3D analysis of induced micro-seismic event records compared with geology and structure: Preliminary results of a Cooper Basin project

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Abstract

The concept of an EGS geothermal prospect is based on fracture network permeability enhanced by hydraulic stimulation. Characterisation of fracture/fault mechanisms and geometries are therefore an important part of prospect development.

In this study, building a prospect-scale 3D geology and structure model of the Cooper Basin geothermal field has assisted prospect exploration and evaluation, but even greater advantage will come from the ability to integrate (in the same workspace) information from induced seismic events records such as location, magnitude, timing, focal mechanism, and shear plane orientation.

Keywords: Induced seismicity, fracture/fault networks, clustering, focal mechanisms, 3D geology models.

Introduction

The Cooper Basin geothermal field is located near the common borders of Queensland and South Australia. Since geothermal exploration began in 2002, 4 wells have been drilled into the underlying granite, with final depths around 4300 metres. Of these, the designated injection well, Habanero-1 was hydraulically stimulated in 2003 and again in 2005. Both stimulations induced detectable micro-seismicity centred on TD of Habanero-1 (4421 m).

Detailed studies by Geodynamics, Geoscience Australia, and Q-Con (Baisch et al, 2006) concluded that the hydraulic stimulations successfully enhanced hydraulic permeability between the injection well (Habanero-1) and one of the production wells (Habanero-2). Compared with the earlier stimulations, those in 2005 extended the previous stimulated reservoir, as well as further enhancing permeability.

Beyond the goal of increased permeability, hydraulic stimulations also provide an opportunity to gather induced seismicity event records which enable studies on:

- Fracture / fault mechanism and geometry characterization, and
- likelihood of seismic risk to infrastructure from geothermal reservoir activities.

Joint R&D project outline

Since March 1st 2010, Intrepid Geophysics and Geodynamics have been engaged in a collaborative project with the following goals:

1. Develop a 3D micro-seismic time records viewer so that new knowledge about fault geometries and fault mechanisms can evolve and be integrated in the context of all available geology and geoscience observations.

2. Investigate clustering or condensing of the event records in a manner that is coherent with geological and geomechanical principals, with the aid of filtering capabilities.

3. Characterize focal mechanisms in a suitable viewing format, e.g., triangular state diagram.

4. Synthesize and integrate other disparate observations of the geothermal field in a 3D workspace, such as: tectonic stress, well fracture records, and rock velocity data. The aim here is to facilitate creation of workable 3D velocity models, and hence to improve the accuracy of locating the hypocenters of micro-seismic events.

Induced Seismicity Database

The primary database underpinning this project is the induced seismicity events records from the mid-September 2005 hydraulic re-stimulation of Habanero-1. Over a period of 13 days 22,500m^3 of water was injected into 4421 m. (For details of the injection flow rate and wellhead pressure, see Baisch et al., 2009.)

In April 2005 a continuous seismic monitoring system was installed at the Cooper Basin geothermal field, and this captured the events of the September 2005 re-stimulation. The seismic station network includes instruments at depths varying from surface, to shallow depths (80-370m) and one deep station at 1780m. (See Baisch 2009 for details.)

During the mid-September 2005 injection of Habanero-1, approximately 16,000 detectable seismic events were recorded. From this total, Q-Con determined absolute hypocentre locations for 8886 events, that is, events for which at least five P-phase and three S-phase onsets could be identified (Baisch et al. 2009).

The data processed by Q-con (containing hypocenter locations, magnitudes and focal mechanism data for 8886 micro-seismic events) was selected for use in the joint R&D project, ahead of an alternative dataset available from a Japanese processing team.

3D model of the Copper Basin geothermal field

A preliminary 3D geology model of the Cooper Basin geothermal field site has been constructed in [1]3D GeoModeller software (e.g., see Calcagno et al, 2008) using formation tops data from the three Habanero wells, and McLeod-1 drilled in 1983 on a site approximately 440 m east-north-east of Habanero-1 (Table 1).

Wells names	Latitude	Longitude	Depths (m)	Dip	Date
Habanero 1	27°48'57.0''	140°45'15.9''	4420.82	90°	14/10/03
Habanero 2	27°49'9.7''	140°45'4.9''	4357.73	90°	31/03/05
Habanero 3	27°48'43.3''	140°45'28.9''	4221.48	90°	05/02/08
McLeod 1	27°48'53.2''	140°45'31.3''	3806.34	-	08/10/83

Table 1. Location and description of the Habanero-1, -2, -3, and McLeod-1 wells.

