New Method for Seismic Identification of Fluid Conduits or Barriers Challenges Several Industry Paradigms*

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Abstract

During the last two decades, volume interpretation techniques have revolutionised traditional 3D seismic interpretation workflows in the Oil and Gas industry. While traditional interpretation mainly relies on an interpreter to work through a large volume of data to identify and manually characterise subsurface geology and resources, volume interpretation allows one to filter and classify subsurface features and extract 3-dimensional geological information through automated processes at a much faster pace, with higher accuracy and at higher resolution.

This paper presents new techniques and workflows in automated fault extraction (AFE) that have been developed to integrate highest-resolution 3D seismic image processing results with the detailed calibration and review of various seismic, well, mining, production, and flow data, allowing to delineate fluid barriers, fluid conduits, fault-related mineralisations or drilling and mining hazards in the subsurface.

Examples from fractured Carbonate reservoirs from around the world (North America, Europe, Africa, Middle East, and Asia), including examples of fractured Chalk and karstified Carbonate Basement, demonstrate that high-resolution AFE methods can deliver groundbreaking insights into the 3-dimensional geometry and distribution of fracture networks, and how these can affect fluid flow in the subsurface (Figure 1).

The insights that have been gained through high-resolution AFE challenge a number of current Oil and Gas industry paradigms:

- Automated fault extraction can support or replace manual fault mapping efforts, which are typically labour-intensive, time-consuming, and imprecise. While manual fault interpretation creates an interpretation of a measurement, fracture extraction creates a new measurement from an existing measurement. This measurement may prove to directly represent (deterministic) fracture networks, or can be used as a starting point for subsequent manual interpretation and model generation. Automated fault extraction ultimately offers the opportunity to replace the subjective interpretation of faults with the objective measurement of faults and their properties directly from seismic data.

- Presently, most 3D surveys in the resource industries are under-utilized with respect to the detailed, high-resolution delineation of fracture systems in the subsurface. The techniques presented can be applied to already existing 3D seismic data and help to identify the true fault resolution of a particular data set, not the perceived fault resolution that is typically established by visual (Interpreter) mapping only. With decreasing fault throw (i.e. reflector offsets) visual interpretation becomes more and more challenging and subjective, and visual fault mapping confidence decreases significantly, resulting in under-sampling of fault populations. This is where automated fault extraction allows a more objective, certain and complete delineation of fault populations in true 3-dimensional space, particularly 'sub-visual' faults with small displacement. This leads to an improved quality and achieves higher reliability compared to manual fault mapping and removes potential model-bias of an Interpreter. Automated fracture 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.

- *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. 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. As not all seismic attributes produce reliable and meaningful results, careful screening of a variety of different algorithm results and calibration with other data is required to find the best method for a particular objective level within a seismic data set. Specifically designed calibration workflows ensure that seismically derived fracture networks are properly calibrated and groundtruthed with e.g. fault indications from other seismic, well, mine, drilling, or production/flow data.

- The application of automated fault extraction techniques can help in narrowing or closing the *scale gap* between seismic and well data. Detailed integration work has e.g. revealed that perfect matches between seismically identified fractures and fractures identified from well data (image logs, cores, correlation, well tests, productivity, fluid losses etc.) can be found, thus allowing to close the scale gap between well and seismic data. In Oil and Gas, large-scale faults are normally identified by 3D seismic interpretation, whereas small-scale faults are identified by spatially isolated 1D well data (primarily core and image logs). Faulting at medium scale (with displacements between ca. 30 m and a few decimeter), however, is commonly neither recognized on seismic data nor well data (Gauthier and Lake 1993; Needham et al., 1996; Lohr et al., 2008). This typical scale gap between Oil and Gas well and seismic data is depicted in Figure 2. Large-scale faults that were visually interpreted from seismic and small-scale well-core fractures appear in this example to belong to the same continuous displacement population, which is described by a power law (Needham et al., 1996). The figure illustrates that medium-scale faults with throws between 30 m and about 10 cm are under-sampled or not sampled at all in both seismic and well data domains, creating a data gap. The cut-off (or left-hand truncation) for confident visual fault identification from seismic in this offshore U.K. field example is 20-30 m, which is a typical cut-off for many deep reservoirs (e.g. Maerten et al., 2006). Automated fault extraction resolves the sub-visual fault domain and helps to shift the cut-off for fully sampled fault recognition to typically 5-8 m of fault throw in deep seismic data sets (Figure 2). This shift helps to reduce the observed scale gap between seismic data and well data, and results in a multi-fold increase in the number of identified faults. It also results in an improved understanding of the effects that faults can have on fluid flow and hydrocarbon development activities, which are often masked by the scale gap. The Mining industry, in contrast to the Oil and Gas industry, is not affected by the scale gap between seismic and well data due to the generally higher density of data that is acquired in mining: high-resolution seismic, many wells and also mine tunnels that allow to sample faults over a wide range of scales. Shallow high-resolution seismic data acquired by the coal mining industry for example allows to visually map faults with throws as low as 1-3 m (e.g. Hearn and Hendrick 2001).

