Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Development of Australia's First Hot Fractured Rock (HFR) Underground Heat Exchanger, Cooper Basin, South Australia

Doone Wyborn, Lambertus de Graaf, Stephen Davidson, and Simon Hann

PO Box 2046 Milton, Queensland, 4064, Australia

dwyborn@geodynamics.com.au

Keywords: hot dry rock, hot fractured rock, microseismic monitoring, granite, underground heat exchanger, overpressure.

ABSTRACT

Geodynamics Limited has successfully completed the first half of its "Proof of Concept" hot fractured rock (HFR) program to extract hot water for electricity generation from granite buried beneath the Cooper Basin in NE South Australia. Difficult drilling conditions were discovered in the target granite when the Habanero-1 well penetrated permeable sub-horizontal fractures at more than 4,000m depth. The well was completed at 4,421m. The static rock temperature at the bottom of the well is 250°C.

The overpressures (>5,000 psi) assisted in the development of the world's largest zone of artificially enhanced permeability, a volume of rock more than 0.7 km^3 defined by more than 11,700 microseismic events during the injection of 20Ml of fresh water into the granite fracture network. The horizontal heat exchanger is more than 2km NS, 1km EW and 300m thick. During its development it showed no evidence of upwards growth towards the sedimentary cover at around 3,700m.

The development so far indicates that there is a very good potential for economic energy extraction in the future. This potential has been considerably enhanced by the discovery of the overpressures in the granite fracture network which could add a large convective heat component into the original design which was based purely on conductive heat transfer within the heat exchanger volume.

1. INTRODUCTION

Geodynamics Limited, a publicly list company on the Australian Stock Exchange, obtained the right to explore for geothermal resources over an area of approximately 1000 km^2 in the vicinity of Innamincka in northern South Australia in October 2001 (figure 1). The company's "Proof of Concept" development of an engineered underground heat exchanger for the production of high temperature fluid and electricity generation consists of:

- Drilling an injection well into high temperature granite beneath the sedimentary basin in the region known as the Cooper Basin
- Engineering an underground heat exchanger in the granite through the stimulation of natural fractures by high pressure fluid injection
- Drilling a production well to intersect the periphery of the heat exchanger
- Carrying out a circulation test to demonstrate the economics of heat extraction and electricity generation without the CO_2 production associated with the burning of fossil fuels

This paper outlines the results of the first half of the program, the drilling of the injection well and the development of the underground heat exchanger.

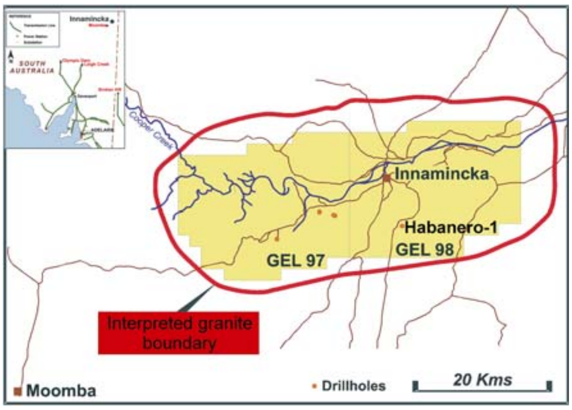


Figure 1. Location of the Geodynamics Limited Cooper Basin Geothermal Exploration Licenses and the first well Habanero-1. The interpreted outline of the granite buried around 4km beneath the surface is also shown.

2. CONCEPT OF HOT FRACTURED ROCK (HFR) GEOTHERMAL ENERGY EXTRACTION

HFR geothermal energy has been a renewable energy prize first recognised and developed by the Los Alamos National Laboratory in New Mexico in the 1970s. The concept was known as Hot Dry Rock (HDR), and it promised huge energy resource potential across the world (Armstead & Tester 1987), without the need to burn fossil fuels. Projects were developed, initially in New Mexico, followed by UK (Cornwall), Japan (Hijiori, Ogachi), France (Soultz), and more recently Switzerland (Basel), Germany (Bad Urach) and El Salvador (Berlin Field). Most projects were operated in granitic rocks known to have natural fracture systems. With the exception of the last three projects, which are still at their early stages, water was successfully circulated between two or more wells at inter-well spacings ranging up to 700m in the case of the Soultz project.