The geological model was also constrained by formation tops data derived from interpreted conventional seismic lines.

The preliminary geological model has extents of 10 x 10 x 6.5 km, and incorporates the stratigraphic successions of the Cooper and overlying Eromanga Basin (Fig 1). The mainly Triassic-aged basin fill, has an average bedding angle around horizontal, and top of the granitic bedrock lies between 3500 and 4200 m (Fig 2).

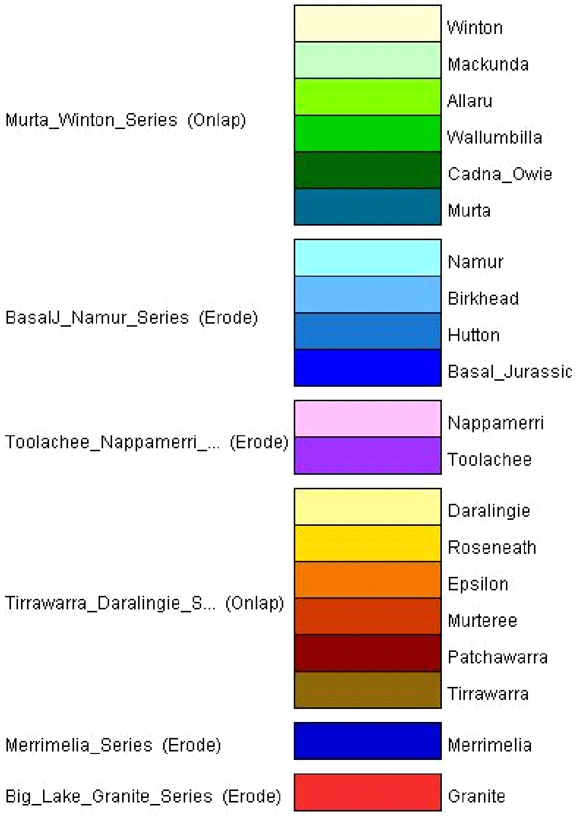

Figure 1. Stratigraphic pile for the Cooper and Eromanga Basins, within the geothermal field (excluding Cainozoic Eyre Fm), as used in the geology model shown in Figure 2, below.

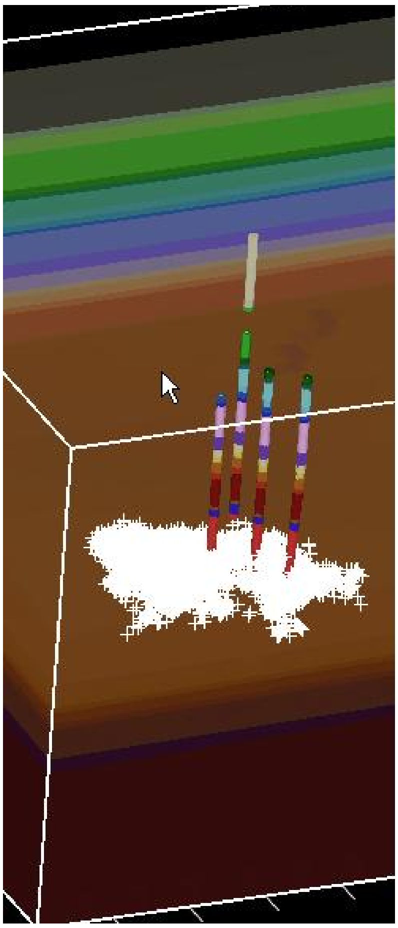

Figure 2.

Preliminary geological model for the Cooper Basin geothermal field (view to the northeast). Exaggerated drill hole intersects are highlighted for Habanero-1, -2 and -3, and for McLeod-1 (at the rear). Hypocentre locations estimated by Q-Con for 8886 micro-seismic events induced during the September 2005 hydraulic simulation of Habanero-1 are shown by the cloud of white symbols.

Interpreted basement fault characterization

As viewed in Figure 2, the hypocentre locations estimated by Q-Con for 8886 micro-seismic events induced during the September 2005 hydraulic simulation of Habanero-1 are localised in a zone approximately 3200 m x 1800 m horizontally (long-axis oriented NNE) and within 600 m vertically, centred on TD of Habanero-1 (4421 m).

Analysis of these event locations by Q-Con suggests induced seismicity aligns along a single, reactivated sub-horizontal fracture system (Baisch et al, 2009; Rothert & Baisch, 2010). Indeed, a best-fit plane to the seismic cloud supports this interpretation.

