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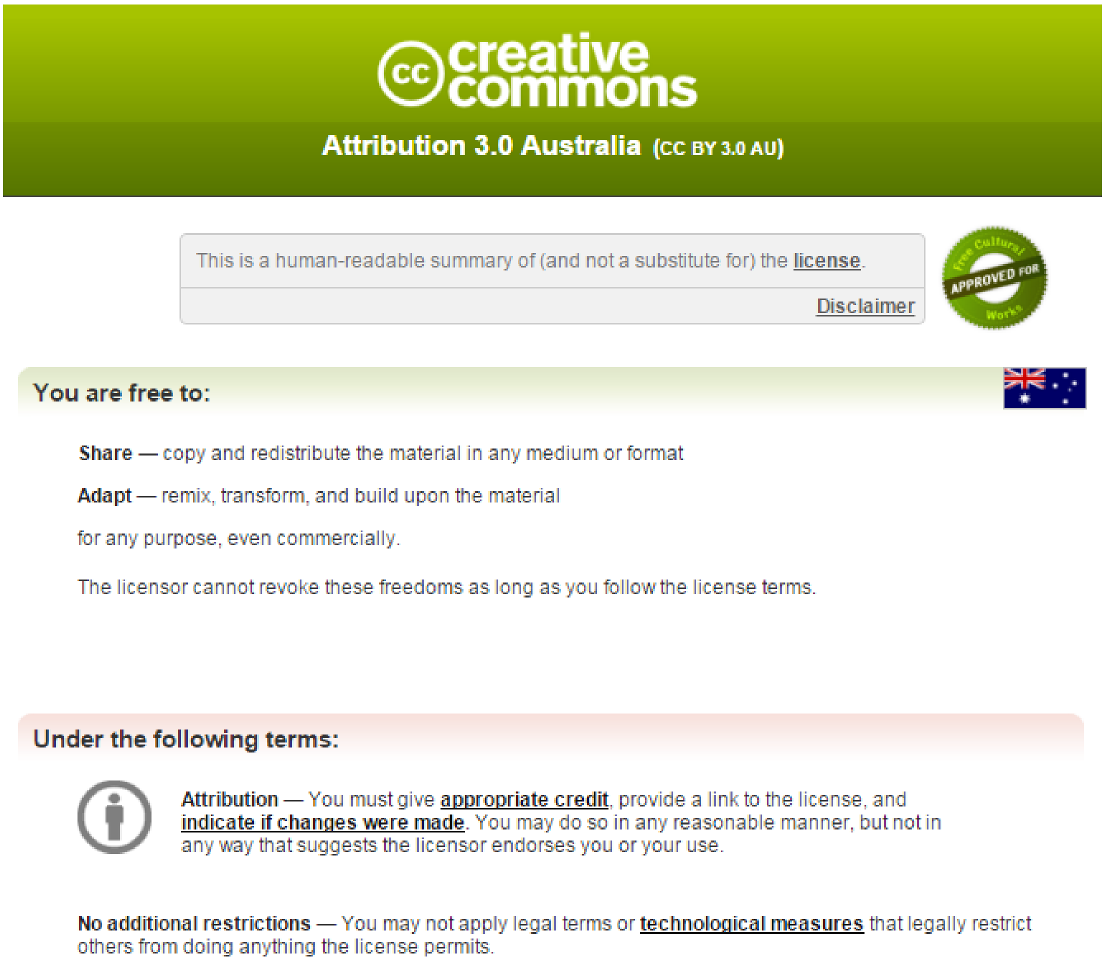

Natural fracture networks enhancing geothermal producibility, mapping or predicting!

Abul Khair, H.[1], Cooke, D.[1], & Hand, M.[2]

[1]Centre for Tectonics, Resources and Exploration (TRaX), Australian School of Petroleum, University of Adelaide, North Terrace, Adelaide SA 5005. [2]SA Centre for Geothermal Energy Research, University of Adelaide, SA 5005, Australia.

