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Olympic Dam EGS Project

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1. INTRODUCTION

This paper presents results from down-hole hydraulic fracturing and laboratory core testing completed for a geothermal energy prospect located in South Australia. The paper describes a process that determined detailed in-situ stress conditions within a slim-hole drilled to almost 2,000m depth into prospective hot granite. Determination of the stress conditions was undertaken as a low cost and low risk way to assess the prospect of successfully fracture stimulating the hot granite at relatively shallow depths. These measurements are the first step before proceeding with the more costly and higher risk steps of drilling and fracture stimulation in much deeper and hotter production wells in the granite.

In September 2005 a geothermal exploration drillhole was completed near the Olympic Dam Copper-Uranium mine to a depth of 1,935m. Blanche 1 was drilled to test the geothermal prospectivity of a location 8kms south west of the mining operation (Figure 1). The area was prospective for granitic rocks with anomalous heat flow and was considered to have potential to support an Enhanced Geothermal System (EGS) electrical power generation project. The main considerations for the drilling were to find a location with high thermal gradients within cover and basement rocks, a thermally insulating cover, granitic rocks with appropriate geotechnical properties amenable to fracture stimulation and proximity to market. The area lies within a broad zone of elevated heat flow referred to as the South Australian Heat Flow Anomaly (SAHFA). Surface heat flows as high as 125mW/m^2 have been measured in the area (Houseman *et al.* 1989) with 94mW/m^2 determined in Blanche 1.

Blanche 1 was drilled near the boundary between Geothermal Exploration Licence (GEL) 128 and the BHP Billiton Limited Olympic Dam Special Mining Lease (SML). The location is 5kms from existing 275kV and 132kV power lines, and 13kms from the town of Roxby Downs (Figure 2).

2. REGIONAL GEOLOGY & GEOPHYSICS

The drill site is located in an area of low gravity near the western edge of the Roxby Downs Granite, which also hosts the Copper-Uranium ore deposit and forms part of the extensive Burgoyne Batholith, one of the 1590 Ma Hiltaba Suite granites in South Australia. The Batholith contains a suite of moderately magnetic, radiogenic granitoids that form part of a geological domain referred to as the Olympic Domain of the Gawler Craton. Olympic Dam is the World's largest Uranium deposit and is considered to be one of the largest copper deposits.

The granites are generally Mesoproterozoic in age and are considered to be the source of the anomalous heat flows. The granites near Blanche 1 are I-type and were further classified as transitional between calc-alkaline and alkaline.

Overlying the Burgoyne Batholith are platform sedimentary rocks of the Stuart Shelf. Notably these contain thick sequences of thermally insulating shales; Yarloo Shale, Tregolana Shale and Tapley Hill Formation. The Tregolana Shale is the most significant insulating cover sequence and can reach a thickness of 250m. The remaining cover sequence comprises sandstones and limestones.

Figure 1: Location of the Olympic Dam Geothermal Project Relative to the National Electricity Grid Transmission Lines

3. LOCAL GEOLOGY & MINERALOGY

Blanche 1 drilled though 1,216 metres of granite in a location where 2D seismic shows it is 6km thick. Several zones of elevated radioactivity within the granite indicate the presence of radioactive minerals, notably uranium and thorium. With the exception of the deepest of these zones (1,716 – 1,717.5 m.), they correspond to the location of thin microgranite dykes. Maximum levels of uranium and thorium were 72 and 138ppm respectively.

Core samples from several depths within the granite were sheared and fractured, massive monzogranite transitional to syenogranite with accessory primary zircon and moderate to locally advanced alteration. Sericite was altered from plagioclase and chlorite and various minerals were altered from titanite. Biotite was rare and altered to sericite. The potassium feldspar orthoclase had red earthy hematite staining.