Much was learnt from the early projects including that natural joints or fractures in granite developed permanent fracture permeability enhancement when fluid was initially injected at high enough pressures to slip fracture planes and emit microseismic waves. This has been the basis of all projects where a stimulation phase of high pressure fluid injection is monitored by a network of microseismic sensors. The progressive flow of the fluid into the rock is determined by tracking the microseismic emissions. The resulting zone of enhanced permeability represents the underground heat exchanger. The amount of heat available for use is dependent on the spacing, number and extent of permeable fractures within the heat exchanger assuming the water is heated solely by conductive heat from the heat exchanger rock mass itself. In such a case of purely conductive heat extraction the term hot dry rock (HDR) might be applied, but where additional convective heat transfer is also likely then the term hot fractured rock (HFR) can be used. As a result of the growing understanding of the Cooper Basin system the project is referred to as a HFR geothermal project.

Another significant outcome of the early projects was to show that the shape of the heat exchanger is dependant on the orientation of the stress field within the rock mass. In all these projects the heat exchanger was flattened perpendicular to the minimum principal stress (S3). In most, if not all, volcanic areas of the world S3 is approximately horizontal. Without this condition the volcanic activity would not have been present in the first place. Thus in volcanic areas of the world, and in environments with strike-slip stress fields, the heat exchanger is oriented vertically, though this is tempered somewhat by the orientation of the natural fracture networks. Such a geometry is not ideal for development of large volume heat exchangers and interconnected multi-well systems, since growth in a vertical direction results in colder rocks closer to the surface being incorporated, and deeper rocks beyond drilling limits potentially being excluded from the flow paths. Essentially a vertical geometry makes it impossible to extract conductive heat from a horizontally extensive volume.

In many non-volcanic areas of the world, particularly in ancient cratonic areas devoid of volcanic activity, such as the Baltic and Canadian Shields and much of the basement parts of the Australian continent, S3 is vertical. Thus we have the dichotomy of, on the one hand, poorly oriented heat exchangers forming in volcanic areas where the rock temperature might be high, but, on the other hand, optimally oriented heat exchangers forming in non-volcanic areas where the rock temperature is likely to be low at reasonable drilling depths.

3. PRE-EXISTING GEOLOGICAL INFORMATION FOR THE COOPER BASIN

There is a wealth of geological information for the Cooper Basin area derived from over 4 decades of oil exploration including tens of thousands of kilometres of seismic traverses, and over 3,000 wells drilled. Almost all of these data are open file from the South Australian Department of Primary Industries and Resources. From this information the following has been established.

- The depth to basement in the deeper parts of the Cooper Basin, in the area known as the Nappamerri Trough, is approximately 3.5-4.5km.
- In the Nappamerri Trough, higher than normal geothermal gradients of 55-60°C/km had been measured.
- The Nappamerri Trough exhibited a gravity low that could not be explained by the additional thickness of sediments.
- A number of drillholes into basement in the Nappamerri Trough area had intersected granite.
- Modeling suggests that the granite underlies the whole of the gravity low of approximately 1,000 km^2. The modeled thickness of the granite is 10km (Meixner et al. 1999).
- Stress conditions in the Nappamerri Trough indicated an overthrust stress environment (i.e. S3 is vertical), in common with many basement areas of the Australian continent (Denham and Windsor 1991), but different to shallower parts of the Cooper Basin to the NW.
- Overpressures had been observed towards the base of the sedimentary sequence in deep wells in the Nappamerri Trough, but the permeability of the sedimentary units was too low for the true overpressures to be established.

As a result of these conditions, it had long been thought that this area could be suitable for HDR development. A paper explaining the state of understanding of the HDR process in 1985, and its practical application in the Cooper Basin was published by a well-respected mining engineer (Koch 1985). As far as is known there is no other location in the world with temperatures as high as the granite beneath the Nappamerri Trough, where the stress field is one of overthrusting, and where large horizontally extensive heat exchangers could be built.