Hani.Abulkhair@adelaide.edu.au

Abstract

Subsurface natural fracture networks that act as conduits for thermal fluids play an important role in geothermal reservoirs. The success of enhanced geothermal systems is mainly reliant on modelling the orientation of the pre-existing natural fracture networks within the reservoir. This will help modelling the direction of movement of the hydrothermal fluids, and in locating sweet spots and/or possible orientation of susceptible fractures for further stimulation programs. We applied both mapping and predicting techniques on sand and shale intervals in the Cooper Basin/South Australia and calibrated these techniques using image logs, well data, and quality seismic in order to validate their ability to model subsurface fracture networks.

We used most positive curvature attribute to generate a workflow for modelling subsurface fractures with high confidence. As the curvature attributes are known to be sensitive to the acquisition direction, we reduced all acquisition artefacts using structural smoothening and generated a seismic cube that is free of data acquisition artifacts. A final curvature volume was produced after eliminating low values that don’t reflect any structural features. A validation procedure was applied using image logs, well data, and seismic sections and a high correlation was found between the curvature mapped fractures and the image logs fractures.

Another technique used in this study was to integrate geological and geophysical data extracted from fault and horizon seismic interpretation with geomechanical analyses of stress, strain, and displacements associated the structural development of the basin. Finite element method (FEM) and boundary element method (BEM) are two ways used to predict fractures generated during the tectonic events of basins. FEM provides a physically-based soluiton for subsurface issues related to fractures and basin evolution taking into consideration horizon geometry, heterogeneous rock properties and stresses generated from structural features. The BEM method considers the effect of fault displacement on generating stress and near the fault. One of the disadvantages of BEM is that it doesn't consider rock heterogeneity or the effect of intra-seismic relaxation on fracture generation. Also, BEM ignores far field stress data, and thus does not predict fracture generation away from the major faults.

The validation procedure was applied on fractures predicted from FEM and BEM, and a good correlation was found between the predicted fracture network and the image logs fractures next to the major faults in both methods as fractures in these areas were mostly generated due to strain exerted during fault displacement. FEM succeeded in predicting fractures close to and away from major faults with higher accuracy while BEM didn’t map fractures away from faults. Thus, both FEM and enhanced most positive curvature attributes can be used successfully to model subsurface fracture networks that will locate productive spots with good permeability.

Introduction

Geothermal energy is increasingly attracting the interest of the governments as a strategic green energy source for electricity generation, especially with the gradual depletion of conventional reservoirs. The traditional geothermal systems consist of injection and production wells drilled to subsurface hot reservoirs. Cold water is pumped to the target reservoir, heated, and returned to the surface via production wells. The success of this type of geothermal systems is highly reliant on water circulation within a network of fractures between the injection and production wells. Accurate detection or prediction of pre-existing fracture network and current day stress regime, is of high importance for enhanced geothermal systems well planning, and fracture stimulation programs.

Cooper Basin is a potential Australian geothermal basin, it is a Late Carboniferous to Middle Triassic basin located in the eastern part of central Australia (Fig. 1). The Cooper Basin floor was carved out of the ground uplifted after the end of the formation of Warburton Basin rocks (Preiss, 2000). Following the deposition of the Cambrian-Ordovician sequences of the eastern Warburton Basin underlying the Cooper Basin, NW-SE compression caused a partial inversion of the Warburton Basin, deformation of the pre-existing sequence and the subsequent intrusion of Middle to Late Carboniferous granites (Gatehouse et al., 1995; Gravestock and Flint, 1995; Alexander and Jensen-Schmidt, 1996). From Early to Late Permian, the basin was filled with around 1200 m of clastic sediments and coals deposited in glacio-fluvial to fluvial to open basin environments (Paten, 1969; Stuart, 1979; Thornton, 1979; Powell and Veevers, 1987).

