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CREATION OF HDR RESERVOIRS UNDER AUSTRALIAN IN-SITU STRESS CONDITIONS

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ABSTRACT

Australia has a huge resource of hot dry rock, most of which is located in Central Australia. As a first step towards experimental field testing of HDR development in Australia, in-situ stresses and natural fractures in Central Australia are being characterised. Preliminary results indicate that three stress regimes may co-exist in Central Australia, with maximum horizontal in-situ stress being approximately east-west oriented. 2D stochastic modelling of HDR reservoir stimulation reveals that the fluid recovery and thermal recovery efficiencies primarily depends on variation of the magnitude between the minimum and maximum horizontal stresses, and the orientation of the injection and production wells with respect to the direction of the dominant natural fracture set. Correctly aligning production and injection wells with the direction of the dominant fracture set minimises fluid loss and increases thermal recovery rate.

INTRODUCTION

Australia has a huge potential for Hot Dry Rock (HDR) geothermal energy (ERDC Report No. 2403, 1995). A major part of this HDR resource is located in the Central Australian Continent where the stress regime is compressive (reverse faulting). This is in contrast to the extensional, normal faulting stress regime in other areas in whch HDR technology has been trialled, such as Fenton Hill (New Mexico, USA), Hijiori (Japan), Rosemanowes (England) as summarised by Willis-Richards et al. (1996), and Soultz, France (Gerard et al., 1997). As such, HDR reservoirs created under Australian in-situ stress conditions will have horizontally dominant geometries which may have advantages over vertical HDR reservoirs in that the number of wells required for accessing the same reservoir volume will be reduced, thus increasing the competitiveness of HDR geothermal energy with other sources of energy.

In collaboration with the industry and Energy Research and Development Cooporation (ERDC), the University of New South Wales (UNSW) has initiated a research program to test the feasibility of HDR geothermal energy in Australia. The major objectives of Australia's first HDR research project are to characterise in-situ stresses and natural fractures, both of which are of essential knowledge for HDR fracture stimulation, and to understand fundamental mechanisms of HDR reservoir creation under Australian conditions. In this paper, we report on the recent progress of the HDR research project in characterisatian of in-situ stresses and natural fractures as well as their effects on HDR reservoir creation.

AUSTRALIA'S HDR RESOURCES

Australia's HDR resources have been identified based on the temperature data from three thousand boreholes, mostly oil and gas exploration wells occurring at 5km depths (Figure 1; Australian Geographc, Oct.-Dec., 1996; ERDC Report ko. 2403, 1995). The resulting estimate of thermal energy stored at these depths and available for electricity generation, is 23 million petajpoules (1 petajoule = 10^{15} joules). This is the energy equivalent of 4 trillion barrels of oil. The current yearly consumption rate of energy in Australia is 0.5 billion barrels of oil, equivalent to 3000 petajoules (ERDC, 1995). Assuming, an efficiency of 30%, the HDR resources could potentially accommodate Australia's energy requirements, at the current rate, for another 2,300 years.

Over 80% of Australia's HDR resource is located in the Eromanga Basin, an area covering the north-eastern comer of South Australia and south-western comer of Queensland (Figure 1). The Cooper Basin is a sub-basin of the Eromanga Basin and has the largest HDR resource in the region (see Table 1; ERDC Report No. 2403, 1995).

The Sydney Basin, near Muswellbrook in the Hunter Valley (Figure 1), is another ideal site for HDR power generation. This is a high temperature granite body, close to the electricity distribution gnd, neap a