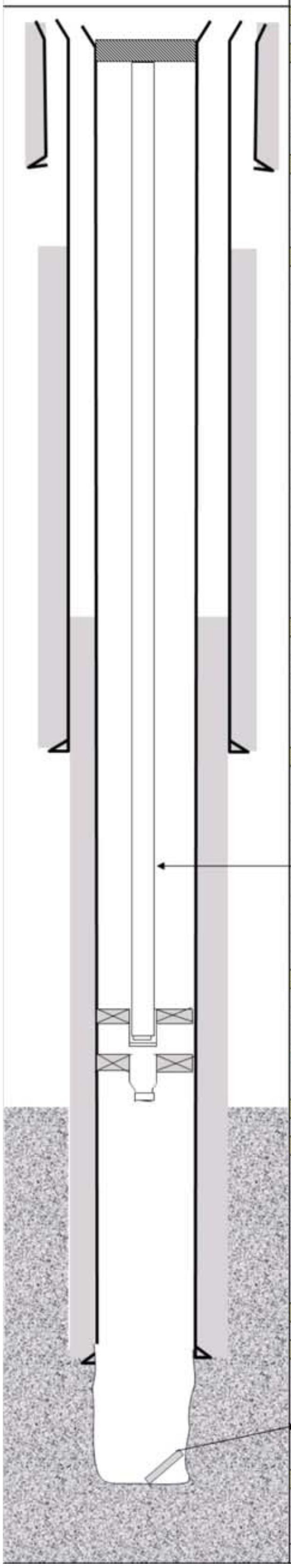
4. DRILLING OF HABANERO-1

Habanero-1 is located 10 km south of Innamincka and 450m WSW of the McLeod-1 well. McLeod-1 was drilled into granite basement at 3,747m depth in 1983, and a temperature of 230°C was recorded at 3,755m in May 1984. The location for Habanero-1 was chosen to be above the flood plain of the Cooper Creek, and adjacent to McLeod-1 so that it could be used for locating a deep seismic monitoring sensor. Evaluation of existing reflection seismic data had not indicated the presence of any major faults in the basement at this location.

The well was spudded at 8am on 15 February 2003 using Century Rig 27. The rig was released on 14 October at a total depth of 4,421m (figure 2). The main components of the well history are as follows:

Event	Day	Depth (m)
Spud 17 ½ inch hole	15 Feb.	0
Cement 13 3/8 inch casing	18 Feb.	284
Drilling ahead 12 ¼ inch hole	20 Feb.	284
Completed 12 ¼ inch section	10 March	2,257
Cement 9 5/8 inch casing	11 March	2,250
Drilling ahead 8 ½ inch hole	13 March	2,250
Reached granite basement	18 April	3,668
Completed 8 ½ inch section	29 April	4,150
Cement 7 inch casing	6 May	4,139
Drilling ahead with 6 inch hole	9 May	4,139
Rig placed on stand-by for pressure control equipment	19 May	4,209
Rig back in operation	2 July	4,209
Drilling completed at 4,421m	17 Sept.	4,421
Set 4½ inch tubing into casing packer at 3,091m	12 Oct.	4,421
Rig release	14 Oct.	4,421

Habanero #1 Well Completion Diagram



Description	Dev Deg	Depth m (TVD)	Minimum ID	Maximum OD
Rotary Table		Zero		
BPV in tubing				
13 3/8" casing 48# H40 BTC			12.56	14.37
13 3/8" casing cementation: Class A				
Lead: 142bbl, 13ppg. Tail: 80bbl, 15.6ppg.				
13 3/8" casing shoe		284		
Theoretical TOC- volumes		488		
7" casing 29# P110 BTC			6.18	7.66
9 5/8" casing 47# N80 BTC			8.68	10.63
TOC - Estimated from SBT Log		1463		
9 5/8" casing cementation: HTB cmt (Class G + 35% SSA-1 BWOC)				
Lead: 364bbl, 13ppg. Tail: 36bbl, 15.6ppg.				
9 5/8" casing shoe	1.0	2250		
4 1/2" Tubing 21.6# C95 NVAM				
X-O 29# P110 BTC to 32# P110 NVAM special drift		3031	6.03	7.68
Top of the second Packer to be set at around 3,091m				
Top of the first packer is at 3,109m				
7" casing 32# P110 NVAM 6" SD			6.03	7.68
Top granite		3668		
7" casing cementation: N2 foam cmt HTB (Class G + 35% SSA-1 BWOC)				
350bbl, 16.43ppg unfoamed, 14ppg uniform density foamed.				
7" casing shoe	0.5	4139		
Junk Left in Hole -1 1/2" x 3ft pipe				
6" hole - TD		4421		

Figure 2. Habanero-1 well completion diagram

Drilling of the granite section in 8 ½ inch hole to 4,150m was completed with four tri-cone inset (TCI) bits without incident and an average rate of penetration of 2.62 m/hour. A mudweight with a density of 1.75 (14.6 ppg) was maintained because of suspected overpressures across the uncased sedimentary formations above. At the end of the section the well began flowing (taking fluid from the formation), and the mud had to be weighted up to a density of 1.8 (15 ppg) before successful logging and setting of 7 inch casing.

