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Geothermal Energy Conference
19-22 AUGUST Rydges Hotel Melbourne

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Record
2008/18

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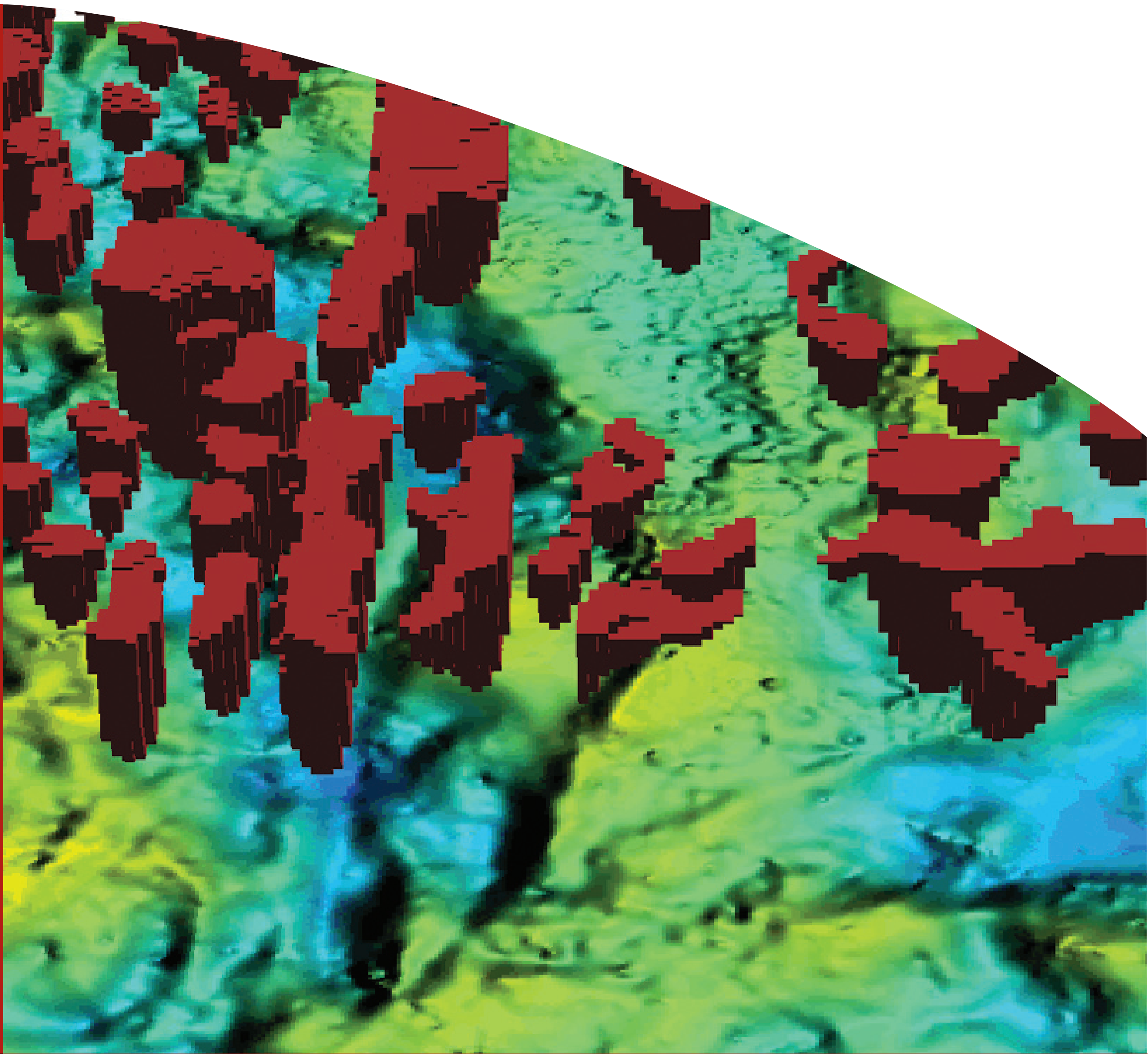

APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

Proceedings of the Sir Mark Oliphant International Frontiers of Science and Technology Australian Geothermal Energy Conference

GEOSCIENCE AUSTRALIA
RECORD 2008/18

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Geothermal Energy Conference
19-22 AUGUST Rydges Hotel Melbourne

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Cover illustration: 3D image of gravity inversion modelling in southern Cooper Basin region of South Australia, viewed obliquely from the west. The maroon bodies enclose regions of low density interpreted as granites located at depth beneath Cooper Basin sediments. The interpreted granites are shown projected above an image of the Bouguer Gravity field, from which the inversion model was generated. Courtesy of Tony Meixner, Geoscience Australia.

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Introduction

This volume is a compilation of Extended Abstracts presented at the 2008 Australian Geothermal Energy Conference, 19-22 August 2008, Rydges Hotel, Melbourne, organised by the Australian Geothermal Energy Association and the Australian Geothermal Energy Group.

This Conference is the first dedicated conference organised by the geothermal energy community in Australia and has been made possible by seed funding from the Australian Government under the Sir Mark Oliphant International Frontiers of Science and Technology Conference funding scheme with additional sponsorship of the companies acknowledged earlier and paying delegates.

This Conference is being held at a time of rapid growth in all sectors of the geothermal community. The number of companies engaged in exploration stands at 33, the number of leases held or applied for is 320, and the value of the work program for these companies exceeds $850 million between 2002-2013. The Australian Geothermal Energy Association has been incorporated to serve as the peak industry representative body. The Universities of Queensland, West Australia, Adelaide and Newcastle have new funding specifically for geothermal research programs. The Australian Government has continued its strong support of the sector through the Geothermal Industry Development Framework and Technology Roadmap, the Geothermal Drilling Program, and the Onshore Energy Security Program. All of the States now have legislation regulating geothermal exploration activity in place, and the Northern Territory has drafted legislation for presentation to parliament.

This volume of Extended Abstracts starts with a summary snapshot of the global and national geothermal energy sectors.

The rest of the volume is organised under three headings:

- Underground Science and Technology
- Power Conversion Technologies
- Legislation, Policy and Infrastructure

As editors of these proceedings, we first would like to thank the Technical Committee who have been very generous with their time to review the submissions and to work with the authors of the accepted submissions to improve the quality of the Abstracts and the presentations.

We also thank the Conference Chair Alan Knights and the rest of the Organising Committee who were brave enough to take on the job organising this inaugural event on behalf of the Australian Geothermal Energy Association and the Australian Geothermal Energy Group. Jem Hansen and Impact Environment Conferences have done an excellent job in assisting the organisation.

We also thank again the sponsoring companies for their generous support.

We thank Geoscience Australia for printing the proceedings.

Finally, we thank all delegates without whose participation none of this is worthwhile.

Anthony Budd

Hal Gurgenci

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Contents

Introduction i

National Outlook

Budd, A.R., Holgate, F.L., Gerner, E., Ayling, B.F. and Barnicoat, A.
Pre-competitive Geoscience for Geothermal Exploration and Development in Australia: Geoscience Australia's Onshore Energy Security Program and the Geothermal Energy Project 1

Goldstein, B.A., Hill, A.J., Budd, A.R., Holgate, F.L., and Malavazos, M.
The National Outlook - Australia's Hot Rocks 9

Tester, J.W.
The Future of Geothermal Energy as a Major Global Energy Supplier 19

Underground Science and Technology

Alehossein, H. and Hooman, K.
Coupled Thermomechanical Boundary Element Modelling (BEM) 23

Asanuma, H., Kumano, Y., Niitsuma, H., Wyborn, D., Schanz, U. and Haring, M.
Current Status of Microseismic Monitoring Techniques for the Stimulation of HDR/HFR Reservoirs 29

Baria, R., Petty, S. and Beardsmore, G.R.
Economic and Technical Cases for the Commercial Exploitation of Engineered Geothermal Systems . 37

Beardsmore, G. R.
Hot Rock Exploration Methods 39

Cibich, W., Malavazos, M., and McDonough, R.
A Steady-State Pressure Model for Water Flow in a Hydraulically Fractured Geothermal Reservoir. 43

de Graaf, B. and Gunter, J.
The Limestone Coast Project – a unique geothermal project targeting 'blind' geothermal resources. 51

Ghori, K.A.R.
Perth Basin's Geothermal Resources 55

Gibson, H., Stüwe, K., Seikel, R., FitzGerald, D., Calcagno, P., Guillen, A. and McInerney, P.
Forward Prediction of Temperature Distribution Direct From 3D Geology Models 63

Gordon, K.
The Thermal Structure of Continental Lithosphere: a Review 71

Häring, M.O., Ladner, F. and Schanz, U.
Lessons Learnt from the Deep Heat Mining EGS Project in Basel, Switzerland 77

Hidalgo R. and Ungemach P.
Madrid Basin District Heating Potential 79

Hillis, R.R.
In-Situ Stress in Australia and Subsurface Fluid Flow 81

Horowitz, F.G., Regenauer-Lieb, K., Wellmann, J.F., Chua, H.T., Wang, X. and Poulet, T.
Evidence for Hydrothermal Convection in the Perth Basin, Australia 85

Larking, A.
Hydraulic Fracturing at the Olympic Dam Geothermal Energy Project 89

Lawless, J.
Progress on the AGEG Code and Lexicon for Geothermal Resources and Reserves Reporting. . . 91

Leary, P.C. and Malin P.E.
Advection Heat Flow and the 1/F-Noise Fracture Nature of Crustal Rock 93

Lewis, R.J.G., Ward, M.A. and Bishop, J.R.
New Heat Flow Data From Tasmania and the Emergence of Eastern Tasmania as a New EGS Province 97

Malin P.E., Shalev, E., and Kahn, D.
Big Boom in Basel: is Oz next? 103

McAllister, L., Bendall, B., Reid, P., Hasting, M., Englehart, E., Malin, P.E., and Shalev, E.
Applying Lessons Learned in Borehole Seismology to the Paralana Geothermal Development in South Australia 109

Morelli, C.P., and Malavazos, M.
Analysis and Management of Seismic Risks Associated With Engineered Geothermal System Operations in South Australia 113

Regenauer-Lieb, K., Chua, H.T., Wang, X., Horowitz, F.G. and Wellmann, J.F.
Direct-Heat Use for Australia 117

Sanyal, S.K.
Optimisation of Geothermal Resource Economics 123

Thorsteinsson, H.H. and Tester, J.W.
Geothermal District Heating Development 127

Wang, Y.C.
Discrete Element Simulation of Hydraulic Fracturing and Induced Seismicity in Engineered Geothermal Systems 129

Webb, G., White, D., Stafford, C. and Beardsmore, G.R.
Recent Developments in the Measurement of Down-Hole Temperatures and Thermal Conductivity for Heat Flow Determination: a Review 135

Wyborn, D.
Habanero Circulation Test – Connection Between Two Wells in Granite at 4,200 m Depth 143

Xing, H. L., Xu, H., Wyborn, D., Liu, E., Yu, W. and Muhlhaus, H.
Towards High Performance Simulation of Geothermal Reservoir Systems 145

Power Conversion Technologies

Atrens, A.D., Gurgenci, H. and Rudolph, V.
Carbon Dioxide Thermosiphon Optimisation 149

Langman, A.S., Battye, D., Nathan, G.J., Ashman, P.J., Dally, B.B. and Oakeshott, C.
Preliminary Assessment of the Effect of Ambient Temperature on the Performance of Air-Cooled Geothermal Power Plants at a Typical Site in South Australia 153

Berndt, M.L. and Philippacopoulos, A.J.
Improving the Performance of Geothermal Heat Pumps through Borehole Grout Materials. 157

Dally, B.B., Hew, F.L., Nathan, G.J. and Ashman, P.J.
Feasibility of Underground Cooling for Geothermal Power Plant Applications. 163

Ejlali, A. and Hooman, K.
A Comparative Study on Dry Cooling of Different Working Fluids for Geothermal Applications 165

Hooman, K. and Gurgenci, H.
Air Cooled Porous Matrix Heat Exchangers for Geothermal Applications 169

Jacobs, P.A. and Gurgenci, H.
A Small Turbomachinery Laboratory for Geothermal Energy 173

Kaieda, H., Kubota, K., Wakahama, H., Mito, S., Ueda, A., Ohsumi, T., Yajima, T., Satoh, H., Kaji, Y., Sugiyama, K. and Ozawa, A.
Experimental Study on CO_2 Injection Into HDR Geothermal Reservoir 177

Legmann, H.
Efficiencies, Availabilities, Reliabilities and Environmental Impact of Commercial Geothermal Power Plants 181

Moghtaderi, B.
The State of the Art in Geothermal Power Plant. 183

Nas, S. and Toralde, J.S.S.
Controlled Pressure Drilling Applications for Engineered Geothermal Systems in Australia 185

Reichman, J., Bresnehan, R., Evans, G. and Selin, C.
Electricity Generation using Enhanced Geothermal Systems with CO_2 as Heat Transmission Fluid . 189

Legislation, Policy and Infrastructure

Augustine, C., Thorsteinsson, H.H. and Tester, J.W.
The Impact Of Drilling Costs on Determining Optimal Well Depth for Geothermal Exploitation . 199

Hinchliffe, S., Lawless, J. and Lee, G.
Engaging Stakeholders in the Formation of Policy for Geothermal Developments 201

McKenzie, G.C.
Geothermal Energy Regulation 203

Miller, W.A., Gomez, J. and La Ferla, D.
Advancing Geothermal Energy — Opportunities, Options and Strategies 205

Saha, T.K.
Challenges for a Future Australian Electricity Network Dominated by a Geothermal Hub 215

Pre-competitive Geoscience for Geothermal Exploration and Development in Australia: Geoscience Australia's Onshore Energy Security Program and the Geothermal Energy Project

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INTRODUCTION

Work conducted at the Bureau of Mineral Resources (now Geoscience Australia) in the early 1990s was instrumental in bringing Hot Rocks geothermal research and development to Australia. Following the announcement of the Australian Government's Energy Initiative in August 2006, a new Geothermal Energy Project has been started at Geoscience Australia. Pre-competitive geoscience previously made available for the minerals and petroleum industries has been extremely useful in assisting the geothermal exploration industry to date. This paper outlines the scope of Geoscience Australia's Onshore Energy Security Program and the development, implementation and progress to date of the new Geothermal Energy Project, including new data acquisition programs specifically aimed at assisting geothermal explorers. Geoscience Australia is the Australian Government's geoscience and geospatial information agency within the Department of Resources, Energy and Tourism.

THE ONSHORE ENERGY SECURITY PROGRAM (OESP)

A program to acquire pre-competitive geoscience information for onshore energy prospects has begun following announcement of the Onshore Energy Security Program. The initiative provides Geoscience Australia with AUS$58.9 million over five years for the acquisition of new seismic, gravity, aeromagnetic, geochemistry, heat flow, radiometric, magneto-telluric and airborne electromagnetic (AEM) data to attract investment in exploration for onshore petroleum, geothermal, uranium and thorium energy sources. The program will be delivered in collaboration with the State and Territories under the existing National Geoscience Agreement. A set of principles has been developed to guide the program. According to these, all proposed work must: (1) promote exploration for energy-related resources, especially in greenfields areas; (2) improve discovery rates for energy-related resources; (3) be of national and/or strategic importance; and (4) data acquisition must be driven by science.

The program is structured with national-scale projects for each energy commodity (geothermal, petroleum, uranium and thorium) and for geophysical and geochemical acquisition. Regional scale projects in Georgetown-Isa, Gawler-Curnamona, Northern WA and the Northern Territory areas will assess the energy potential of these areas in detail. Other regions will be prioritised at a later stage of the OESP. Further information on the OESP can be found at: http://www.ga.gov.au/minerals/research/oesp/index.jsp.

FORMULATING THE GEOSCIENCE AUSTRALIA GEOTHERMAL ENERGY PROJECT

Extensive consultation with State and Territory geological surveys and geothermal companies identified a list of key impediments faced by geothermal companies exploring in Australia. The Geothermal Energy Project aims to address those impediments that may be mitigated through geoscience input.

The greatest identified geological need is an improved understanding of the distribution of temperature in the upper crust of Australia. With no active volcanic systems, geothermal plays in Australia are dominated by conductive Hot Rock systems. There are few surface expressions indicating thermally anomalous areas, and explorers must use indirect methods in such blind systems. The two existing datasets that map temperature and heat distribution - the Austherm05 map of temperature at 5 km depth, and a database of heat flow measurements (Cull 1982) - both suffer from insufficient data points compounded by poor data distribution. Geoscience Australia aims to compile further information for both of these datasets, and acquire new data where possible. Predictions of heat distribution can also be made based on geological models, such as the co-location of high-heat-producing granites with overlying low-thermal-conductivity sediments. These three ways of mapping heat, and the work that the project will do in each of these areas, is described in more detail in later sections.

Other geoscience inputs that will help improve discovery rates and/or reduce risk to explorers and investors include a comprehensive and accessible geothermal geoscience information system, a better understanding of the stress state of the Australian crust, better access to seismic monitors during reservoir stimulation, and a Geothermal Reserve & Resource reporting scheme. Increasing the awareness of Australia's geothermal potential amongst decision makers and the general public may also help to fund the development of industry through Government support and investor confidence. The Geothermal Energy Project has an involvement in all of these activities and this is outlined in later sections.

MAPPING HEAT

Temperature increases with depth in the crust. Currently drilling technology limits economic development of Hot Rock geothermal extraction systems to about 5 km maximum depth. Temperatures of >200 °C are required at such depths to make the generation of electricity commercially feasible. Temperature is not evenly distributed across the continent, and a temperature of 200 °C at 5 km is anomalous. Therefore it is necessary to find 'hot spots' or areas with above average crustal temperature. There are three ways in which this problem may be approached and each is detailed below. Combined, the ultimate aim of this work is to divide the continent into geothermal provinces with defined geothermal potential in each province.

Temperature at 5 km depth

When bore holes are drilled, temperature measurements are often taken downhole including at the bottom of the hole. This is particularly true for petroleum, as temperature is important information for understanding the maturity and therefore the grade of oil or gas that may be expected. Temperature measurements, combined with other information such as thermal gradient, allow the temperature expected at 5 km depth to be vertically extrapolated. This extrapolated temperature can be horizontally interpolated between drillholes and then contoured to produce a continuous map of temperature at 5 km depth across the entire continent. This technique was pioneered by Somerville et al. (1994 - Geotherm94 database) at the Bureau of Minerals Resources (now Geoscience Australia) and the Energy Research and Development Corporation. Additions and refinements were subsequently made to the database by Chopra and Holgate (2005 - Austherm05 database)

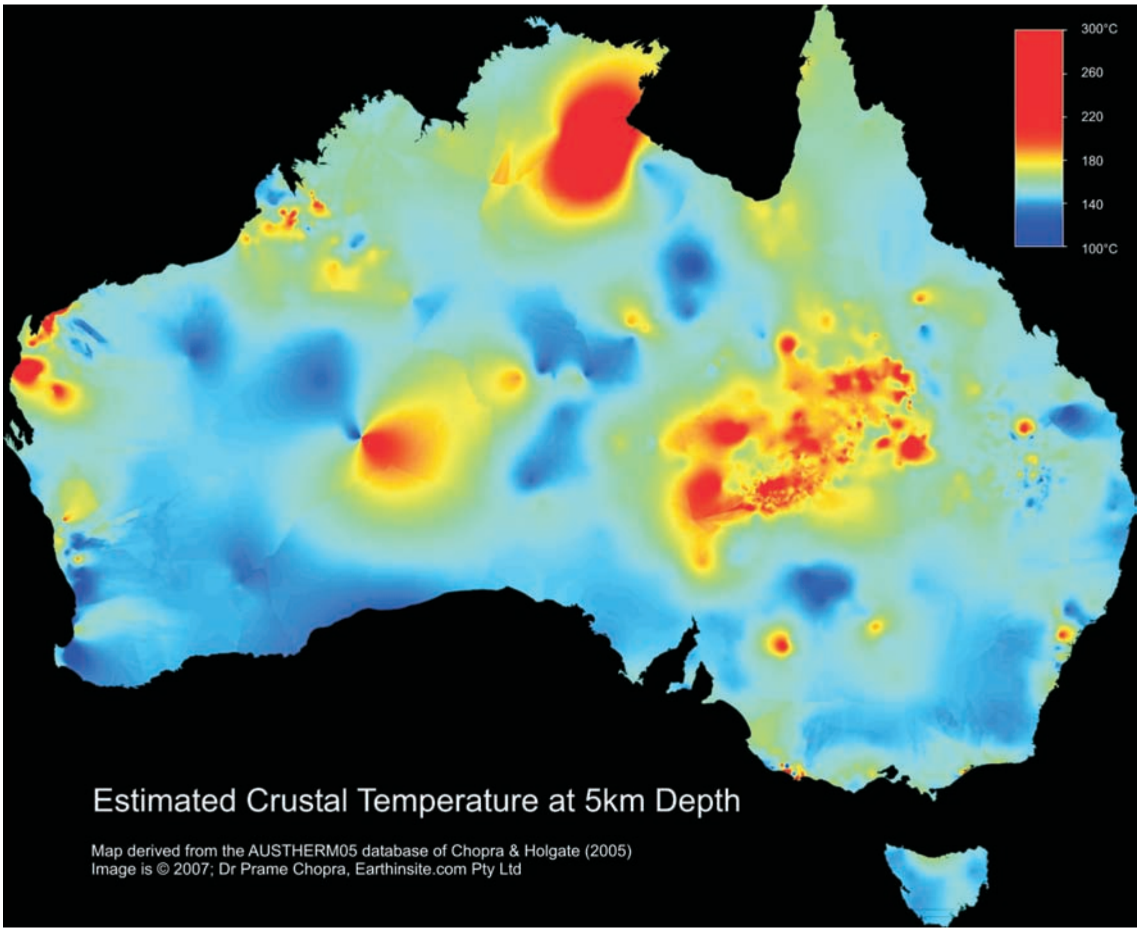

Figure 1. Modelled crustal temperature at 5 km depth using data from the AUSTHERM05 database (Chopra & Holgate 2005). The temperature data contained in this image has been derived from proprietary information owned by Earth Energy Pty Ltd ABN 078 964 735.

(Figure 1). In 2007 Geoscience Australia purchased the Austherm05 database from Dr Chopra (Earth Energy Pty Ltd) and has been making further improvements. These include utilising the OZ SEEBASE™ [1] sediment thickness data to better constrain the depth at which geothermal gradients change from those typical of sedimentary basins to the lower gradients typical of crystalline basement rocks, and dividing the continent into areas of different temperature gradient based on recognised heat flow provinces.

The Austherm05 database has also been used in a new way to estimate the geothermal energy contained within the Australian crust. The 5 km economic drilling depth was used as a lower depth extent: in the USA a similar estimation was based on a depth of 10 km (Tester et al. 2006). The database was interrogated to provide the depth at which 150 °C would be predicted to form an upper depth layer. Grids with 5 km x 5 km cells were made and the average temperature, volume and an estimation of the contained heat was calculated for each cell (Figure 2). This provides an estimate of 1.9×10^{25} Joules of energy contained in the upper 5 km of Australia's crust, which is the equivalent of about 2.6 million years energy supply at 2004-2005 consumption levels[2]. Not all of this energy will be accessible for extraction: but even if a low estimate of 1 % were taken, geothermal sources could still provide 26,000 years of energy supply. Future drilling and extraction

[1] OZ SEEBASE™ available as a free download from www.frogtech.com.au.

[2] 2004-2005 gross energy consumption = 7258.1 PJ: ABARE Energy in Australia 2006.

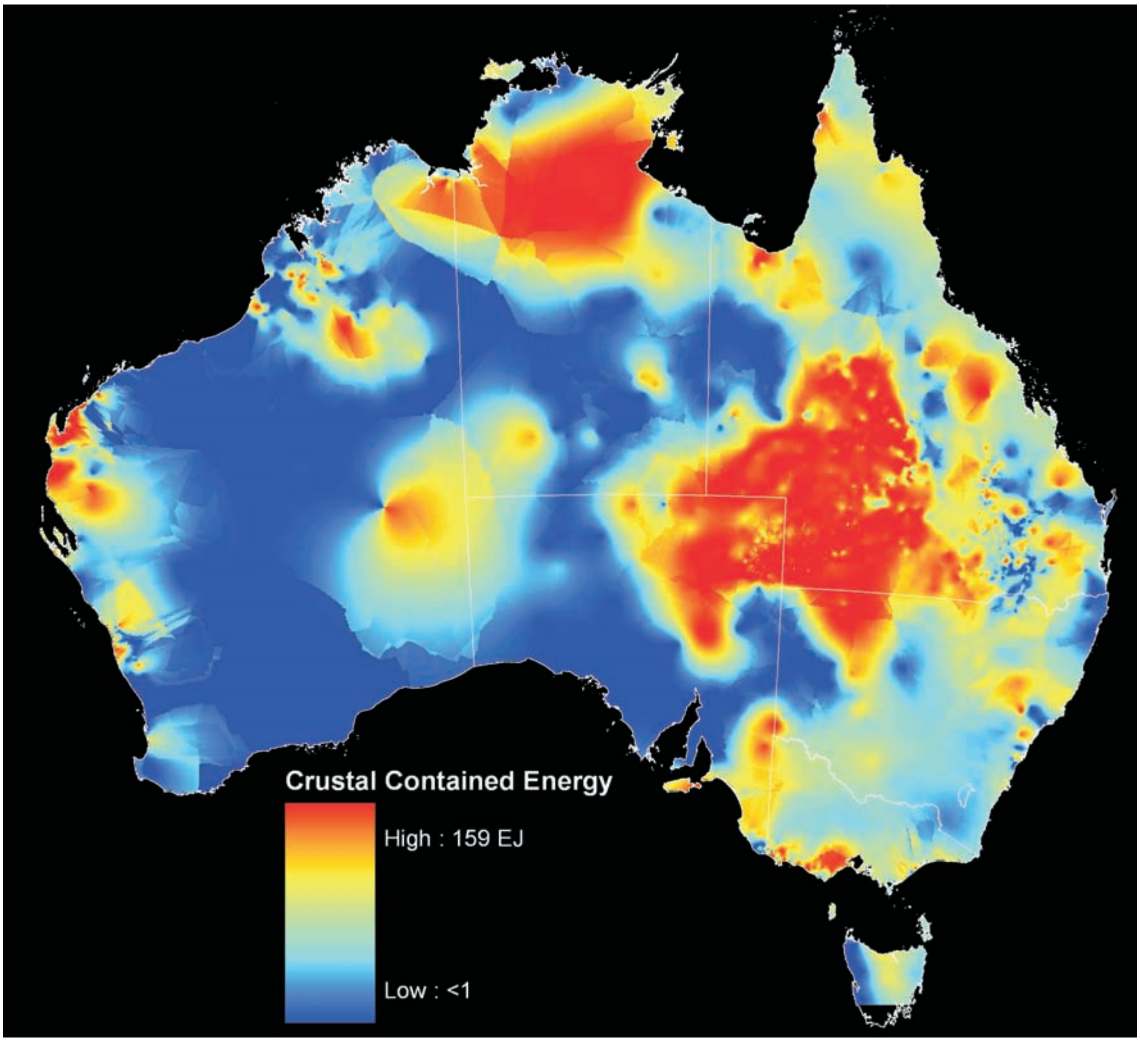

Figure 2. Map of distribution of contained crustal energy. See text for calculation method. The total resource is 1.9 × 10^{25} J, equivalent to 2.6 millions times the gross energy consumption in Australia during 2004-2005. The temperature data used in this image has been derived from proprietary information owned by Earth Energy Pty Ltd ABN 078 964 735.

technologies will undoubtedly allow extraction of heat at depths greater than 5 km, meaning that this figure is conservative.