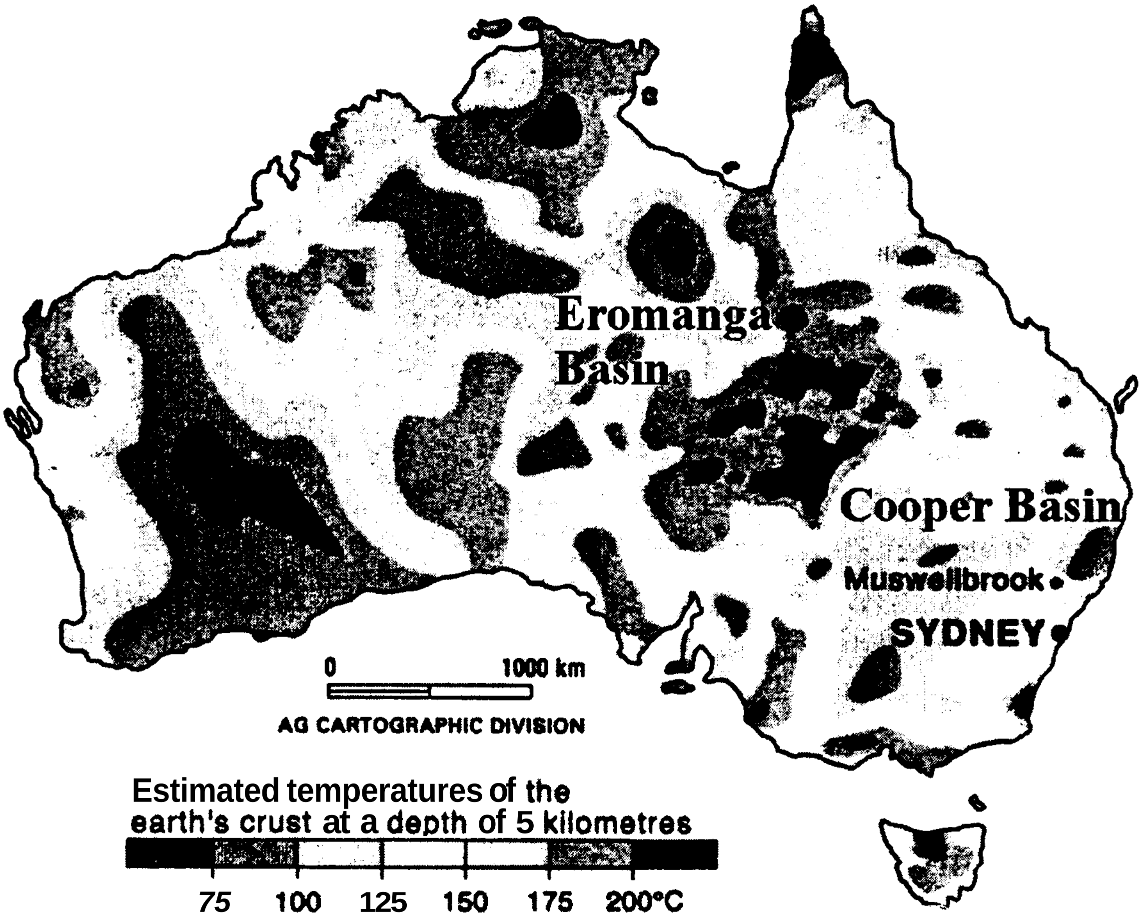

Figure 1. Thermal condition in Australia at 5km depth level

Locality	Sub-locality	Estimated heat energy available (thousand petajoules)	
Erornanga Basin	Cooper Basin	7,821	
	Galilee Basin	6,237	
	Cacoory	2,079	
	Mulkarra West	1,089	
	Denbight Downs	990	
	Brookwood	297	
	Ayrshire	178	
	Banrnirra	119	
	Yanbee	69	
	Chandos	70	
		Subtotal_1	18,94
McArthur Basin		2,871	
Otway Basin		495	
Murray Basin	Hunter Valley	119	
Perth Basin		49	
Sydney Basin		15	
East Queensland		8	
		Subtotal_2	3,557
		TOTAL	22.506

Table 1. Estimated energy resources in granite bodies

major power station and conveniently located near population centres and transport. The HDR resource in the Hunter Valley is estimated at 3,000PJ, equivalent to the total hydrocarbon reserves in the Bass Strait, Australia. This site could supply 4.5 times Australia's annual consumption of energy. The best power generating scenario for this site would be an output of about 4,600MWe. For comparison, this figure far exceeds the capacity of the nearby Bayswater Power Station at 2,600MWe and is equivalent to 75% of the average demand of 6000MWe in New South Wales.

The occurrence of high temperature rocks in the upper crust in Australia, specifically in the Cooper Basin, is controlled mainly by two factors:

- the abundance of high heat-producing granites in the Earth's upper crust, especially in north-eastern South Australia and south-western Queensland (the Cooper Basin); and
- the thermal blanketing effect of the sedimentary basins which cover nearly half of the continent's land surface.

It is noted that the mechanisms for creating Australia's HDR resources are different from those in the other HDR provinces, such as Fenton Hill, New Mexico, **USA,** Hijiori, Japan and Soultz, France where recent magma intrusions provide the heat for hot granite bodies.

STRESS [illegible] IN [illegible]EN AUSTRALIA

Stress Regime

In-situ stresses are normally represented by three orthogonal principal stresses, namely two horizontal stresses (S_H and S_h) and one vertical stress (S_V). The relative magnitudes of the three components of in-situ stresses determine the stress regime in a region. There are three possible states for stress regimes:

- normal faulting ($S_V > S_H > S_h$)
- strike-slip faulting ($S_H > S_V > S_h$)
- reverse faulting ($S_H > S_h > S_V$).