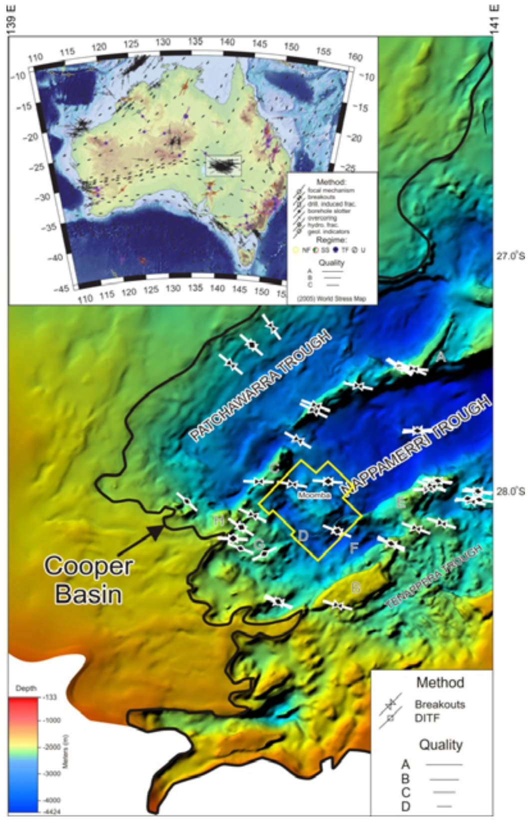

Figure 1: Top Warburton Basin (Pre-Permian Basement, seismic horizon Z) in the Cooper Basin. Map shows NE-SW major troughs separated by ridges. Study area is located at the south-western termination of the Nappamerri trough (Moomba-Big Lake 3D seismic cube outlined in yellow). A: Innamincka Ridge; B: Murteree Ridge; C: Gidgealpa-Merrimelia Ridge; Wooloo Trough; E:Della-Nappacoongee Ridge; F: Allunga Trough; H: Warra Ridge. Top left: Australian stress map (Modified after Hillis and Reynolds, 2000 and World Stress Map, 2010).

The granites bodies underlying the 4 km thick Cooper Basin sediments in some areas are believed to be the source of high temperatures and high geothermal gradients recognized in deep sediments within the basin (Deighton & Hill 1998). This led to considering the basin as the most significant Australian geothermal basin recognized to date (Somerville et al. 1994).

Curvature attributes

Seismic attributes are currently used and abused in mapping fracture networks. In the current study, we used seismic attributes and validated them using seismic and well controls. Among the many seismic attributes used in geophysical studies, structurally smoothed, non-steered and dip steered curvature attributes including most-positive curvature (MPC) and most negative (MNC), have proven most successful in delineating features that are mostly folds, faults and/or fractures (Fig. 2). Ant tracking and automatic fault extraction were used in order to help modelling the mapped features in 3D for better validation.

