Ralf Opperman

A new workflow for high-resolution fault imaging delivers groundbreaking insights into resource operations and recoveries

Fault and fracture networks can have significant effects on drilling, mining and the safety of resource operations. Due to this, various automatic fault extraction techniques have been developed for 3D seismic data in recent years. These techniques aim to support or (partially) replace manual fault mapping efforts, which are typically labour-intensive, time-consuming and subjective.

This paper presents innovative techniques and workflows that have been developed to integrate 3D seismic visualization and highest-resolution image processing results with the detailed calibration and review of various seismic, well and mining data.

From the application of these workflows, groundbreaking insights into the physical description of resources can be gained. Fault and fracture networks can be identified faster, more reliable and at a much higher resolution than achieved by other current seismic methods. With the increased resolution, much higher fault/fracture densities are found than previously mappable or recognised, and a better understanding of structural geometries and fault populations can be achieved.

New workflows developed for Oil & Gas projects have demonstrated that the new techniques can provide a step-change in understanding drilling, production and safety issues in existing wells. They furthermore can be utilised to optimise future resource activities and recoveries, and increase the safety of future operations.

A new workflow for high-resolution fault imaging has been developed for the Coal Mining industry. This workflow helps to push fault resolution down to the true fault resolution from 3D seismic data, not the perceived fault resolution that is typically established by visual (Interpreter) mapping only. The new technique helps in resolving the 'sub-visual' fault domain, and as such helps to bridge the scale gap between seismic data and well & mine data. With 'sub-visual' imaging there is now a means to minimise drilling, production and safety issues that are caused by faults in wells and mines.

Where faults pose geotechnical, production and/or safety hazards in underground mines, high-resolution fault imaging can support Mine Design & Planning and Fault Zone Management activities.

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 (Oppermann 2010).

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 & others 2007).

The successful application of new techniques in automated fault identification in Oil & Gas projects has demonstrated a number of key benefits that can be realised with these techniques (Stephenson, Cassidy & Warrlich 2005; Oppermann 2010).

This paper discusses how these Oil & Gas workflows can be applied in the Coal Mining industry, and likely provide a step-change in understanding and addressing drilling, production and safety issues in current and future wells and mines.

FAULTS AND UNDERGROUND COAL MINING

In underground coal mines, fault and fracture networks can result in significant geotechnical, production and/or safety hazards. As a result of this, ground control strategies typically include mine designs that minimize fault exposure (Molinda & Ingram 1990).

Through coal seam offsets, faults can cause major interruptions to production and can affect the economic viability of a coal mine (Cocker, Urosevic & Evans 1997; Driml, Reveleigh & Bartlett 2001; Kecojevic & others 2005).

Faults can affect floor and roof stability and cause e.g. 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 outbursts during mining, again posing significant risks to production and the safety of mining personnel. All fatal outbursts in Australia, except Leichhardt Colliery, have occurred on faults (University of Wollongong 2010).

Fault penetrations can also lead to incidents related to fluid losses or gains, gas kicks or geomechanical problems in boreholes (wellbore instability, breakouts, casing damage due to slippage along reactivated fault planes etc.).

FAULT DETECTION

Fault (i.e. hazard) identification from seismic and well data plays a key role in coal mining. It is of key interest to improve the prediction and confidence in fault mapping from seismic, as this can help in avoiding costly production issues or life-threatening incidents in underground mines.

In recent years, various seismic processing techniques and software packages focused on 3D fault visualisation, auto-extraction and also semi-automated fault picking have been developed and are increasingly being applied in the Oil & Gas industry. Various attributes are in use for imaging discontinuities in seismic data, e.g. coherence, semblance, curvature, similarity, dip & azimuth, 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 & Bejarano (2005).

Automated fault detection techniques have been developed to support or (partially) replace manual fault mapping efforts, which are labour-intensive and time-consuming (Admasu, Back & Toennies, 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 can 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 (Figure 1), and is as such free of bias and interpretation. Fault extraction therefore allows making a distinction between measurement and the interpretation of this measurement, as e.g. manifested in visual reflector offset mapping. A further benefit of fault extraction is that the significance of faults and the confidence in fault presence can be objectively evaluated.