- Automated fault extraction increases fault resolution and results in a dramatic increase in the number of faults that are identified from seismic (Figure 1 and Figure 2). Significantly higher fault/fracture densities are found than previously mappable or recognised. Instead of mapping e.g. 20 faults in a field, 200 or 2,000 faults can now be made visible, and their possible impact on drilling, mining, and production activities can be examined.

- With the increased fault resolution, stochastic modelling of fracture networks may not be required, as deterministic fracture network data can be directly derived from seismic data and used to generate fully deterministic static fracture models. When combined with fracture flow properties and geomechanical data, well-constrained and spatially exact flow simulations should result, that are of direct relevance for the understanding of historic well production data or the prediction of future well production.

- While it is recognized from outcrop studies that a few large faults are accompanied by many smaller-scale faults, it is most times unclear how these smaller-scale faults are spatially organised in the subsurface and how they may enhance or inhibit fluid flow. High-resolution fracture network extractions performed by the author for many different plays and in many different locations around the world have consistently delineated larger tectonic faults and also smaller-scale fault networks that show 3-dimensional *polygonal* symmetries. These polygonal fault cells may represent diagenetic or compaction fractures which are formed during early burial and diagenesis and are likely related to diagenetically-induced shear failure (Cartwright 2011). Later reactivation of polygonal fault traces during tectonisation of rocks may lead to forced alignments of polygonal fault traces and the formation of larger tectonic fractures.

- There are a lot more faults penetrated in wells than realised in the Oil and Gas industry, and these faults are often directly linked with a number of drilling and production problems, or production opportunities, in compartmentalised, tight, fractured, and unconventional reservoirs, where faults in the subsurface can form fluid barriers or fluid conduits. Fault penetrations are often linked with drilling problems (e.g. gas kicks, fluid losses, borehole instability), as well as production issues (water production along fault planes, compartmentalisation) or production opportunities (access to productive natural fracture networks, 'sweet spots'). The new techniques can therefore provide a step-change in understanding drilling, production and safety issues in existing wells or mines.

- The new techniques can also be utilised to optimise future resource activities and recoveries, and increase the safety of future operations. Detailed fault imaging can reduce operational risks and costs, and can deliver exploration success as well as 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 and fracture network.

In most resource industries, it is critical to improve the understanding, detection, modeling, and prediction of fault and fracture networks. The key problem for the development of fractured resources is the difficulty to visualise the exact location and geometry of fractures (Lonergan et al., 2007).

This is where novel techniques and workflows in Automated Fracture Extraction offer new opportunities to visualize fracture networks at extremely high resolution. The workflows provide a completely new basis for the reliable identification and quantifiable prediction of fracture networks in the subsurface, and allow one to reliably delineate fractures and predict fluid pathways in the subsurface.

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 exploration and development planning and execution.

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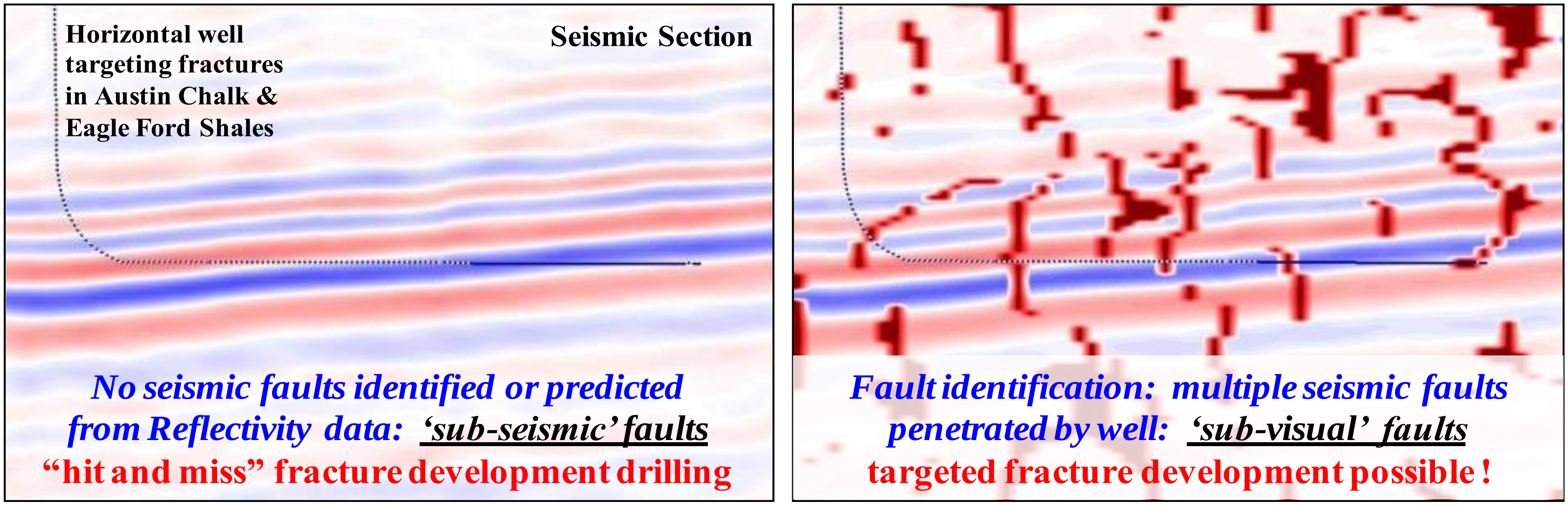