Heat flow measurements

Heat flow is the preferred method of quantifying the amount of thermal energy that is available at a particular geographic location. Heat flow is the product of thermal gradient and thermal conductivity, and may be measured in the crust via drill holes. There are approximately 200 heat flow measurements throughout Australia, a coverage that is far too sparse to provide a meaningful map of heat flow on a continental scale. Geoscience Australia has purchased a thermal conductivity meter and downhole logging equipment in order to acquire new heat flow measurements to improve the definition of heat flow provinces throughout the continent. The project will operate a field crew full-time to measure the temperature gradient in selected holes across the continent and will also sample drill core from State and Territory core libraries to make new thermal conductivity measurements.

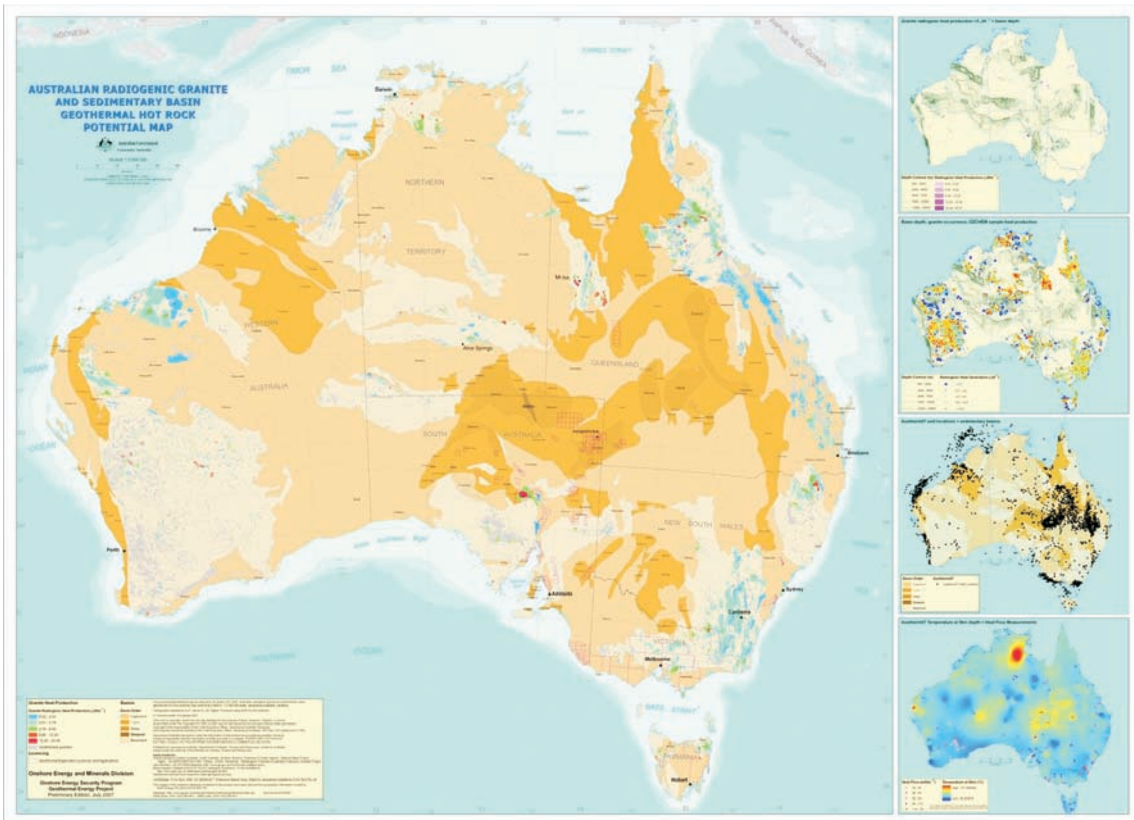

Figure 3. Map showing distribution of granites and their radiogenic heat production, combined with location and depth of sedimentary basins (main panel). Right-hand panels include information on the distribution of geochemical samples and their U-Th-K contents, distribution of downhole temperature measurements, depth of sedimentary basins, and temperature at 5 km depth. The map can be downloaded at http://www.ga.gov.au/minerals/research/national/geothermal/index.jsp.

Granite + sediment map

The key geological ingredients of the Hot Rock geothermal model are high-heat-producing granites overlain by thick accumulations of low-thermal-conductivity sediments. The decay of low concentrations of radiogenic elements (mostly uranium, thorium and potassium) over millions of years produces heat in the granite. This heat may be trapped at depth within the crust by the sedimentary cover which, lying above the granite, acts like a blanket. By mapping out deeply buried granites and having knowledge of both their chemistry and the thermal conductivity of any overlying sediment, it will be possible to make predictions about crustal temperature. Unfortunately most of the available granite chemistry comes from samples at surface, rather than from those that are buried. It is possible however to identify buried granites using remote sensing methods such as gravity and magnetics. By mapping granite outcrops it is also possible to make predictions of the composition of buried granites as they trend from outcrop areas to beneath sediments. In this way the heat production beneath sedimentary basins may be estimated. With information about the thicknesses and thermal conductivity of the overlying sedimentary strata, the heat production of the buried granites and estimation of heat flow upwards from the mantle, local temperature profiles of the crust in that location may be estimated.

Initial stages of this work have been undertaken with the compilation of information about outcropping granites and their chemistry. The heat production of the granites has been calculated, and combined in a GIS with maps of basin thickness (Figure 3). This provides a first-pass map of prospective areas, but also highlights where more granite geochemical data is needed.

OTHER ACTIVITIES

Geoscience Australia is currently involved in five of the Technical Interest Groups of the Australian Geothermal Energy Group (AGEG). The AGEG comprises the majority of government, industry and academic workers with an active interest in geothermal in Australia, and has grown from the early involvement of the IEA GIA signatories.

Land Access Protocols

Several aspects of Hot Rock developments have possible environmental impacts that will need to be assessed on a case-by-case basis. These include the potential mobilisation of radioactive elements, induced seismicity, and impacts on surface or groundwater. It must be stressed that experience to date suggests that none of these environmental impacts will provide insurmountable impediments to development. Geoscience Australia aims to have input into each of these areas from both a geoscience research and information perspective. In addition, Geoscience Australia may take an active role in seismic monitoring during reservoir stimulation, as the information gained may be useful for neotectonic hazard studies.

Direct-Use Applications of Geothermal Energy

The majority of current geothermal exploration activity in Australia is focused on electricity production, yet most of the existing developments use low-temperature geothermal resources in direct-use applications, e.g. for spas and space heating. Direct-use applications of geothermal energy have two key advantages, firstly they are generally very energy efficient, and secondly low-temperature geothermal resources are likely to be more widespread than the high-grade resources necessary for electricity generation. In a sub-project called "Geothermal for Cities" Geoscience Australia will compile detailed information on possible geothermal resources near major energy markets (i.e. cities and industrial centres) with the aim of targeting new drilling for infill heat flow measurements.

Geothermal Database

Geoscience Australia has developed an Information Management Plan for the capture, storage, manipulation and delivery of geothermal-related geoscience data. The first stage of the plan is to develop a heat flow database. This database will be populated with new data acquired by this project, as well as legacy data compiled during an extensive literature search, contributions from geothermal companies, State and Territory geological surveys, and universities. As well as complete heat flow measurements, this database will store temperature-only and thermal conductivity-only records. Other data layers that will be captured in either a relational database system or GIS include:

- Extrapolated and interpolated temperature at 5 km grid
- Geochemistry
- Drill hole locations and attributes
- Bouger gravity (and stations), magnetics, and radiometrics coverages
- Topographic information (population centres, infrastructure)
- Gamma logs
- Geology layers (outcrop, solid, faults etc)
- Seismic lines
- Digital Elevation Model
- Mean Average Surface Temperature
- Thermal IR
- Hydrogeology

Reserves & Resources Scheme

Geothermal explorers in Australia have been increasingly successful in raising money through the Australian Securities Exchange. However, as some companies move toward the project development stage, a formally defined reporting system is desirable for the purposes of ongoing capital raising. Individual developments require very large investment, with costs anticipated to be in excess of AUD$100 million. Work has commenced on a draft public reporting scheme and guidelines for geothermal resource and reserve definitions. This will be directly analogous to the Joint Ore Reserves Committee (JORC) Code for Mineral Resources and the SPE/WPC/AAPG Petroleum Resources Classification and Definitions. The geothermal scheme is being developed in collaboration with both local and international stakeholders.

Outreach

The function of this Technical Interest Group is to communicate the potential of geothermal energy to decision makers, investors and the general population. As well as describing the well-known positive aspects of geothermal developments (a cost effective low-emission renewable energy source), this TIG aims to provide information on potential areas of concern, including possible mobilisation of radioactive elements, induced seismicity during reservoir stimulation, and effects on groundwater. These are issues that will need to be addressed at each prospective development. Providing information about these concerns at an early stage will ensure informed and even debate regarding the true risks involved rather than misinformed reactions based on incorrect assumptions. Geoscience Australia is writing factsheets and other materials that aim to educate about these and other geothermal issues. The education unit of Geoscience Australia will assist in this goal, by providing information to school children, their teachers and parents. Other outreach opportunities will be taken as they arise. The Geothermal Energy Project has recently set up its own web page at http://www.ga.gov.au/minerals/research/national/geothermal/index.jsp.

Provision of Advice

Geoscience Australia provides advice to policy makers within government. This includes the formulation of the Geothermal Drilling Program, a AUD$50 million dollar-for-dollar grant scheme to progress proof-of-concept drilling and reservoir development projects in Australia, and the Geothermal Industry Development Framework and Geothermal Technology Roadmap. Both of these programs are delivered by the Australian Government Department of Resources, Energy and Tourism. Geoscience Australia also provides impartial advice to groups including the Clinton Foundation's Climate Change Initiative.

SUMMARY

New data acquisition by the Geoscience Australia Geothermal Energy Project will be conducted as part of the Onshore Energy Security Program and will include heat flow measurements across the continent. Other activities undertaken by the project will focus on compiling and interpreting relevant geoscience datasets, developing and implementing a geothermal geoscience information system, participating in the development of a Reserves and Resources reporting schema and guidelines, and helping to educate the Australian community about the Nation's geothermal potential.

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The National Outlook - Australia's Hot Rocks

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INTRODUCTION

Geothermal energy from amagmatic Hot Rocks (HR) is a source of inexhaustible, 24/7, free fuel for zero-emission power generation. These characteristics make Hot Rock (HR) geothermal resources a desirable addition to the world's portfolio of safe, secure and competitive energy supplies. Australia's vast HR resources (Figure 1) and comparative advantages for the development of Engineered Geothermal Systems (EGS) have attracted global interest, finance and government support for several HR – EGS proof-of-concept projects. Australia's long history of shared investment in mining and energy operations is also a key factor in Australia being recognised as leading the world in 'exploiting subterranean heat' (The Economist, 2008).

To 20 July 2008, 33 companies have applied-for 320 geothermal exploration licences[1] covering more than 245,000 km^2 in Australia with work program investment over the term 2002-13 totaling more than $853 million (Figures 2 and 3). This forecast excludes up-scaling and deployment projects assumed in the Energy Supply Association of Australia's scenario for 6.8% (about 5.5 GWe) of Australia's base-load power coming from geothermal resources by 2030 (ESSA, 2006).

This rapid growth has stimulated both whole-of-sector and industry alliances to form and mature. Formed in 2006, the Australian Geothermal Energy Group (AGEG) is Australia's whole-of-sector alliance of companies, government agencies and research organisations with an interest in the advancement of the use of geothermal energy. AGEG members share information and undertake high priority studies to foster efficiency on the road to commercialising Australia's geothermal resources. The Australian Geothermal Energy Association (AGEA) formed in 2008 as the peak representative Directorate for Australian geothermal industry companies. All AGEA member companies are also members of the AGEG. The AGEG's Technical Interest Groups (TIGs) are national networks that enable Australia's geothermal sector to reduce critical, shared uncertainties that left unsolved, act as impediments to geothermal energy development. Notably, the relevant AGEG TIG has developed a Code for Geothermal Resource and Reserves Reporting (AGEG, 2008a) to facilitate consistent public reporting of geothermal resources and reserves and to foster understanding of Australian HR projects. This Code has sustained considerable peer review and will be released for public consideration at the AGEG-AGEA Geothermal Energy Conference in August 2008.

Bi-partisan government support has and will be instrumental in progress attained by the geothermal sector, especially for HR-EGS projects, which are currently, all, in a pre-competitive state. It is heartening to note, that to 20 July 2008, government has committed more than $100,000,000 for geothermal projects (Table 1), and further support is expected. High priorities for government action will be articulated in the Australian Government's Geothermal Industry Development

[1] Includes 38 West Australian Perth Basin blocks covering 320 km^2 (each) that attracted bids.

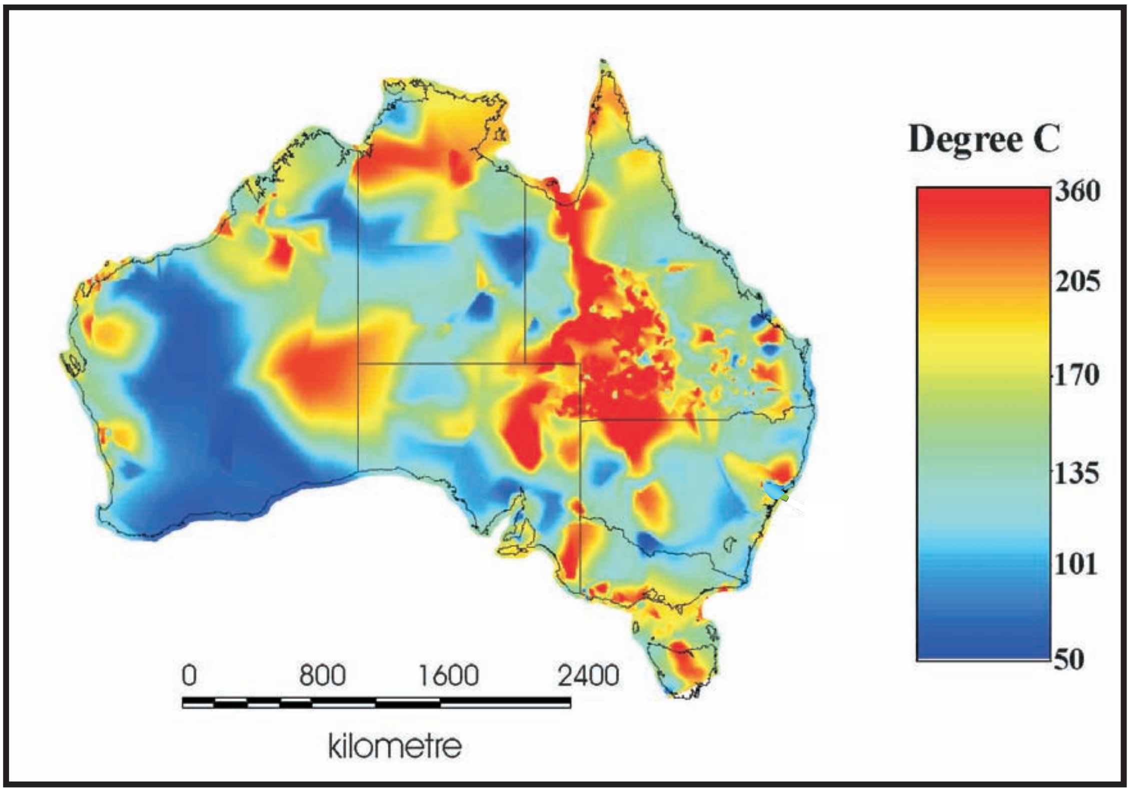

Figure 1. Estimated temperatures at 5 km in Australia (Sommerville et al., 1994).

Framework, (GIDF) and the associated Geothermal Technology Roadmap that is now being developed for consideration by the Council of Australian Governments (CoAG).

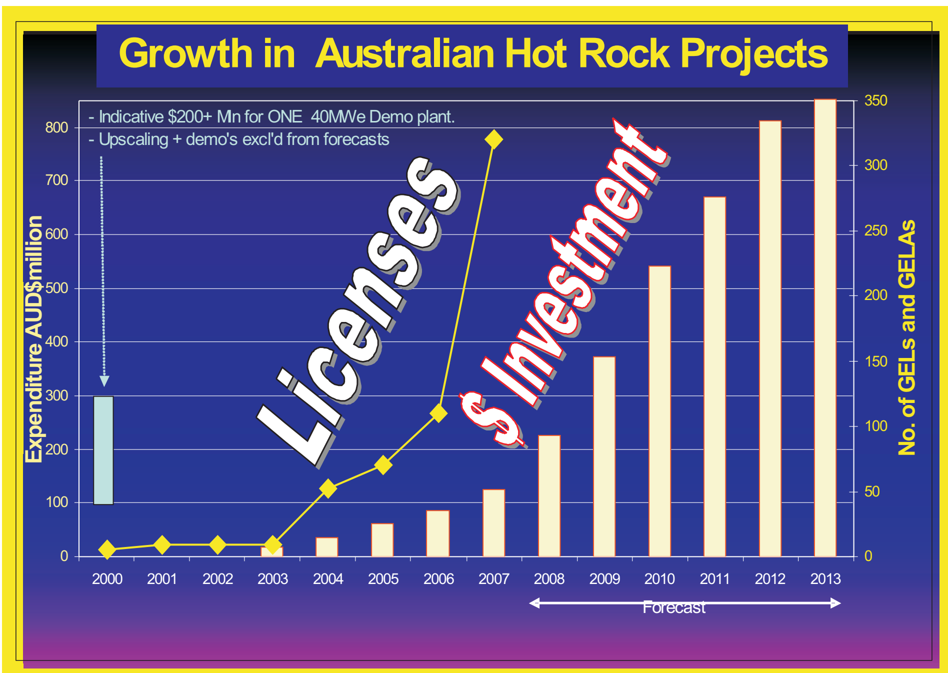

Figure 2. Cumulative actual (2000-07) and forecast (2008-13) expenditure on geothermal proof-of-concept projects and growth in Australian geothermal licences.

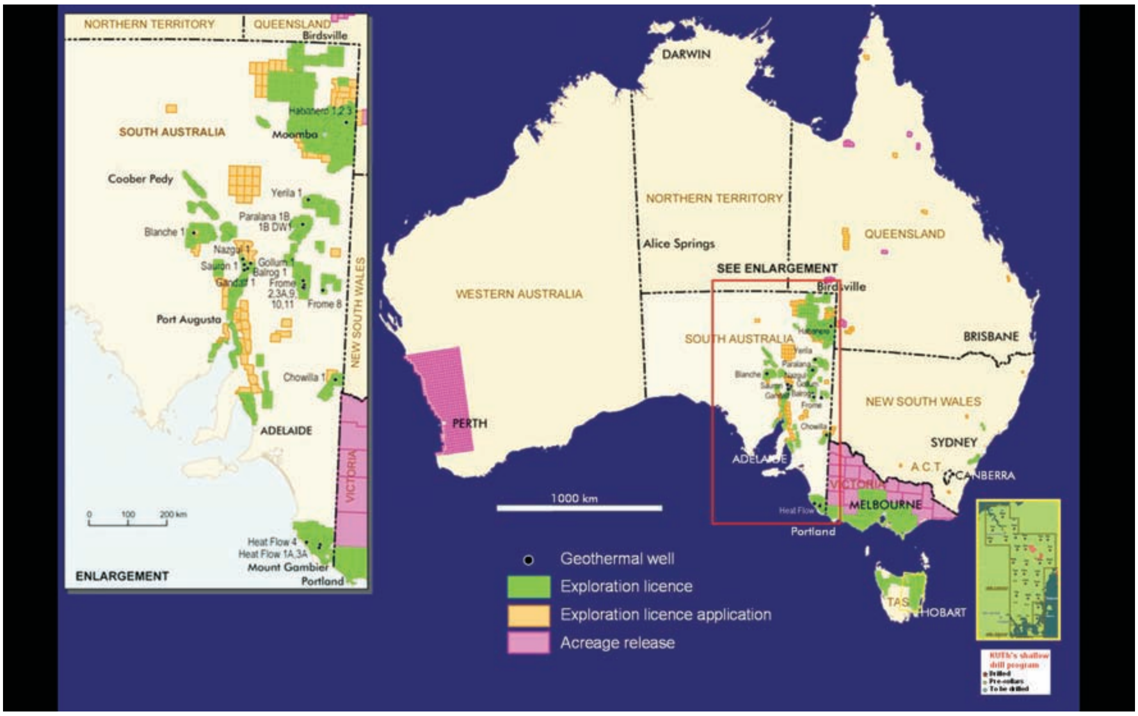

Figure 3. Geothermal licences, licence application areas and wells drilled in Australia to 1 July 2008.

Given compelling success in current proof-of-concept and subsequent demonstration projects, Australia's world class 'amagmatic' HR resources have potential to fuel competitively-priced, emission free, renewable baseload power for centuries to come (AGEG, 2008b).

Table 1. Government grants for geothermal energy projects since 2000.

Grant	Date	Recipient	Project	A$ Amount
Fed. RECP	2000	Pacific Power/ANU	Hunter Valley Geothermal Project	$790,000
Fed. START	2002	Geodynamics	Habanero Project	$5,000,000
Fed. REEF	2002	Geodynamics	Habanero Project	$1,800,000
Fed. GGAP	Mar-05	Geodynamics	Kalina Cycle to produce energy from waste	$2,080,000
Fed. REDI	Dec-05	Geodynamics	Habanero Project, Cooper Basin, SA	$5,000,000
Fed. REDI	Dec-05	Scopenergy	Limestone Coast Geothermal Project, SA	$3,982,855
SA PACE 2	Apr-05	Petratherm	Paralana Geothermal Project, SA	$140,000
SA PACE 2	Apr-05	Scopenergy	Limestone Coast Geothermal Project, SA	$130,000
SA PACE 2	Apr-05	Eden Energy	Witchellina Project, SA	$21,000
SA Grant	Jun-05	U of Adelaide	Induced seismicity – Cooper Basin	$50,000
SA Grant	Dec-05	Geodynamics	Cost: benefit of hot rock development	$40,000
SA PACE 3	Dec-05	Geothermal Resources	Curnamona Geothermal Project, SA	$100,000
SA PACE 3	Dec-05	Green Rock	Olympic Dam Geothermal Project, SA	$68,000
Fed. REDI	Jul-06	Geothermal Resources	Frome Geothermal Project	$2,400,000
Fed. REDI	Dec-06	Proactive Energy	Adapting supercritical cycles to geothermal power application	$1,224,250
SA PACE 4	Dec-06	Torrens Energy	Heatflow Exploration in Adelaide Geosyncline	$100,000

Grant	Date	Recipient	Project	A$ Amount
SA PACE 4	Dec-06	Eden Energy	Renmark Geothermal Project, SA	$100,000
SA PACE 4	Dec-06	Geodynamics	High Temperature Borehole Image logging of Habanero 3, Cooper Basin, SA	$100,000
Fed. REDI	Feb-07	Petratherm Ltd	Paralana Geothermal Project, SA	$5,000,000
SA Grant	May-07	U of Adelaide	Induced seismicity protocols – SA	$50,000
SA Grant	Jun-07	U of Adelaide	Research posed by the AGEG	$250,000
Fed. REDI	Aug-07	Torrens Energy	3D modelling of hot rock resources, SA	$3,000,000
Qld Grant	Oct-07	U of Queensland	Geothermal energy research	$15,000,000
SA PACE	Feb-08	Petratherm	Shear wave splitting for Hot Rock exploration	$100,000
SA PACE	Feb-08	Torrens Energy	2D seismic on a Hot Rock play in the Adelaide Plains	$100,000
REDI	2008	KUTh	Tamar Conductivity Zone (TCZ)	$1,800,000
WA Grant	Mar-08	U of WA	WA Geothermal Centre of Excellence	$2,300,000
SA Grant	Jun-07	U of Adelaide	Research posed by the AGEG	$250,000
SA Grant	Jun-08	U of Adelaide	Research posed by the AGEG	$250,000
Fed. Renewable Energy Fund	Announ ced	TBD	Geothermal Drilling Program	$50,000,000

AUSTRALIAN HOT ROCK PLAYS

HR plays have a heat source, insulating strata to trap and store heat, and permeable fabrics that combine to provide at least enough heat transfer to be useful. The Australian continent has extensive sources of prospective radiogenic heat trapped by and stored within overlying sedimentary rock units. Included are the Proterozoic granitoids in the Cooper Basin that have been described as the hottest amagmatic rocks in the world. The Cooper Basin HR play is part of a more extensive prospective region that exhibits an anomalously high mean heat flow of 92±10 μWm^{-2} which is almost twice the global average for continents of 51–54 μWm^{-2} (Neumann et al., 2000). Elsewhere in Australia, radiogenic iron oxides, hydrothermal systems, high-heat producing granites of Archaean and Palaeozoic age and hot depocentres associated with recent volcanic activity also constitute attractive source rocks for geothermal energy resources

The map in Figure 1 shows estimated temperatures at a depth of 5 km; the areas shown in orange and red represent temperatures in excess of 175 °C, and exploration now underway is expected to add to the inferred extent of prospective HR plays.