The in-situ stress regime has a significant impact on the geometry of HDR reservoirs. In a normal faulting stress regime, the dominant HDR reservoir will be vertical, whereas in a reverse faulting regime, the HDR reservoir zone of enhanced conductivity will probably be horizontally oriented. Horizontal reservoirs are considered more economical than vertical HDR reservoirs, (ERDC Report 2403,1995). This economic advantage stems from the fact that multiple horizontal reservoirs require fewer vertical wells to extract heat, thus reducing the cost associated with drilling of wells.

In-Situ Stress **Regimes** in Central Australia

As stated previously, Central Australia **hosts** a vast amount of HDR geothermal resources. Hydraulic fracture treatments have been carried out by the petroleum industry in the Cooper Basin for more **than** three decades, allowing researchers to gathe**r a large** amount of stress **data** during **this** period. **Pressure** records from hydraulic fracture **tests** have been analysed from wells throughout the **basin,** giving a large-scale picture of the prevailing stress regimes. **This** analysis **has** highlighted a marked lateral variation in the horizontal stresses, to the degree that all three stress regimes coexist in the **basin.**

The basin can be divided into three distinct regions on the basis of stress regimes. Region 1 **(Figure 2)** **has** a normal faulting stress regime, **bordering on** strike-slip; region 2 (Figure 3) has **a strike-slip** faulting stress regime; and region 3 **(Figure 4) has** a predominantly reverse faulting stress regime. **In** region 3, the difference between the maximum **and** the minimum horizontal stresses is large, indicating a strongly deviatoric stress regime that is probably of tectonic origin.