Extraction 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 faults that are identified from seismic. 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

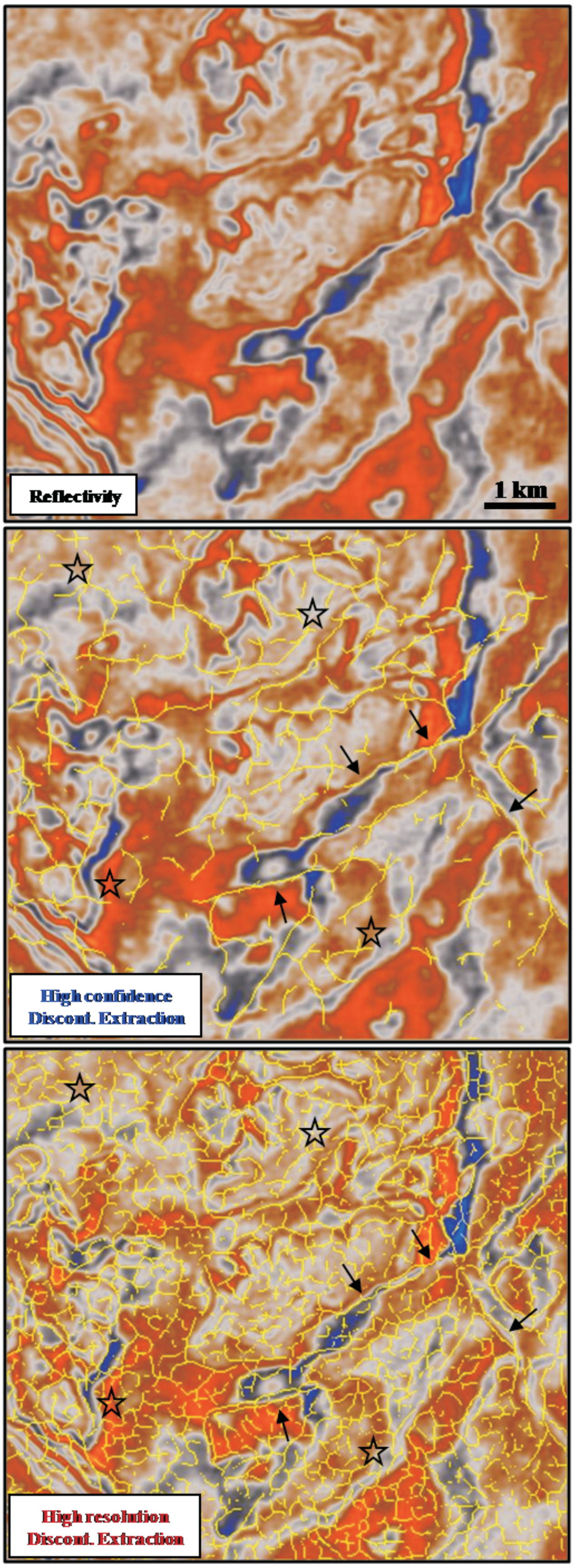

*Figure 1: Visual comparison of time slices (at 1,398ms) through a reflectivity volume, a high **confidence** discontinuity extraction and a high **resolution** discontinuity extraction. Faults that show clear offsets are picked (arrows), and smaller scale faults are picked in both extraction volumes that only the analysis of spatial variation in amplitude, phase and frequency resolves (stars). Extraction data generated from Myall Creek 3D Land Seismic Survey 2004 (Surat Basin/Queensland; open file data, Queensland Govt. DEEDI).*

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 under-utilized, as an entire medium-sized, 'sub-visual' (but not sub-seismic) fault population could be extracted from already existing data with relatively little effort (Oppermann, 2010). Overall, much improved and multiple 3-dimensional fault & fracture network models can be generated from fault extraction data.

PROPOSED NEW WORKFLOW

New workflows developed for Oil & Gas projects have demonstrated that the new techniques can provide a step-change in understanding drilling, production and safety issues in existing wells. They furthermore can be utilised to optimise future resource activities and recoveries, and increase the safety of future operations. The following new workflow is proposed, which integrates new Oil & Gas fault extraction methods with established coal mining workflows. The workflow has been designed to be applicable to a new coal mining project, but can be adapted for the evaluation of an existing coal mine. The presented workflow will likely require refinement in future applications to coal mining assets.

Generally, 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.

1. Discontinuity Processing / Fault Extraction

Processing of 3D seismic data and visualisation of 3-dimensional fault networks at different extractable resolution levels.

1.1 Generation of *structural attribute volume*s: Dip, Azi, DipAzi volumes.

1.2 Discontinuity highlighting using a number of different methods/algorithms. Generation of a *first set of fault volumes*, for each utilised algorithm: Fault Network (FN), Fault Network Reflectivity (FNR; e.g. Figure 1), Fault Density (FD), Fault Density Network (FDN), Fault Trend (FT) volumes.

