuity extractions represent structural features rather than artefacts. There are a number of key steps to help with this validation process:

- *Visual inspection:* on sections, time slices and in volume view. Key question to address: Are fault patterns & geometries meaningful and have horizon offsets been identified?
- *Calibration against previous (manual) fault interpretation:* A good match is typically observed between faults mapped by an Interpreter and the extracted seismic discontinuities. In high-resolution extraction mode, however, there are always many more (smaller-scale) discontinuities identified than have been mapped by the Interpreter, due to the higher resolution achieved by auto-extraction.
- *Calibration against other structural highlighting data:* Often a good match is observed between seismic discontinuities and features indicated by other structural highlighting data (e.g. Dip, Azi, DipAzi, Semblance, Coherence, etc). Fault auto-extraction, however, usually delivers a much higher resolution than other structural highlighting tools.
- *Calibration against faults & fractures identified from log correlation, cores, dipmeter and borehole images or faults encountered in mines:* Faults identified in these data sets play a key role in proving that seismic discontinuities are faults.
- *Generation of histograms/rose diagrams of extractions:* This allows a more in-depth analysis of discontinuity population statistics and discontinuity geometries.
- *Calibration against drilling observations:* e.g. drilling breaks, fluid losses, well kicks, gas peaks, borehole instabilities, well losses, etc.
- *Calibration against well test observations:* e.g. test results, interpreted boundaries or baffles (or lack thereof), permeability pathways, etc.
- *Calibration against production observations:* e.g. production logs, water or gas channelling, evidence for presence of compartmentalisation, baffles or boundaries, production enhancement through natural fracture system, reservoir pressure, 4D seismic data, etc.
- *Repeatability:* Stephenson et al. (2005) performed fault extractions (using Shell proprietary software) on two seismic surveys of different vintages that cover the same field. They found that all larger and most smaller fault bodies were co-located and showed the same structural trends in both seismic vintages. This result was seen as a strong confirmation that the extracted faults represented actual structural discontinuities rather than survey related artefacts.

Thorough and careful calibration can help to turn discontinuity data sets into calibrated fault & fracture network volumes, that can be utilised for further evaluation of identified issues in wells, or for predicting and avoiding, or ensuring, fault intersections in future wells.

BENEFITS OF FAULT EXTRACTION

The key benefits that can be gained by applying automated fault extraction techniques to 3D seismic data sets are:

✓ *Quality, Objectivity & Confidence:* Automated fault extraction allows a more objective extraction of resolvable geological features in true 3-dimensional space. This leads to an improved quality of the interpretation, achieves higher confidence compared to manual fault mapping and removes potential model-bias of an Interpreter.

✓ *Geometry:* Automated fault extraction delivers an increased and more reliable fault definition, and enables a better understanding of structural geometries and fault populations. Traditional mapping pitfalls, e.g. fault aliasing, oversimplification or the generation of geometrically unrealistic faults, can be avoided.

✓ *Speed:* Automated fault extraction leads to a significant increase in mapping speed compared to Interpreter (i.e. manual) mapping efforts. Hours or days of extraction work compare favourably to weeks or months of manual fault interpretation.

✓ *New structural volumes:* A number of new structural fault volumes can be generated for each algorithm with which extractions are performed: fault network volumes, fault network reflectivity volumes, fault density volumes, fault density network volumes and fault trend volumes. For all of these, sensitivity volumes can be also generated, reflecting different extraction parameterisations, for example to evaluate confidence in the picking of a discontinuity by a certain algorithm.

✓ *Identification of fault penetrations in existing wells*: High-resolution fault/fracture network volumes typically help in identifying (previously unrecognised) fault penetrations in wells. Results from high-resolution fault extraction projects around the world have made it clear that there are a lot more faults penetrated in wells than realised in the Oil & Gas industry. Vertical wells (with Total Depths of ca. 3,500m) penetrate between 5 and 25 seismic faults that were visualised through hi-res automated fault extraction. For horizontal wells, the fault number can go up to 40. Typically, very few of these faults were identified before fault extraction had been performed. This new information can provide a lot of insights into the often underestimated effects that fault penetrations have on a number of drilling and production problems, or production opportunities, in hydrocarbon reservoirs.

✓ *Resource development optimisation:* With hi-res fault extraction, there is now a means to better understand drilling and production observations in existing wells or mines, and to optimise drilling and production results in future operations. 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.

Key Benefit: Resolution

The application of seismic discontinuity processing workflows allows to resolve structural features faster and at a much higher resolution than a human observer can (Stephenson et al., 2005). The algorithms pick up even small spatial variations in amplitude, phase and/or frequency content of the seismic data, which are too small to be detected easily by the human eye (without extreme zooming and extreme colour maps) and would also take too long to map in detail and at high confidence. Automated fault extraction therefore leads to the identification and visualisation of fault and fracture

networks at a much higher resolution than is achieved by manual (i.e. visual) interpretation.
With the increased structural resolution, much higher fault & fracture densities are found than previously mappable or recognised. Instead of mapping e.g. 20 faults in a hydrocarbon field, 200 or 2,000 faults can now be made visible, and their potential impact on the drilling, mining and production of resources can be evaluated.

Many tectonic fault systems have power-law size distributions over a wide range of scales and down to displacements as small as 1 cm (Childs et al., 1990; Yielding et al., 1992; Gillespie et al., 1993). Fault throw (or fault length) frequency plots (Figure 1) for seismically-mapped faults show that below a certain cut-off faults are under-sampled or not sampled at all, as identification from seismic becomes problematic or not possible due to the seismic resolution.