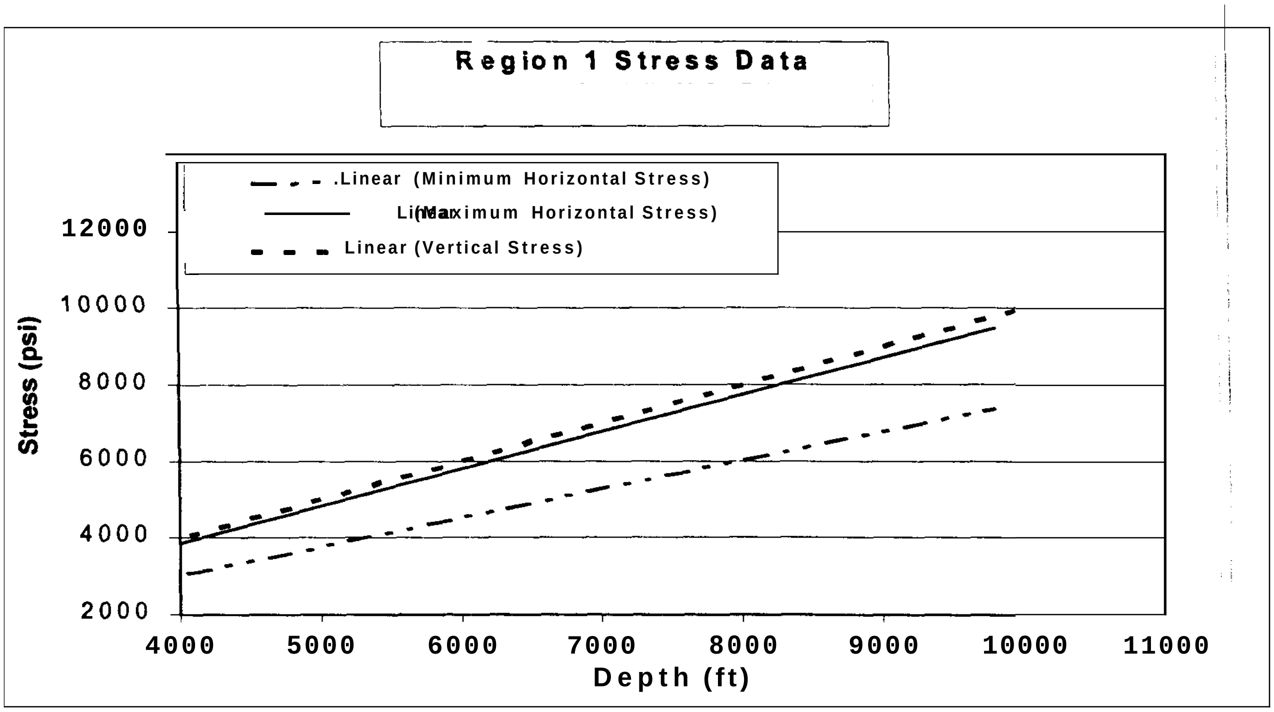

Figure **2.** Normal faulting regime in Cooper Basin, Central Australia

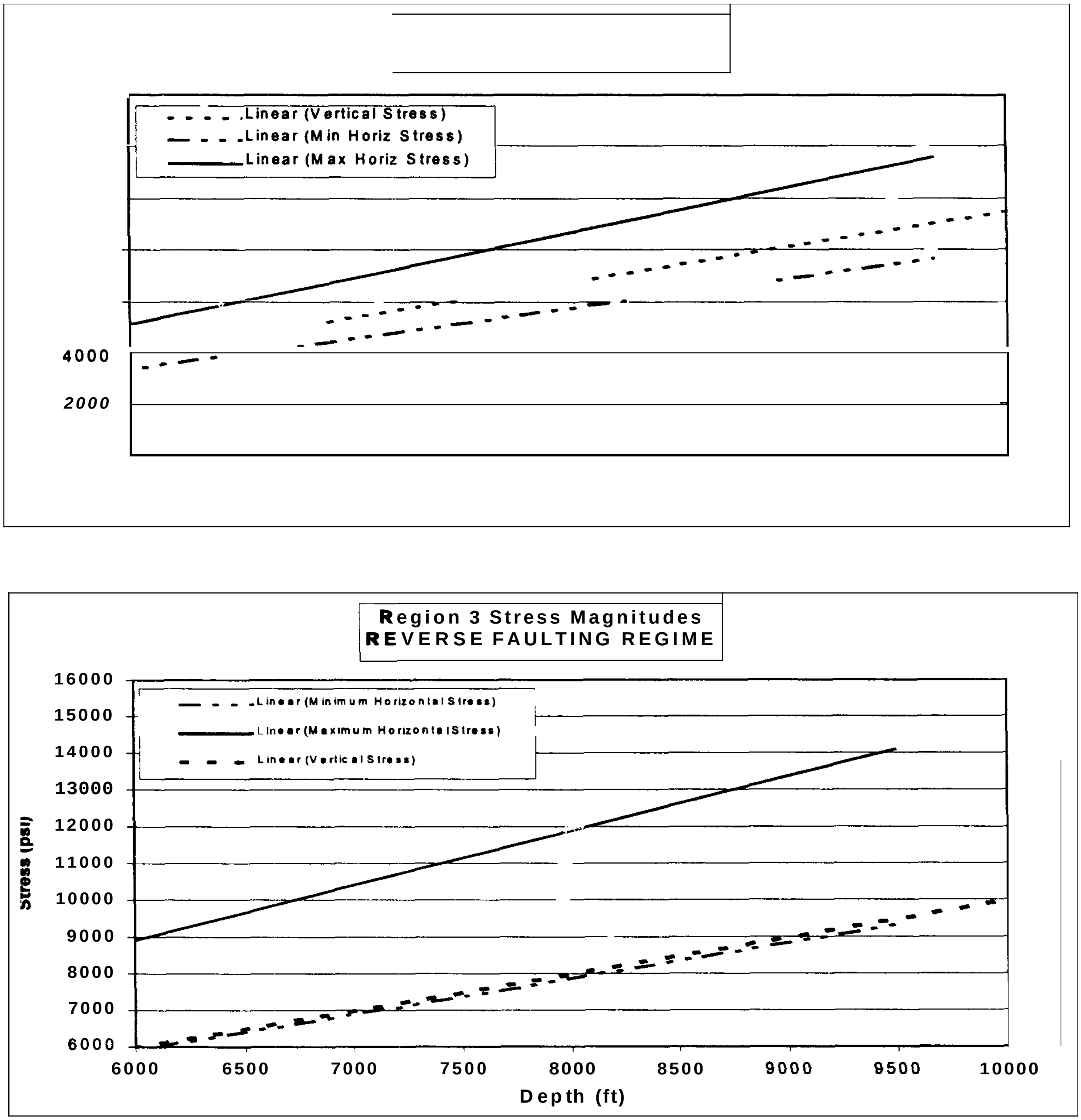

Figure 4. Reverse faulting stress regime in Cooper Basin, Central Australia

Due to the extreme variability of the horizontal in-situ stress regime in Central Australia, stress measurement estimates should be carried out on a field stress regime basis. Caution should be taken when extrapolating stress measurements from one field to another, from shallow to greater depths, from stress regimes derived from earthquakes to those from hydrocarbon fields. However, the complex stress regime in Central Australia provides a good opportunity to select a favourable site for an experimental HDR reservoir stimulation, in terms of in-situ stress regime.