Figure 1. High-resolution fault extraction visualises small-scale spatial changes in amplitude, frequency, or phase content of 3D seismic data, and challenges perceptions of what can and cannot be identified with seismic data. Comparison and calibration of seismic fault extractions with faults identified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

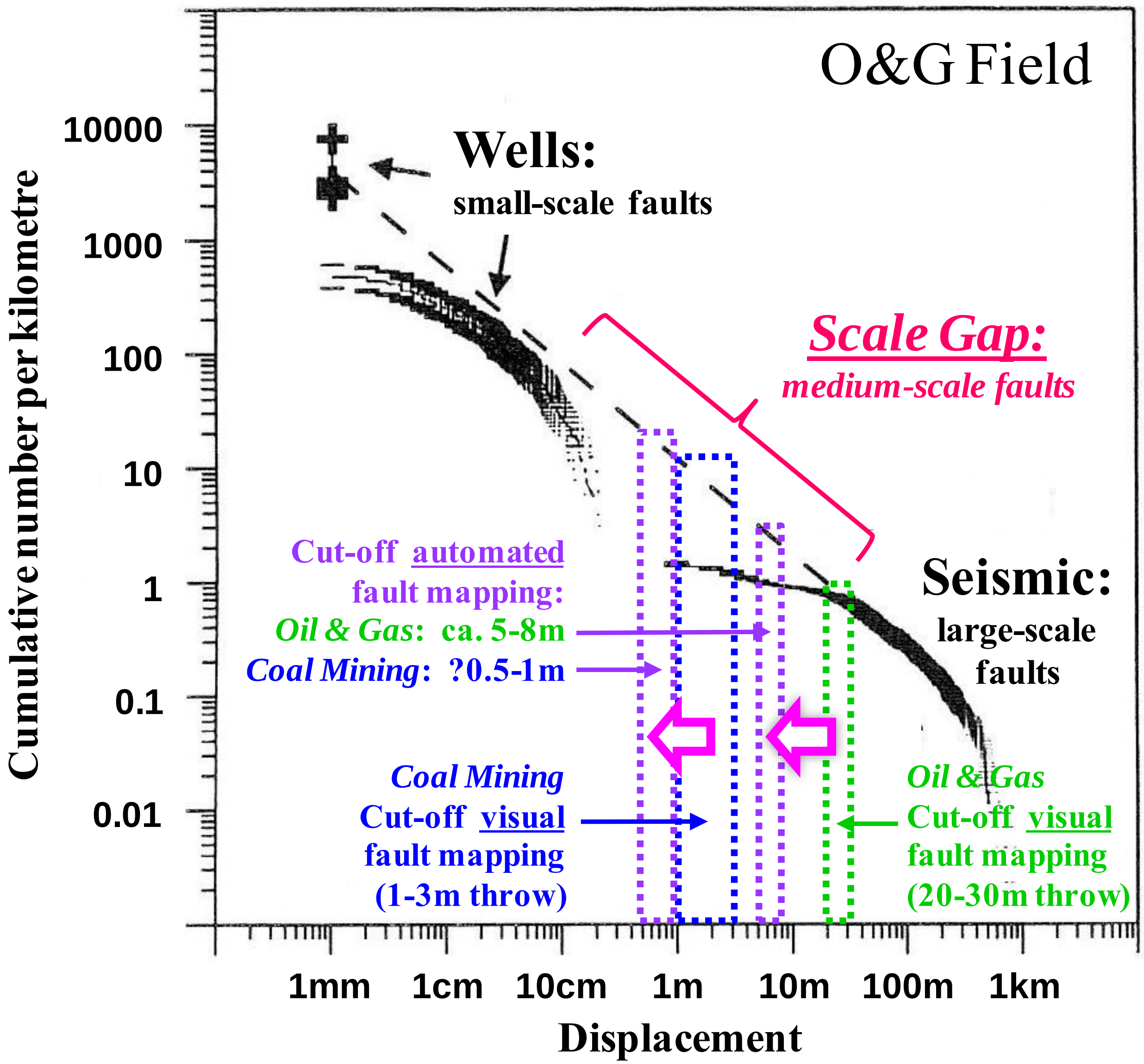

Figure 2. Comparison of visually mapped seismic fault throw data with well displacement data (modified from Needham et al., 1996). Displayed are also the cut-off ranges for visual fault mapping of faults from Oil and Gas and Coal Mining 3D surveys. These cut-offs can both be lowered by automated fault extraction.