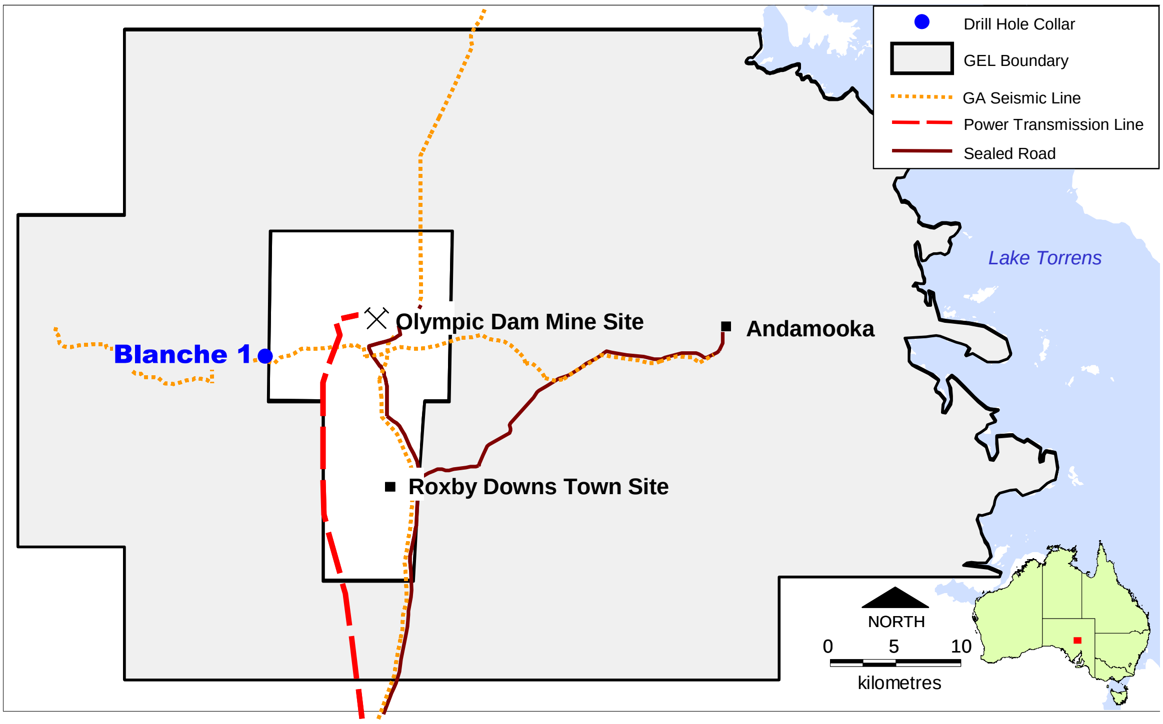

Figure 2: Location of Geothermal Exploration Licenses

Above 1,034m depth there were several zones within the granite containing structures. Below this depth the dominant structural feature seen in the core was discing. This consisted of the core breaking into flat, concave downward or saddle-shaped discs that were generally sub-perpendicular to the core axis. Discing is the result of unloading of the compressive load on a section of core caused or abetted by release of the mass of overlying rock as a result of the coring operation. The in-situ stresses were evaluated using a novel statistical-mechanical analysis of the distribution of discs lengths. The results, which give an estimate of the maximum horizontal stress that is in good agreement with the values reported in this paper, are given in Bunger (2009). Only high angle structures were recognised in zones where there were significant amounts of discing as the discing obscured any low angle structures. The combination of high angle structures and discing resulted in zones of very broken core.

Core samples from 1,059 and 1,142m depth had minor micro fractures at both high angle and low angle to the core axis. These were filled with extremely fine carbonate, quartz, sericite and iron-chlorite. Core samples taken at various depths from 1,184 to 1,659m had open, non-sealed fractures, probably representing early stage of discing.

4. GEOMECHANICAL TESTING

Several stages and levels of geomechanical and hydraulic fracture testing have been completed within the granite sequence at Blanche 1. Initial geomechanical testing included seven core samples from the cover as well as the granite. These were tested to determine Unconfined Compressive Strength (UCS) as well as elastic properties, Poisson's Ratio and Young's Modulus. UCS strengths in the granite progressively increased with depth and ranged from 83MPa at 719m depth to 210MPa at 1,922m depth. The tests caused breakage of the core by the multiple cracking failure mode.

Rock densities were measured on nineteen core samples. Densities within the granite ranged from 2.59 to 2.72 and averaged 2.65g/cm^3.

5. STRESS ANALYSIS

In situ stresses were estimated by the CSIRO Exploration and Mining Division using break-out analyses derived from the acoustic televiewer logs (Shen and Rinne 2007). Several runs of the log resulted in several estimates of stress parameters. The initial run covered the granite sequence to a depth of 1,400m only. The key results obtained from this study were:

- Maximum and minimum principal horizontal stresses (σ_{Hmax} and σ_{hmin}) were both higher than the vertical stress.
- Maximum horizontal stress was in an east-west direction and the ratio of σ_{Hmax} / σ_{hmin} / σ_v was (2.5-2.75) / (1.25-1.5) / 1.0.
- Reverse thrust faulting conditions were expected in the granite. These conclusions were consistent with the surrounding regional stress regime. Current active faults are therefore likely to be sub-horizontal and tension joints are likely to be horizontal.