Direction of Maximum Horizontal In-Situ Stress

Despite variability of the magnitudes of horizontal in-situ stresses, an extensive study of wellbore breakout data available in the basin has shown a great deal of consistency in the orientation of the in-situ stresses. Wellbore breakouts are regions of wellbore failure in which shear failures in the near wellbore region, caused by insufficient mud support, result in an elliptical hole. The direction of breakouts in a vertical borehole is parallel to the minimum horizontal in-situ stress.

Breakouts are identified and characterised using from four-arm caliper logs or imaging tools. Thus far, only caliper logs have been studied in-depth, due to the restriction in the number of imaging logs run in the basin. A rose diagram (Figure 5) shows the consistency of the stress direction in over 60 wells analysed. The mean orientation of the minimum horizontal in-situ stress, on the basis of this analysis, is 004’. Logically it follows that the direction of maximum in-situ stress is orthogonal to this, at 094^0, or approximately east-west trending.

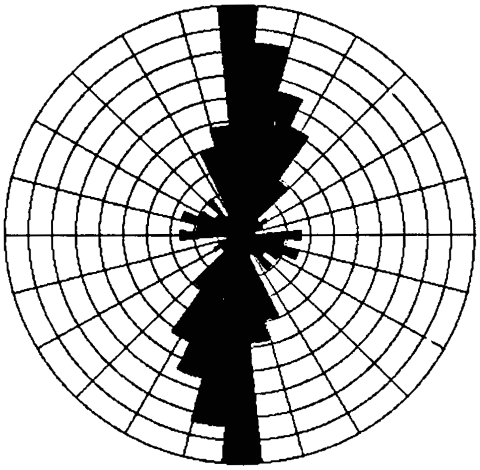

Figure **5.** Rose diagram of breakout azimuths in Cooper Basin

CHARACTERISATION OF NATURAL FRACTURES IN CENTRAL AUSTRALIA

Natural fractures play a critical role in the creation of HDR reservoirs as HDR stimulation seeks to extend and interconnect existing natural fractures. Characterisation of natural fractures, in terms of orientation, dimension, spacing, permeability and other geomechanical or hydraulic properties, has been one of the major tasks of any HDR reservoir development. As such, a study of natural fractures present in the basement of the Cooper Basin has been undertaken for the simulation work in this project. Imaging logs (in this case FMS and FMI logs) were examined to determine the fractal dimension of the natural fractures, thus characterising them at a variety of different scales. The tool and technique readily employed to perform fracture characterisation are discussed in the following section.

Formation Microscanner Tool (FMS)

The Formation Microscanner tool, or FMS, produces an oriented picture of the borehole wall by mapping its conductivity with a dense array of electrodes. A series of microresistivity curves are recorded every 0.1 inch by a series of sensors distributed azimuthly. The microresistivity variations of the borehole surface are converted to variable intensity colour pictures, so that high resistivity zones are light and low resistivity zones are dark. In crystalline rocks such as granite, a conducting fracture can be detected as a dark anomaly on the image. About 50% of the borehole area is covered by the four pads of the tool. The tool position and orientation is determined through the use of an inclinometry system.

A typical section of borehole image is shown in Figure 6. Note that the dark bands are interpreted as natural fractures. The natural fractures observed in the course of this study are shallow dipping and trending approximately east – west.

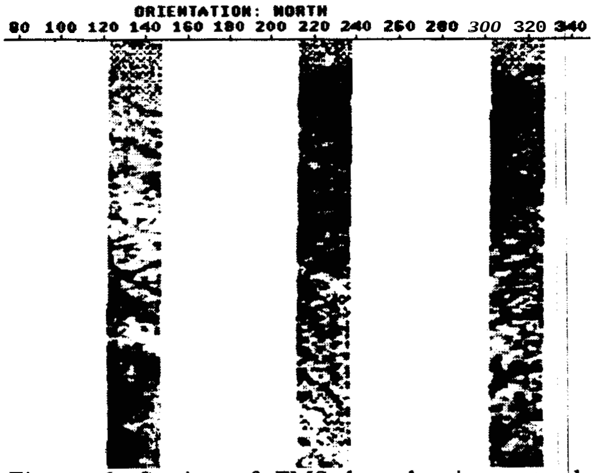

Figure **6.** Section of FMS log showing natural fracture

Fractal Analysis

A fractal object is one that is irregular or interrupted and self-similar when examined at smaller and smaller scales, and can be characterised by its fractal dimension, D, which evaluates its degree of irregularity.