The logging included a circumferential borehole imaging log (CBIL) and 4 arm caliper log from Baker Atlas. The CBIL log showed that a sub-horizontal fracture system had been penetrated at 4,134-4,135.5m.

The 7 inch production casing was successfully run and landed at 4,139m, and then cemented in a single stage using nitrogen foamed cementing technology for enhanced ductility and long term integrity at the shoe. Halliburton ™ Well-life™ simulations of the service conditions expected in the well predicted significant advantages of this approach over conventional high-temperature blend (HTB) technology. This job represents the second and largest application of this cementing technology in Australia.

With the gas-bearing sediments cased off, the drilling of the 6 inch hole section was thought to be a matter of reducing the mud weight and accepting shorter bit runs due to the temperature limitation of the 6 inch bits at the predicted circulating temperature. Smith tri-cone insert (TCI) bits dressed with high temperature copolymer blend (AFLAS) seals were selected in the absence of metal-to-metal bearing seal technology in 6 inch bits. The first bit run achieved 59m at an average penetration rate of 3.4 m/hour with a mud density of 1.4 (11.8 ppg).

After the first bit run the well was shut-in due to slight flow with a shut-in wellhead pressure of 600 psi. Losses of 425bbl in two hours with 11.8 ppg mud in hole occurred during circulation and weighting up operations which were cured with cellulose lost circulation material (LCM). After a second well flowing event and higher shut-in pressures the well was successfully killed with mud of density 1.9 (15.8 ppg). Although it was determined that the influx was water, there was also some dissolved gas, mostly CO_2. Following these events, the well was temporarily suspended with a bridge plug set at 3,971m and a cement plug above while a 10,000 psi blow out preventer was mobilised from Singapore. The natural joints in the granite appear to be overpressured by 5,000 psi above hydrostatic pressure with fluid containing dissolved CO_2 and very minor methane. This pressure is close to the pressure required to cause any natural fractures in the granite oriented favourably with respect to the principal stress axes to slip. Two conditions arise from this conclusion.

1. Fractures oriented favourably with respect to the stress field could easily be slipped by the drilling process when equivalent circulation densities (ECDs) were high. This could cause mud losses and gains as the fracture porosity changed during a slip event. If cool mud was lost into the formation, thermal effects would further complicate the down-hole pressure conditions.

2. It is probable that many existing favourably oriented fractures had already slipped due to natural overpressures, and such fractures could already have enhanced permeability. Based on the predicted stress field, these fractures are likely to be shallow dipping, and they may be interlinked over large areas. The hot granite beneath the Nappamerri Trough extends over 1,000 km^2, and the overpressured conditions may extend through all of it. High temperatures in the overlying sedimentary rocks may have sealed the sedimentary porosity resulting in a pressure barrier.

Further problems were encountered as drilling continued relating to the difficulty of operating with conventional overbalanced practices in an environment of fractures that were much more permeable than expected. Both lost-circulation and influx events were experienced with severe mud degradation as a consequence of CO_2 contamination of the mud system. Samples of formation water were brought to the surface on a number of occasions during these problem events. The formation water has a salinity of 21,000 mg/l or two thirds that of seawater. The main ions in decreasing order of abundance are Cl, Na, HCO_3, K, and minor SO_4, Fe, Si, and Ca. Minor dissolved CO_2 and trace CH_4 in the ratio 10:1 were measured in selected samples.

The well was completed for injection with a Halliburton permanent high pressure high temperature (HPHT) production packer set at 3,091m. This was stabbed with a floating seal stack and 4 ½ inch premium production tubing set in compression and landed with a 10,000psi mandrel hanger and metal to metal seals.

5. GRANITE COMPOSITION

The granite intersected in Habanero-1 is a medium to coarse grained white two-mica granite with a colour index of around 3. The granite is intersected by many dykes and veins of white aplite or alaskite. Biotite in the granite is almost completely altered to chlorite throughout, but in the deeper sections of the well the biotite appears less altered, and in the top section the colour index is lower. Tourmaline is a common accessory. Much of the feldspar is altered. In places it is slightly green and in others slightly yellow. The yellowish alteration is related to oxidisation associated with known permeable fractures, particularly prevalent in the section of the well from 4,130m to 4,300m. Further evidence of such oxidation is present near the bottom of the hole, suggesting a permeable fracture near that depth.

Chemical analyses indicate that the granite is moderately fractionated and high in potassium, with SiO_2 around 75%, over 5% K_2O and Rb/Sr of 10. The abundance of radiogenic elements are high, but not excessively so, with Th/U around 2. The heat productivity is 7-10 µwatts/m^3.