A second and third run was completed to the full depth of the hole before and after a program of in situ hydraulic fracture testing

6. HYDRAULIC FRACTURE STRESS TESTING

Hydraulic fracture (hydrofrac) testing was completed in the open section of the granite rocks using a small trailer mounted winch and wireline packer system supplied and operated by MeSy GmbH (Figures 3 and 4) (Klee and Rummel 2008 and Klee *et al.* 2008). The objective of the testing was to derive reliable data on the magnitude and orientation of the in situ stress regime. The open hole section of Blanche 1 had a diameter of only 76mm.

During March 2008 a total of 12 hydraulic fracture stress measurement tests were carried out between depths of 881 and 1,739m using a 71mm diameter inflatable straddle packer system. The system was capable of operating at temperatures up to 100°C and maximum operating pressures up to 60MPa.

Figure 3: Hydrofrac Equipment MeSy MKW-2000 set up at Blanche 1

The maximum differential pressure that could be applied to the hole wall was 40MPa and the maximum water injection rate was 12L/min. The water was injected using 10mm diameter coiled tubing. The test interval between the packers was 0.7m (Figure 5).

Figure 4: Hydrofrac Equipment MeSy MKW-2000. The straddle packer tool is shown being prepared for running into Blanche 1

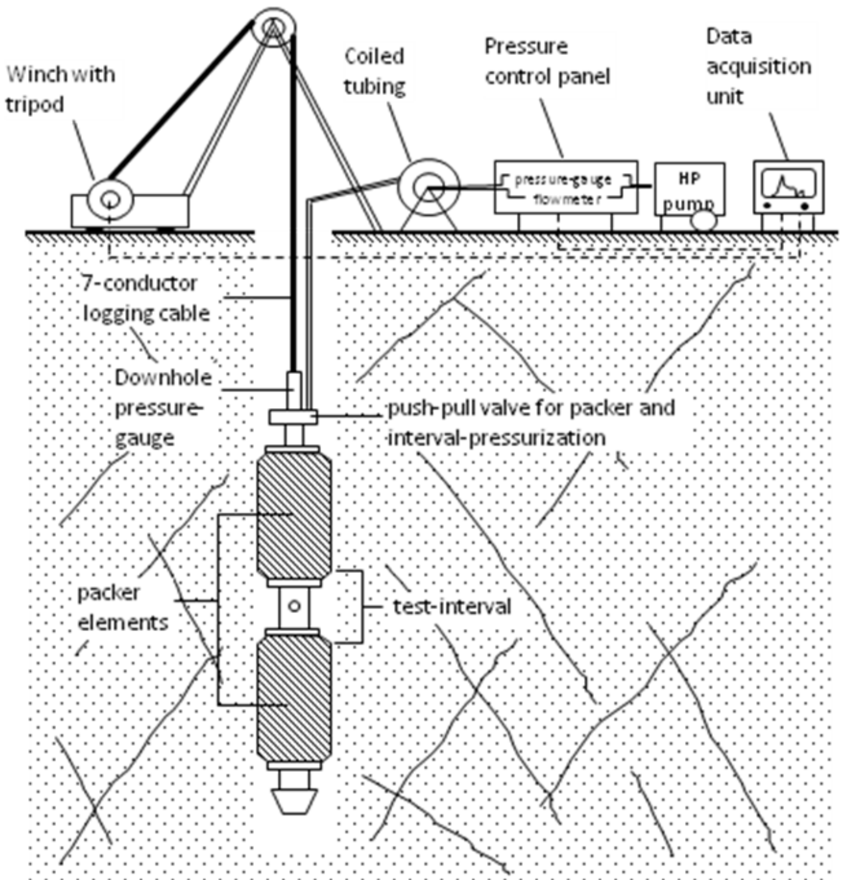

Figure 5: Down-hole Duel Packer System PERFRAC II

The depths for each test were determined from an initial acoustic televiewer log run. Several fractures were mapped as shown on Figure 6 but in most cases the hydraulic fractures were east-west striking; steeply dipping or sub-horizontal. The injections were designed to form new fractures or to reopened existing natural fractures.. Therefore, for the new fractures, zones were selected from the televiewer images that contained no visible natural fractures while for the measurements designed to open pre-existing natural fractures, zones were selected with vertical natural fractures oriented more or less in the hydraulic fracture (maximum stress) direction. Reopening followed by measurement of the fracture closure pressure on natural fractures with several orientations is used in the Psi method to determine the normal stress acting across these fractures. Provided data for 5 or more fractures can be obtained, the data can be inverted to determine the principal stresses (Cornet 1986, Baumgärtner and Rummel 1989).