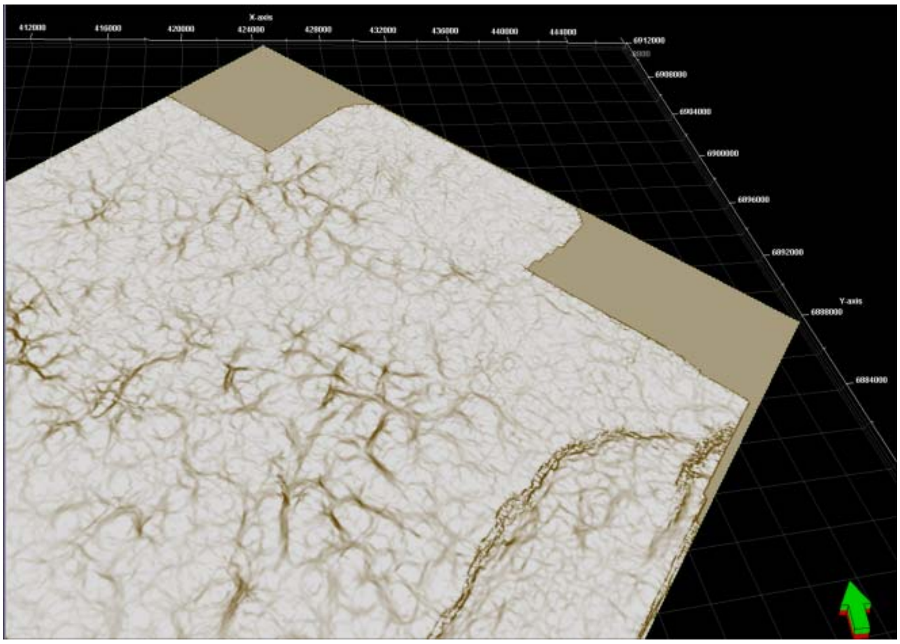

Figure 2: *Most positive curvature attribute of the Moomba-Big lake fields. Features represent faults, accompanying large fractures ,and anticlines.*

Curvature is defined as the reciprocal of the radius of a circle that is tangent to the given curve at a point (Chopra and Marfurt, 2007). An observed high value of curvature corresponds to a curved sufrace, whereas curvature will be zero for a straight line). The curvature attribute enables mapping of geological structures, such as folds or faults, which are characterized by high curvature (Backe et al., 2011; Abul Khair et al., 2012). MPC attribute delineates up-thrown fault blocks and crests of antiforms, whilst MNC attributes delineates the down-thrown faulted blocks of faults in addition to synclines (Chopra and Marfurt, 2007). In this study we used around 300 wells to calibrate the curvature results.

Image logs

A total of 7 wells containing image logs were analysed and compared with the curvature signatures. More than 70% of fractures interpreted using image logs were found to correspond to the seismic curvature attribute. By comparing the structures that appear on seismic, it was clear that whenever an anticline is present, the signature on the curvature will be reflecting the fold axis, and the fractures on image logs will mostly be perpendicular to the fold hinge with less percentage parallel to it (Fig. 3).

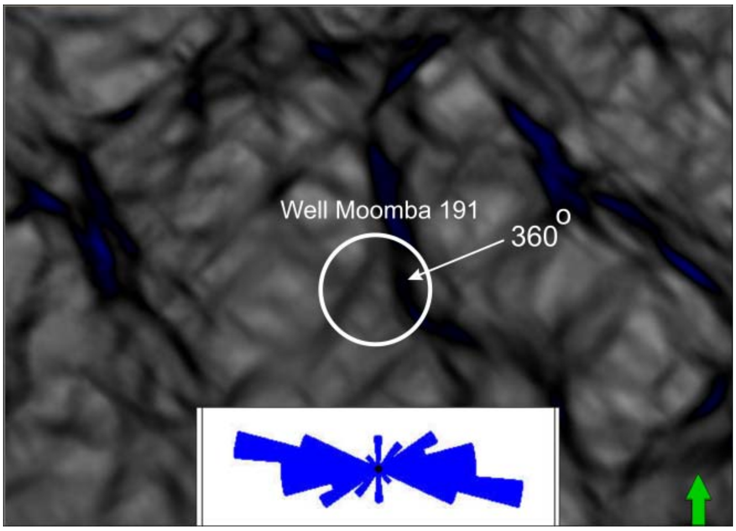

Figure 3: *Most positive curvature attribute at the depth of 8776 ft showing a main signature striking north-south, and a rose diagram of image log fractures showing east-west.*

During the formation of an anticline, the maximum horizontal stress (SHmax) is perpendicular to the fold axis, this will cause the rocks to fracture in the direction of SHmax if the rock reached failure conditions and if the deviatoric stress was relatively high. Due to the maximum bending at the hinge of the anticline, weakness of rocks will generate a new set of fractures parallel to the hinge and perpendicular to the old set. If we added to this scenario the existence of an old set of fractures that was generated due to an older tectonic event in a direction other than the event that caused the formation of the fold, then we will have a group of fractures as in figure 4. Thus, curvature attributes will map fractures caused by the formation of the current fold and faults, in addition to other tectonic events.