In addition to having some of the hottest amagmatic geothermal source rocks in the world, Australia's convergence with Indonesia on a plate scale gives rise to stress fields manifested by extensive horizontal fracture fabrics. Examples include the water-saturated Hot Fractured Rocks (HFR) found at ~ 4km in Geodynamics' Habanero wells in the Cooper Basin. These HFR reservoirs are susceptible to hydraulic fracture stimulation to enhance and extend connectivity and form EGS.

The threshold for economic heat exchange efficiency defines the top of a geothermal play and can be characterised as the minimum flow of a useable level of heat energy.

The practical maximum depth-range for HR targets is limited by drilling and completion technologies (defining a base). It is worth noting the current depth record for oil well drilling is 10,421 m below sea level in a water depth of 1,067 m.

HR reservoirs within the lower reaches of insulating cover in the Paralana area in South Australia have been called Heat Exchange Within Insulator (HEWI) targets. Stress conditions favoring the development of near-horizontal reservoirs are likely to exist at many of the Australian EGS project areas.

HR sandstone reservoirs in the depocentres of the Eromanga, Otway and Gippsland Basins have been referred to as Hot Saline Aquifer (HSA) targets. If enhanced with reservoir stimulation methods, both HEWI and HSA are also forms of EGS.

In general, HFR and HEWI plays are being explored for at depths below 3.5 kms of insulating cover. Australian HSA plays now being investigated tend to lower temperature resources at shallower depths as compared to current HFR and HEWI targets.

High permeability and somewhat lower temperature targets are also widespread in Australia. The world's largest artesian groundwater basin, underlying about 22 % of the Australian continental landmass, is the Great Artesian Basin. Groundwater comes out at wellheads at temperatures ranging from 30–100 °C. The very permeable sedimentary aquifers in the West Australian Perth Basin are expected to be an excellent source of high flow rates of water at temperatures of around 80 °C and these moderately hot waters can to used for MW-scale direct heat applications to generate power for local use (Regenauer-Lieb et al., 2007, 2008).

PROSPECTIVE MATERIALITY OF AUSTRALIA'S HOT ROCK RESOURCES

As one measure of materiality, converting just 1 % of the Australia's estimated crustal energy between the depths to 150 °C and 5 km (190 million PJ) to electricity would supply around 26,000 years of Australia's primary power usage in 2005, and that neither takes into account the renewable characteristics of hot rocks, nor the resource below 5,000 m.

The potential materiality of Hot Rock project areas remains to be fully demonstrated but proponents of geothermal energy development believe there is sufficient information to conclude:

- Hot, wet, fractured granites in Geodynamics' South Australian Cooper Basin geothermal tenements (covering 1,983 km^2) represent a potentially accessible *in-situ* resource of 282,150 PJ in 10 GRL's and 115,200 PJ in GEL99 that may in future be able to support > 10,000 MW of emissions-free power generation (note: this estimate does not comply with the Australian Code for Reporting of Exploration Results, Geothermal Resources and Geothermal Reserves ~ The Geothermal Reporting Code ~ 2008 Edition);
- Heat exchange within insulator (HEWI) hot rocks covering just 20 km^2 area by 1 km thick with an average temperature of 200 °C in Petratherm's Paralana project area in the northern Flinders Range in South Australia could support the generation of 520 MW of electricity to the National Electricity Market over 25 years; and
- Hot wet sandstones in Panax's Limestone Coast Geothermal Project in the South Australian Otway Basin geothermal tenements (covering 2,674 km^2) represent a possibly accessible generating potential in excess of 1,500 MW_e.

THE AUSTRALIAN GEOTHERMAL ENERGY GROUP

The Australian Geothermal Energy Group (AGEG) is Australia's whole-of-sector representative body for the organisations with an interest in the advancement of the use of geothermal energy. AGEG members:

- are representatives of companies, government agencies, research organisations and non-profit organisations with an interest in the advancement of geothermal energy development; and
- cooperate to attain a shared aspiration, which is to realise the vision of geothermal resources providing the lowest cost emissions-free renewable base load energy for centuries to come.

The AGEG's purposes and terms of reference are to:

- provide support for Australia's membership in the IEA's Geothermal Implementing Agreement (GIA) and facilitate engagement with the international geothermal community.
- foster the commercialisation of Australia's geothermal energy resources by:
  - cooperating in research and studies to advance geothermal exploration, proof-of-concept, demonstration and development projects;
  - cooperating to develop, collect, improve and disseminate geothermal-related information;
  - identifying opportunities to advance geothermal energy projects at maximum pace and minimum cost; and
  - disseminating information on geothermal energy to decision makers, financiers, researchers and the general public e.g. outreach

Many of the company members of the AGEG are also members of the Australian Geothermal Energy Association (AGEA) – the peak representative Directorate for Australian geothermal industry companies.

To 20 July 2008, the AGEG has 75 member organisations (57 companies, 10 Universities and lead agencies (for geothermal) within the Australian, State and NT governments. The AGEG's current TIGs are described in Table 2.

Table 2. Australian Geothermal Energy Group's Technical Interest Groups.

	TIG TOPICS	**Purpose:** **Share Information to Learn While Doing with Maximum Effect & Efficiency**
1	Land Access Protocols (induced seismicity, emissions, native title, etc)	Management of environmental concerns and potential impacts of geothermal energy and devises protocols to avoid or minimise impacts.
2	Reserves and Resource (Definitions)	Align with similar International forums.
3	Policy Issues Industry Forum (AGEA) Whole-of-Sector Forum (AGEG)	Industry advice to Governments. Formative whole-of-sector discussion of policy. Submission to Garnaut Review on behalf of the Geothermal Sector (AGEG 2008c).
4*	Engineered Geothermal Systems	Investigate technologies for enhancing geothermal reservoirs for commercial heat extraction.
5	Interconnection with Markets Industry Forum (AGEA) Whole-of-Sector Forum (AGEG)	Transmission, distribution, network, NEM issues. Industry advice to Government.
6*	Geothermal Power Generation	Develop scenarios as a basis for comparison of cycles, plant performance and availability, economics and environmental impact and mitigation. The output would be a database and guidelines of best practice.
7*	Direct Use of Geothermal Energy (including geothermal heat pumps)	Direct use for heating and cooling, with emphasis on improving implementation, reducing costs and enhancing use.
8	Outreach (Including Website)	Create informed public through accessible information. Provide educational kits for media, K-12 and university education.
9	Data management	Database design, contents and ongoing enhancements.
10*	Wellbore operations	Cover drilling, casing, logging, fracture stimulation, testing, etc.

* Parallels an IEA R&D Annex

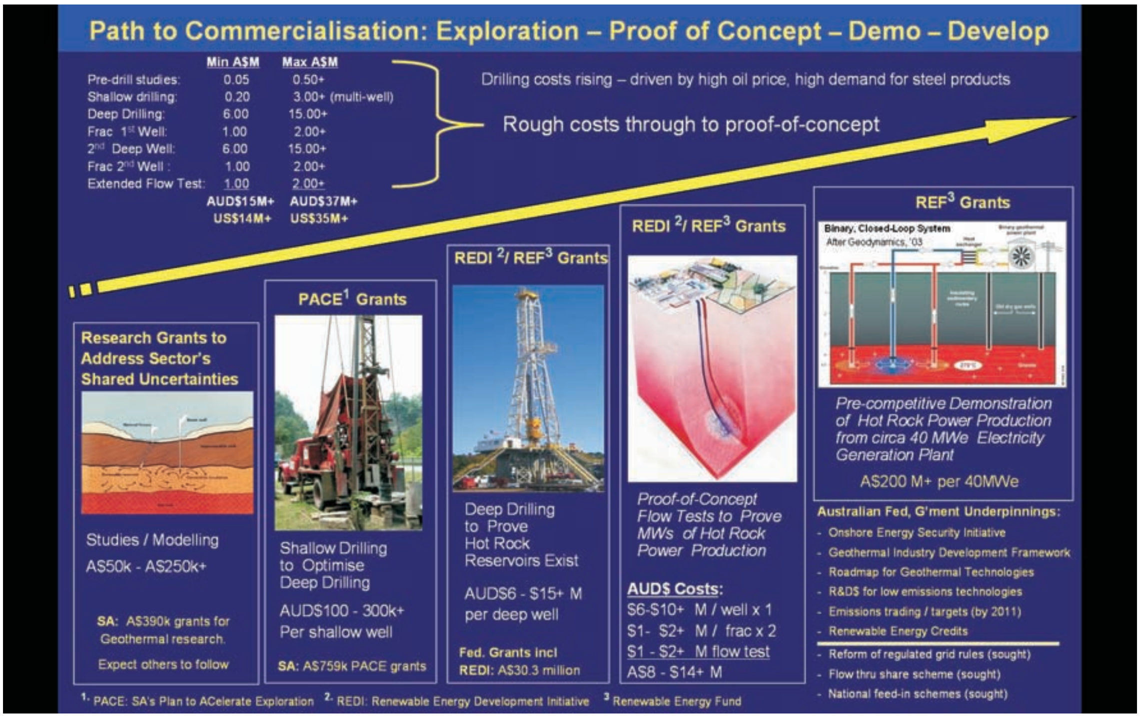

Figure 4. The life-cycle of Hot Rock Engineered Geothermal Systems projects and Federal initiatives that underpin such projects.

THE LIFE CYCLE OF HOT ROCK PROJECTS

The path to developing a HR-EGS supply of power entails HR play selection; licensing; reconnaissance exploration (research), including geophysical surveys and shallow drilling;

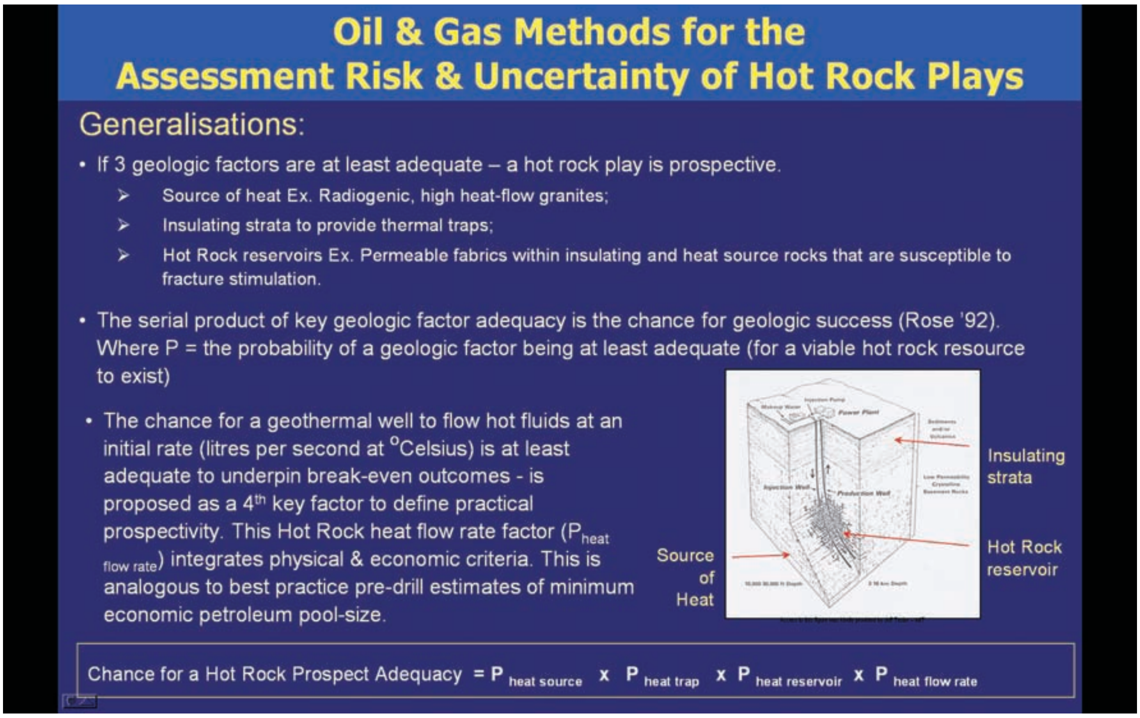

Figure 5. Risk and uncertainty assessment for hot rock plays.

proof-of-concept deep drilling; fracture stimulation and flow testing; pre-competitive demonstration of power generation; and up-scaling to a marketable power supply. Figure 4 illustrates that the cost of proving HR-EGS closed-loop production of prospective geothermal energy from one production and one injector wells is expected to be $15 to $37+ million. Also shown is the array of Australian Government initiatives underpinning such investment in addition to the grants listed in Table 1.

GEOLOGIC RISK ASSESSMENT OF HOT ROCK PLAYS

Standard investment management methods including the aggregation of risk-weighted (expected) net present values will inevitably be applied to steward funding for efficient and effective exploration, proof-of-concept and pre-competitive demonstration projects.

Goldstein et al. (2008) proposed a portfolio approach to foster efficient investment in HR-EGS plays. The methodology posed enables consistent estimates of the costs and benefits of precompetitive learning-while-doing (cost curves) through research (drilling), proof-of-concept (stimulating and flow testing) and demonstration (pre-competitive power generation) phases of HR-EGS projects. The methods are as defined by Capen (1992) and Rose (1992) for dealing with exploration uncertainties and estimating the chance of economic success in petroleum exploration. These methods are well recognised as world's best practice for petroleum exploration, and have proven to be effective in managing geologic uncertainties in very competitive oil and gas markets. The process for assessing a single HR-EGS play is described in Figure 5.

KEY TAKE-AWAYS

Australia's comparative advantages for HR-EGS development are:

- Extensive radiogenic basement (heat source) at drillable depths below insulating cover;
- Plate scale compression creating extensive horizontally fractured HR that are attractive EGS candidates;
- Receptive investors experienced in buying shares in green-field exploration projects;
- Bi-partisan political support leading to government programs and policies that support meritorious proof-of-concept, demonstration, demonstration and deployment of low emissions and renewable energy technologies to sustain Australia's diverse portfolio of safe, secure, socially accepted and competitively priced energy supplies.

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The Future of Geothermal Energy as a Major Global Energy Supplier

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ABSTRACT

Recent international focus on the value of increasing the supply of indigenous, renewable energy underscores the need for re-evaluating all alternatives, particularly those that are large and well-distributed on a national or global basis, to expand and diversify the portfolio of options we should be vigorously pursuing. One such option that is often ignored in national assessments is geothermal energy from both conventional hydrothermal and enhanced or engineered geothermal systems (EGS). Although geothermal energy is used for both electric and non-electric applications worldwide from conventional hydrothermal resources, these natural resources are limited in extent and their eventual impact on a global scale will be restricted to relatively few locations that have all the ingredients needed for successful operation – that is the presence of large volumes of confined steam or hot water close the surface contained in well-connected, permeable reservoirs.

If we are to transition our global energy system and have geothermal play a significant role in that transition, it will be necessary to exploit EGS resources on a large scale for base load type applications for heating, cooling and electric power generation.

Overall, the geothermal resource can be viewed as a continuum of grades or regions, as depicted in Figure 1. The continuum ranges from high grade hydrothermal resources, which have high average

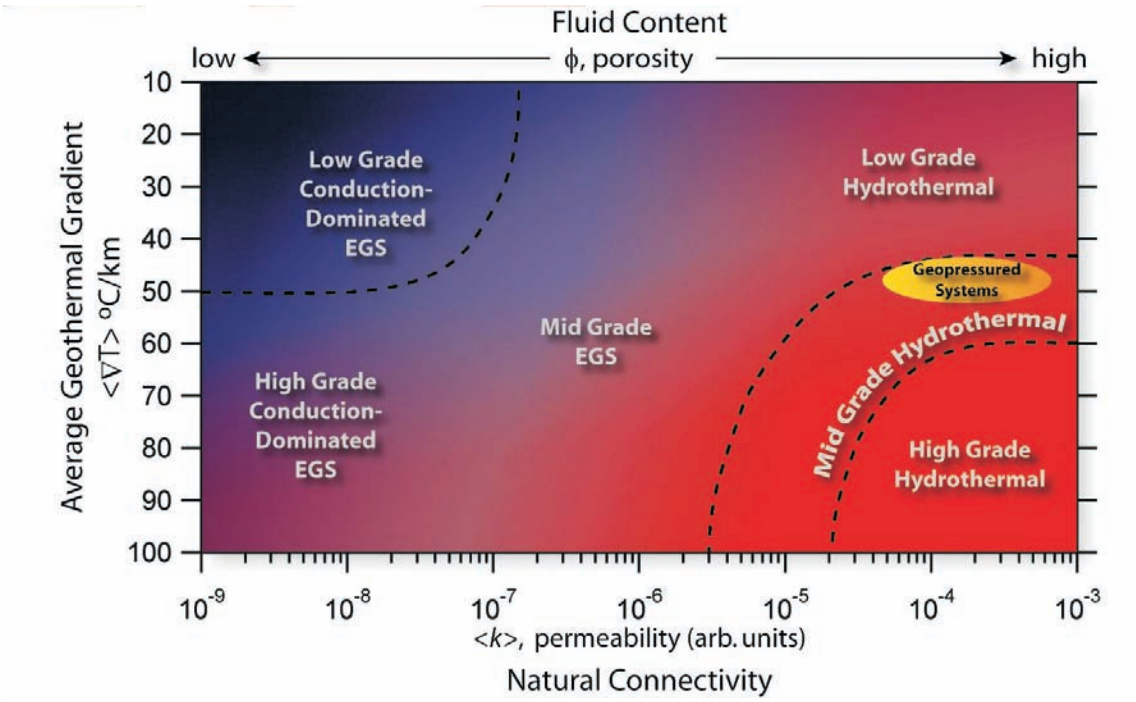

Figure 1. Conceptual view of geothermal continuum of as a function of average temperature gradient, natural connectivity and fluid content.

temperature gradients and the presence of naturally occurring high reservoir connectivity and high fluid content, to low grade EGS resources, which have lower temperature gradients, little or no natural connectivity, and no significant fluid content. Fortunately, the magnitude of the EGS resource base is large, with over 100,000,000 EJ of the stored thermal energy contained in the Earth's crust to accessible depths of 6 to 10 km virtually everywhere. However, to use the vast EGS resource requires the development of heat mining technology to create and stimulate reservoirs that emulate the production characteristics that nature has provided in today's high-grade hydrothermal systems.

A comprehensive assessment of EGS, carried out in 2006 by an MIT-led, 12-member international panel, provides a basis to evaluate the potential of geothermal to become a major global energy supplier. That study specifically focused on estimating the potential for EGS to provide 100,000 MWe of base-load electric generating capacity in the US by 2050. For the most part, the criteria that were utilised in the US study are relevant to evaluation of the global potential of EGS.

Our evaluation of EGS technology and its potential considered criteria in three areas:

- Resource assessment and exploration
  - The magnitude and distribution of the EGS resource over a range of grades;
- Technology requirements for successful heat mining
  - Requirements for extracting and utilising energy from EGS reservoirs including drilling, reservoir design and stimulation, and thermal energy conversion to electricity; and
- Economic requirements for commercial scale exploitation
  - Projected costs for EGS supplied electricity in evolving energy markets as a function of investments in R&D and early demonstration and deployment assistance.

High and mid-grade EGS resources can achieve economic feasibility by creating sufficient reservoir productivity using today's drilling and stimulation methods. In both mid- and high grade systems where the average geothermal gradient varies from 50 °C/km to more than 100 °C/km, drilling costs play an important role that is inherently linked quantitatively to reservoir productivity. To economically utilise geothermal energy for electricity generation from lower-grade, lower-gradient (<50 °C/km) EGS conduction-dominated resources, more costly drilling will be required to reach depths of 6 km or more. Regardless of the produced fluid's temperature or enthalpy content, the lower the productivity the reservoir system per well more wells are needed to achieve a given energy production rate. Consequently as productivity decreases, individual well costs become increasingly important in determining economic feasibility.

In facilitating EGS deployment, one often trades off drilling costs with reservoir or well including costs for multiple lateral well sections and fracturing operations. Cost trends and limitations of conventional drilling and stimulation methods were reviewed to illustrate how advanced approaches will be needed if we are to universally utilise geothermal energy at levels that could make a difference in meeting national and international energy supply and environmental objectives.

To sum up, our analysis shows that the future of EGS in the near term strongly depends on the success of commercial-scale field demonstrations at multiple sites in the US, Australia, Europe and elsewhere, and for the longer term on technological advances in resource assessment, exploration, drilling and reservoir stimulation allowing lower grade EGS resources to become economically feasible. Both near and long term objectives require strong national commitments and sustained, multi-year support from government and industry.

One of the major recommendations of our US EGS assessment was the need to enhance international collaboration among geothermal scientists and engineers. Given the enthusiastic support of geothermal development and the enormous progress that has occurred in just a few years in Australia, we have much to learn by working together in the years ahead. Demonstration of EGS at commercial scale in different regions with similar geologic settings will have significant and lasting impacts on improving technology and lowering development cost and risks which will encourage private investment.

If the US Congress appropriates funds at the levels recommended in recently passed authorisation bills it will be possible to re-energise the US geothermal field program and its supporting R&D and will enable international collaborations to be both workable and productive.

Coupled Thermomechanical Boundary Element Modelling (BEM)

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ABSTRACT

As a renewable source of energy, extraction of thermal energy experiments from deep underground hot rock masses and resources is becoming increasingly more feasible, economical and attractive to the research scientists and engineers engaged in this industry. However, because of the harsh environmental conditions, complex coupled hydro-thermo-mechanical behaviour of the rock remains as the main unknown and normally too difficult to determine from direct experiments. That is why analytical and numerical methods such as the BEM and FEM have increasingly been used for such complex coupled boundary value problems (Crouch, 1976; Carter and Alehossein, 1990; Banerjee, 1994; Xiao et al., 1994).

One major issue with most of the BEM research codes is that they can handle either thermal or mechanical and not both in an interactive, coupled manner. Furthermore, one normally needs to develop another interface code to communicate between any two uncoupled codes, otherwise it becomes impossible or too expensive to do it manually. In this paper, a simple practical semi-coupling superposition method of analysis is introduced which can simply be implemented into any interface or even un-coupled BEM code to mimic coupled behaviour of the hot rock. This technique has successfully been implemented into the thermo-coupled boundary element code (BEAN) for simulation of real problems with real geological, geotechnical and geometrical parameters.

BEM for geotechnical and geothermal engineering problems

One major disadvantage of the more familiar numerical methods, i.e. the finite element methods (FEM) and the finite difference and/or distinct element methods (FDM), is that the whole body volume, including the surface boundary of the boundary value problem, needs to be discretised, although solutions for few points might only be required. This expensive volume discretisation problem will be more pronounced when analysing semi-infinite or infinite boundary problems in geotechnical and geothermal engineering. However, Green and Gauss integral theorems inspired mechanical and geotechnical engineers to develop one of the most efficient numerical techniques, i.e. the boundary element method (BEM), where only the bounding surface needs to be discretised. Not only the amount of input data required to describe a problem is greatly reduced this way, but also the influence of the infinite part of the space can automatically be considered in a BEM analysis (Xiao et al., 1994). It is generally more accurate than the similar compatible FEM, by the fact that *discretisation* or *approximations* of the governing equations only occur on the boundary of the problem domain in the BEM. While normally the boundary contains all the problem unknowns, solutions inside the domain, i.e. at the internal points, are normally determined in terms of their corresponding known boundary values. Hence there is no need to solve multiple simultaneous equations for non-boundary or internal-point unknowns. These internal solutions satisfy equilibrium and compatibility equations exactly.

As an application, the excavation ream movement predicted by BEAN for a jointed rock, in Sydney CBD sandstone, was not only impressively close to the field measurement, but also it took orders of magnitude less of the CPU time when compared with those from the similar finite element (FE) and finite difference (FD) models. In particular, the CPU time of the BEM model was only 1/10th of the FE model and 1/500th of the FD model (Alehossein and Carter, 1991).

The numerical solution of most problems in engineering mechanics by the boundary element method is based on the application of the *weighted residual method*, similar to the Galerkin method in the FEM formulation. One major disadvantage of the BEM, when compared to FEM, is that it requires availability of solutions for semi-infinite space or infinite space problems (with no boundaries) due to a unit charge/force/perturbation or the so called the *fundamental* or *Green's function*. As another alternative branch of BEM, the displacement discontinuity BEM (DDBEM) has found an impressive acceptance and attractiveness in geotechnical and geothermal engineering applications (Alehossein and Carter, 1990, 1991; Alehossein, 2000).

Semi-Coupled Thermo-Mechanical BEM

Most practical problems in geomechanics and geothermal engineering are complex and coupled and hence require temporal interactions between various governing equations. A coupled boundary element solution should certainly satisfy all the governing equations valid for each possible individual phenomenon in the coupling process.

Only the application of the method to a simple 1D bar is demonstrated in this paper to prove the method and reveal its salient capability feature. The method can obviously be extended as a tool to analyse any 2D and 3D practical problems in geotechnical and geothermal engineering without any loss of generality. Results of these coupled applications will be published elsewhere.

The governing equations of all the coupling components, together with the BEM formulation, should be satisfied at any time and at any point on the boundary and in the domain of the rock mass. Notice, in the following equations, θ represents temperature, x is coordinate vector, t is time, q is flux or heat flow, u is displacement vector and σ is stress tensor.

Governing Equations:

1. Thermal equilibrium equation
2. Thermo-mechanical equilibrium equation
3. Thermal and flux initial conditions at any given point (i)
4. Thermo-mechanical initial condition
5. Thermal and flux boundary conditions, e.g.
   $\theta_i(x,t) = \bar{\theta}_i(x,t)$ on the thermal boundary Γ_θ
   $q_i(x,t) = \bar{q}_i(x,t)$ on the flux boundary Γ_q
6. Mechanical displacement and stress boundary conditions
   $u_i(x,t) = \bar{u}_i(x,t)$ on the displacement boundary Γ_u
   $\sigma_i(x,t) = \bar{\sigma}_i(x,t)$ on the stress boundary Γ_σ
7. Stress-strain relationships (Hooke's law)
8. Thermal strain (& potential elastic thermal stress) (Hooke's law)
9. Heat conduction-flux-thermal gradient relationships (Fourier Law)
10. Heat conduction-storage-flux-thermal gradient relationships

11. Heat convection-flux-thermal gradient relationships (Newton's law)

Solution procedure for a simple illustrative 1D Example

Two convenient steps are needed to couple thermal with mechanical in any numerical code at any given computational or time step. First, at any given time or time step *t*, we need to do a pure thermal analysis, using the thermal equations by any numerical code or method (e.g. Finite Difference, Finite Element or Direct or Indirect Boundary Element Method), to determine the thermally induced displacements and stresses everywhere and particularly at the mesh boundaries. In the second step, once we found these thermally induced quantities at the mechanical boundaries, we then solve the thermo-mechanical equations, subject to the same mechanical solutions, but now less the thermal solutions, i.e. we should update our mechanical boundary conditions to the new thermally-induced mechanical boundary conditions.