Each test consisted of the following injection cycles after the packers were set in place and inflated to about 10-15MPa above hydrostatic pressure to seal the test interval:

- Pulse hydraulic permeability index test of about 3 to 5MPa and pressure decline measured over 5mins.
- Inject and measurement of the critical breakdown pressure (Pc) at fracture initiation.
- Shut-in and then flowback test interval.
- Measurement of the shut-in pressure (Psi). The upper limit of Psi was determined by plotting pressure against hydraulic flow to determine the exact pressure value at which the hydraulic flow terminated. The lower limit was determined using a Muskat-type plot.
- Step flow test after fracturing (permeability test).
- Fracture orientation from a final run of the acoustic televiewer log.

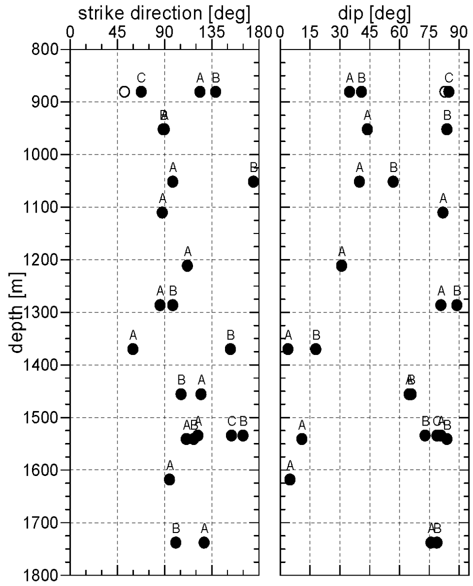

Figure 6: Orientation of Tested Fractures (Open symbol from impression test, solid symbols from televiewer log analyses. A, B & C represent different fractures)

The breakdown (P_c), re-opening (P_r) and shut-in pressures (P_{si}) were measured from the test and plotted graphically (Figure 7).

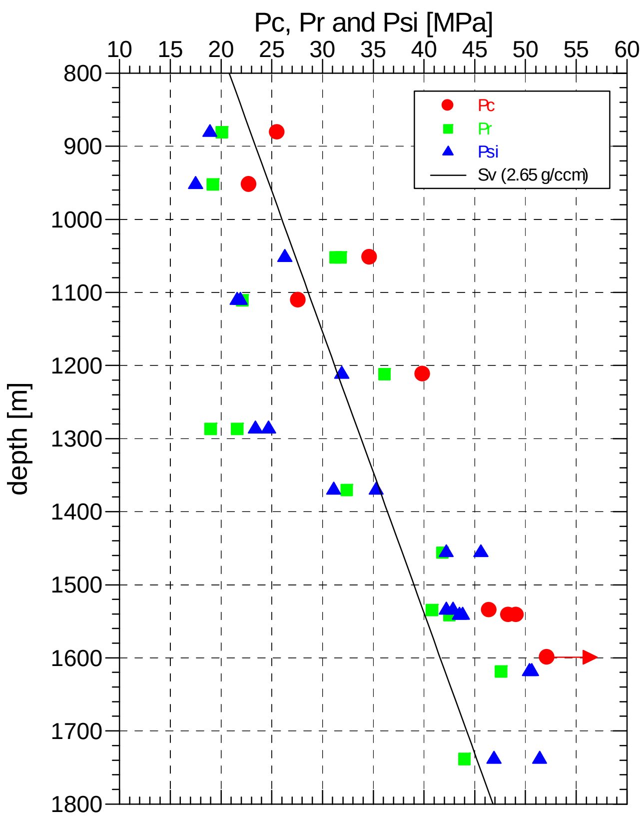

Figure 7: Breakdown (Pc), Re-opening (Pr) and Shut-in (Psi) Pressures

The in situ tests demonstrated frac cycles with breakdown pressures ranging from 23 to 52MPa and subsequent rapid pressure drop during frac growth.