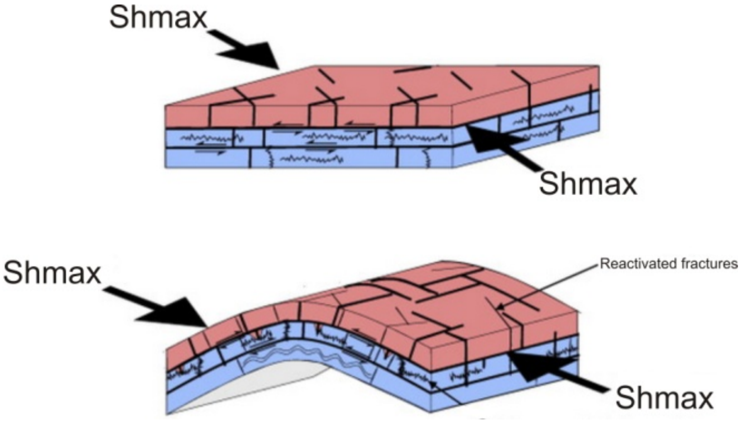

Figure 4: *Schematic figure showing the generation of different sets of fractures at different tectonic stages.*

Seismic amplitudes

By comparing the curvature signatures to the seismic structures, a high correlation was found with more than 70% of the curvature signatures presented in seismic as either anticlines or small faults with offsets 1 ms or more. A new seismic volume was generated using all the curvature signatures more than a cut-off value that doesn't map any structure. This value should be examined for every survey by comparing the curvature values to seismic structures before generating the new volume that represents only the available structures (Fig. 5)

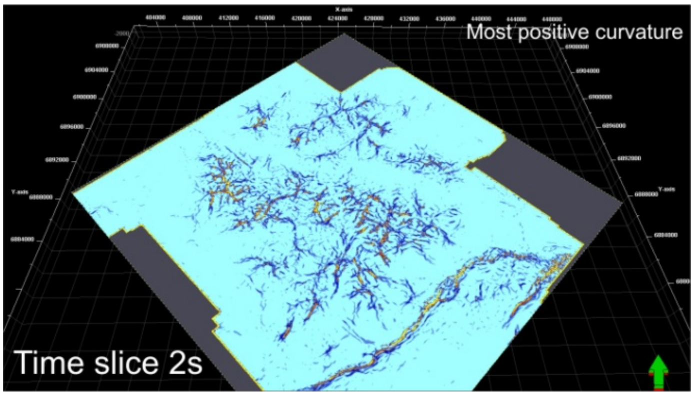

Figure 5: *Most positive curvature attribute calculated after eliminating the values less or equal to 0.2, which is the cut off for Moomba field.*

Well control

Considering the fact that any fault cutting a well will cause thickness change, isopach maps were generated and compared to seismic and curvature signatures.

A consistent relationship was found between the isopach anomalies and the seismic and curvature signatures. It was found that whenever an anomalie exists, a deep fault will be seen on seismic, although it may not cut target horizon, and a strong curvature signature will be obvious. This indicates that the fault is present, but because of the seismic resolution, faults with small offsets aren`t apparent, on the other hand, curvature will map it (Fig. 6).

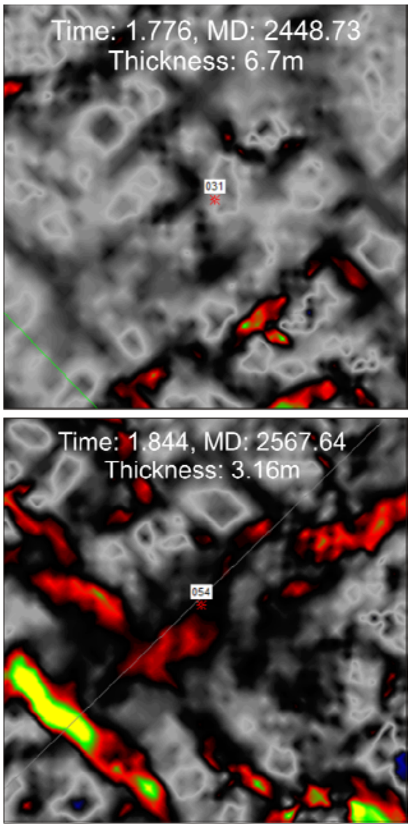

Figure 6: *Time slice showing weak MPC signature due to normal formation thickness (upper photo), and strong MPC signature due to thickness reduction (lower photo). Normal thickness is measured to be 7 m.*