Consider a simple one dimensional (1D) bar subject to the mechanical boundary displacements and thermal initial and boundary conditions, as depicted in Figure 1.

For simple presentation and quick clarification, a few reasonable assumptions have been made to mainly simplify the mathematical formulations for the sake of proof without any loss of generality.

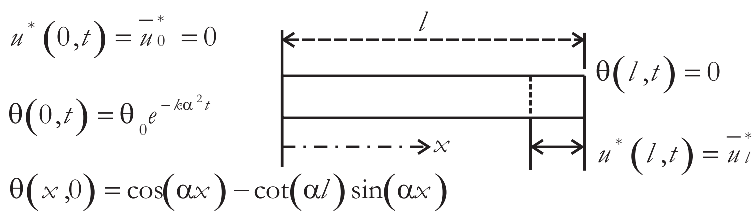

Figure 1. Coupled thermal and mechanical analysis for a 1D bar .

Applying all the above governing Equations to this simple 1D problem, we have:

$$\frac{\delta^2 u}{\delta x^2} = 4\alpha \frac{\delta\theta}{\delta x} \tag{1}$$

$$\frac{\delta^2\theta}{\delta x^2} = \frac{1}{k}\frac{\delta\theta}{\delta t} \tag{2}$$

Equation (2) results in the following solution:

$$\theta(x,t) = \theta_0 e^{-k\alpha^2 t}\left[\cos(\alpha x) - \cot(\alpha l)\sin(\alpha x)\right] \tag{3}$$

Let's call $\Theta(x,t)$ the x-integral of (3), i.e.

$$\Theta(x,t) = \int_0^x \theta dx = \theta_0 \alpha^{-1} e^{-k\alpha^2 t}\left[\sin(\alpha x) + \cot(\alpha l)(\cos(\alpha x) - 1)\right] \tag{4}$$

The value of this function at the points x=0 and $x = l$ are as follows:

$$\Theta(0,t) = \Theta_0 = 0 \tag{5}$$

$$\Theta(l,t) = \Theta_l = \theta_0 \alpha^{-1} e^{-k\alpha^2 t}\left[\csc(\alpha l) - \cot(\alpha l)\right] \tag{6}$$

Hence, the coupled thermo-elastic displacement solution pertinent to Equation (1) takes the following form:

$$u = u^{\theta} + u^{*} = \left[4\alpha\Theta\left(x,t\right)\right] + \left[\frac{\bar{u}_l^{*}}{l}x + \bar{u}_0^{*}\right] \qquad (7)$$

u^* is the mechanical or the homogeneous solution of Equation (1) and u^{θ} is the particular or the thermally induced component of the displacement.

Therefore, at any given time, *t*, we can calculate u^{θ} and u^* from Equation (7) and add them together to find the general solution.

However, special treatments are required here if we want to maintain the same *mechanical* boundary conditions at the two points of $x = 0$ and $x = l$. We now verify the solution at these two points:

$$u\left(0,t\right) = \bar{u}_0^{\theta} + \bar{u}_0^{*} = 0 + 0 = 0 \qquad (8)$$

$$u\left(l,t\right) = 4\alpha\Theta_l + \bar{u}_l^{*} = \bar{u}_l^{\theta} + \bar{u}_l^{*} \qquad (9)$$

Hence, to maintain the same mechanical boundary conditions at the boundary points, we need to solve the homogenous form of Equation (1), but now subjected to the difference between the mechanical and thermal boundary conditions. We now identify this new homogenous solution with two superscripted stars. We can therefore, write:

$$u^{**}\left(0,t\right) = \bar{u}_0^{*} - \bar{u}_0^{\theta} \qquad (10)$$

$$u^{**}\left(l,t\right) = \bar{u}_l^{*} - \bar{u}_l^{\theta} \qquad (11)$$

The new homogenous solution is:

$$u^{**}\left(x,t\right) = \left[\frac{\bar{u}_l^{*} - \bar{u}_l^{\theta}}{l}x + \bar{u}_0^{*} - \bar{u}_0^{\theta}\right] \qquad (12)$$

This approximate solution obtained from the homogeneous solution should be compared with the analytical solution expressed by Equation (7). Indeed, the results from the two methods match impressively well, as shown in Figure 2. For these results the following material properties were assumed in a consistent system of units. $E = 2$, $k_{\text{thermal}} = 1$, $l = 1$, $t = 1$, initial temperature $\theta_0 = 10$, coefficient of thermal expansion $\alpha = 0.785398$, $\Theta_l = 2.235268$, $\Theta_{coeff} = 16.95334$, $U_{\theta l} = 7.022302$.

In the results of Figure 2, u** corresponds to u^{**} in Equation (12), uth corresponds to u^{θ} in Equation (7) and u* corresponds to u^* in Equation (7).

CONCLUSIONS

Application of a simple practical semi-coupling superposition method of analysis was discussed, which can simply be implemented into any interface or even un-coupled BEM code to mimic coupled behaviour of the hot rock in geothermal applications. This technique has successfully been implemented into the thermo-coupled boundary element code (BEAN) for simulation of real problems with real geological, geotechnical and geometrical parameters. In particular, the application of the method to a simple 1D bar is demonstrated in this paper to prove the method and reveal its important modelling feature. The method can be easily extended and generalised for the analysis of more sophisticated and complex 2D and 3D problems in geotechnical and geothermal engineering.

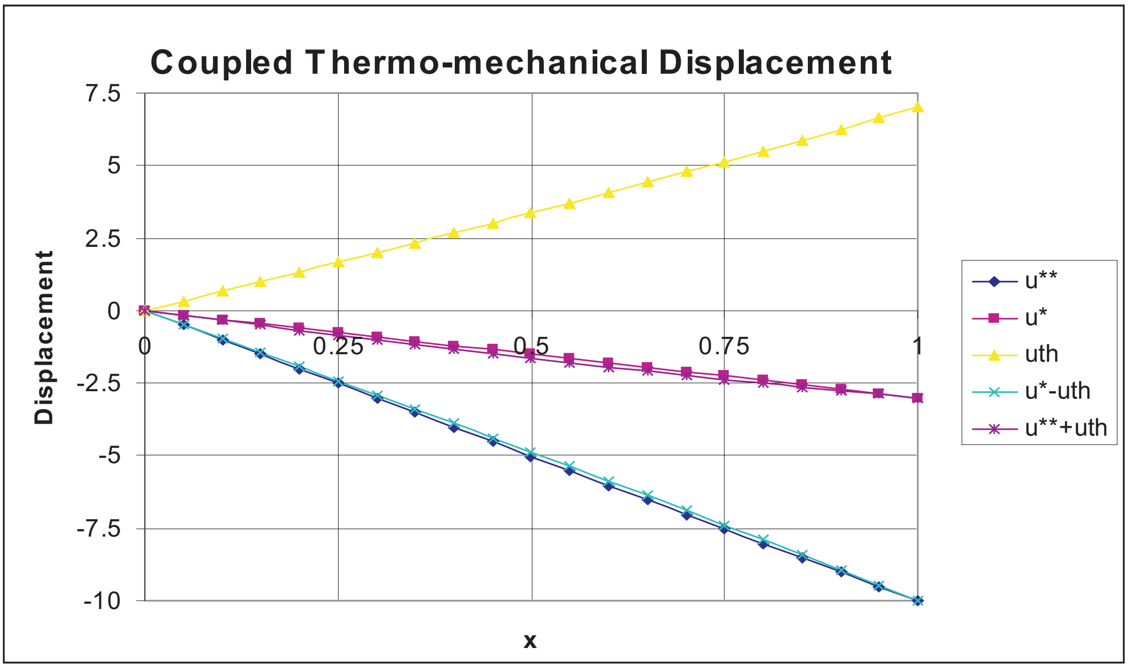

Figure 2. Results of various components of displacement and their combinations for coupled thermo-elastic analysis.

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Current Status of Microseismic Monitoring Techniques for the Stimulation of HDR/HFR Reservoirs

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ABSTRACT

Microseismic monitoring has been used in Hot Dry/Fractured Rock (HDR/HFR) projects worldwide as one of the standard techniques to monitor stimulation. The authors have been investigating uper resolution mapping techniques of the microseismic events to obtain more reliable locations of the hypocenters and more detailed analyses of the response of the fracture system to the stimulation. In this paper, we illustrate the concept of coherence-based analysis and demonstrate results from stimulations carried out in the Cooper Basin and at Basel, Switzerland.

Keywords: Coherence Collapsing, double differential method, super resolution mapping

INTRODUCTION

It has been widely accepted that the microseismic mapping/imaging method is one of the few methods that can estimate the time/spatial distribution of reservoir growth in HDR/HWR/HFR Engineered Geothermal Systems (EGS). The mapping of the locations of the microseismicity is the most fundamental analysis process in the microseismic method and research aiming to improve the accuracy and reliability of this mapping has been carried out in a worldwide project which is referred to as 'TC/MURPHY International Collaborative Project' (Murphy et al., 2000).

Most of the mapping techniques are developed to estimate the 'absolute' location of the hypocenter. Because of uncertainty in the velocity structure and observational errors in the picking of arrivals, it is believed that the absolute locations typically have errors in the order of several tens of metres for microseismic locations in the case of seismic mapping of Engineered Geothermal Systems. The Joint Hypocenter Determination method (JHD; Frohlich, 1979) has been developed in global seismology to reduce the uncertainty caused by the velocity structure. The JHD is one of the standard methods for absolute mapping although it still has uncertainty mainly due to the error in picking. Jones and Stewart (1997) developed an optimising relocation method which is referred to as the 'collapsing method'. This method has been used with success in a number of studies. However, because of the initial assumption that the original seismic structure is actually a point, the ability to resolve structures that are comparable to or smaller than the spatial confidence ellipsoid is not high in this original collapsing method.

In the population of recorded microseismic events from an EGS stimulation some of the seismic events are known to have very similar waveforms although their origin times have wide separations. These events are referred to as 'Multiplets' and highly precise relative mapping techniques of their locations have been investigated (Moriya et al., 2002).

The authors have been investigating a mapping method that tries to bridge collapsing and multiplet analysis techniques thereby utilising the advantages of each of the methods. The objective of this development is to offer similar information as is obtained from time intensive multiplet analysis but in the relatively shorter analysing time available with the JHD and collapsing methods. It is hoped that this new method will provide better locations and permit a more meaningful interpretation of the physical meaning of the seismic cloud of results. Because coherency among events is used as an input, we have named this variation of the collapsing method as 'Coherence Collapsing' (Asanuma et al., 2003).

A multiplet is assumed to arise from repeated shear slip on one fracture, because highly similar waveforms can only be produced through a combination of similar source mechanism and nearly identical source-to-receiver raypaths. We capitalise on waveform similarity for precise estimation of differential travel times among events at each receiver. These differential times are then used as input into the relative location technique. Because raypaths are nearly identical among multiplet members, the relative location technique eliminates location errors introduced by velocity model inaccuracies over most of the path, providing improved accuracy for relative locations within the source region (Waldhauser et al., 2000). This technique is referred to as the 'Double Differential method' (DD method) and is now one of the standard mapping techniques in global seismology.

In this paper, we discuss the potential of these newly developed coherence-based mapping techniques using data sets collected during the stimulation of Engineered Geothermal Systems.

COHERENCE COLLAPSING METHOD

Principles

In the Original Collapsing method of Jones and Stewart (1997), an event is selected as a target event and is then moved slightly toward the centre of gravity of all the events that are located within its confidence ellipsoid. This implicitly assumes that the original seismic structure was a point. The movement is normalised by the size of the spatial confidence ellipsoid. The process is repeated for all events in the data set and a new 'generation' of locations is formed. This procedure is repeated for several generations until the distribution of normalised movements fits to the Chi distribution with three degrees of freedom.

The movement of events in the Original Collapsing method is determined only by the residual and the location of neighbouring events, without any relationship to waveforms. However multiplet analysis studies have already resolved that a part of the microseismic dataset, which has higher mutual coherency, can be relocated to a very small seismic structure. This suggests that it is reasonable to correlate the movements in the Original Collapsing method to the similarity of events. Thus the concepts of Coherent Collapsing are:

- The events which have higher mutual coherency are relocated to a point (or to a very small structure); and
- The events with lower mutual coherency are relocated to reduce uncertainty of the whole seismic cloud.

The main procedure of the Coherence Collapsing method is based on that of the Original Collapsing method. The coherence of the events to the target event is again used as a weight coefficient in the calculation of the centre of gravity. It is reasonable to use the coherence to multiply the weighting factor as we expect these events to come from small scale structures, however the optimum weight is unknown. We decided to determine the optimum weight using a study of synthetic events and we currently use the 8th power of the coherency (Asanuma et al., 2003).

Application to the data set collected in the Cooper Basin.

The Coherence Collapsing method was applied to the microseismic data set collected during the stimulation of reservoirs in the Cooper Basin, Australia (Asanuma et al., 2004). The location of microseismic events determined by JHD, the original collapsing method, and the coherence collapsing method for the data sets from the simulation in 2003 are shown in Figure 1.

Because of the horizontal maximum stress and sub-horizontal pre-existing fractures, it is expected that a horizontal over-pressured fracture, which was not plugged in the drilling, and its subset fractures are stimulated in the Cooper Basin HFR Project, Australia. The location of microseismic events in the fracture initiation tests and main stimulation in 2003 showed a sub-horizontal seismic cloud extending horizontally approximately 1,500 m from the injection well with thickness around 150 m (Asanuma et al., 2004). The coherence collapsing method, applied to this dataset, showed several sub-horizontal seismic structures. Because it is accepted that multiplets are correlated to a single fracture with multiple slip, this result suggests the existence of a set of sub-horizontal fractures in this site.

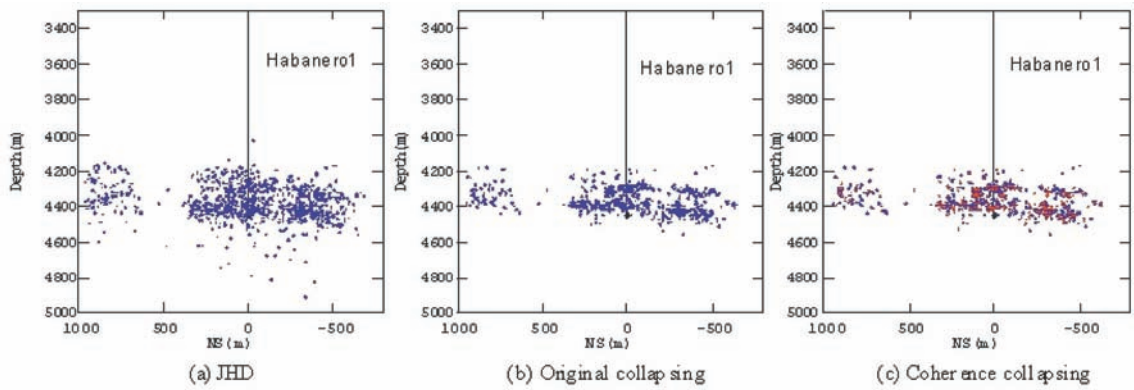

Figure 1. Relocation of the microseismic data collected at Cooper Basin in 2003 by Coherence-collapsing.

DOUBLE DIFFERENTIAL (DD) METHOD

Principles

The DD method is a precise relative location technique (Waldhauser et al., 2000) using relative time of arrival for a group of events. A double differential equation from the relative delays is solved to obtain the absolute location of the microseismic events. Because relative time of arrival is used as an input, it is believed that the ability of the DD method to estimate absolute location is lower than for relative location. The residual error after DD has been investigated by Kumano et al. (2006). It has been revealed that the orientation of the spatial distribution of the error is dependent on the geometry of the network in the same manner as JHD.

There are several methods to estimate the relative time of arrival among a set of events. Cross spectra and coherence can bring the most accurate information on the delay and similarity of the events, although processing time may be longer than for other techniques in the time domain. Because the DD method can be used as a pre-processing of the multiplet analysis to estimate orientation and behavior of each fracture, the authors have been using cross spectra for the delay estimation (Moriya et al., 2002).

Application to data set collected at Cooper Basin and Basel

Because the number of events with higher similarity was large (>10,000) in the data collected in the Cooper Basin in 2003, we selected a part of the seismic cloud where more complex seismic/ reservoir structure is expected from the analysis using the conventional single event location (SED) technique. A total of 3,687 events were located using SED. Approximately 30 % of the located events did not have adequate signal to enable determination of waveform similarity. We discuss here the remaining 70 %, whose source locations we adjusted using the DD method (Kumano et al., 2006). Figure 2(b) shows the result of DD re-location in the western part of the microseismic cloud. The re-located hypocenters illuminate sub-horizontal, quasi-parallel, planar clusters that dip ~15° toward the West. The thickness of each cluster is less than 50 m, and the horizontal extent is as great as 100 m.

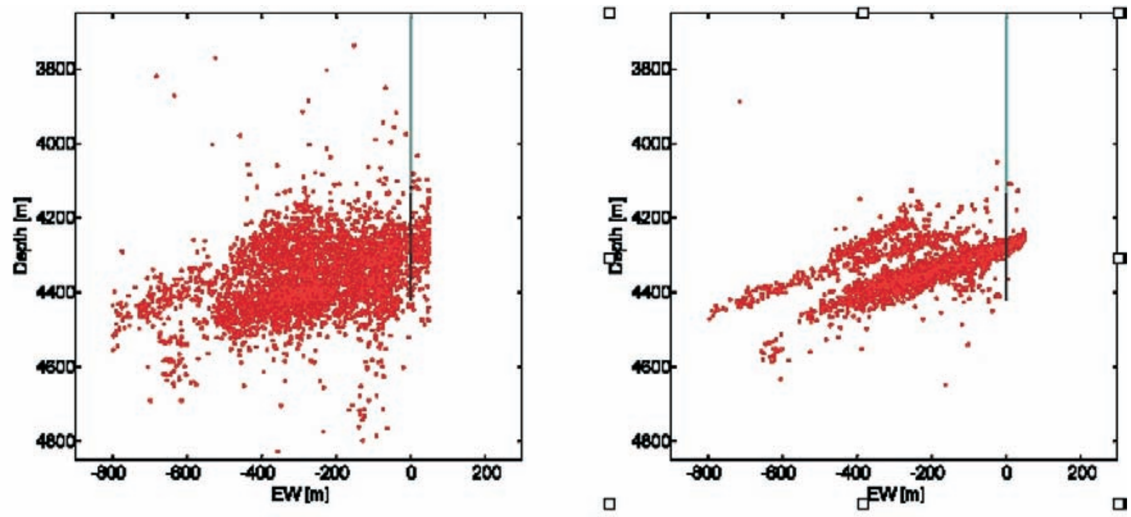

Figure 2. Relocation of the microseismic data collected at Cooper Basin in 2003 by DD, (a) JHD (left), (b) DD (right).

In order to develop an enhanced geothermal reservoir as part of the Deep Heat Mining project at Basel (Switzerland) a hydraulic stimulation program was conducted in deep geothermal well Basel 1 during December 2006. This EGS project is financed by Geopower Basel AG. The stimulation was operated and monitored for microseismic activity by Geothermal Explorers Ltd. More than 13,000 microseismic events were observed during the stimulation and afterwards. Hypocenters of approximately 2,900 events were located onsite. During subsequent analysis, we analyzed microseismic multiplet events that exhibit similar waveforms to those among the located events. Seventy percent of the located events comprise multiplets which may be assigned to over 100 distinct multiplet clusters. We estimated relative hypocenters for 1,635 of the multiplet events using a double differential hypocenter location technique (Asanuma et al., *in press*). Figure 3 shows the hypocenter distribution determined by the DD technique. Each multiplet cluster has dimensions of several tens to hundreds of meters and delineates a planar or linear structure having vertical inclination and predominant strike in two directions: N25W or N50W. Although the tectonic stress state has not been clearly investigated near this site, it has been reported that the tectonic stress at the Soultz Hot-Dry-Rock geothermal field, also located within the Rhine Graben, exhibits a maximum horizontal stress of NW-SE, consistent with local tectonic activity around the graben (Baria et al., 2000). We thus conclude that the orientation of multiplet clusters in the Basel field arises from local tectonic stresses.

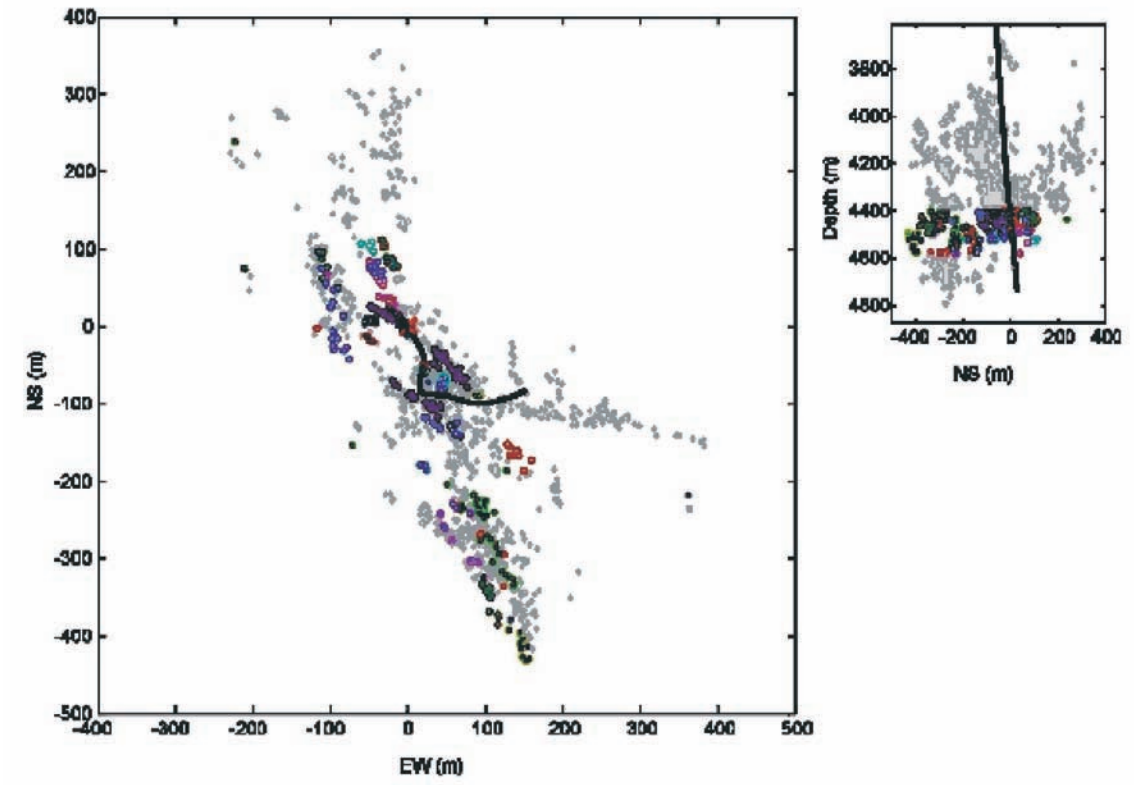

Figure 3. Location of microseismic multiplets at Basel. Hypocenters were re-located by DD.

OTHER TECHNIQUES

In the Cooper Basin case, source distribution determined by the DD technique indicates that the reservoir structure consists of sub-parallel, planar clusters. However, we could not estimate the more detailed structure inside each of these clusters because the thickness of each cluster is only of the order of tens of metres.

Waveform similarity is related to similarity of both the source mechanism and travel path. Similar waveforms can be assumed to be radiated from repeated, consistent shear slip on a fracture, which results in a similar focal mechanism. Therefore, we can discuss the complexity of the fracture system within clusters by examining the spatial distribution of multiplets, which are defined by their waveform similarity. By using the coherence function as a measure of waveform similarity, we examined the multiplets and associate the coherency among member events with the source locations. Figure 4 shows the spatial distribution of microseismic sources (Kumano et al., 2006). In this figure, the varied color of source locations indicates the coherency between the events and a reference event, indicated by a square. We can see that coherency is lower between different clusters than within the same cluster. Moreover, within a single cluster the coherence function varies smoothly with distance from the reference event and there is no discontinuity of the spatial variation of coherency. These results suggest that the fracture system within each seismic cluster is very simple and may be a single fracture plane.

If the collected data has a wideband nature and contains information of the corner frequency f_c , the similarity of the waveform is correlated to the f_c , which is determined by the size of the ruptured area (source radius), and the hypocentral distance, as well as the focal mechanism. Vertical projections of the distributions of multiplet hypocenters for Basel data are shown in Figure 5, where the colour of the circles correlates to each multiplet group, the size of the circles indicates the

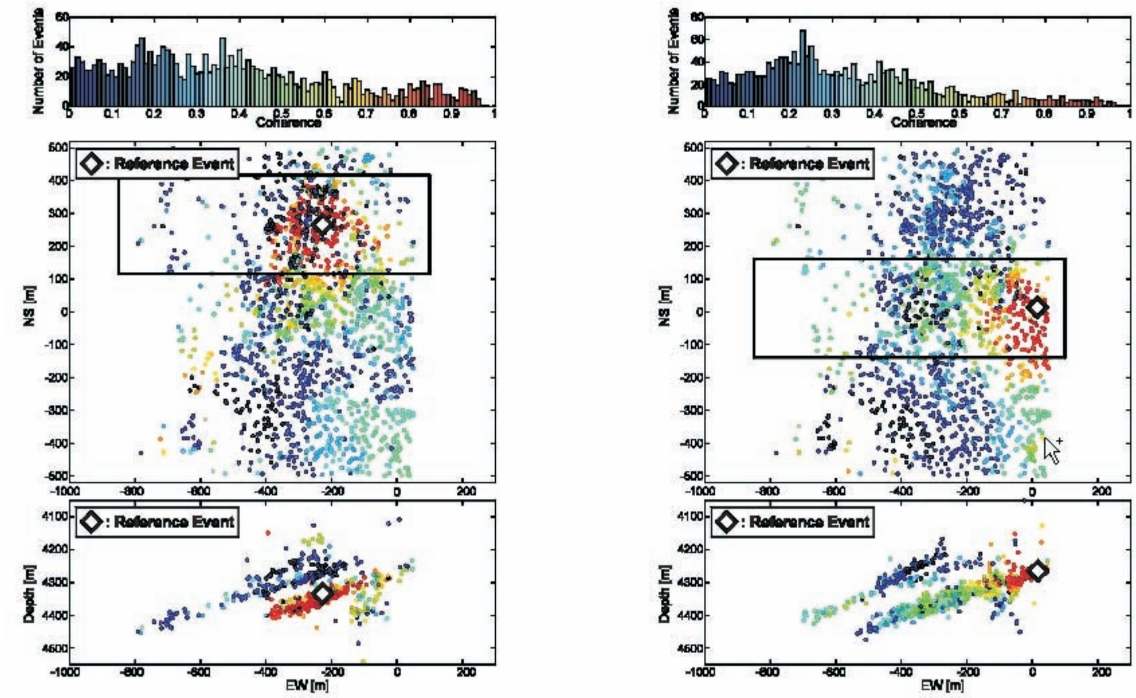

Figure 4. Spatial distribution of coherence relative to a reference event (square) for a data set collected at Cooper Basin.