6. HYDRAULIC STIMULATION

Hydraulic stimulation operations commenced in October 2003. An extensive array of high pressure injection and vent system piping and valves were rigged up, with the Century 27 drill rig remaining over the hole.

Following the removal of a temporary plug, which had been placed below the packer to facilitate safe installation of the completion tubing and Christmas tree valves, a temperature gradient log was recorded. Several down-hole temperature measurements over a period of a week indicated that the well had not yet reached a static equilibrium. The final measurement in this period was 248.5°C at 4,390m, but the temperature in the bottom section of the well was still increasing. The static bottom-hole temperature is expected to exceed 250°C.

Stimulation injection commenced in early November 2003. In the initial stages much of the flow into the fracture network appeared to take place at one location at a depth of 4,254m. The lower part of the well was filled with salt in attempts to divert flow into fractures above this level. This stage was known as the fracture initiation phase (FIP), and from the start it produced quite widespread seismicity.

After some 1,600 cubic metres of water had been injected in various pulses and diversion attempts, it was concluded from micro-seismic and additional injection profile bore hole logging data using a memory pressure-temperature-spinner (PTS) tool that sufficient vertical spreading of the injected fluid was occurring and that further development of the injection network would probably occur naturally.

The main stimulation commenced on 30 November. A rate of 5bpm was pumped for the first two days. It was then increased in steps to 7bpm and then 9bpm over several days each until a cumulative volume of 16,350 cubic metres had been injected by 9 December.

A simple estimate of stimulated volume was 0.7 km^3 assuming parallelepiped geometry. The stimulated volume is significantly greater than initially expected from previous overseas projects, and larger than that required for the economic model of heat extraction over a 25 year period, assuming conductive heat transfer only. The reservoir is the largest so far of any HDR or HFR project. This is probably due to the extensive (pervasive) nature of the sub-horizontal joints and to the reservoir fluid overpressure.

Following stimulation 1, perforation of the 7" casing for stimulation 2 was commenced. Perforations were made over four intervals between 4136m and 3994m. As each interval was perforated, attempts were made to break it down using high pressure. PTS logging was used to monitor the injection profile development. This quickly showed that the lowest set of perforations, which had been made across 5 sub-horizontal fractures with large apparent aperture were taking 25l/s and obviously in communication with high permeability. These fractures had appeared to act as a roof for the Stimulation 1 interval and it was apparent that this interval was readily communicating with the first stimulation and not allowing the other higher perforated intervals to properly develop. After several days of injecting and diversion using salt and perforation balls it was decided to suspend further stimulation operations. It was reasoned that sufficient stimulation had been achieved on the first treatment to allow the second well to be drilled and a successful circulation test to be conducted.

7. MICROSEISMIC NETWORK

The microseismic network consisted of 8 wells, four 100m deep each set at approximately 5km from Habanero-1 (WA1-WA4), three 850m deep and 2km from Habanero-1 (MW1-MW3), and the previously drilled McLeod-1 450m from Habanero-1. The sensor in McLeod-1 was set at 1,791m where the rock temperature was 134°C. As a result of cable-head leaking of the sensors deployed in the 850m wells, these sensors were subsequently re-deployed at 450m, 220m and 450m respectively. Figure 3 shows the location of the monitoring wells compared to the main well.

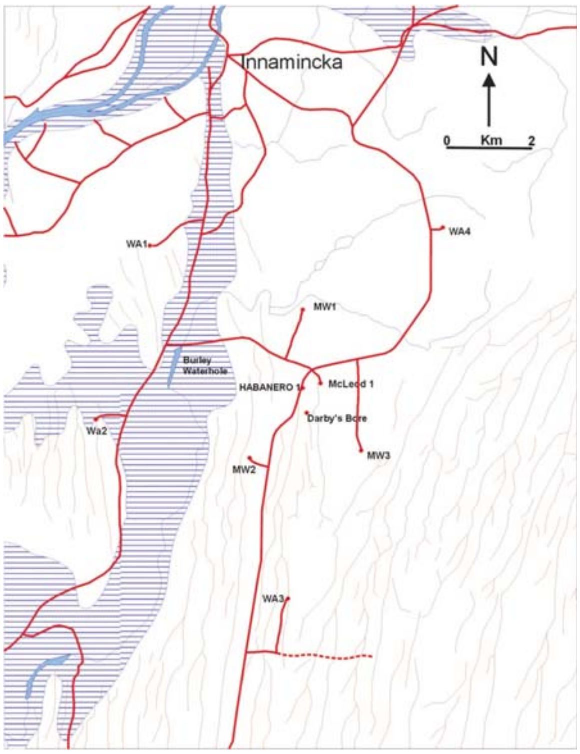


Figure 3. Map showing the location of the Geodynamics infrastructure south of Innamincka.