The fractal dimension has been estimated in this case by finding the slope of a log-log plot of fracture separation against frequency (Genter and Castaing, 1997). Work is currently being undertaken to obtain and analyse a statistically representative sample of natural fractures from FMS logs. Figure 7 shows preliminary results based on the limited data available thus far. Note that the “tails” of the ideal linear section are dominant over the linear section. The fractal dimension obtained from the slope of the linear section is used for stochastic modelling of fracture stimulation, which will be discussed later.

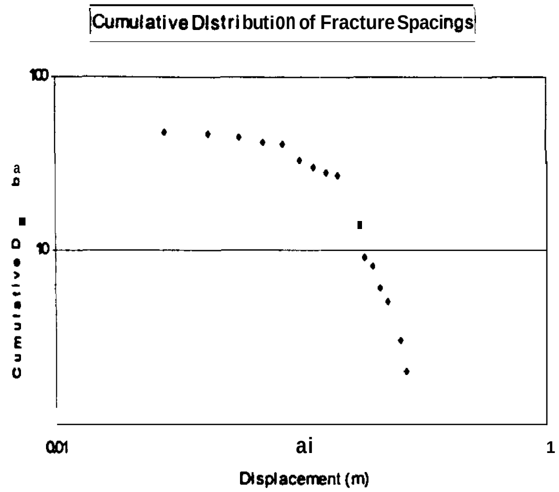

Figure **7.** Fractral analysis of fracture spacing in the Cooper Basin

MODELLING OF RESERVOIR STIMULATION

So far, HDR reservoir stimulation treatments have been carried out in many sites in other countries, e.g. Fention Hill (USA) (Brown, 1997), Rosemanowes (England) (Richards-Willis, 1996), Hijiori (Nagai and Tenma, 1997) and Ogachi (Japan) (Kitano, 1997), and Soultz (France) (Gerard et al., 1997). All these HDR sites are located in normal faulting stress regimes. However, the geometries of created HDR reservoirs, derived from microseismic events, are remarkably different. Also their short term tests show different behaviours. It is apparent that there are many factors, in addition to stress regime, that affect creation of HDR reservoirs. Unfortunately, few studies in this regard have been reported in the literature. As no HDR stimulation has been carried out in Australia, it will be interesting to know what kind of HDR reservoirs will be created under the local conditions. This can only achieved through numerical modelling of HDR reservoir stimulation.

As part of the fracture stimulation modelling, a sensitivity study was carried out to investigate how individual factors, such as magnitude and direction of in-situ stresses (S_H and S_h), fracture azimuth and dippings, well location and spacing affect a simple three-well HDR system. The preliminary results of the sensitivity study are presented in this section.

FRACSIM-2D

FRACSIM-2D (Willis-Richards et al., 1996) was used in this study to simulate HDR well stimulation and performance under Australian in-situ stress conditions. A brief description of the model is given here. FRACSIM-2D is a two-dimensional, stochastic network model of hydraulic stimulation, steady state flow and heat extraction through fractured crystalline rock. Natural fractures are assumed to be represented by fractals and are generated stochastically in the simulation. Only shearing of existing fractures (model II fracture propagation) is considered in the model. For the purposes of heat extraction, the model assumes that thermal equilibrium is reached instantaneously between each element and the water passing through it. A constant temperature boundary condition is assumed and all significant heat transfer takes place far from the boundary, close to the well locations.

The model geometrically assumes a horizontal slice of rock containing steeply dipping fractures penetrated by vertical wells. Fluid may flow from the injection well up to four recovery wells. FRACSIM-2D is best suited to simulate rock masses in which strike-slip movements predominate (Willis-Richards et al., 1996). The input data required for FRACSIM-2D include in-situ stresses, mechanical properties of rocks, rock fracture properties and fluid properties.

RESI [illegible] OF SENSITIVITY STUDY

A simple [illegible] t **2D** model of **800m** x [illegible] as set-up **for** the sens [illegible] **study**. The [illegible] d as divided t [illegible] **200** x **200** blocks. [illegible] t [illegible] ra [illegible] t rs are given in Table 2. A **trike-slip** t [illegible] regime is **assumed**, with alues of three [illegible] ij al t [illegible] l ng [illegible] **from** **draulic** **fracturing** t [illegible] N [illegible] al fracture data are based on **field** d ta or best [illegible] ss. Other parameters have [illegible] en taken from other [illegible] R sites. Three w [illegible] l f [illegible] m a **straight** line f a **direction** f 45° **NE** w [illegible] used for **long** [illegible] n **circulation** modelling, with **an** [illegible] tic **well in** [illegible] e id and two [illegible] ti [illegible] wells lying on its [illegible] ite sides. The three **wells** were stimulated [illegible] te i [illegible] began.