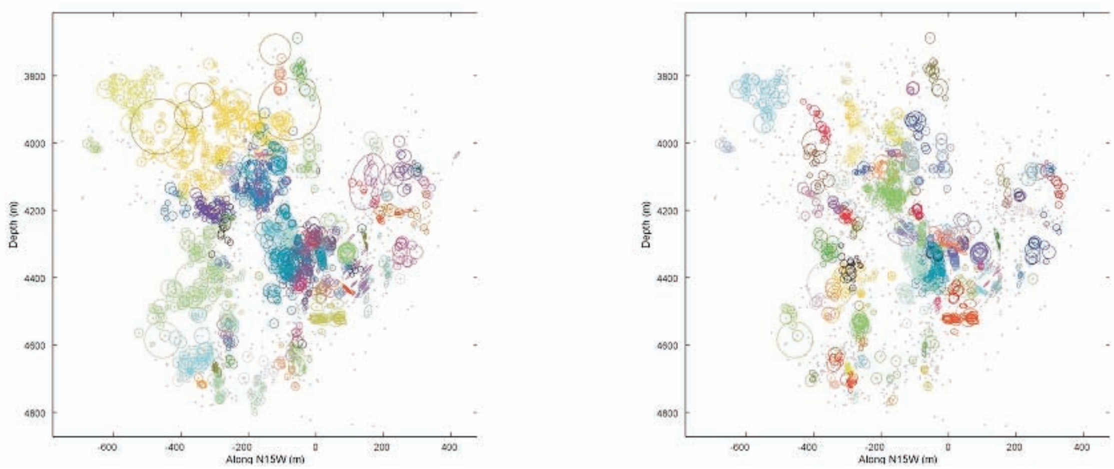

Figure 5. Location of multiplet by different criteria for Basel dataset, (a) lower frequency (left), (b) higher frequency (right).

estimated source radius, and grey dots show the hypocenters of uncorrelated (single) events. Figure 5(a) shows the hypocenter distribution of multiplets identified in lower frequency and Figure 5(b) is for higher frequency. The multiplets identified in the lower frequency domain show large sub-vertical seismic structures up to 400 m and heterogeneous source radii (10-100 m), while the multiplets identified in the high frequency domain show smaller sub-vertical seismic structures less than 200 m and their source radii are more homogeneous. It is also noticeable that large multiplet clusters in the south part of the seismic cloud identified in lower frequency are found to be sub-clustered into smaller clusters by applying the identification in higher frequency (Asanuma et al., *in press*). It is interpreted that a mechanism involving an identical direction of shear slip on single or sub-parallel macroscopic pre-existing fractures may be responsible for the multiplets identified in the low frequency analysis, while the multiplets identified in high frequency correlate to repeating slip of a part of the fracture system mainly around the feed point and the gradual rupture of one small-scale fracture.

It has been reported that origin time and distance from the injection point of the multiplets are highly correlated to the flow rate and wellhead/downhole pressure (Asanuma et al., *in press*). This kind of information can also be effectively used to interpret the stimulation process and reservoir characteristics.

SUMMARY

As described in this paper, the coherence of the microseismic events is one of the parameters of importance in understanding the structure and extension process of the stimulated zone. In this paper we introduced two mapping methods which use information on coherency. The Coherence Collapsing method uses absolute picking of each event and a table of coherency among all the events. These inputs can be prepared on a semi-realtime basis, and the CPU time for the determination of the hypocenters is as small as that for JHD and original collapsing. The Coherence Collapsing method has an ability to provide absolute location of the multiplet groups but it cannot resolve the seismic structure within each multiplet group. This means that the orientation and stress state of the multiple slipping fractures cannot be estimated. On the other hand, the DD method has the ability to precisely estimate the relative location of the multiplets. However this method does not have realtime capabilities because of the complex processing required to estimate the relative time of arrivals. As shown in this paper, the distribution of the multiplets may be affected by the arrangement of the stations especially in the case of a sparse

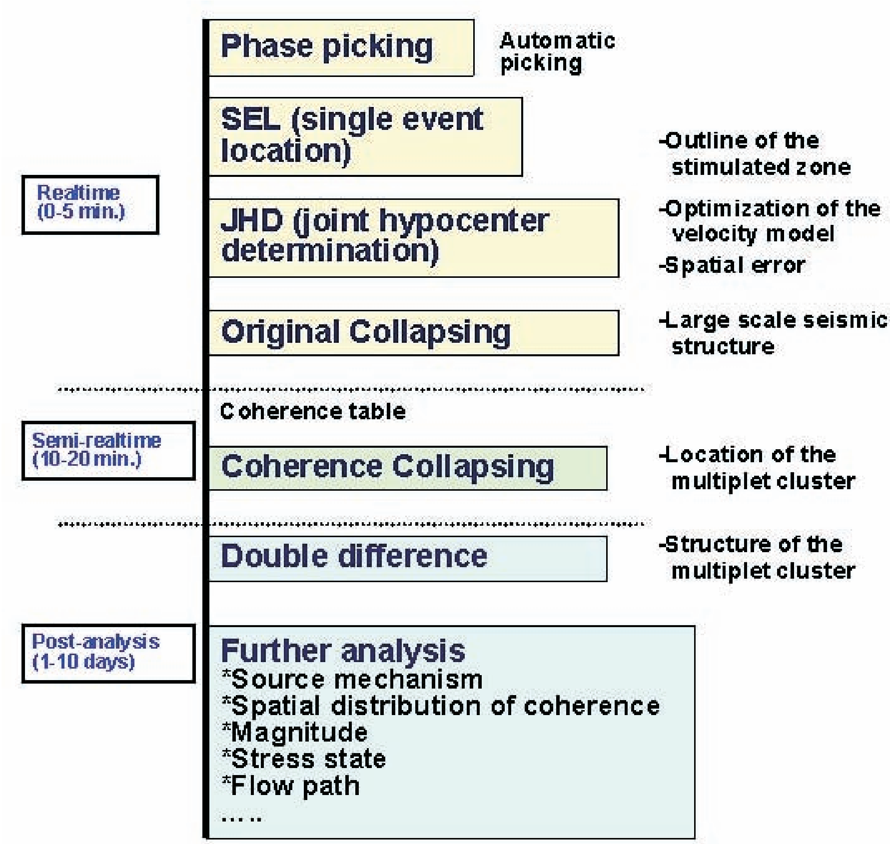

Figure 6. A flow chart of microseismic processing in the authors group.

downhole network. The absolute location by the DD method is normally less reliable than the relative locations.

Considering the abovementioned advantages and disadvantages, a flow chart of microseismic analysis in our group is shown in Figure 6. The re-location by Coherence collapsing can be done on-site in semi-realtime (~20 min.) by updating the coherence-table among the events. This enables the results to be used to help plan the continuing stimulation program. The DD re-location and the other analysis can be made as a post-analysis and provide information for more detailed interpretation and understanding of the reservoir that has been created.

ACKNOWLEDGMENTS

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Economic and Technical Cases for the Commercial Exploitation of Engineered Geothermal Systems

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ABSTRACT

The supply, availability and price of energy resources, like many other commodities, are to a large extent influenced by the supply and demand criteria. World demand for hydrocarbons, among other commodities, has increased significantly and that may have changed the outlook for renewable power sources such as Engineered Geothermal Systems (EGS). Additionally, the environmental issues associated with climate change will also influence governments, industries and public to support environmentally friendly base load energy sources such as EGS, and that should reflect in the economics of EGS by mechanisms such as feed-in tariffs or CO_2 levies.

The development of EGS has taken over 30 years to evolve from a basic concept to an exploitable technology based on modelling, experimentation and observations. It is sometimes forgotten that the economic argument to commercially exploit this technology dictated the technical or engineering parameters. In other words, economic parameters dictated the technical goals that have to be met to make this commercially viable. It has been noted recently that the economic case made for raising capital in the market, in most cases, does not address the engineering parameters needed to make it economically viable. Additionally, the key issue is net power generation (including management and maintenance), and not gross power generation that is generally quoted in economic evaluations.

Some of the engineering parameters to be addressed for economic evaluation are:

- Access to the high temperature heat reservoir at shallow depth as possible;
- Life of the system;
- Separation between wells (injector and producers);
- Maximum fluid production;
- Water losses;
- Flow impedance;
- Thermal drawdown;
- Heat transfer area;
- Reservoir rock volume;
- Water resource;
- Power line;
- Interest rate; and
- Preferential tariff.

The presentation will discuss to what extent commercial levels of these parameters have been achieved, and where we stand in terms of addressing them.

Hot Rock Exploration Methods

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THE PURPOSE OF EXPLORATION

Hot rock exploration is not about finding hot rocks. Drill a well at any location on Earth and you will find hot rocks. The deeper you drill (generally), the hotter the rocks will get. The purpose of hot rock exploration is to find locations with the greatest probability of producing substantial flows of hot fluid to the surface of the Earth over significant time periods. Exploration is best carried out as a Geothermal Systems Analysis—a systematic assessment of the available data and risks associated with each of the essential parameters required for a successful geothermal development.

GEOTHERMAL SYSTEMS ANALYSIS

The two factors most critical to the success of a geothermal energy development are the temperature and the flow rate that can be achieved from each production well. A scorching hot well that does not flow is of no value. Neither is a well that flows cold water at a rapid rate (no geothermal value, anyway). It is the product of these two parameters that effectively defines the thermal power of the well. The chemistry of the fluid and technology for converting the thermal power into other forms of power are also important, but secondary, controls on economic success.

A Geothermal Systems Analysis is a framework for reducing the exploration risk associated with temperature and flow rate. In a conductive thermal regime where the prospective geothermal project is a deep sedimentary aquifer or EGS type development, there are four factors that effectively control the viability of flowing hot fluid to surface. They are:

- the conductive heat flow;
- total thermal insulation;
- reservoir permeability-thickness; and
- availability of an adequate water supply.

An efficient and effective exploration program should focus on reducing the risk (i.e. uncertainty) associated with each of these parameters. A number of tools are available for that purpose.

Heat flow

Conductive heat flow is a measure of the thermal power naturally emanating from the Earth. It is arguably the most direct indicator of "heat in ground". Over any given depth interval, heat flow (mW/m^2) is calculated from the product of the average thermal gradient (°C/km) and the average thermal conductivity (W/mK). The First Law of Thermodynamics ("conservation of energy") dictates that heat flow remains relatively constant with depth, except in situations where there is significant internal heat generation or lateral heat flow. Except in regions where there is compelling reason to believe otherwise, it is reasonable to assume that conduction is the dominant means of vertical heat transport in the upper 5 km of crust over much of Australia, and that a measurement of heat flow at the surface can be confidently extrapolated to arbitrary depth. The reliability of temperature predictions based on such extrapolations is constrained not by the underlying physics of heat transfer, but by the precision and uncertainty of the heat flow estimate, the geological model and the vertical extent of the extrapolation.

Existing data sets that allow a preliminary assessment of heat flow include:

- the Global Heat Flow Database;
- previously published heat flow data;
- bottom hole temperatures from existing deep bore holes;
- flow test temperatures from existing boreholes;
- lithological logs from existing bores;
- existing core or cuttings samples; and
- average surface temperature records.

An early stage of many exploration programs is the drilling of a series of dedicated shallow heat flow measurement holes. Dedicated heat flow holes allow the collection of thermal gradient and thermal conductivity data over the same depth interval, a prerequisite for a heat flow measurement. The precision of the heat flow measurement is proportional to the precision of both the gradient measurement and the thermal conductivity measurement. Of these two parameters, thermal conductivity typically introduces the greatest uncertainty.

Indirect indicators of heat flow may provide valuable supporting evidence for uncertain heat flow measurements, or an initial indication of the possible prospectivity of an area. An example of this is a Bouguer gravity map of an area. Elevated heat flow over large parts of Central Australia is assumed to be related to buried radioactive granitic bodies. The Big Lake Suite Granodiorite intruding the Warburton Basin sequence beneath the Cooper Basin is associated with a negative gravity anomaly. By analogy, negative gravity anomalies in other parts of the country may indicate buried radioactive granites and, hence, regions of elevated heat flow. Several geothermal permits have been applied for (and awarded) on the basis of such assumptions, but high geological risks are associated with targets based on such indirect evidence. Another indirect indicator of heat flow is helium concentration in groundwater. Helium, like heat, is a by-product of radioactive decay.

Thermal insulation

Elevated heat flow indicates the presence of an anomalous heat source, but not necessarily elevated temperature at depth. The temperature increase between surface and a given depth (average thermal gradient) in a conductive setting is the product of heat flow and thermal resistance. Average thermal gradient is maximised over a given depth interval when heat flow and total thermal resistance are both high. Thermal resistance (m^2K/W) is physical thickness (m) divided by average thermal conductivity (W/mK). The thermal conductivity structure of a prospect, therefore, exerts a first order control on the temperature distribution.

Existing data sets that allow a preliminary assessment of thermal insulation (thickness and conductivity) include:

- published thermal conductivity values;
- reflection seismic profiles;
- stratigraphic formation top data from previous deep drilling;
- lithological descriptions from driller's logs;
- core or cuttings samples from deep boreholes; and
- inversion models from potential fields data.

When investigating the risk associated with thermal insulation, it quickly becomes apparent that a good three-dimensional geological model of the prospective area is invaluable. Efforts to reduce thermal insulation risk, therefore, should focus on improving geological models and our understanding of the thermal properties of all formations. Steps might include:

- shooting new seismic reflection surveys;
- undertaking new inversion studies of potential fields data;
- geological mapping and/or structural analysis; and
- making thermal conductivity measurements.

Reservoir

As mentioned above, a scorching hot well that does not flow is of no value. A primary purpose of exploration, therefore, is to identify rock formations with potential to hydraulically conduct water at flow rates sufficient to extract adequate thermal power. For example, a 200 °C hot rock reservoir will need to flow about 700 litres of water per second in order to generate 50 MW_e of electricity. The number of wells needed to achieve this total flow rate will depend in part on the hydraulic properties of the reservoir rock.

Ideal geothermal reservoirs are naturally permeable. Almost all commercial geothermal operations around the world tap into naturally permeable reservoirs. Several companies in Australia are exploring for deep sedimentary basin aquifers in the hope that their natural permeability will be adequate for geothermal fluid production.

Much of the exploration work in Australia, however, is focussed on engineered geothermal reservoir developments, where the probability of encountering adequate natural permeability is low. Not all formations are conducive to having their permeability enhanced. Susceptible formations are brittle (so that fractures can propagate), strong (so that grains can support open fractures), clay-poor (so clay doesn't swell into the open fractures) and already contain joints or fractures in arbitrary directions (features that can be shear-reactivated). In addition to their geo-mechanical properties, the formations must be thick enough to enhance the permeability of an adequate volume of rock, and the physical extents of the engineered reservoirs need to be relatively impermeable to minimise fluid loss. Many granitic bodies have these properties, but other rock types could also perform mechanically as engineered reservoirs.

The prevailing tectonic stress field, in part, controls the shape of the engineered reservoir, so the stress field is also an important exploration parameter. Optimum enhancement of horizontal fracture networks is achieved when the minimum compressive stress direction is vertical. This is not the same as saying that maximum compressive stress is horizontal, as vertical fractures can also be enhanced in strike-slip stress regimes (maximum and minimum compressive stress directions are both horizontal).

Exploring for potential reservoir units is, again, largely an exercise in understanding the three dimensional geological structure of the prospective area. Data sets that help in this regard include:

- existing reflection seismic profiles; and
- existing reservoir data from nearby deep boreholes.

Exploration techniques that might be used to search for potential reservoir units include:

- magnetotellurics (to detect natural saline permeable units);
- reflection/refraction seismic profiles (to image crystalline basement);
- passive seismic (to detect natural seismic events due to crustal fluid movement);

- shear wave splitting (to detect the orientation and extent of dominant fracture sets);
- helium sniffing (to detect naturally permeable zones); and
- gravity and magnetics (to map basement composition).

Water

Although largely ignored as a factor in exploration programs, no geothermal project will succeed unless there is sufficient fluid in the system to maintain circulation. If the geothermal development is naturally permeable, then reinjection of the produced fluid back into the reservoir may be sufficient to indefinitely maintain flow rates throughout the life of the project. In EGS developments, however, there is typically no fluid in the system to start with. So a source of water is required to initially "charge" the system. In addition, should there be any fluid loss per circulation cycle, then fluid needs to be made up from some other source.

For example, if the 50 MW_e project described earlier experienced an average loss of 1 % of fluid per cycle, then the project would need 7 litres per second, or 600,000 litres (~15 semi-trailer tankers) per day, of water from somewhere to maintain reservoir pressure. This would be required over the full lifetime of the project, which would typically be decades. In arid parts of Australia this could prove to be a serious issue.

Primary exploration should, therefore, consider where significant water sources are located relative to potential development sites. Such sources could be the ocean, surface drainage (i.e. rivers), lakes or productive aquifers. In any case, licences are likely to be required and may not necessarily be granted.

EXPLORATION PROGRAMS

A geothermal systems assessment should reveal where the greatest risk lies in any exploration program. Resources should be targeted towards reducing that risk before others. For example, if there is a reasonable expectation of a productive reservoir at depth, but the temperature of that reservoir is uncertain, then resources are best put towards determining the heat flow and thermal properties of the intervening layers. A shallow drilling program to measure heat flow could well be a major component of that program.

If, on the other hand, temperature at depth is well constrained through previous drilling, but the extent of a viable reservoir is unknown, then magnetotellurics or reflection seismic programs may be the best use of exploration dollars. Ultimately, however, only drilling into a reservoir formation and conducting physical tests will determine its hydraulic properties. The exploration program up until that point is about maximising the probability of drilling that first deep hole in the right location.

A Steady-State Pressure Model for Water Flow in a Hydraulically Fractured Geothermal Reservoir

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ABSTRACT

The flow of water in an Engineered Geothermal System (EGS) is an issue of considerable importance for the emerging Geothermal Industry. A steady-state mathematical model was developed for the purposes of modeling water flow through horizontal fractures of an EGS. Using classical fluid mechanics the model provided approximate values of reservoir pressure drop, injection wellhead pressure and production wellhead pressure. The model has enabled the Petroleum and Geothermal Group of the Department of Primary Industries and Resources of South Australia (PIRSA) to carry out sensitivity studies. PIRSA has used the model in its evaluation of the technical feasibility of EGS in the Cooper Basin in South Australia.

INTRODUCTION AND THEORY

The Geothermal industry in South Australia has expanded significantly in recent years. As industry regulators, the Petroleum and Geothermal Group of PIRSA has conducted independent research into the issue of fracture flow in EGS. This paper is the product of that research. A steady-state pressure model has been created to predict flow pressure drops within EGS. The model provides approximate values of required injection pressure at the injection wellhead and resulting production pressure at the production wellhead. These values in turn provide an idea as to whether EGS can operate in natural convection mode or whether it will require reinjection pumping resulting in parasitic energy losses.

The geometry of the model is shown in Figure 1. It consists of a fractured reservoir and two wells; one for injection and the other for production. Pressure drop for both the injection and production well was modeled using Equation 1 (Munson et al., 2006).

$$\Delta P_{i,p} = \rho g h_L - \rho g(z_1 - z_2) \qquad \text{(1) well flow}$$

Where $\Delta P_{i,p}$ is the pressure drop in a well, ρ is the density of water, g is gravitational acceleration, $(z_1\text{-}z_2)$ is the distance of vertical displacement and h_L is the pressure head given by

$$h_L = f\left(\frac{D}{d_w}\right)\frac{\bar{u}^2}{2g} \qquad \text{(2) pressure head}$$

Where f is the friction factor, D is the depth of the well, d_w is the diameter of the well and $\bar{u}$ is the average flow velocity in the well. The wells were assumed completely vertical and of constant diameter. Water properties in each well were determined at constant temperature and at a pressure averaged between wellhead and wellbore. This component of the model is currently being reviewed by the author.

Flow in the fractures was modeled as flow between horizontal parallel plates (Jones et al., 1988). The fractures were assumed horizontal as over-thrust stress conditions in the Cooper Basin produce predominately horizontal fractures when granite is hydraulically stimulated (Wyborn et al., 2004). The reservoir model consists of two flow regimes: radial at the wellbores and linear in between. The model does not account for discontinuities between flow regimes. Total reservoir pressure drop was approximated by summing the pressures drops of each flow section (Slider 1983).

$$\Delta P_r = \Delta P_{lin} + 2\Delta P_{rad} \qquad \text{(3) total reservoir pressure drop}$$

Where ΔP_{lin} and ΔP_{rad} are given by equations 4 and 5 respectively.

$$\Delta P_{lin} = \frac{12\mu L' q_{pf}}{h^3 w} \qquad \text{(4) linear flow}$$

$$\Delta P_{rad} = \frac{12\mu q_{pf} \ln\left(\frac{r_e}{r_w}\right) l}{h^3 \theta} \qquad \text{(5) radial flow}$$

Equation 4 is an exact solution to the Navier-Stokes equations for steady incompressible linear flow between parallel plates (Munson et al., 2006). Equation 5 is an approximate solution to the Navier-Stokes equations for purely radial flow between parallel discs (McDonald, 2000). Water properties were determined at reservoir temperature Tr and reservoir pressure Pr. This assumption

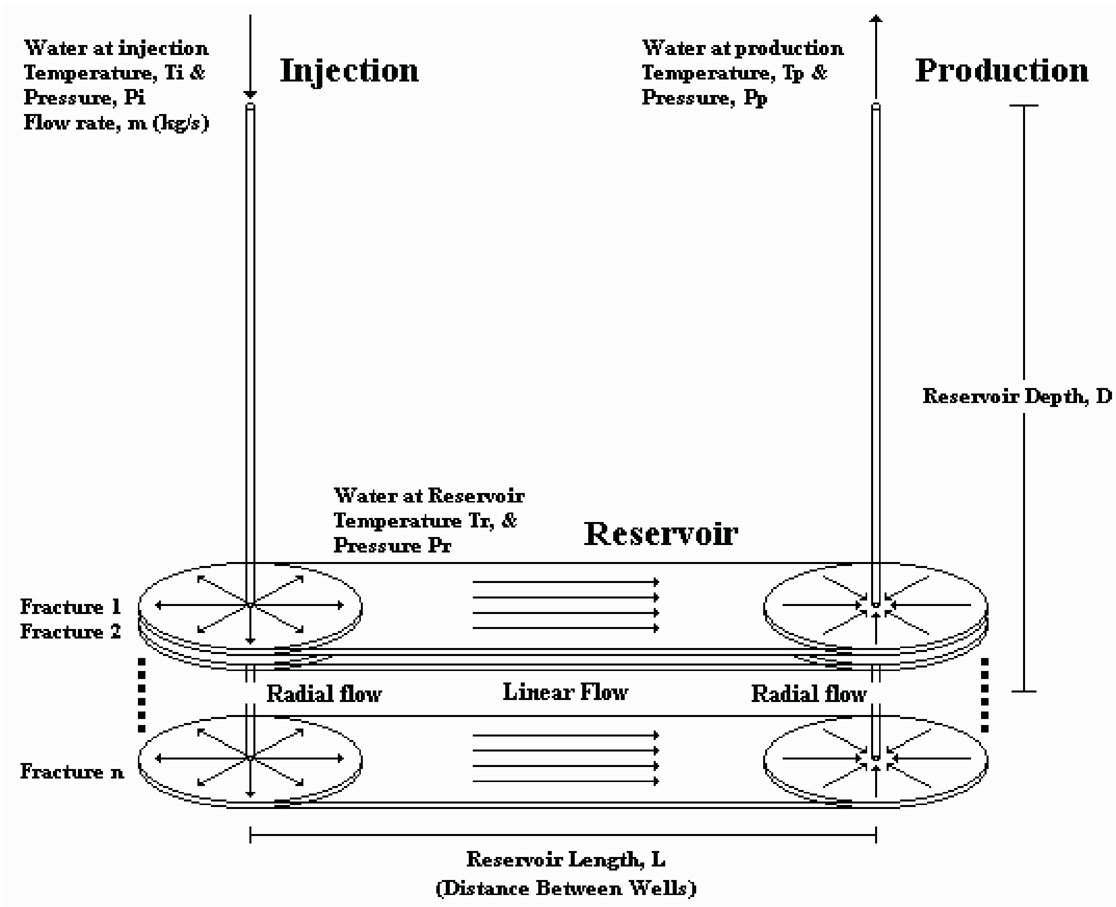

Figure 1. Geometry of EGS model.

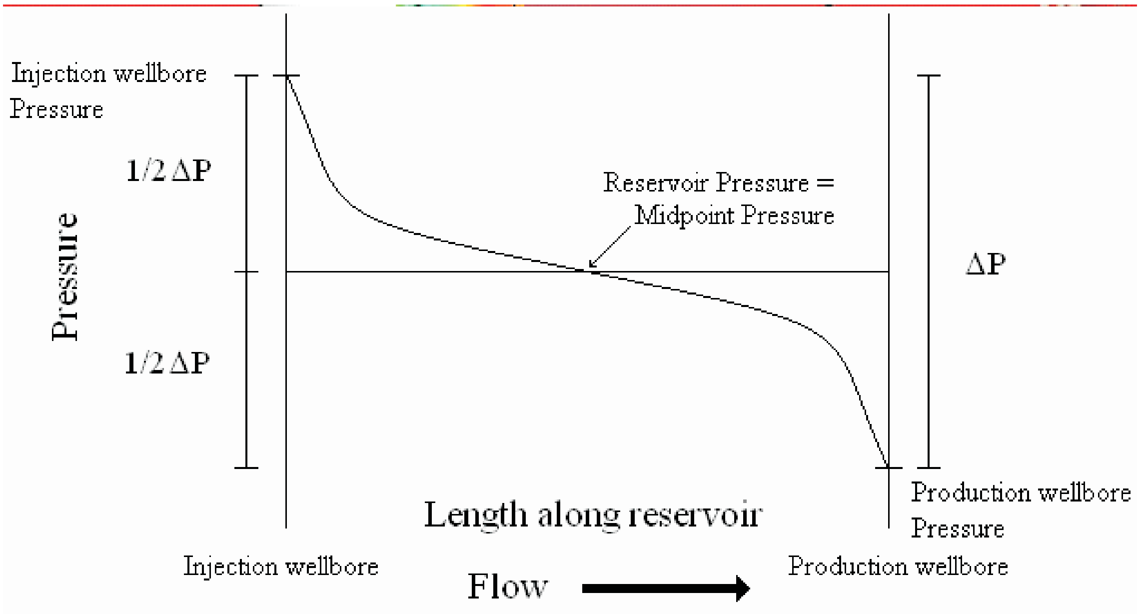

Figure 2. Reservoir pressure profile assumption expressed pictorially.

can be considered valid as heat transfer calculations have shown water to heat up to reservoir temperature not long after injection (Holman, 1997).