The WA sensors were manufactured by the Central Research Institute of the Electric Power Industry of Japan (CRIEPI). They contain a 3-axis geophone array, with each geophone having a sensitivity of 1.6 volts/cm/second. The sensors are similar to ones used at the Ogachi Hot Dry Rock test site operated by CRIEPI (Hori et al. 1999).

The MW sensors were built by Auslog of Brisbane. Each sensor contains a triaxial array of six geophone elements (2 for each direction). The geophone elements are Geospace, model GS-20DX, with sensitivity of 0.346 volts/cm/sec. As two geophone elements are wired in series, the total sensitivity is 0.692 volts/cm/sec.

All sensors were connected to the recording centre with multi-conductor surface cabling. Two independent sets of recording equipment were provided by Tohoku University, Sendai, Japan and CRIEPI, Japan. Operation of the equipment was shared between Tohoku University, CRIEPI, Japex and AIST (National Institute of Advanced Industrial Science and Technology, Japan). Both manual picking of P-wave arrival times, and automated picking using the software of N. Soma of AIST (Soma et. Al, 2004) were used to locate seismic events in semi-real time using a 6-layer seismic velocity model.

7.1 Seismic Velocity Model

The McLeod-1 vertical seismic profile run by Velocity Data Pty Ltd in October 1983 was analysed by CRIEPI to design a 6 layer velocity model. Initially the velocity of the granite was estimated from knowledge of other locations (5,030m/s). Based on this velocity, the first events recorded on 6 November were located too deep at close to the bottom of the well where PTS (pressure-temperature-spinner) logging indicated no fluid flow at that stage. Seismicity during injection on 9 November was remarkably aligned along a plane dipping SW at 25°, and at the same time the PTS tool indicated almost all the flow was exiting the well at a fracture at 4,254m. The granite velocity in the model was increased in order that the dipping plane of seismic events intersected the well at 4,254m. The resulting granite velocity and velocity of other layers is shown below.

Depth (metres)	Velocity (m/s)
0-472	2,134
472-792	2,591
792-1,557	2,896
1,557-2,022	3,962
2,022-3,673	4,572
3,673 + (Granite)	5,525

7.2 Microseismic Monitoring results

Up until the end of the stimulation (22 December), the analogue to digital recording system from Tohoku University had recorded 32,000 triggers and 11,725 of these have been located in 3D space and time on-site. The location method used proprietary software developed by Tohoku University. The early development of the seismic cloud provided considerable insight on the character of the fracture network in the granite, more so than later when the cloud is complicated by many overlapping events.

8. FRACTURE INITIATION PHASE (FIP)

During the fracture initiation phase seismicity initially grew outwards and downwards to the SW along a planar feature. The depth of this feature was adjusted to align with the main fracture taking flow at 4,254m by adjusting the P-wave velocity of the granite. By the end of the Fracture Initiation Phase (FIP) on 16 November, the seismic cloud of 2,750 located events had grown dominantly in 3 branches:

• to the NNW about 500m, where seismicity appeared to be controlled by a steeply dipping N-S trending structure;

• to the south more than 1300m, where a large fault around 600m from H1, and trending NW, displaces events 100m deeper across the fault, and;

• to the NE about 500m where the seismicity is broadly distributed.

Between the two northern branches there is a zone with sparse seismicity. The NNW events are slightly deeper and more concentrated than the NE events which are located on a broad horizontal band around 400m wide at around 4,200m depth. The NE branch could correspond to one major planar feature, but the events in the other directions (S and NNW) show more complicated behaviour. The earlier fears that the dominant fracture at 4,254m may represent a major regional thrust fault are not supported by these data.

9. MAIN STIMULATION

The main stimulation ran from 30 November to 9 December, initially at 5 bpm, then 7 bpm and finally around 9 bpm. At 9 bpm the pumping pressure was consistently around 9400 psi. This restricted the pump rate beyond this value because the casing and wellhead equipment was limited to 10,000 psi.. Pumping at higher flow rates was carried out for short periods using friction modified injection water. Over 7900 events were located mainly using the automated picking routine of N. Soma (Soma. Events averaged around 700 per day, with more events at the commencement of pumping at each different flow rate (5, 7 and 9 bpm). Towards the end of each period of pumping the event rate was declining. Seismicity grew mainly to the NE and NNW.