Pre-existence of this sub-horizontal fracture and it's primary tectonic origin, is evidenced by logging data acquired before any reservoir tests began (D. Wyborn unpublished data, in: Baisch et al, 2009).

Viewing focal mechanism information

Goal number 3 of the joint R&D project being undertaken by Geodynamics and Intrepid Geophysics is the ability to visualize focal mechanism information about faults at the hypocentres of induced seismicity. Plots created on-the-fly from a whole or filtered database are required in order to differentiate discrete faults / fractures activated during hydraulic stimulation, and to determine their stress state, orientation, and slip direction, etc. This requires a pre-processed dataset to be loaded, and demands sophisticated plotting and visualization options.

Plotting of triangular state diagrams is likely to be implemented. These will allow groups of seismic events representing similar focal mechanisms, to be identified, and conclusions about the presence of single or multiple structures to be made. For each diagram, the 3 poles will represent an end-member sense of movement on a fault: normal, thrust, or strike-slip. Two complete triangular state diagrams are required: one each containing dextral strike-slip and sinistral strike-slip sense.

Fracture orientations in the Cooper Basin geothermal field

As above, focal mechanism information for 8886 micro-seismic events recorded during the September 2005 stimulation of Habanero-1 was processed by Q-con, and provided for this R&D project by Geodynamics. From this information, we imported the fracture orientations of all seismic events, noting (on a first-pass) the existence of two distinct populations of fracture orientations:

a) 96% of fractures orientations are similarly oriented, with a mean dip of 9° towards 247° (pale blue discs in Fig 3)

b) 3% of fractures orientations are similarly oriented with a mean dip of 20° towards 164° (red discs in Fig 3)

c) 1% of fracture orientations are not defined as belonging to any population.

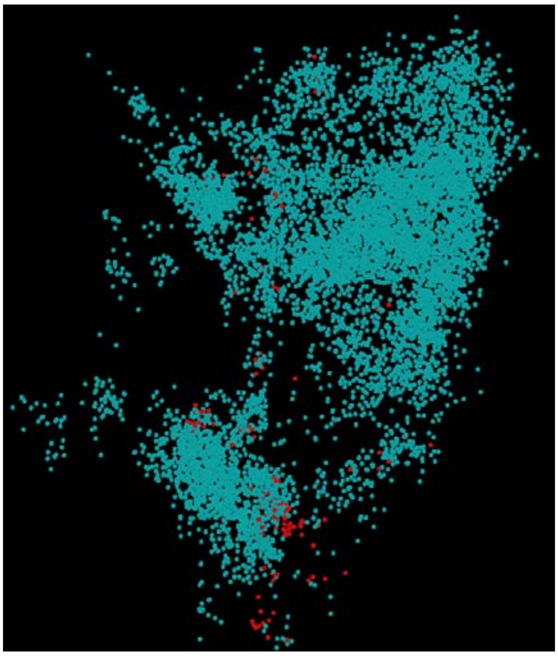

Figure 3. Visualisation in 3D GeoModeller of fracture orientations of the seismic cloud captured during the 2005 hydraulic stimulation of Habanero-1. One dominant and one minor population constitute the dataset. (See text.)

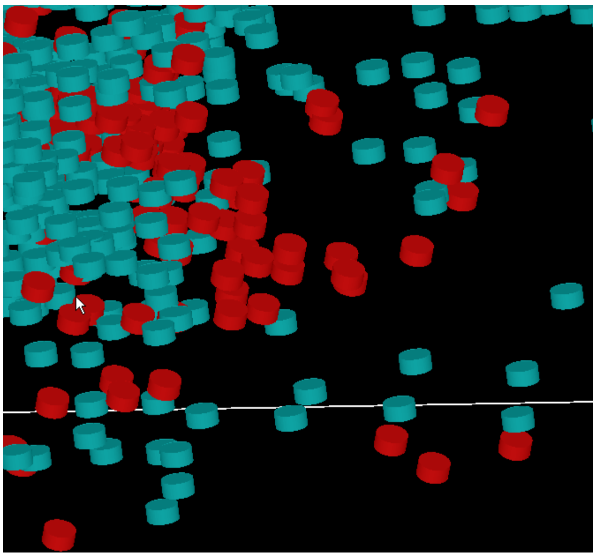

Figure 4 Enlargement of part of the seismic cloud from Fig 3, to highlight the variations in orientations.