It was assumed that injection wellbore pressure needed to be equal to P_r plus half the reservoir pressure drop. It was also assumed that pressure at the production wellbore would be equal to P_r minus $\Delta P/2$. Figure 2 demonstrates this assumption in terms of reservoir pressure profile. Injection wellhead pressure was thus given by equation 6 and production wellhead pressure by equation 7.

$$P_i = P_r + \frac{\Delta P_r}{2} + \Delta P_i \qquad \text{(6) injection pressure}$$

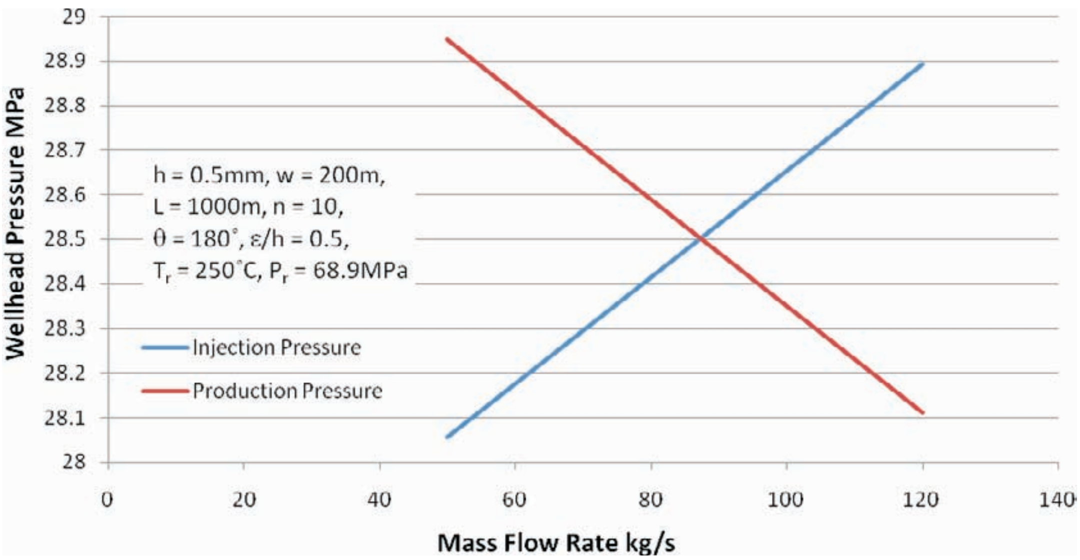

Figure 3. Wellhead injection and production pressure versus mass flow rate.

$$P_p = P_r - \frac{\Delta P_r}{2} - \Delta P_p$$ (7) production pressure

The model was only able to provide solutions for laminar flow regimes in the reservoir as turbulent flow behaviour was indeterminable for radial flow. Further study is being conducted to rectify this issue. The critical Reynolds number for linear flow was

$$\mathrm{Re}_f = \frac{2h\bar{u}\rho}{\mu} \leq 2300$$ (8) local Reynolds number for linear flow

For radial flow the laminar threshold was given by the overall Reynolds number

$$\mathrm{Re}_0 = \frac{q_{pf}\rho}{h\theta\mu} \leq 1.0\times 10^8$$ (9) overall Reynolds number for radial flow

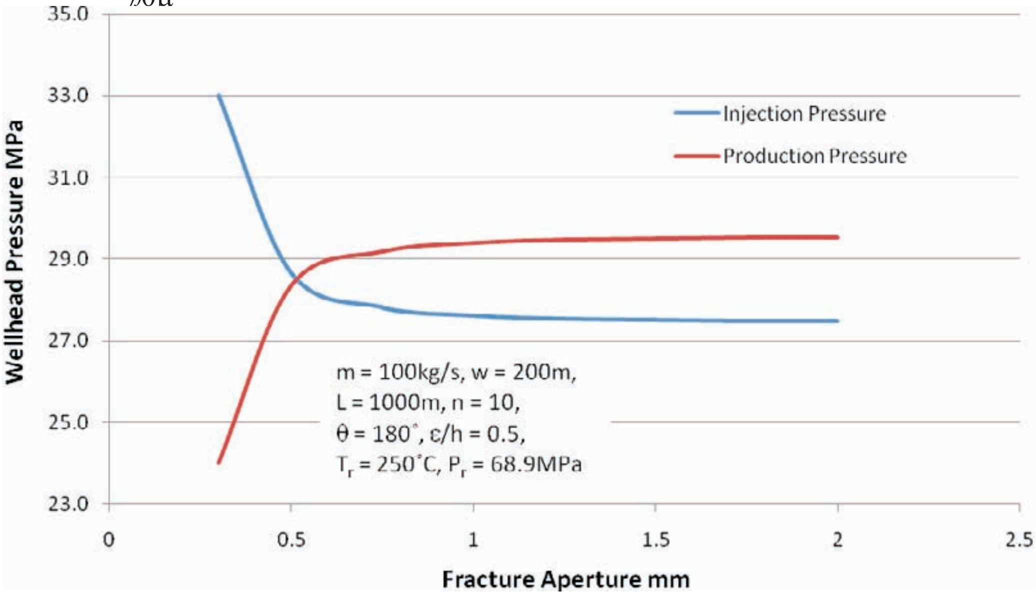

Figure 4. Wellhead injection and production pressure versus fracture aperture.

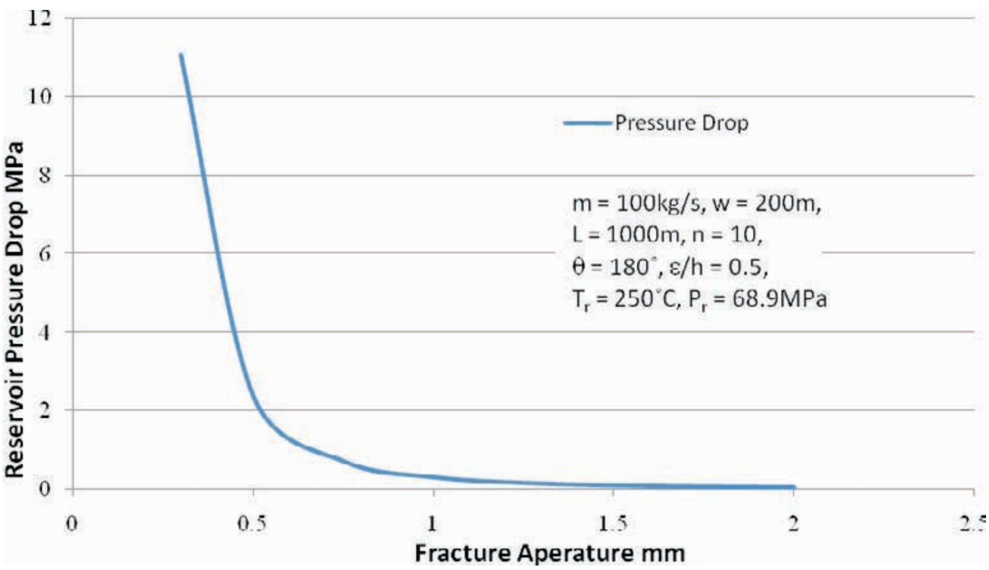

Figure 5. Reservoir pressure drop versus fracture aperture.

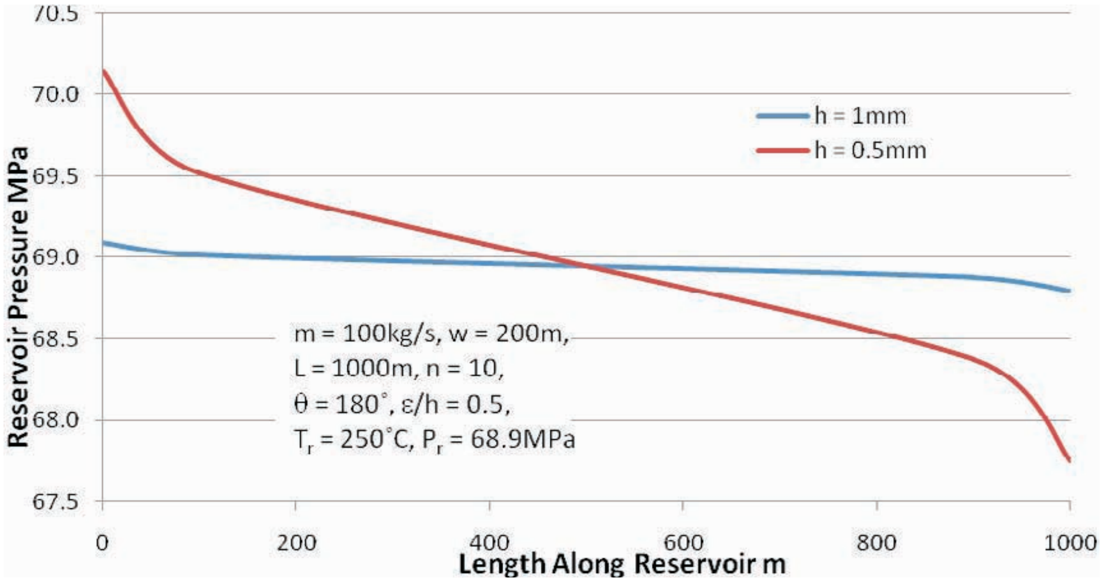

Figure 6. Reservoir pressure profile for fracture aperture 1mm and 0.5mm.

Adopted from Patel & Head (1968), the overall Reynolds number takes into account acceleration effects associated with radial flow. These acceleration effects cause flow to remain laminar despite large local Reynolds numbers (Murphy et al., 1978). The model is summarised in Table I.

Table 1. Model summary.

Modelling	Equation	Assumptions
Well flow	1 & 2	Completely vertical; and of constant diameter
Linear fracture flow	4	Completely horizontal; and uniform temperature
Radial fracture flow	5	Completely horizontal; and uniform temperature
Critical linear flow Reynolds	8	Critical value is 2300
Critical radial flow Reynolds	9	Critical overall Reynolds number is 1×10^8 due to acceleration effects
Reservoir pressure drop	3	Pressure drops are additive; and discontinuities of flow are ignored
Required injection pressure	6	Is equal to $1/2\Delta P_r + P_r$ to achieve flow into fracture
Resulting production pressure	7	Is equal to P_r - $1/2\Delta P_r$ for flow out of fracture

SENSITIVITY ANALYSIS

Using Microsoft Excel® a sensitivity analysis was conducted on the model. The effect on the model of water mass flow rate, fracture aperture and number of fractures was determined. Conservative reservoir geometries at a depth of 4,500 m were used for the analysis. Additionally a reservoir temperature of 250 °C was assumed whilst a reservoir pressure of 68.9 MPa (10,000 psi) was used to simulate the overpressure conditions of the Cooper Basin. However, the model can be used to simulate reservoirs without the existence of overpressure.

RESULTS AND DISCUSSION

Figure 3 shows the effect of mass flow rate on pressure at the injection and production wellheads. Due to the mathematics of the model the relationship between mass flow rate and pressure is

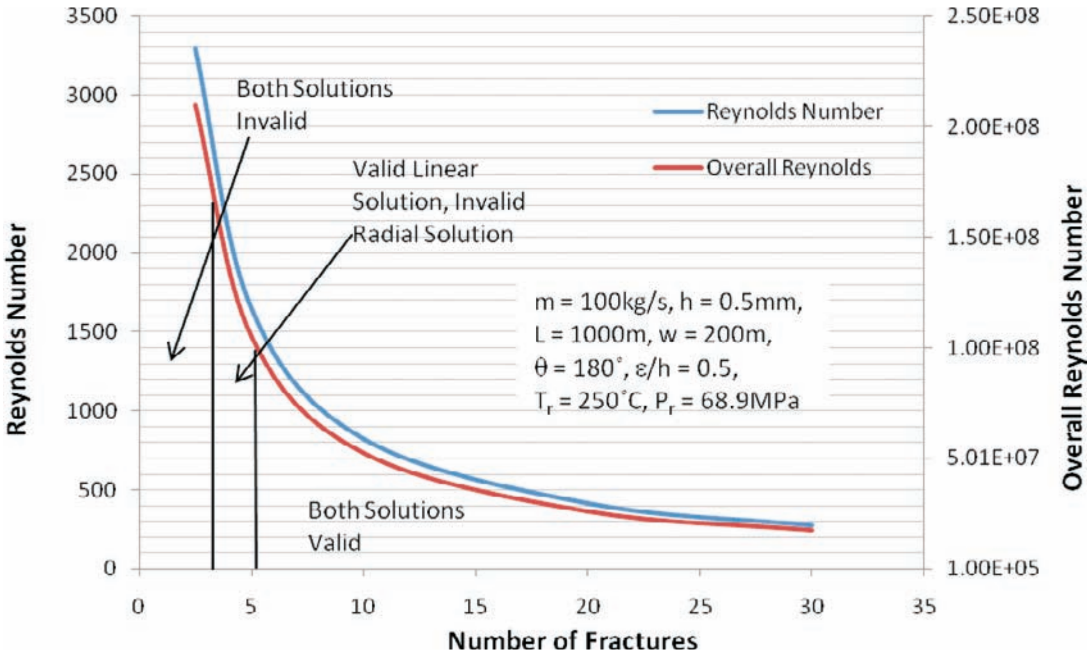

Figure 7. Reynolds number and overall Reynolds number versus number of fractures.

linear. It can be seen on the chart that up until a certain point production pressure exceeds injection pressure. This result can be reasoned by the model assuming that water in the production well is at a higher temperature than the injection well. The less dense water being produced is therefore flowing against less hydrostatic head than the amount of head that is gained with higher density water flowing in the injection well. As a consequence it may be possible to operate EGS as a naturally convective system, that is, parasitic energy losses would be minimised.

Figure 4 shows the effect of fracture aperture has on wellhead pressures. It can be seen that for certain fracture apertures production pressure can exceed injection pressure. Again this is due to less dense water flowing in the injection well than in the production well coupled with increasing fracture aperture which results in decreasing reservoir pressure drop. This second factor is demonstrated in Figure 5 which shows reservoir pressure drop falling significantly with increasing fracture aperture. Figure 5 therefore also emphasises the importance of obtaining a good fracture network.

The model was able to determine flow pressure at any point along the reservoir. Figure 6 shows the reservoir pressure profile for fracture aperture equal to 1 mm and 0.5 mm along the length of the reservoir. It can be seen that the greatest pressure drops occur around the wellbore where the slope of the profile is greatest. This is due to increasing velocity as the water approaches the wellbore.

The model obtained solutions for most reservoir geometries. Turbulent flow would only be expected in cases of geometries which would render a reservoir uncommercial; that is pressure drops would be too high. Figure 7 shows the applicability of the model with respect to number of fractures in the network.

CONCLUSIONS AND RECOMMENDATIONS

The model showed that, for given reservoir geometries, it is possible for wellhead production pressure to exceed wellhead injection pressure. This was reasoned to be the result of less dense and less viscous water flowing in the production well than in the injection well. This means that it may be possible to flow the injection well without the assistance of an injection pump thereby avoiding the parasitic energy losses of running the pump. This preferred operational mode may be called naturally convective. The reservoir pressure profile plots showed that the larger pressure drops within the reservoir occur at the wellbores where the flow regime is radial. The sensitivity analysis on reservoir pressure drop demonstrated that fracture aperture is the most important element of a geothermal reservoir with respect to flow. This emphasised the requirement of a well fractured reservoir to operate EGS effectively. The model was found to be applicable to many reservoir geometries. It was inapplicable for reservoir geometries that would not be considered commercially viable.

The model is simplistic but it is a good basis for further sophistication and refinement. Further study will be conducted commencing July 2008 to investigate non-isotropic well flow and to incorporate a heat exchanger at the surface. In addition the model will be compared to pressure data in literature and altered to model flow for a five-spot well arrangement.

NOMENCLATURE

Symbol	Meaning	Units
D	Well depth	m
ΔP	Pressure drop	psia
d_w	Well diameter	m
ε	Roughness	m
f	Friction factor	-
g	Gravitational acceleration	m/s^2
h	Fracture aperture	m
h_L	Pressure head	m^2/s^2
L	Distance between wells	m
L'	Length of linear flow section	m
m	Total mass flow rate	kg/s
μ	Fluid dynamic viscosity	Pa.s
n	Number of fractures	-
v	Kinematic viscosity	m^2/s
P	Pressure	Psia
q	Volumetric flow rate	m^3/s
θ	Angle of radial flow	°
R_e	Reynolds number	-
ρ	Fluid density	kg/m^3
T	Temperature	°C
$\bar{u}$	Average velocity	m/s
w	Fracture width	m
z	Vertical Displacement	m

Subscripts

avg	Average
b	Bulk
e	External
f	Fracture
i	Injection
lin	Linear flow
o	Overall
p	Production

Symbol	Meaning	Units
pf	Per fracture	
rad	Radial flow	
r	Reservoir	
w	Well	

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The Limestone Coast Project – a unique geothermal project targeting 'blind' geothermal resources.

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INTRODUCTION

The Limestone Coast Project represents a new concept in the exploration for conventional geothermal resources, a first for Australia. It targets hot geothermal brines in buried (or blind) reservoirs. The key geological components of this new exploration model comprise:

- A region of high heat flow;
- A productive reservoir formation; and
- A thick low thermal conductivity layer acting as an insulating blanket.

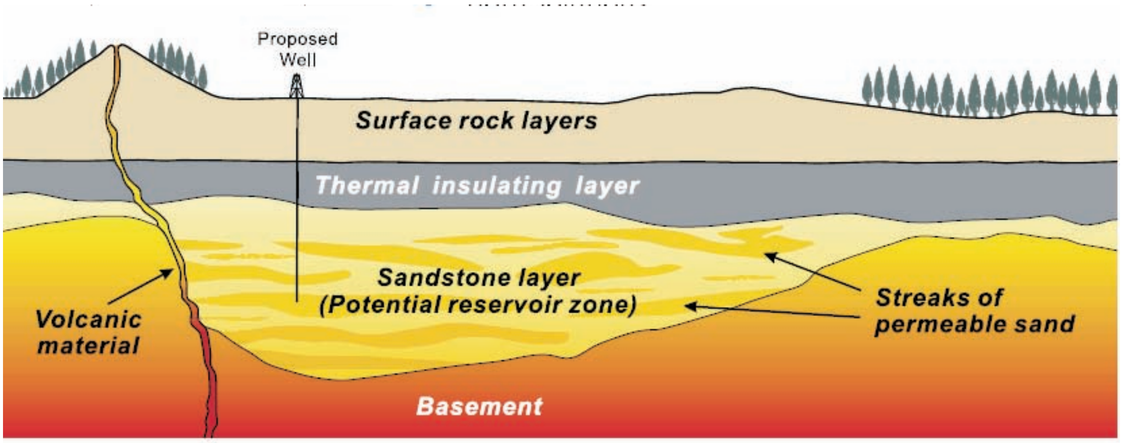

Figure 1. Basement heat source for a sedimentary reservoir.

A schematic diagramme illustrating the geological setting of the Limestone Coast Project is shown in Figure 1.

Extensive geological and geophysical studies as well as modelling have been carried out by Scopenergy, whom Panax recently acquired. This work has confirmed that all components are present in three buried sub-basins in the Limestone Coast area. High heat flow has been established through temperature measurements in 19 existing petroleum and 26 water wells. The regional presence of a productive reservoir formation (the Pretty Hill Formation) and the presence of a thick insulating layer has been inferred from detailed stratigraphic studies of petroleum wells in the nearby Penola Trough (Katnook wells), as well as from re-interpretation of open file seismic data, magnetic and gravity data.

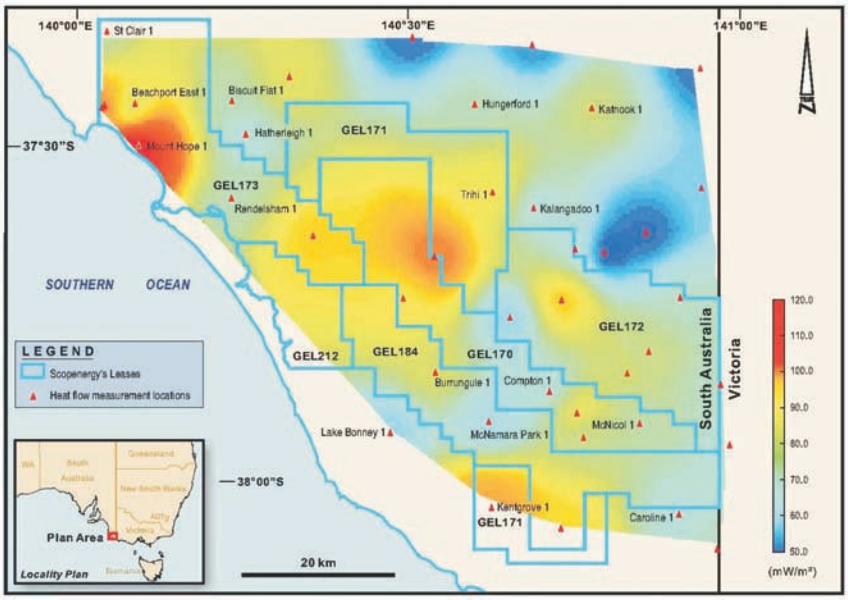

Figure 2. Heat flow map of the Limestone Coast Geothermal Project area. The areas shaded yellow to red indicate heat flow above 90 MW/m².

The high heat flow in the region (Figure 2) is attributed to a combination of the geologically speaking recent volcanism (4,000 to 2,000,000 years ago), crustal thinning during the Otway Basin initiation and anomalous basement heat production.

As a result of the studies carried out to date, three target areas have been delineated (see Figure 3):

- The Rivoli Trough;
- The Tantanoola Trough;
- The Rendelsham Trough.

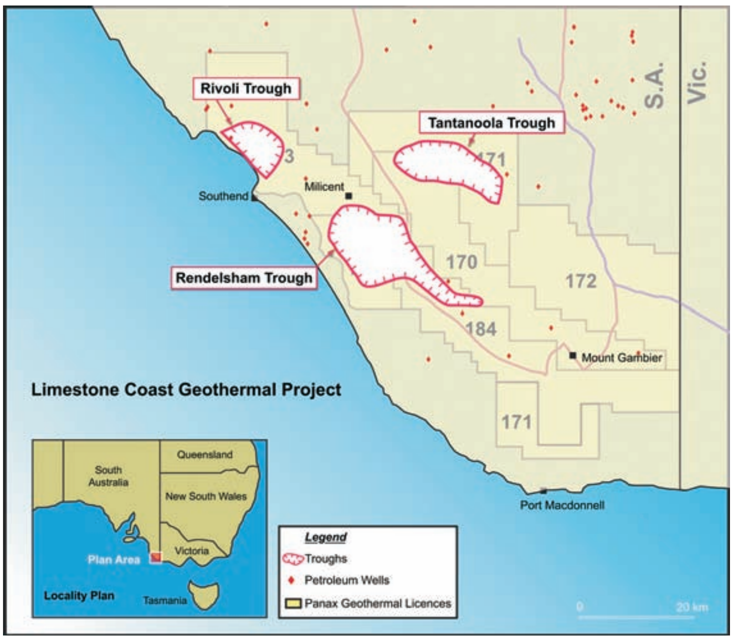

Figure 3. Outlined troughs indicate prospective geothermal areas.

Detailed work by Dr Gaeme Beardsmore has estimated that temperatures ranging from 170 °C – 200 °C will occur at depths of 3,500 m to 4,000 m.

Using this information, and SRK's Potential Reservoir volume estimate, GeothermEx (a prominent US based geothermal consultancy group) has estimated the total generating potential of the above three troughs. As there is not yet an accepted standard within the geothermal industry for the methodology for assessing the geothermal energy potential from a reservoir, GeothermEx used three different approaches; the US Geological Survey Approach, the Single Phase Heat Extraction Approach, and the *In-Situ* Vaporisation Model. Results compared closely, increasing confidence in the estimates, with results ranging from 1,590 MWe to 1,627 MWe for a 30 year life.

This project could represent a new geothermal exploration concept which will open up the potential for geothermal energy to be used globally in a range of geological settings.

Detailed plans are in place to drill a 'proof of concept' deep appraisal well in the first quarter of 2009 (January – March 2009).

Perth Basin's Geothermal Resources

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EXTENDED ABSTRACT

New Era—Western Australia commenced a new era in the search for energy from geothermal resources to broaden the State's energy base with the first acreage release for geothermal exploration covering the Perth Basin on 22 January 2008 (Figure 1). The geothermal acreage release followed amendment to the State's Petroleum Act 1967, which was proclaimed in January 2008 as 'Petroleum and Geothermal Resources Act 1967'.