The results of the sensitivity study are given in Table 3, in terms of fluid recovery efficiency and five-year thermal recovery. Fluid recovery efficiency is defined as a ratio of fluid recovered over fluid injected. Thermal recovery is calculated by dividing heat recovered by the original total stored heat. An explanation is given below on the effects of individual factors on HDR system performance. First, increasing minimum in-situ stress can significantly reduce both fluid recovery efficiency and thermal recovery. For instance, when minimum in-situ stress increases from **55** MPa to 75 MPa, fluid recovery efficiency decreases from 60% to 44%, and thermal recovery decreases from **0.54%** to 0.05% (Table 3).

Azimuths of dominant natural fracture sets have a profound effect on HDR reservoir performance.

Table 2. Model Parameters for HDR Simulation in Australia.

nput values as Base Case	
Discretisation	
Element size, m	4
No. of elements in X,Y	(200x200)
No. of joint sets	2
Rock fracture properties	
	Fracture set1
Azimuth	(35,45)
Dip	(25,35)
Fraction of total set	0.7
	Fracture set2
Azimuth	(70,80)
Dip	(60,70)
Fraction of total set	0.3
Stress values (Mpa)	
Vertical stress	80
Maximum Hoz. Stress	105
Minimum Hoz. Stress	65
Azimuth of Max. Hoz. Stress	095"
Well location	
Well–1	(-106,-106)
Well–2	(0,0)
Well–3	(+106,+106)
Stimulations	
1Location	(-106,-106)
1Pressure	70
1Area	3600
1Well name	Well–1
2Location	(0,0)
2Pressure	63
2Area	100000
2Well name	Well–2
3Location	(+106,+106)
3Pressure	63
3Area	100000
3Well name	Well–3
Injection well	
Location	(0,0)
Pressure (MPa)	20
Name	Well–I
Recovery wells	
1Location	(-106,-106)
1Pressure	0
1Name	Well–2
2Location	(+106,+106)
2Pressure	0
2Name	Well–3
Heat extraction	
Duration (days)	1800

Table 3. Sensitivity Analysis for HDR simulation in Central Australia

Varaible	Value/ Range	Fluid Recovery(%)	Thermal Recovery (%)
Fracture Azimuth	15,25	49.7	0.298
	25,35	50.8	0.267
	35,45	61.2	0.254
	45,55	56.1	0.213
	55,65	55	0.167
Fracture Dips	15,25	61.3	0.258
	25,35	61.2	0.254
	35,45	61	0.249
	45,55	60.7	0.244
	55,65	60.8	0.242
	65,75	60.6	0.238
Min. Horiz. stress	55	60.6	0.542
	65	61.2	0.254
	75	44.6	0.054
Well location****	Case_1	61.2	0.254
	Case_2	53.9	0.202
	Case_3	57.3	0.207
	Case_4	57.2	0.278
Well spacing (radius,m)	100	79.2	0.357
	150	61.2	0.254
	200	43.7	0.208

****Location
Case_1 (+106,+106), (0,0), (-106,-106)
Case_2 (0,+150), (0,0), (0,-150)
Case_3 (-106,+106), (0,0), (+106,-106)
Case_4 (+150,0), (0,0), (-150,0)

When the main fracture set has an azimuth of 35" to 45" **NE**, fluid recovery efficiency is the highest, and thermal recovery is moderate. It is noted that the average direction of the main fracture set (40° NE) is very close 45° NE, the direction of the straight line connecting injection and production wells. This implies that aligning injection-production wells along the dominant fracture set will reduce fluid loss. Dips of natural fractures do not seem to have a great impact on reservoir stimulation and thermal recovery. This may be due to the two-dimensional nature of the model where vertical connections of natural fractures have been ignored. 3D models will overcome this difficulty.

The effect of well layout on well performance was investigated by varying locations of two production wells while maintaining the distance between injection and production wells. Among four layouts (NS, NE, EW, SW) investigated, the highest fluid recovery efficiency and thermal recovery rate are achieved when the straight line between three wells is in a **NE** direction, which is the closest to the azimuth of the dominant fracture set. This confirms the results obtained by slightly varying the azimuth of the dominant natural fracture set.

The last factor that has been investigated is well spacing. Three well spacings: 100, 150 and 200m were studied. For the three well spacing investigated, the 100m spacing gives the highest fluid recovery efficiency and thermal recovery rate. It is possible other well spacings may have lower fluid recovery efficiency but higher thermal recovery rate in long term, say 30 years. It is clear that well spacing has a large effect on both fluid recovery efficiency and thermal recovery rate. An optimal spacing which balances fluid recovery efficiency and thermal recovery rate can be found, given an economical life of a HDR reservoir.