The in situ tensile strength of the granite was calculated as $P_{co} = P_c - P_r$. Values ranged from 2.85 to 6.2MPa and the mean was 4.8±1.2MPa, typical for crystalline rocks.

7. STRESS ESTIMATION

Stress magnitudes and orientations were calculated by MeSy GmbH using both the "classical" Hubbert and Willis (1957) method and the Psi method. Both analyses methods yielded similar results. The Psi method results are plotted on Figure 8.

Using the Psi method, the direction of the maximum horizontal stress S_{Hmax} was determined as 97°±3°. The magnitude of S_{Hmax} and S_{hmin} vary with depth according to the following inversion equations:

$$S_{hmin}\,[\text{MPa}] = (12.4 \pm 1.2) + (0.038 \pm 0.003) * (z[\text{m}]-880)$$

$$S_{Hmax}\,[\text{MPa}] = (35.8 \pm 2.8) + (0.060 \pm 0.010) * (z[\text{m}]-880)$$

These inversions were valid for a depth (z) interval between 880 and 1,740m. Above approximately 1740m the minimum principal stress was horizontal, resulting in vertical hydraulic fractures. Below this depth the trends are expected to continue, owing to the fact that seismic surveys show that the granite fabric continues unchanged down to 6km. This stress trend needs to be verified by deeper stress measurements in any wells drilled to access deeper heat reservoirs. Horizontal stresses ranged from 15 to 45MPa for the minor and 35 to 90MPa for the major horizontal principal stress. Results confirm a reverse thrust stress regime prevails at Blanche 1. Current active faults are expected to strike at an orientation perpendicular to S_{Hmax} and to dip at a critical angle to the horizontal. Open tensional joints are expected to lie on a horizontal plane.

8. LABORATORY TESTING

Further laboratory analyses were completed by MeSy GmbH as a supplement to the hydrofrac tests performed on Blanche 1 (Weber 2008). The results from the laboratory tests can be summarised as follows:

Density, g/cm3	2.64±0.028
Velocities, km/sec	5.00±0.56 (P-wave) and 2.91±0.33 (S-wave)
Young's modulus, GPa	56±11 (dynamic)
Poisson's ratio	0.24±0.01 (dynamic)

Fracture toughness, MN/m3/2 2.21±0.68 (4 valid tests)