1.3 Generation of *sensitivity volumes*, to assess the impact that different parameterisations have on results, and to assess fault picking confidence.

2. Calibration of initial Discontinuity Volumes

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). 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:

2.1 Calibration by *visual inspection* on sections, time slices and in volume view. Key questions to address: Are fault patterns & geometries meaningful and have horizon offsets been identified (Figure 1)? Are features being consistently identified when comparing different algorithm results? Any obvious noise pollution or artefacts? And is structure-oriented filtering required?

2.2 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 (Figure 2).

3. Reflectivity Data Conditioning with Noise Reduction / Structural Smoothing

Noise-contamination of seismic data can be addressed by running spatial filters that attenuate or remove a possible noise contamination but retain the geometric detail such as small-scale fault breaks (Chopra & 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 & Fehmers 2002).

3.1 Structural smoothing of reflectivity data.

3.2 Generation of a *second set of fault volumes* (as in 1.2)

3.3 Generation of a *second set of sensitivity volumes* (as in 1.3)

3.4 *Compariso*n of the unsmoothed, first volume set with the smoothed, second volume set, to assess and quantify how smoothing has modified the data and possibly affected fault identification, e.g. by sharpening discontinuities.

4. Optimally Placing Wells for the Pre-Drainage of In Seam Gas

The degasification of coal prior to mining is an important commercial and safety-increasing activity (Cocker, Urosevic & Evans 1997). The early detection of faults on 3D seismic data can allow coal companies to more effectively degasify the coal seam in advance of mining operations (Gochioco & Cotten 1989). The new seismic fault network volumes provide detailed fault information, which can be used to optimise well locations and with this, the pre-drainage of mine gas.

5. Further Calibration of Fault Volumes with Faults identified from Log Correlation, Cores and Image logs in Pre-Drainage Wells

New fault information acquired in pre-drainage wells can be used to further calibrate fault extractions. Image logs can play a key role in proving that seismic discontinuities represent faults (e.g. Richard & others 2005; Stephenson, Cassidy & Warrlich 2005; Warrlich & others 2009; Oppermann 2010).