DISCUSSION AND *SUMMARY*

In-situ stress conditions in Central Australia, as discussed earlier, are complex: three stress regimes coexist in the same region. An advantage of such stress conditions is that the most appropriate HDR test site can be selected in terms of in-situ stress regime. Despite assertion that the dominant HDR reservoir should be horizontal in a reverse faulting stress regime, field observations do not seem to support such a claim. As in most existing HDR sites (Fenton Hill, Rosemanows, Hijiori and Soultz), the HDR reservoir is effectively three-dimensional. Microseismic events in a plan view at Hijiori (Nagai and Tenma, 1997) and Soultz (Gerard et al., 1997) roughly followed the maximum horizontal stress direction. At Fenton Hill, on the other hand, seismic events (Brown, 1997) had little to do with the current maximum horizontal stress. At Rosemanowes, the fracture stimulation showed a strong downward development. All these observations show that although in-situ stress regime plays an important role in HDR reservoir creation, it is not the only factor that control HDR reservoir geometry. Moreover, 2D numerical modelling demonstrates that little contrast between maximum and minimum horizontal insitu stress, whch is the case of reverse faulting stress regimes, has an adverse effect on HDR reservoir creation and heat extraction performance.

In addition, numerical modelling results from this study and that of Willis-Richards et al. (1996) demonstrates the strong effect of properties of natural fracture on HDR reservoir creation and performance. This seems to suggest that when choosing the pilot HDR site, natural fractures should be taken into account as well. Characterisation of natural fractures is being carried for the sedimentary rocks lying above the granitic basement in Central Australia. Completion of this task will provide insight into basin-wide fracture patterns of the sedimentary section. It is unclear whether fracture patterns existing in sediments extend to the basement. However, they are probably indicative of relatively young and open natural fractures in the granitic basement.

The current study has investigated HDR development only in a strike-slip stress regime. In near future, 3D modelling of HDR stimulation will be carried out to predict HDR reservoir geometry and long term performance under reverse faulting regime existing in Central Australia. The modelling results will provide a basis for the selection of Australia's first HDR site. In summary, Central Australia hosts a vast amount of HDR geothermal energy resources. Preliminary results of characterisation of in-situ stresses and natural fractures have revealed complex stress regimes in Central Australia, i.e. three stress regimes may coexist in the region. The direction of maximum horizontal in-situ stress in the region is dominantly east-west. 2D stochastic modelling of fracture stimulation demonstrates that small difference between the magnitudes between minimum and maximum horizontal stresses, and large difference between the orientation of injection and production wells with respect to dominant fracture set has adverse effect on reservoir stimulation and well circulation performance. Correctly aligning a pair of injection-production wells with respect to the direction of dominant fracture set enhances the fluid and thermal recovery efficiencies.

REFERENCES

Brown, D. (1997): Review of Fenton Hill HDR test result$. Proceedings of NEDO International Geothermal Symposium, March 11&12, 1997, Sendi, Japan. pp. 316-323.

ERDC (Energy Research Development Corporation) (1995): Hot dry rock feasibility study. Report 2403 (unpublished).

Genter, A. and Castaing, C. (1997): Scale Effects in the Fracturing of Granites. In "Earth and Planetary Sciences" Academie des Sciences, Elsevier Paris.

Gerard, A., Baumgartner, J. and Baria, R. (1997): An attempt toward a conceptual model derived from 1993-1996 hydraulic operations at Soultz. Proceedings of NEDO International Geothermal Symposium, March I 1& 12, 1997, Sendi, Japan. pp. 329-341.

Hot Rock Energy Pty Ltd (1997): Background briefing. August 1997.

Hot Rock Energy Pty Ltd (1997): Investment proposal. April 1997.

Kitano, K. (1997): Present status and tasks of the Ogachi HDR project. Proceedings of NEDO International Geothermal Symposium, March 11&12, 1997, Send/, Japan. pp. 363-372.

Nagai, M. and Tenma, N. (1997): Development of hot dry rock technology at Hijiori Test Site - Program for a long term circulation test. Proceeedings of NEDO International Geothermal Symposium, March 11&12, 1997, Sendi, Japan. pp. 351-356.

Willis-Richards, J., Watanabe, K. and Takahashi, H. (1996): Progress toward a stochastic rock mechanics model of engineered geothermal system. Journal Geophysical Research) March, 101, B8. pp. 171481-96.