In the SE there was virtually no more outward growth beyond that of the FIP.

In the SW all the growth was westwards beyond the fault delineated in the FIP. Most events to the SW lie within a 100m thick zone dipping 20° to the SW. Within this zone there are several major fractures suspected as well as antithetic minor fractures. A second well-defined parallel structure lies above the main zone, approximately 100m above, and events higher again suggest another parallel structure a further 100m above.

NNW growth resulted in a much greater concentration of events out as far as they had grown in the FIP (500m). A concentration of events also extends out another 500m beyond the FIP growth. Events are distributed in this zone of concentration over a thickness of 300m. Overall, the structure in the NNW is quite complex with a mass of events that makes it difficult to determine the structure. Probably there are many small planar structures in this direction, and few major planes. The density of events in this direction is the highest of any direction.

NE growth continued as a broad diffuse band beyond the extent defined by the FIP (500m) out to 1500m from Habanero-1, further than growth in any other direction.

10. SECOND STIMULATION

The second stimulation followed perforation of the casing over the period 15 to 18 December. The stimulation was a complex series of operations which somewhat overlapped with perforating, but was completed by 22 December. The seismic system was switched off at 6pm on 22 December when seismicity was still very active at around 45 located events per hour.

Although fluid entered the granite from the bottom set of perforations at 4,135m, evidence from as early as the early part of the FIP indicated that a fracture at this level was already seismically active on 10 November. It is therefore not surprising that seismic activity continued mostly in the main cloud rather than in a layer above.

The overall dimensions of the seismic cloud increased to more than 350m x 1000m x 2000m by the end of stimulation 2. Figures 4, 5, and 6 show the distribution of events in plan, SN and WE elevations colour coded by time. Yellow represents events in the FIP, red for the main stimulation phase and blue for the second stimulation.

11. CONCLUSIONS

The first half of the Geodynamics Limited “Proof of Concept” hot fractured rock project in granite beneath the Cooper Basin, has been successfully completed. Despite difficult drilling conditions relating to the unexpected discovery of high overpressures (5,000psi above hydrostatic) in the fracture network of the granite, Habanero-1 was drilled to a depth of 4,421m, and stood up to pressurizations of almost 10,000psi surface pumping pressure during stimulation. The well penetrated 754m of white two-mica granite and discovered a number of sub-horizontal fractures that are thought to have had their permeability enhanced by natural slippage associated with the overpressures. The measured rock temperature at 4,390m is 248.5°C, but static conditions had not been reached.

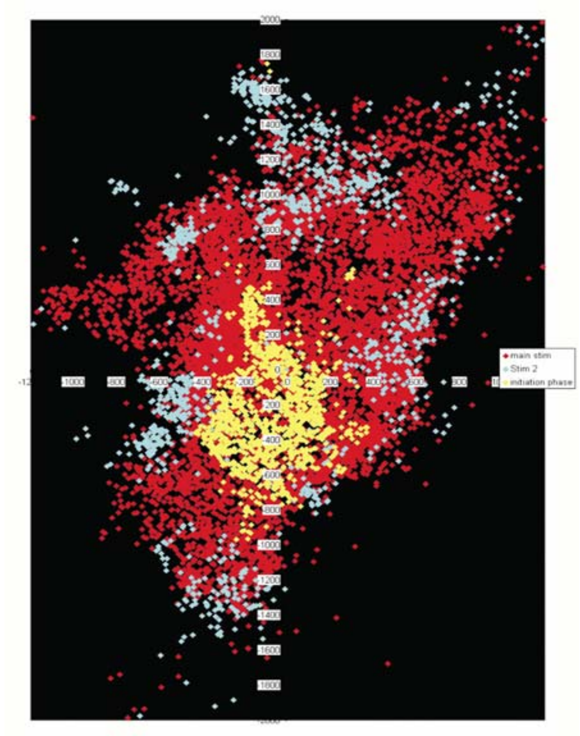


Figure 4. Plan view of all seismic events with fracture initiation phase (FIP) in yellow, main stimulation in red and second stimulation in blue. Habanero-1 is located at the centre at coordinates 0,0. Scale is in metres.