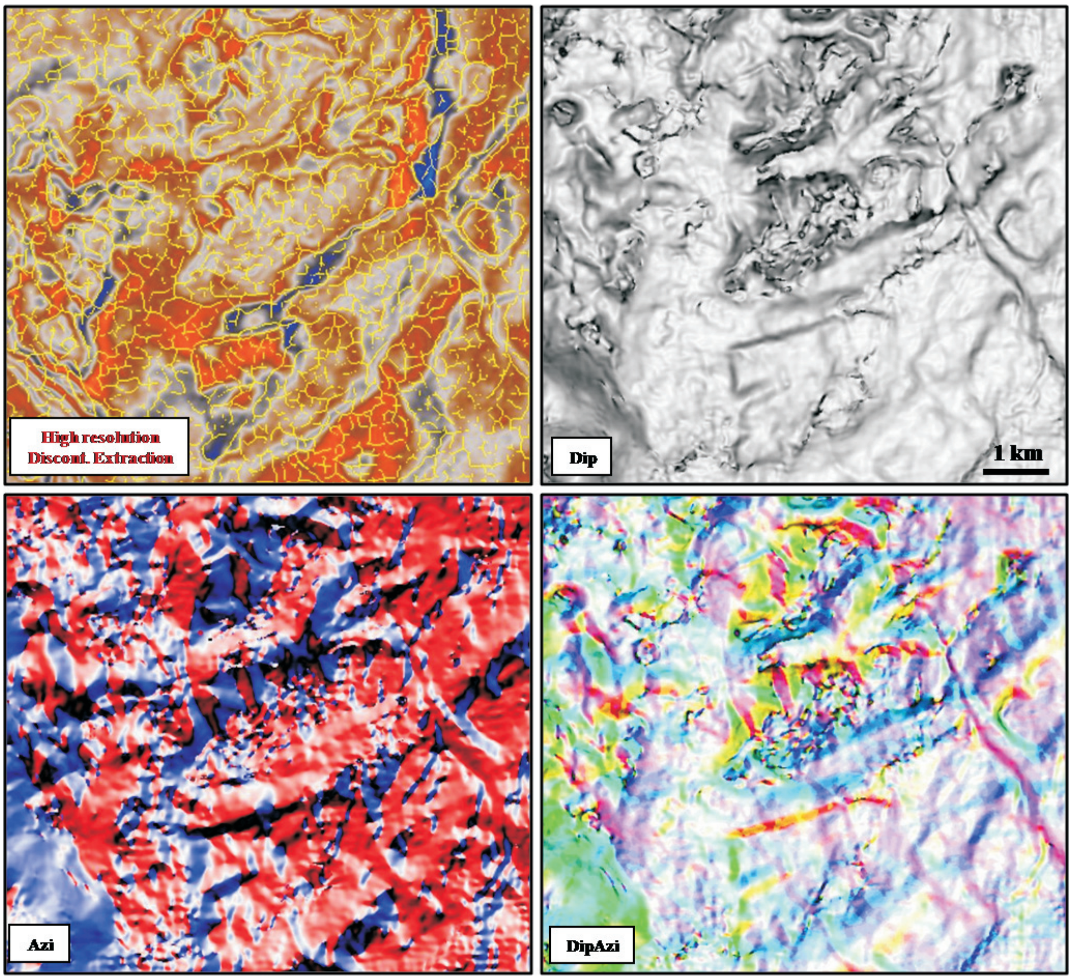

Figure 2: Comparison of high-resolution fault extraction results with other structural highlighting data (Dip, Azi, DipAzi). Structural volume data generated from Myall Creek 3D Land Seismic Survey 2004 (Surat Basin/Queensland; open file data, Queensland Govt. DEEDI).

6. Detailed Mine Design & Planning and Fault Zone Management activities

Currently, manually interpreted faults are integrated with well data and considered during mine design and detailed mine planning, as well as during coal extraction (Peters & Hearn 2001). Faults encountered in the subsurface during mining are evaluated in detail and compared with faults mapped from 3D seismic to calibrate and improve fault prediction capabilities of the (manual) seismic interpretation effort.

The use of calibrated seismic fault network, fault density and fault trend volumes for general and detailed mine planning has the potential to significantly improve Mine Planning and Fault Zone management efforts.

6.1 Initial focus on the *prediction of larger full seam fault*s (with offsets larger than the seam thickness), to identify faults that could be major production or safety hazards ('mine stoppers'). Inventorisation of key faults and their parameters (location, depth, throw, strike and dip direction, etc.).

6.2 Subsequent focus on the *prediction of smaller-scale faults*, to identify faults that also could have geotechnical and/or safety relevance (e.g. coal seam correlation, roof collapse, outbursts).

6.3 Evaluation of *fault mapping confidence* (or uncertainty), using fault network sensitivity volumes (run for each algorithm).

6.4 For existing mines: comparison of seismic fault extractions with *previous efforts to map faults* (manual fault mapping, curvature, similarity, gradient, dip/azi, semblance, etc.), or with *faults encountered during drilling and mining*.

6.5 *Comparison of seismic fault predictions with actual fault penetrations* in wells and mines (full calibration): assessment of true seismic fault resolution that is achieved with different fault extraction algorithms and parameterisations; calibration of fault confidence (or uncertainty) assessments.

6.6 *Comparison of seismic fault predictions with possible drilling and mining issues*: assessment of links between faults and possible fluid losses or gains, gas kicks, outbursts, geomechanical problems (wellbore instability, breakouts, casing damage, floor and roof failures), incidence reports etc. *Incidence inventorisation and analysis* with respect to faulting, with the aim to improve gas compliance, outburst and roof stability control.

6.7. Assessment of the *variability* in results from the running of different fault extraction algorithms, with the aim to identify a *Base Case method* (after full calibration).

6.8. Application of volume interpretation tools for the *prediction of other production hazards*, e.g. dykes, sills, basalt channels, sandstone channels, etc.

6.9. Continuous integration of latest results and possible *re-calibration* of the model throughout mining operations ('feedback loop').

7. Planning and Optimisation of Post Drainage of Gas

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 & 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.

The application of automated fault extraction workflows in Oil & Gas projects around the world has shown that 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. Due to a marked increase in fault resolution, automated fault extractions also provide a more comprehensive sampling of fault populations and an in fact dramatic increase in the number of faults that are identified from seismic.

A new coal mining workflow 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.

The application of this new workflow in the Coal Mining industry could provide a step-change in understanding and addressing drilling, production and safety issues in current and future wells and mines.

Where faults pose geotechnical, production and/or safety hazards in underground mines, high-resolution fault imaging has the potential to significantly improve mine design & planning and fault zone management activities.

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R. Oppermann, OPPtimal Exploration & Development Pty Ltd, PO Box 225, Wembley, WA 6913, Australia,
Tel./Fax +61 (8) 9287 1028, Ralf.Oppermann@OPPtimal.com