Elastic Dislocation (ED)

Elastic dislocation theory (ED) predicts the distribution of strain and stress in the rocks surrounding major faults by using mapping of fault geometry and slip distribution in 3D data sets (Dee et al, 2007). ED is a BEM in which faults are represented as dislocations in an isotropic elastic medium (Crouch and Starfield, 1983). It addresses the effect of large faults displacements on the distribution of strain in the rocks surrounding them using the algorithms of Okada 1992, and software Traptester (Fig. 7).

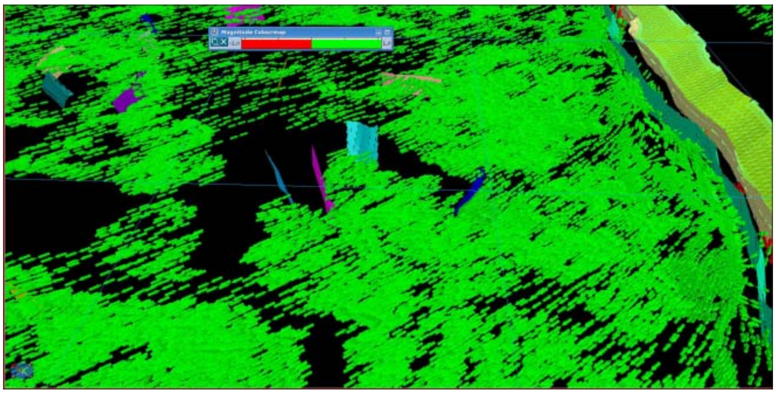

Figure 7: *Variation of maximum principle stress around Big Lake fault. Notice the major stress disruption close to the fault and the consistency away from the fault.*

Like other modelling techniques, ED doesn`t consider all factors that might influence fracture generation particularly variations in rock properties. Another point in ED is that considering an elastic rheology for the medium is valid for "infinitesimal" strains rather than finite strains (Ramsay, 1967). Also, experiments proved that better results can be achieved in reverse and normal faults stress regimes compared with strike-slip stress regimes as in Cooper Basin (Dee et al, 2007).

Comparing the predicted fractures from ED method with image logs fractures showed a clear correlation within the wells close to the major fault (Fig. 8). Whereas, wells away from the major fault didn`t succeed in predicting the fractures that can be seen in the image logs. This is clear as most of the fractures close to big faults are likely to be generated due to stresses exerted from the faults during major slip movements rather than other factors.

Other fracture trends seen in image logs (Fig. 8), which are not correlating with predicted fractures, emphasise the fact that generation of fractures is controlled by combination of factors rather than one specific methodology.

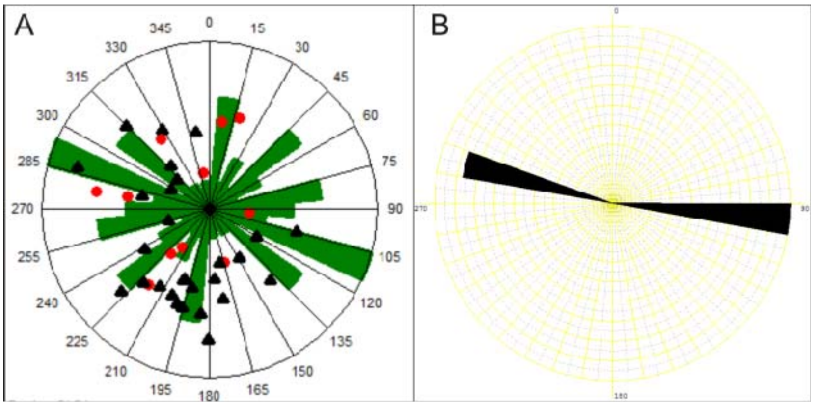

Figure 8: *Rose diagram of well Big Lake 54 showing A: fractures interpreted from image logs, B: fractures predicted from ED method.*

Finite element method

Using FEM for modelling the behaviour of complex geological structures such as folds, fractures, and faults is proved to be the most powerful tool for mimicking the tectonic history of sedimentary basins. We used software Dynel 3D for geomechanically restoring the interpreted horizons in the Moomba-Big Lake field in order to predict the fracture network generated during the major tectonic events.