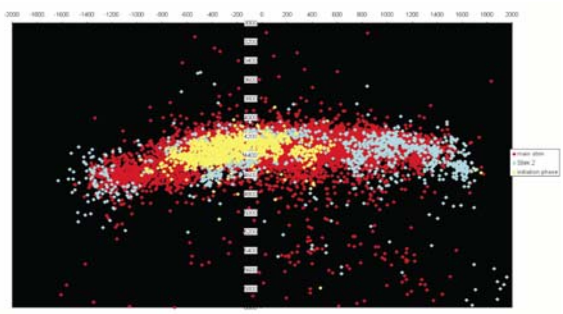


Figure 5. As for figure 4, south-north cross-section. Habanero-1 is located at 0 metres on the horizontal axis.

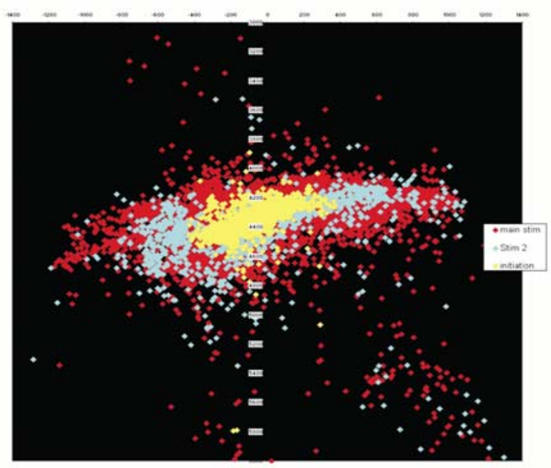


Figure 6 As for figure 4, west-east cross-section.

The stimulation consisted of the injection of 20 Ml of fresh water into the granite fracture network between 4,135m and 4,421m. One major fracture at 4,254m dominated the entry into the formation, but seismic evidence indicated that other known fractures, including at least one plugged by LCM during drilling, and another accessed through perforated casing at 4,135m were also seismically activated.

More than 11,700 located seismic events mapped out a seismic cloud with a volume of 0.7 km^3, the largest ever produced in a hot rock stimulation. The seismicity developed in three major sub-horizontal branches with differing character.

(1) A NE branch that forms a flat-lying sheet extending 1.5km from Habanero-1, at a depth of 4200m.

(2) A SW branch extending 1.2km, consisting of a number of parallel flow paths dipping at 20° to the SW and displaced down by 100m by a fault 600m from Habanero-1.

(3) A NW branch extending 1km with complex flow paths, and intense seismicity in the 500m closest to Habanero-1.

We believe the stimulation shows great promise for the development of the underground heat exchanger by drilling a second well and successfully circulating between the wells to produce high-temperature fluid. The presence of high overpressures indicates that a considerable proportion of the produced energy could come from convective flow from beyond the stimulated volume, adding to the longevity of energy extraction. Such flow is likely to extend over a substantial volume, and if the permeable fractures are interconnected on a large scale the region could constitute the largest geothermal field in the world.

ACKNOWLEDGEMENTS

The authors would like to thank all those associated with the project, in particular the Japanese team for microseismic monitoring and their associated Institutions, our contractors including Century Resources, Geoservices, IDFS, Halliburton, Baker Atlas, Schlumberger, KJM Contractors and Innamincka Earth Moving.

REFERENCES

Armstead, H.C. and Tester J.: 1987. Heat Mining. E.F. Spon, London.

Denham, D., and Windsor, C.R., 1991.: The crustal stress pattern of the Australian Continent. Exploration Geophysics, 22, 101-105.

Koch, R.D., 1985.: Geothermal – South Australia’s future energy bonanza. Journal of South Australian Chamber of Mines (Johnny Green’s Journal), 5 (4), April 1985, 22-26.

Hori, Y., Kitano, K., Kaieda, H., and Kiho, K.: 1999. Present status of the Ogachi HDR Project, Japan, and future plans. Geothermics, 28 (4/5), 637-645.

Meixner, A.J., Boucher, R.K., Yeates, A.N., Frears, R.A., Gunn, P.J., and RICHARDSON, L.M., 1999. Interpretation of the Geophysical and Geological Data sets, Cooper Basin Region, South Australia. Australian Geological Survey Organisation, Record 1999/22, 1-25.

Soma, N., Takehara, T., Asanuma, H., Niitsuma, H., Baria, R., and Michelet, S., 2004. Precise automatic wave picking technique for on site microseismic monitoring in Hot Dry Rock development. Geothermal Resources Council Transactions, 28, 239-244