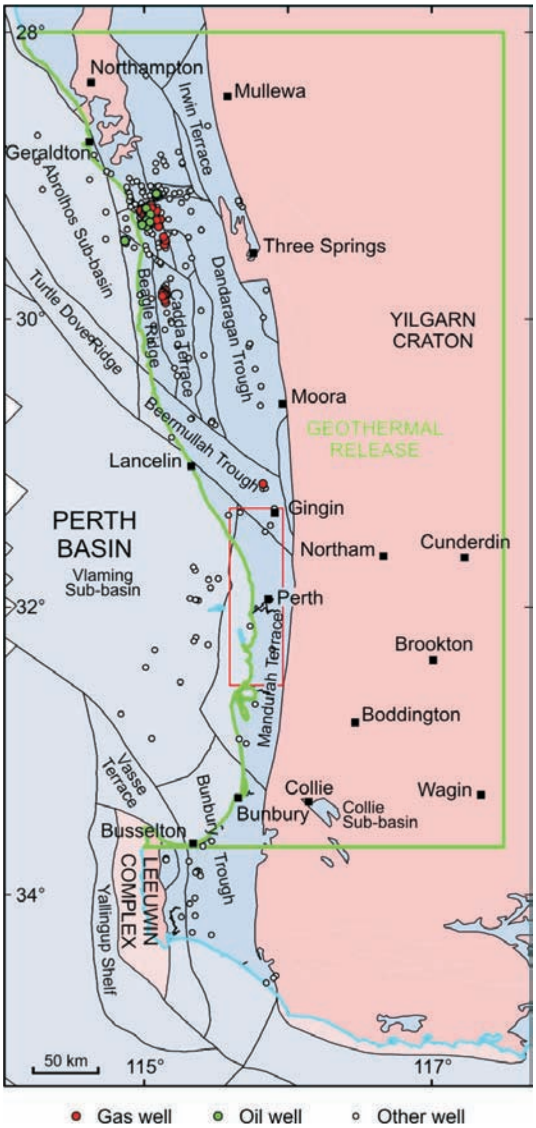

Figure 1. Map showing acreage released area, petroleum wells including current oil and gas producers, and area of water bores (red boundary).

The first study to specifically evaluate geothermal energy resources for Western Australia was initiated in the 1980s for hydrothermal resources. It recognised low temperature reservoirs (65–85 °C) at depths of 2.0–3.5 km, with the best economic potential in the Perth Basin (Bestow, 1982). The next study was initiated in 2006 to evaluate hot rock resources, especially where the depth to 200 °C is less than five kilometres. Petroleum wells in parts of the Canning, Carnarvon, and Perth basins indicate two favourable factors for developing Engineered Geothermal System (EGS); potentially high-heat generating granitic basement and stress environments that are favourable for stimulation, leading to development of horizontal geothermal reservoirs. The Carnarvon Basin has

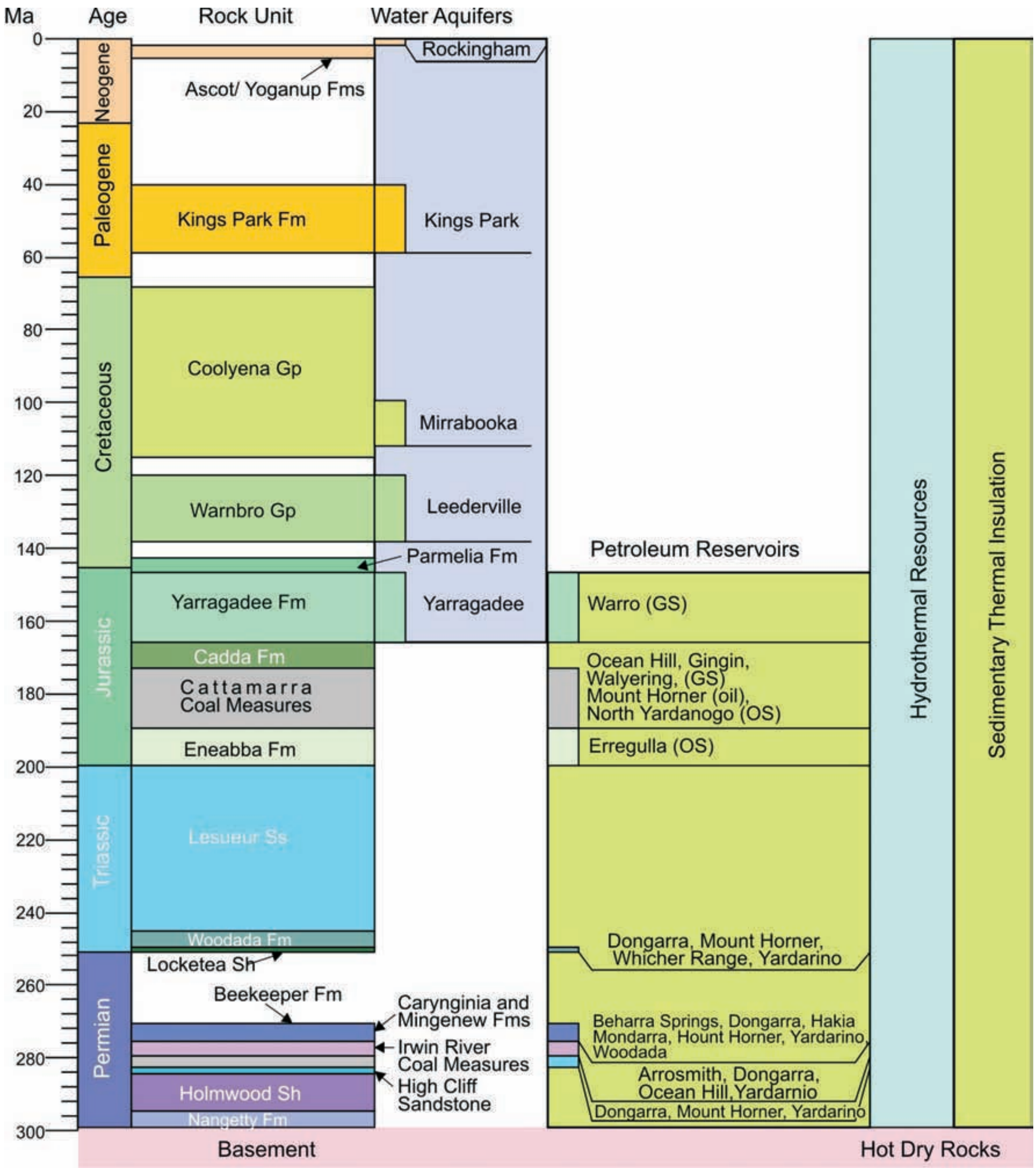

Figure 2. Generalised stratigraphy and distribution of water aquifers, petroleum reservoirs, and potential geothermal resources in the Perth Basin.

the greatest number of wells with high temperature gradients, followed by the Perth and Canning basins (Chopra and Holgate, 2007; Ghori, 2007 and 2008).

This evaluation of the Perth Basin is mainly based on studies archived in the GSWA Library, including GSWA publications:

- for geothermal resources—Bestow (1982), Chopra and Holgate (2007), Ghori (2007 and 2008);
- for hydrogeology—Thorpe and Davidson (1991), Davidson (1995); and
- for petroleum geology—Mory and Iasky (1996), Crostella and Backhouse (2000), Owad-Jones and Ellis (2000) and unpublished companies reports submitted to GSWA.

Perth Basin—is a north–south elongated trough in the southwest of Western Australia (Figure 1), containing mostly a Permian to Lower Cretaceous succession under a thin cover of Tertiary. The eastern boundary is the Darling Fault and the basin extends offshore to the continental–oceanic boundary.

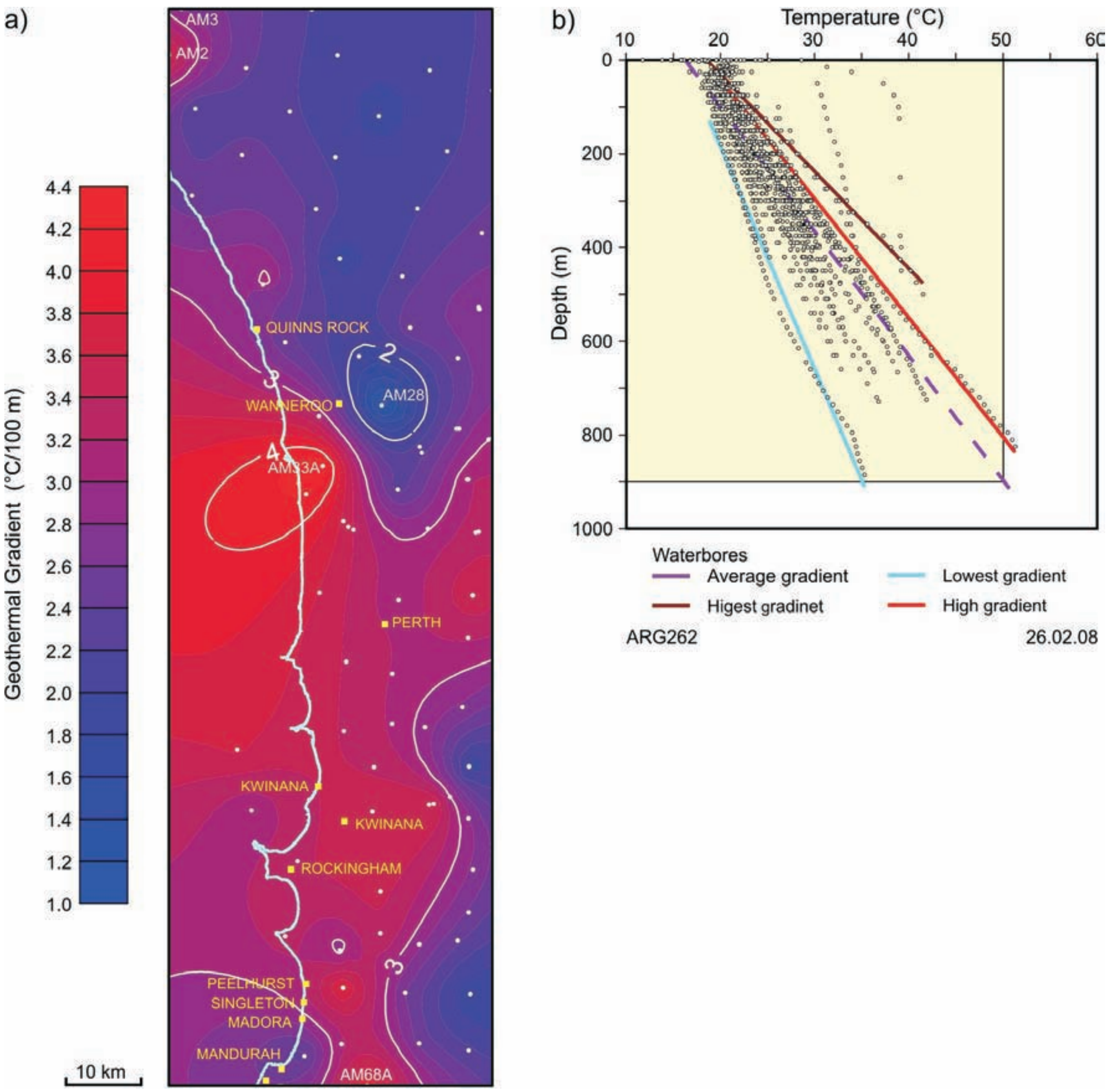

Figure 3. Average subsurface temperature gradient recorded in water bores of the Perth Region: a) geographic distribution of average geothermal gradient; b) subsurface temperature as a function of depth.

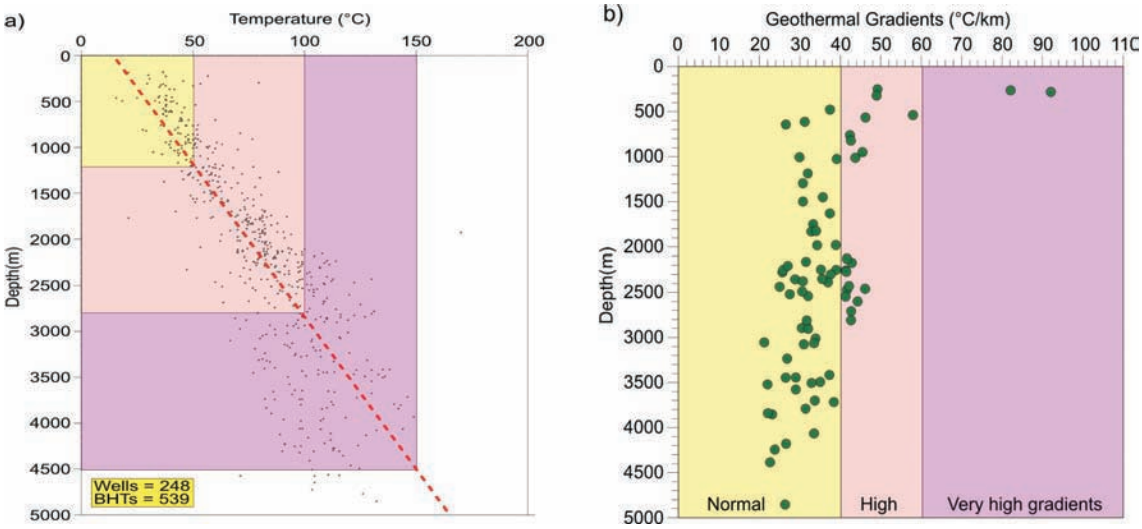

Figure 4. Subsurface temperature recorded in the Perth Basin: a) BHTs as a function of depth; b) equilibrium geothermal gradient as a function of depth from Chopra and Holgate (2007).

The groundwater resources of the Perth region have been systematically investigated by drilling since 1961, and Neogene to Jurassic aquifers down to a depth of 1,100 m are exploited to supplement the industrial and domestic water supply. Petroleum exploration commenced in the 1950s and has resulted in discoveries of at least 13 oil and gas fields. Figure 2 shows the generalised

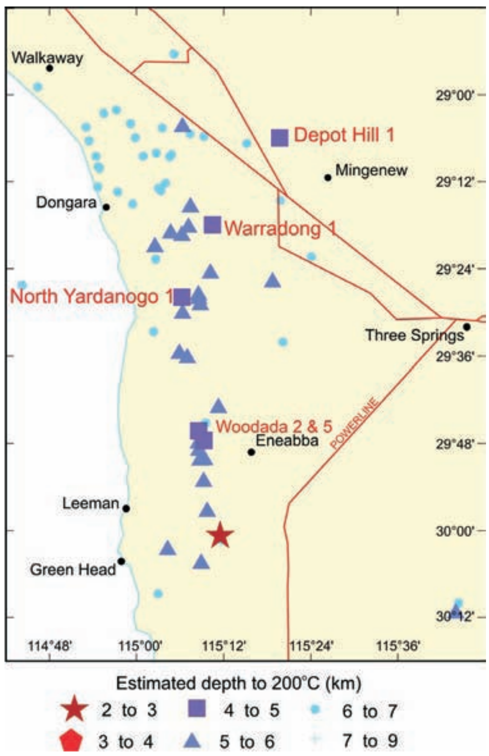

Figure 5. Wells with estimated depth to 200 °C shallower than 5 km in the Perth Basin.

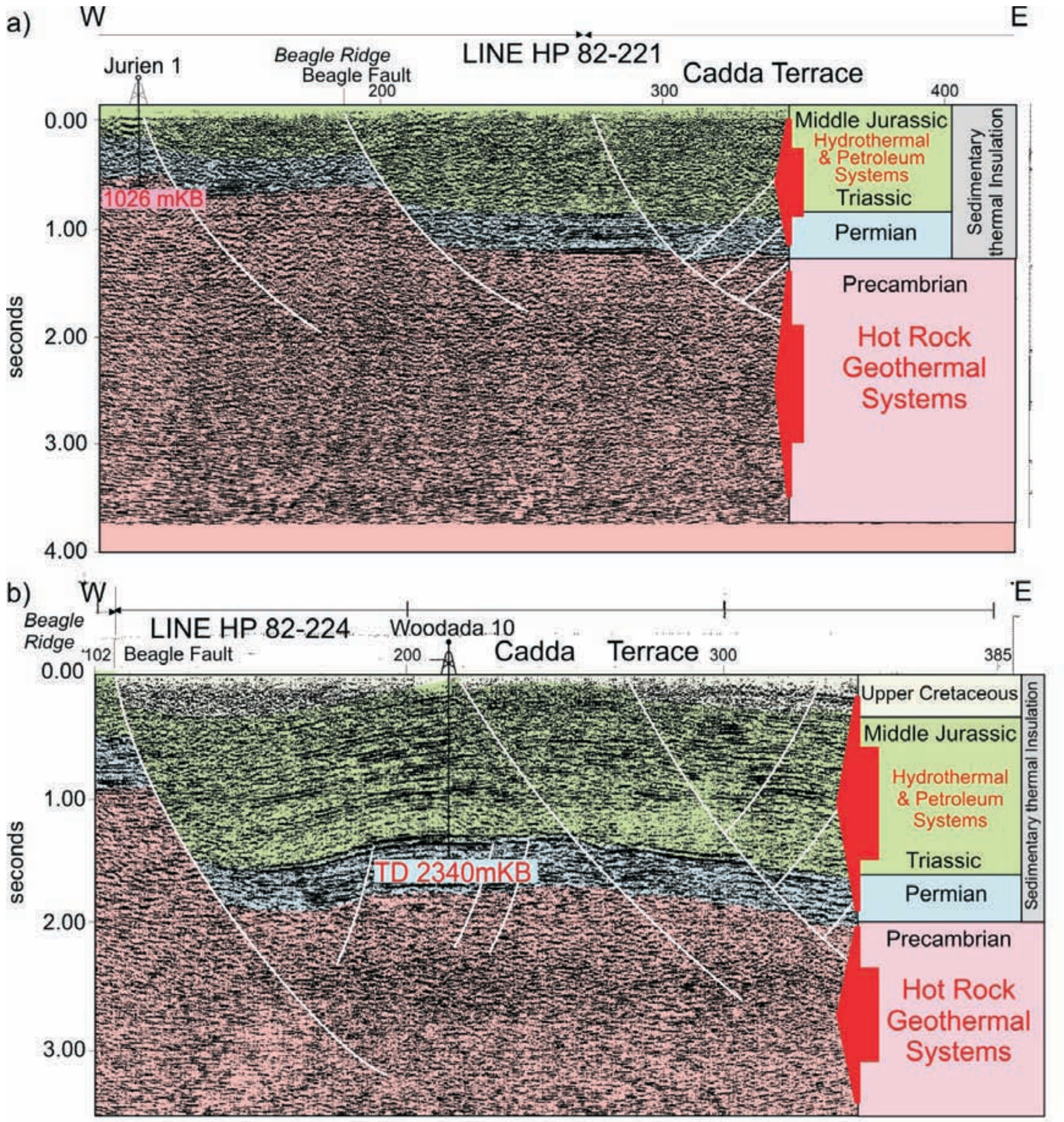

Figure 6. Conceptual model for petroleum and geothermal resources of the Perth Basin: a) Beagle Ridge; b) Cadda Terrace.

stratigraphy of the Perth Basin and distribution of water aquifers, petroleum reservoirs and potential geothermal resources.

The prediction of subsurface temperature distribution in the Perth Basin is based on temperature logs recorded in 47 artesian monitoring water bores, and bottom bole temperatures (BHTs) recorded in about 335 petroleum wells. For each water bore, temperatures at different depths were compiled and geothermal gradients were computed. The recorded gradients range from 1.1 °C/100m to 4.4 °C/100m at depths less than one kilometre. The highest, as well as the lowest, subsurface temperatures are recorded around the Wanneroo area (Figure 3). The lower temperatures extend towards the north and the higher towards the south of the Wanneroo area. These temperatures indicate low temperature resources up to 50 °C at a depth less than one kilometre in areas of high geothermal gradients.

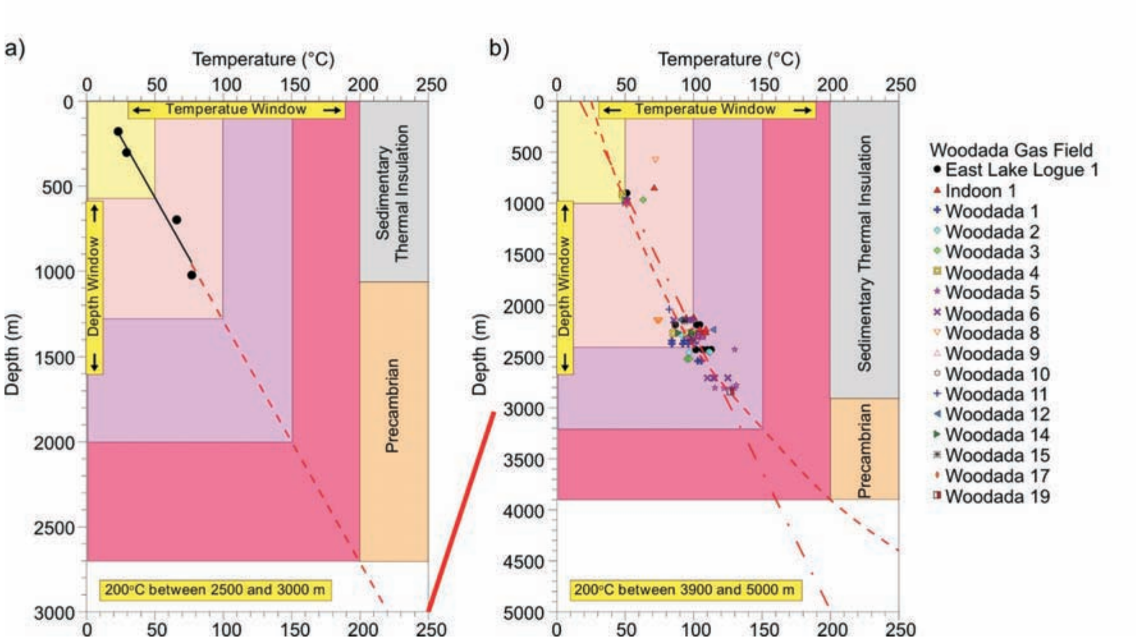

Figure 7. Subsurface temperature as a function of depth of the Perth Basin: a) Jurien 1; b) Woodada Gas Field.

The recorded BHTs in Petroleum wells provide temperature distribution for a larger area and a greater depth (850 m) than the Perth region water bores (Figure 1). Figure 4 shows the Perth Basin subsurface temperatures as a function of depth: a) recorded BHTs (540) in 242 petroleum wells; b) estimated equilibrium geothermal gradient as a function of depth (Chopra and Holgate, 2007). These plots show that the recorded temperatures and depths are up to 150 °C and 4.5 km, respectively. The corrected estimated equilibrium temperatures are expected to be 10% to 20% higher than these recorded temperatures.

For the Perth Basin, the estimated geothermal gradients in 83 wells (Chopra and Holgate, 2007) indicate the presence of wells with very high to normal gradients, ranging from 90 °C/km to 20 °C/km (Figure 4b and 5). Gradients in wells deeper than 2 km are considered more reliable and representative for hot dry rock resources.

Conceptual models for petroleum and geothermal resources have been developed for the Beagle Ridge (Figure 6a) and the Cadda Terrace (Figure 6b) of the Perth Basin, because of the high geothermal gradients in Jurien 1 (55 °C/km) on the Beagle Ridge and Woodada 2 (40 °C/km) within the Cadda Terrace. Jurien 1 was drilled to a total depth of 1,026 m and intersected granitic basement at 967 m. The extrapolated recorded temperatures indicate that 200 °C could be reached between 2.5 km and 3.0 km (Figure 7a). This may be an economical depth for developing geothermal resources, if other factors for developing EGS are found favourable. Figure 7b shows the subsurface temperatures as a function of depth for the 17 wells of the Woodada Gas Field. The extrapolated temperatures indicate 200 °C at depths between 4 and 5 km. The reservoir temperature of the Woodada Gas Field is 120 °C at depth range from 2,125 m to 2,496 m (Owad-Jones and Ellis, 2000).

Whereas an overthrust regional stress regime is ideal to develop horizontal geothermal reservoirs, further studies are required to confirm if such conditions exist within the Perth Basin. Stress data collected *in-situ* exclusively from borehole breakouts in 20 petroleum exploration wells in the Perth

Basin indicate stress E–W orientations (Hillis and Reynolds, 2000). At this stage it is unclear if there are horizontal geothermal reservoirs across the Perth region.

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Forward Prediction of Temperature Distribution Direct From 3D Geology Models

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ABSTRACT

Work is under way to develop a method for rapid calculation of temperature distribution directly from a 3D geology model. A need for this tool stems from Australia's emerging geothermal energy exploration and production industry. The prohibitive cost and huge task involved in acquiring comprehensive sets of heat flow data, means that the ability to accurately model heat flow at surface, and/or predict 3D temperature distribution for a modelled part of the crust, will be key to supporting this industry. Here we explain the approach we have taken.

INTRODUCTION

Providing a sophisticated way to forward model temperatures from 3D geology models will be possible via the marriage of a new geothermal software module, with an existing 3D model-building application: GeoModeller (developed by Intrepid Geophysics and BRGM). The final module will perform temperature calculations on generic voxet models as well as those built in GeoModeller, but will require GeoModeller as the engine.

Here we present: 1) a summary of the relevant theory of heat flow, 2) an explanation of how it was implemented, 3) justifications for the assumptions and simplifications we currently make for the Australian geological setting, 4) a unit test report from the proto-type code, and 5) a brief overview of the Paralana geothermal energy exploration project (South Australia) – the subject of a 3D geology model being built to validate the new software module.

GEOTHERMAL MODULE DESIGN

Heat transfer: Governing equation

Prediction of 3D temperature and heat flow needs to account for all processes that transfer heat in the Earth's crust (Stüwe, 2007). Whilst there are eight main processes possible (Table 1), typical geological settings throughout Australia allow us to neglect several of these processes.

Firstly, only the production of heat via radiogenic sources usually needs to be considered in the Australian continental setting. This is because no highly active tectonism, metamorphism or volcanism is occurring in the upper crust today, which might otherwise contribute to mechanical or chemical heat production.

Secondly, it is usually sufficient to consider only the case of thermal steady state for the Australian crust. Thermal steady state means there is no change of the temperature distribution over time, i.e., the crust has attained thermal equilibration since the last period of tectonic disturbance.

Table 1. Full list of heat transfer processes, with five that can be ignored for the Australian geological setting shown in italic type.

Heat Transfer Processes	
Conduction of heat	
Production of heat by:	Radioactivity
	Mechanical work (friction)
	Chemical reaction
Advection (Convection) of heat by:	Fluids
	Erosion
	Deformation
	Magma

$$\frac{dT}{dt} = \kappa\nabla^2 + u\nabla + \left(S_{rad} + S_{chem} + S_{mech}\right) / \left(\rho c_p\right) \quad (1)$$

Equation 1 is the heat transport equation in 3 dimensions, in its full Cartesian form, for material with constant thermal conductivity. T is temperature and t is time. κ is the thermal diffusivity given by $\kappa = k/(\rho c_p)$ where k is thermal conductivity, ρ is density and c_p is heat capacity. u is the advection rate vector. The heat production: S, is here written as the sum of contributions from radiogenic, chemical and mechanical heat sources.