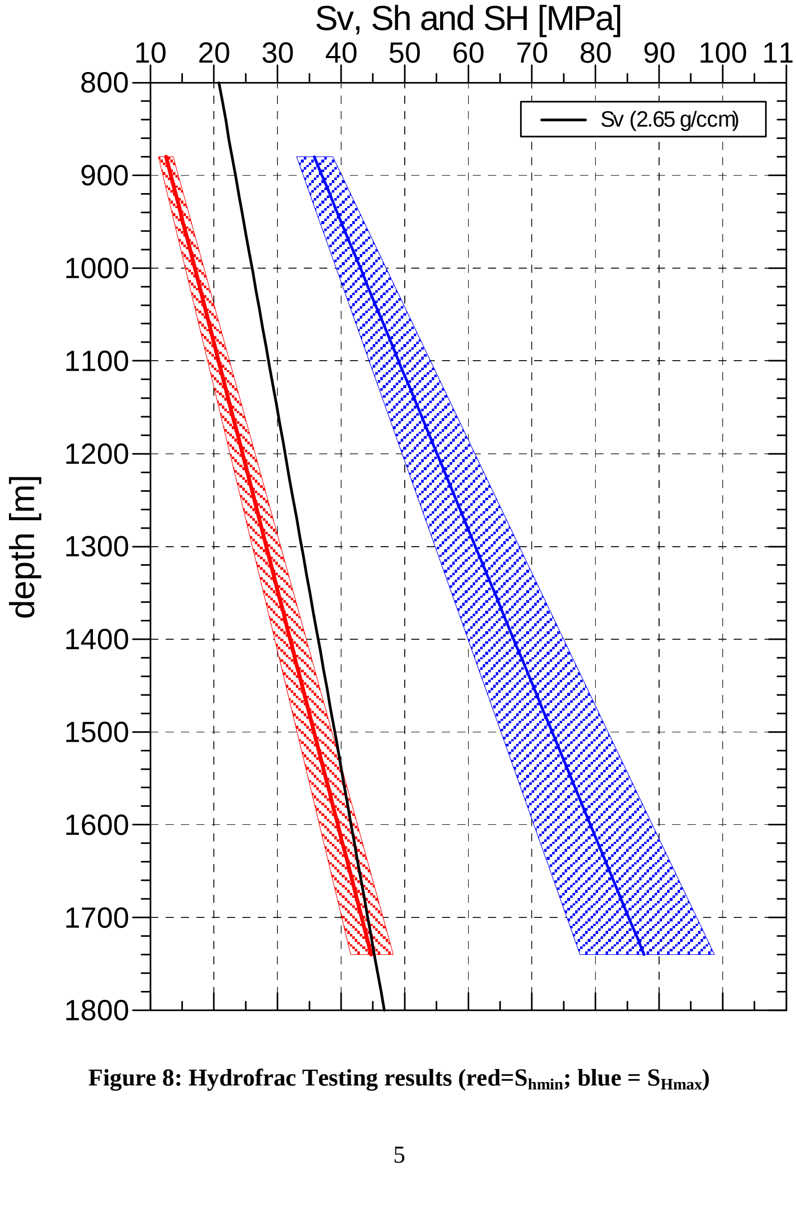

Figure 8: Hydrofrac Testing results (red=S_{hmin}; blue = S_{Hmax})

Fourteen samples were tested using a laboratory mini-hydrofrac apparatus. Samples were subjected to increasing internal pressure while under a confining pressure kept lower than the applied internal pressure. One group of samples yielded low hydraulic tensile strengths of about 2.75MPa and another were about 25MPa. The very low values suggested the existence of microcracks of a length of some millimetres probably originating from the core drilling and subsequent distressing during storage. The high sample hydraulic tensile strength (p_{co}) of 25MPa compares with the in-situ hydraulic strength (P_{co}) of 4.8±1.2MPa using the fracture mechanics relation $p_{co} = P_{co}(R/r)^{1/2}$ of Rummel (1987) that accounts for the difference in the hole sizes. In the equation R is the radius of the hole at Blanche 1 (38mm) and r is the radius of the fluid injection hole drilled into each core sample (1.5mm).

The laboratory and the in-situ hydrofrac tests suggest an intrinsic initial crack length into the wall of Blanche 1 of about 35mm.

9. CONCLUSIONS

In September 2005 a geothermal exploration drill hole was completed near the Olympic Dam Copper-Uranium mine to a depth of 1,935m. Blanche 1 intersected 1,218m of massive granite with an average inferred heat flow of 94.3±4.1mW/m^2. The granite is known as the Roxby Downs Granite and forms part of the widespread Burgoyne Batholith. Evaluation of Blanche 1 found an average temperature gradient of around 60°C/km in the cover sediments and 30°C/km in the granite. The average thermal conductivity in the granite was 3.20±0.16W/mK and the average heat generation was 8.7µW/m^3.

The granite was intersected in Blanche 1 from 718m depth. Twelve in-situ hydrofrac tests were completed in open hole at various depths between 818m and 1,739m using a wireline straddle packer system supplied and operated by MeSy GmbH. The depth of each test was determined by the location of pre-existing fractures mapped using an acoustic televiewer. Critical breakdown pressure in the granite increased with depth and was between 23 and 52MPa. Natural fractures or flaws were opened up to an estimated depth of 35mm which provides a consistent explanation for the breakdown pressures measured. The majority of the initiated or stimulated fractures were east-west striking, steeply dipping or sub-horizontal.

Within the tested interval, horizontal stresses ranged from 15 to 45MPa for the minor and 35 to 90MPa for the major horizontal principal stress. Both in situ testing and core analyses concluded an in situ tensile strength for the granite of about 5MPa.

The in situ hydrofrac testing, interpretation of acoustic televiewer logs and laboratory testing of core samples have all concluded the Blanche 1 site, at depths below approximately 1,700m, is in a reverse thrust faulting stress regime. Below 1,700m the minimum principal stress is vertical, which would result in horizontal hydraulic fracture orientation. The maximum horizontal stress is orientated east-west which means current active thrust faults are likely to strike north-south and to dip at a critical angle to the horizontal. Opening mode or tensional joints are expected to lie on a horizontal plane. Joints opening along a horizontal plane during reservoir stimulation are favoured for a deep Enhanced Geothermal System project and allow wells to be spaced more evenly and widely spaced, reducing drilling costs accordingly.

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