The methodology allows the reconstruction of the current day structural and geometrical placement and the prediction of fractures generated due to stresses released during tectonic events. Input parameters include interpreted faults and horizons, rock elastic properties, fault displacements, and structural relationships (Maerten and Maerten, 2006). Lateral heterogeneity is not considered during restoration, although it affects transit of stresses and thus the generation of failure planes.

Predicted fractures succeeded in mapping sweet spots in Big Lake field, that are the main gas production spots in South Australia (Fig. 9). On the other hand, high variation of fracture trends in predicted sets, compared with low control points, made it hard to validate all the results, although the current predicted fractures are correlating well with the image log fractures.

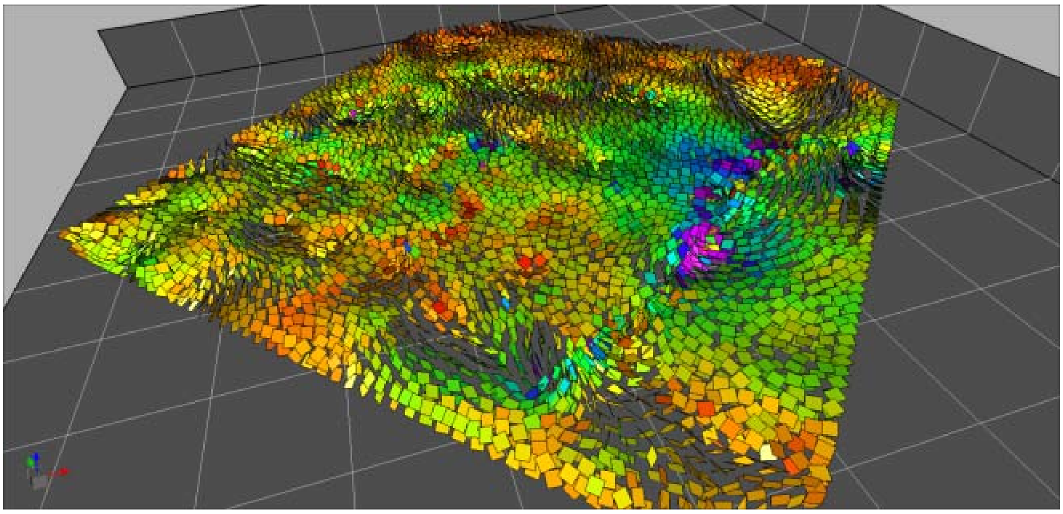

Figure 9: *Predicted fractures using geomechanical restoration showing sweet sots (purple colours).*

Summary

We have compared several methods for mapping and predicting fracture networks and validated them using 3D seismic an dense well control in the Moomba-Big Lake field. MPC attributes can be used for mapping fractures, but after relating their signatures to folds and faults for better understanding the trends. If folds exist, then the attribute signature will be mapping the fold axis and fractures are expected to be parallel or perpendicular to the fold axis. However, if the curvature signature is mapping a fault, then the fractures are most likely to be parallel or in the direction of the mapped curvature signature as they might be fractures in the damage zone of the fault.

ED can be used for predicting most of the fractures generated close to major faults. Caution must be taken while applying this method away from major faults, as fractures mostly will be generated due to other controllers in these areas. FEM can be used for predicting fracture networks generated during tectonic events. The method succeeded in locating fractured sweet spots for potential production in the Big Lake field. The method was found to be very sensitive to any change in the input parameters, so caution needs to be taken during the process. No single method succeeded completely in mapping or predicting fractures taking into consideration all the affecting factors.

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