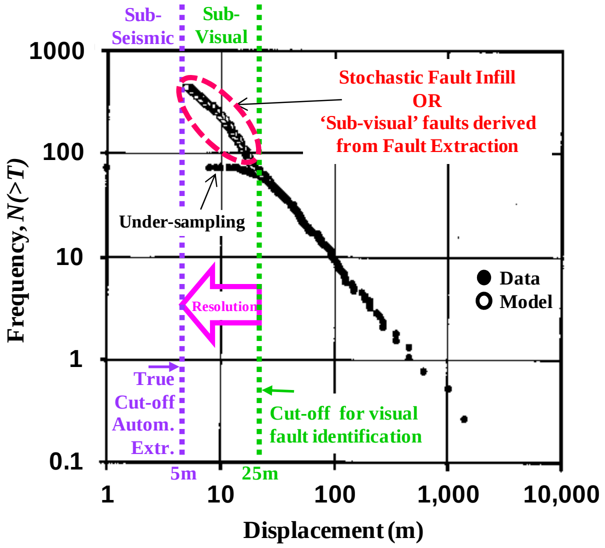

Figure 1. Empirical and stochastic fault populations as examples for an Automated Fault Extraction population (modified from Maerten et al., 2006).

Figure 1 displays an example of a fault throw frequency plot for a fault population from the Norwegian North Sea (Maerten et al., 2006). The (visually mapped) data shows a clear power-law relationship for throws ranging from 2000 to 25m. For this data set, 25m throw appears to represent the cut-off for (confident visual) fault identification. Below this cut-off, faults are under-sampled, or not sampled at all by visual interpretation anymore.
This cut-off is generally, in the resource industries, referred to as the limit of seismic resolution, with faults below this limit often being referred to as sub-seismic. This nomenclature is unfortunately imprecise and misleading, as it implies that faults below this cut-off cannot be sampled from seismic data because the resolution limit of the data has been reached. This is not the case. The limit that has been reached instead is the visual resolution limit of the Interpreter who mapped these faults. The small under-sampled fault population below 25m fault throw, that is displayed in Figure 1, illustrates that the true seismic resolution limit of the data set has in fact not been established, as a number of faults with throws less than 25m were actually mapped by visual means. It is important to realise that most seismic fault throw (or length) resolution limits quoted in the resource industries are only established by visual fault mapping, and as such define a 'perceived' limit of seismic resolution, not the true seismic resolution for faults that can be achieved in a particular data set.
With decreasing fault throw (i.e. reflector offsets) visual interpretation becomes more and more challenging and subjective, and visual fault mapping confidence decreases significantly. This is where Automated Fault Extraction can help to objectively and more confidently visualise faults, particularly faults with small displacement. Automated Fault Extraction reduces the cut-off for fault recognition, both in terms of fault throw and also fault length, and can provide information on faults at sub-visual level, approaching the true seismic resolution limit for the detection of faults in a particular data set. Sub-visual faults are currently incorrectly, but consistently and industry-wide, included into the sub-seismic and 'un-mappable' category by many Geoscientists, but can in fact be extracted from seismic data with latest technology, experience and careful calibration with other data. It follows from this, that most 3D surveys in the resource industries are 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.

It is of particular interest to compare sub-visual fault populations with faults derived from stochastic fault infill and modelling techniques. These techniques are often applied to better understand and improve production behaviours in fields where small-scale structures cause flow enhancement or flow retardation. Maerten et al. (2006) performed this modelling on the data set displayed in Figure 1. They predicted the size distribution of 'sub-seismic' faults by extrapolating the size distribution measured at the seismic scale down to the (perceived) 'sub-seismic' scale. Modelling of 'sub-seismic' faults was constrained at a minimum fault size of 5m fault throw. The modelled stochastic fault population in Figure 1 (open circles) resembles the 'sub-visual' fault population (which can have throw resolutions down to 5m) that is typically visualised with hi-res automated fault extraction. The key challenge in stochastic fault modelling is how to constrain the positions and orientations of 'sub-seismic' faults (e.g. Gauthier and Lake, 1993; Maerten et al., 2006; Lohr et al., 2008). As hi-res fault extraction achieves a high-resolution, and in fact deterministic delineation of small-scale structures, it has the potential to reduce or possibly even replace the need for stochastic fault modelling.

CONCLUSIONS

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 recent years, various automatic fault extraction techniques have been developed for 3D seismic data. These techniques aim to support or (partially) replace manual fault mapping efforts, which are typically labour-intensive, time-consuming and subjective.

A new method has been developed which integrates 3D seismic visualization and highest-resolution image processing results with the detailed calibration and review of various seismic, well and also mining data.

From this, groundbreaking insights into the physical description of resources can be gained. Properly calibrated fault & fracture network volumes deliver faster and more reliable and objective fault interpretations, and a better understanding of structural geometries and fault populations.

The key benefit of automated fault extraction, however, is a marked increase in fault resolution, which results in a significant increase in the number of (medium-sized) faults that are identified from seismic. The resolution increase leads to much higher fault & fracture densities than were previously mappable or recognised, and it also identifies many fault penetrations in wells that were previously not recognised. As such, the technology helps to bridge the scale gap between seismic and well data. The very latest fault imaging technology pushes fault resolution down to the true fault resolution of a particular 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 could be extracted from already existing data with relatively little effort.

Examples from Coal Mining and Oil & Gas projects around the world demonstrate that the new techniques can provide a step-change in understanding drilling, production and safety issues in existing wells or mines. They furthermore can be utilised to optimise future resource activities and recoveries, and increase the safety of future operations.

A focused application of the new technology workflows can deliver increased recoveries from resources. And it can result in cheaper, safer and more successful drilling and mining operations. As such, the techniques are viewed as Best Practise tools for resource development planning and execution.

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