Compared with the simple analysis visualised in Figs 3 and 4, the ability to further filter and sort the fracture orientation dataset is required, so that individual faults and fault-families can be tagged, assisting the interpreter to trial scenarios of possible fault network interpretations – while working with superimposed representations of prior knowledge of geology and structure, and other independent data.

Micro-seismic event magnitude

Additionally, for the Cooper Basin geothermal field we have facilitated visualization of variable magnitudes of micro-seismic event records from the 2005 stimulation of Habanero-1 (Fig 5). Again these data were made available through the processed dataset of Q-con which includes focal mechanism information.

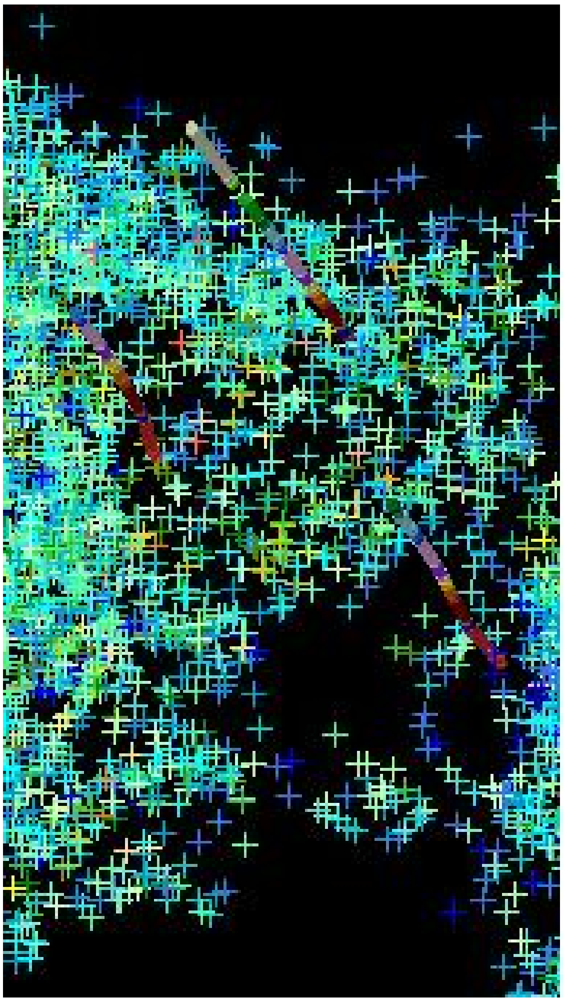

Figure 5. Oblique view to the northeast, through hypocentre locations for micro-seismic events of the 2005 stimulation of Habanero-1, including enlarged well traces for Habanero-1 (lower), Habanero-3 (middle) and McLeod-1 (upper). The variations of event magnitude range from +2.9 to -1.0 (Moment Magnitude Scale), with highest magnitudes in red, mid-scale in yellow, and lowest in blue.

Concluding Note

Beyond customised objectives and early access to the project results for Geodynamics Ltd, a key objective of this joint R&D project is to develop a micro-seismic time records viewer capability in [1]3D GeoModeller. As described above, the viewer will also have the ability to filter and sort records based on attributes such as timing, magnitude and focal mechanism.

These improvements will give reservoir engineers a tool to directly interpret the micro-seismic event record against the background of the prior geological and geoscientific knowledge. In turn, improved knowledge on fault / fracture locations, orientations and connectivity will lead to a better understanding of the overall behaviour of a reservoir in terms of mechanics, and also hydraulics.

Acknowledgements

[1]3D GeoModeller is a commercial software developed by BRGM and Intrepid Geophysics.

References

Baisch S, Vörös R, Weidler R And Wyborn D (2009). Investigation of fault mechanisms during geothermal reservoir stimulation experiments in the cooper basin, Australia, Bulletin of the Seismological Society of America, 99, 148-158

Baisch, S.; Weidler, R; Voros, R; Wyborn, D. And de Graaf, L. (2006). Induced seismicity during the stimulation of a geothermal HFR reservoir in the Cooper Basin, Australia. Bulletin of the Seismological Society of America, 96, 2242-2256

Calcagno, P., Chiles J., Courrioux, G. and Guillen, A. (2008) Geological modelling from field data and geological knowledge. Phys. Earth Planet. Interiors, doi: 10.1016 / j.pepi.2008.06.013

Rothert E And Baisch S (2010). Passive seismic monitoring: Mapping enhanced permeability, Proceeding world geothermal congress 2010.