Whilst neglecting some of these heat transfer processes is valid, Equation 1 assumes constant thermal conductivity. For geothermal energy exploration in hot, relatively dry systems (which is the Australian experience, see Beardsmore (2007)), large conductivity contrasts between different rock types are essential to the exploration model. Therefore, the consideration of variable conductivity is a crucial aspect of the modelling.

Equation for the geothermal module

Therefore, the equation of interest to us for providing accurate-as-possible prediction of upper crustal temperature distribution in Australian settings, for the steady state, can be expressed as in Equation 2. Equation 2 combines conduction, advection and heat production terms (for further details see Stüwe (2007)).

$$\left(\frac{d\left(-k\frac{dT}{dx}\right)}{dx} + \frac{d\left(-k\frac{dT}{dy}\right)}{dy} + \frac{d\left(-k\frac{dT}{dz}\right)}{dz} \right) + \rho c_p \left(u_x \frac{dT}{dx} + u_y \frac{dT}{dy} + u_z \frac{dT}{dz} \right) = -S \quad (2)$$

Equation 2 describes the steady state 3D temperature field under consideration of spatially variable thermal conductivity. This is the equation currently solved by our proto-type geothermal module. For definition of terms see Equation 1.

Implementation

In order to make use of Equation 2 in GeoModeller, equation 2 was discretised with an explicit finite difference scheme. This method of solution allowed us to make use of the existing Cartesian voxelised grid of GeoModeller. This finite difference approximation was iteratively solved with a Gauss-Seidel iteration scheme until the sum of the residual errors was small. For a series of effectively one-dimensional unit tests (see below) a solution was obtained for a 20 x 20 x 20 voxelised grid within about 1 minute using a standard PC.

However, for larger voxelised grids the calculation time would increase rapidly. We are therefore considering implementing an explicit multi-grid algorithm which best operates on a grid with a power of 2 number of nodes in each spatial direction. This algorithm only operates on the errors of the previous solution, making it a very efficient tool to handle 3D heat flow. In further plans we will also consider solving the equations of heat transfer on a properly triangulated finite element mesh which will enable much better handling of problems involving topography at the surface and the full use of GeoModellers main strength: the powerfully interpolated surfaces separating rock types of spatially variable thermal and other physical properties.

Boundary conditions

As with any differential equation, the derived equation for 3D temperature prediction needs boundary conditions to evaluate the integration constants. On the 4 vertical sides, it is assumed that no heat flows through the model boundaries (i.e., Neuman type boundary conditions). This implies that all lithologies and *in-situ* temperatures are mirrored beyond the model boundaries. At the base, either a heat flow or a constant temperature may be applied. Finally, at the top a constant temperature is applied for which we have initially assumed zero °C, but any mean annual temperature can be prescribed there.

Topography effects

Allowing for topography is a key concern for accurate prediction of 3D temperature distribution, as illustrated in Figure 1 where temperature distribution is highly influenced by topography in the shallow sub-surface, and is less influenced at depth.

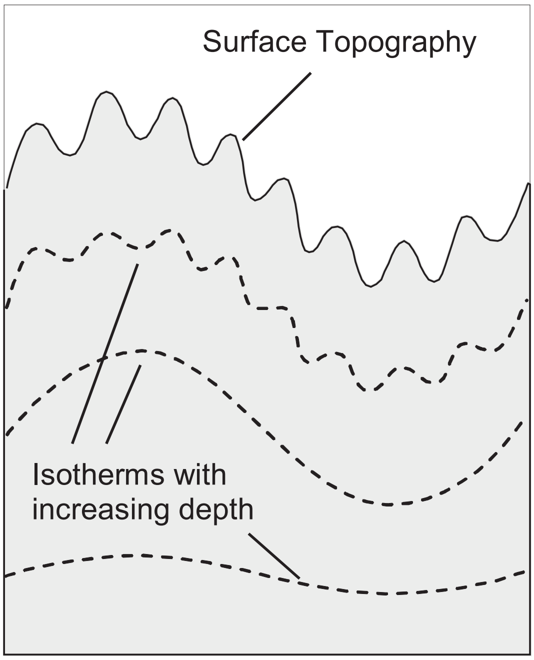

Figure 1. The influence of surface topography on isotherms at depth (after Stüwe K. and Hintermüller M., 2000).

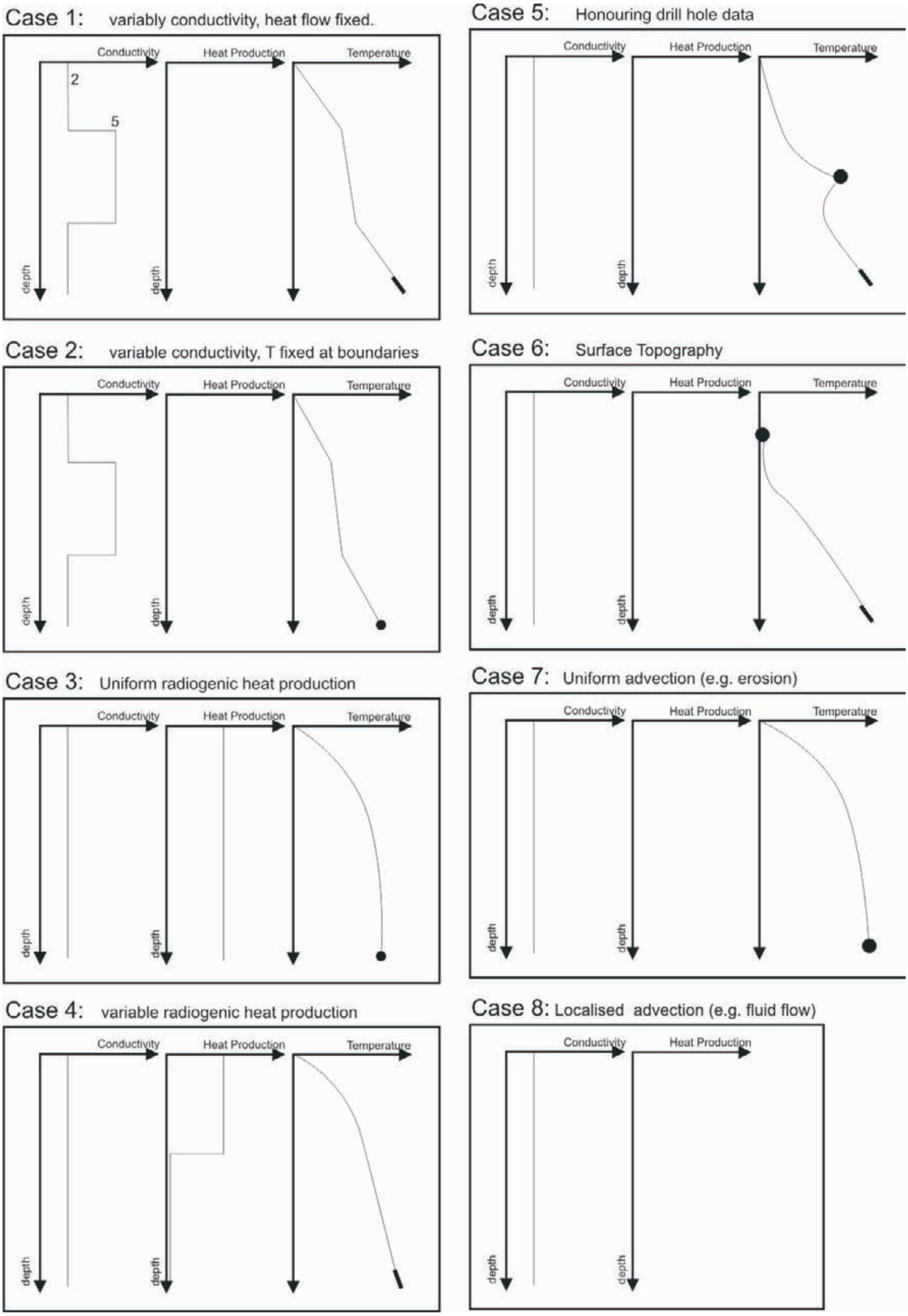

Figure 2. Cartoons illustrating the essence of the unit tests applied to the proto-type geothermal module performing forward 3D temperature modeling.

UNIT TEST RESULTS

In order to test our finite difference approximation, 8 unit tests were performed with the proto-type geothermal module, using different initial settings and boundary conditions (Table 2). The overall design of these tests is illustrated in Figure 2.

All 8 tests passed, as verified by returning the expected pattern of temperature distribution, and by independent analytical solutions where it was possible to derive them. Results are shown in Figure 3, where they are presented in the form of voxelised, 2D temperature distributions rendered to a vertical section cutting the original 3D geology model.

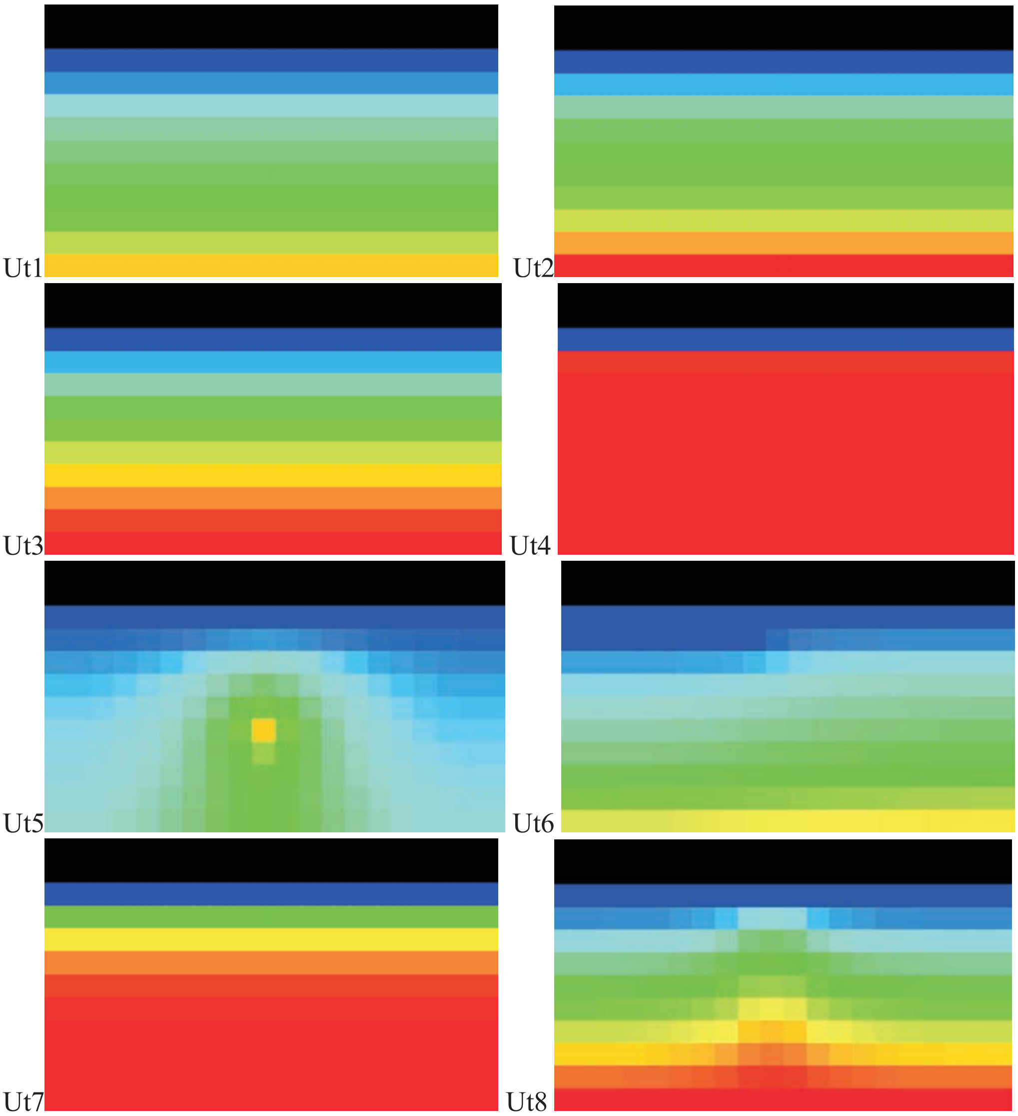

Figure 3. Unit test results: 2D sections rendered from 3D solutions predicting temperature variation for the 8 unit tests. See Table 2 and Figure 2 for test details.

Unit Test	Case Name	Conductivity	Heat Production	Bottom boundary condition
1	Initial condition 1	Variable conductivity (in 3 layers: k = 2, k = 5 and k = 2)	none	constant heat flow
2	Initial condition 2	Variable conductivity (in 3 layers: k = 2, k = 5 and k = 2)	none	constant temperature
3	Initial condition 3	constant conductivity	constant heat production	constant temperature
4	Initial condition 4	constant conductivity	Step-shaped distribution of heat production	constant heat flow
5	Honouring drill hole data	constant conductivity	none	constant temperature
6	Honouring topography	constant conductivity	none	constant heat flow
7	Uniform advection	constant conductivity	none	constant temperature
8	Localised advection	constant conductivity	none	constant temperature

Table 2. The initial settings and boundary conditions for 8 unit tests designed to validate the proto-type geothermal module.

PARALANA CASE STUDY

The Geological Setting

Petratherm Ltd is actively exploring for heat, and thus a viable geothermal energy source in the Poontana Graben, northern Flinder's Ranges (South Australia). Their deepest well to date, Paralana-1B, reveals temperatures of ~109 °C at 1,806 m (Figure 4) and 2D temperature modelling of the project area indicates they can expect temperatures of 200 °C at 3,600 m.

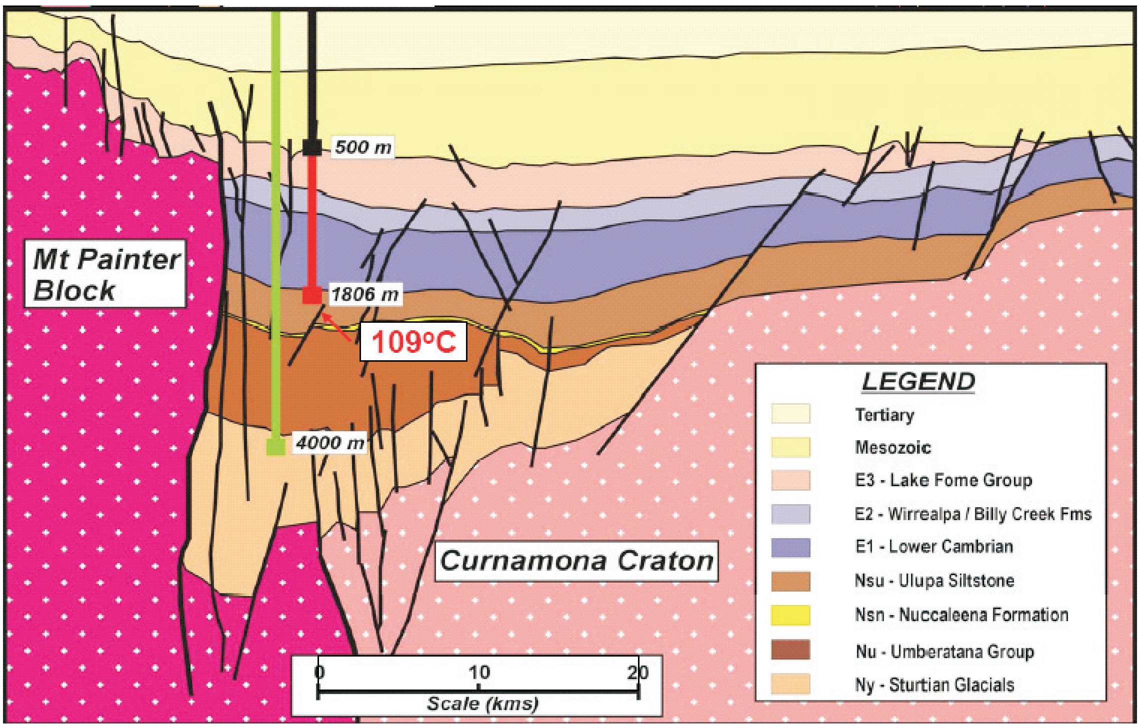

Figure 4. Generalised west-east cross-section through the Poontana Graben, northern Flinders Ranges, South Australia.

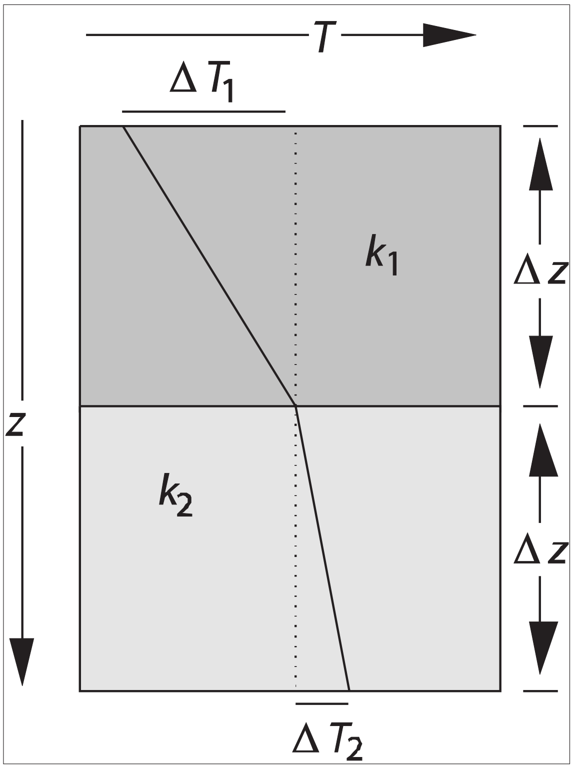

Figure 5. The principle of heat refraction in the crust.

The geothermal energy exploration model

Different thermal gradients will exist in rock units of different conductivity and this is the essence of the typical geothermal energy resource in Australia. As well as other key factors including an ability to enhance natural fractures at depth (to create a circulating system), finding a viable heat resource requires abnormally high rock temperatures close to the surface. In Australian settings, this is most easily achieved near radiogenic granites (with high thermal conductivity), where a sedimentary cover of low thermal conductivity lies above (a thermal insulator). This situation sets up heat refraction in the crust and delivers high temperatures to shallow depths (Figure 5).

At the Paralana Project, radiogenic granites of the Mt Painter Block are providing a high heat flow, which is being blanketed mainly by Cambrian sediments of the Arrowie Basin (units E3, E2 and E1 in Figure 4).

Work is currently underway to build a 3D geology model of the Paralana project in 3D GeoModeller. This model will be used to verify the new software module.

FINAL COMMENT

A planned initiative by Geoscience Australia is to provide and maintain a database of measured heat flow, rock types, thermal conductivities, etc., for geologic terrains throughout Australia. This will be a key information resource for explorers in the geothermal energy industry, greatly assisting the targeting of locations containing shallow, anomalously high heat reserves. Our view is that the database will usefully contain both observed and predicted temperature data. Therefore, we believe our work in developing an accessible method for rapid calculation of temperature distribution directly from 3D geology models, makes a valuable contribution to this initiative.

ACKNOWLEDGEMENTS

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The Thermal Structure of Continental Lithosphere: a Review

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ABSTRACT

The rapidly increasing interest in geothermal energy in Australia, and hot fractured rock (HFR) technology in particular, follows a national and worldwide spurt of research into the thermal properties of plates (e.g., Swenson et al., 2000; Neumann et al., 2000). Much of the interest in geothermal energy is due to the recognition of Australia's particular suitability for HFR energy generation, highlighted by Swenson et al. (2000) and again by McLaren et al. (2003). However, both our understanding of heat flow in the crust and the Australian dataset are still in their infancy. Further investigation of the bigger picture will once again provide valuable information about geothermal prospectivity.

UNDERSTANDING THE THERMAL STRUCTURE OF CONTINENTAL LITHOSPHERE

The temperature in the plates is controlled by four main processes: radioactive decay in the lithosphere, heat transfer from the convecting mantle, displacement of the geotherm due to tectonism, and advective (magmatic or hydrological) heat transfer. By far the majority of radioactive decay occurs in the crust.

Studies of the thermal structure of the crust began in earnest in 1968 with Birch et al. (1968) and Lachenbruch (1968), who both suggested a linear relationship between surface heat production and surface heat flow. Since then, it has been shown that the relationship is not so simplistic (Jaupart and Mareschal, 1999). However based on data from the Canadian Shield, there does appear to be a relationship between the amount of heat producing elements (HPEs) in the crust and differentiation of those HPEs (Perry et al., 2006), as predicted by Sandiford and McLaren (2002): that is, the more the crust is enriched in HPEs, the more differentiated it is (Figure 1).

Elsewhere in the world, the mantle component of surface heat flow is well constrained (e.g., Jaupart and Mareschal, 1999), however Australia's mantle heat flow remains largely unaddressed (although see O'Neill et al., 2003). This is about to change following the publication of three papers (Faul and Jackson, 2005, Goes et al., 2005, and McKenzie and Priestley, 2008) which use seismic velocities to calculate temperatures at different depths in the mantle lithosphere.

Tectonic processes in the Australian plate are unlikely to be a major control on the temperature field, as the majority of Australia's land surface undergoes only very slow erosion (Bierman and Caffee, 2002). A possible exception to this is in the Flinders Ranges (Neumann et al., 2000), however for brevity this feature is not discussed here.

As with tectonic processes, transient magmatic effects on the Australian temperature field are likely to have decayed for the most part and for brevity are not discussed here. However transient effects on the temperature and heat flow due to advection of groundwater, such as in the Great Artesian Basin, are more likely to have an impact on the temperature field.

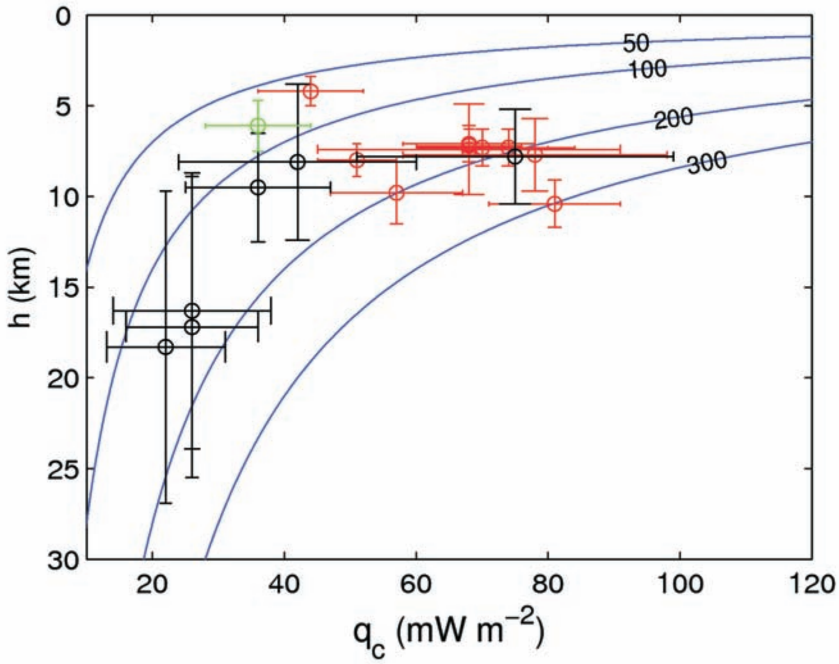

Figure 1. Yilgarn (green), Central Australian Heat Flow Province (red) and Canadian (black) terranes, plotted by characteristic length scale h (assuming single homogenous layer). Contours are the maximum temperature contribution to the geotherm from crustal heat production; thermal conductivity is set to 2.8 W m^{-1} °C^{-1}.

In Central and Western Australia, there is assumed to be negligible input from tectonic and advective processes; thus, the main contributions to heat flow and the temperature field are mantle heat flow and radioactive decay in the crust. In Eastern Australia, however, some transient effects may persist. There is evidence that high temperatures in the Cooper Basin have a transient component (McLaren and Dunlap, 2006), which is not quantified and hence not accounted for in calculations about the life of the resource. This example shows that although Australia lacks obvious transient influences on heat flow, they cannot be ignored.

THE DISTRIBUTION OF HEAT PRODUCING ELEMENTS IN THE CRUST

In tectonically quiescent regions, the only significant contributions to surface heat flow come from the mantle and radioactive decay in the crust. Therefore investigation of one compliments the other; an estimate of mantle heat flow can inform not only an estimate of the crustal contribution to surface heat flow, but the distribution of heat sources with in the crust. Neumann et al. (2000) defined the South Australian Heat Flow Anomaly which is enriched in heat producing elements (twice the amount in average continental crust). The origin of this enrichment is not yet clear, however it makes this region, and the broader Central Australian Heat Flow Province (McLaren et al., 2003) of which it is a part, an ideal place to study heat production in the crust.

In order to describe intracrustal heat production without knowing the distribution, Sandiford and McLaren (2002) defined a value *h*, the characteristic length scale of the distribution of heat producing elements (HPEs) in the crust. It is defined by equation (1):

$$h = \frac{1}{q_c}\int_0^m \left(H(z)z\right)dz \qquad (1)$$

where *m* is the depth to the Moho (estimated from seismic studies, e.g. Clitheroe et al. 2000), *z* is depth, and *H(z)* is heat production as a function of depth. This may be understood by visualising all the heat production in the crust as being concentrated at depth h. While this produces a slightly different geotherm to realistic distributions, it agrees with them on temperature and heat flow at the surface and at the Moho. Low h means that HPEs are concentrated at shallow depths; high h (i.e., half the crustal thickness or greater) means that the crust is undifferentiated or that the HPEs are enriched in the lower crust.

Previously, estimates of h were based on surface heat production, an estimate of mantle heat flow, and a measurement of surface heat flow. Using seismic data to calculate heat flow and temperature has the potential to give not only a more refined estimate of heat flow, but an additional boundary condition in the form of a $T(z)$ in the mantle lithosphere. Once mantle heat flow, Moho temperature and depth, thermal conductivity and surface heat flow are known, an estimate of the distribution can be made:

$$h = \frac{k\left(T_m - T_s\right) - q_m m}{q_s - q_m} \tag{2}$$

where k is thermal conductivity, Tm is Moho temperature, Ts is surface temperature, q_m is heat flow from the mantle at the Moho, m is the depth to the Moho and q_s is surface heat flow. Thus even without the surface heat production, mantle data contributes towards a statement about the location of the HPEs in the crust.

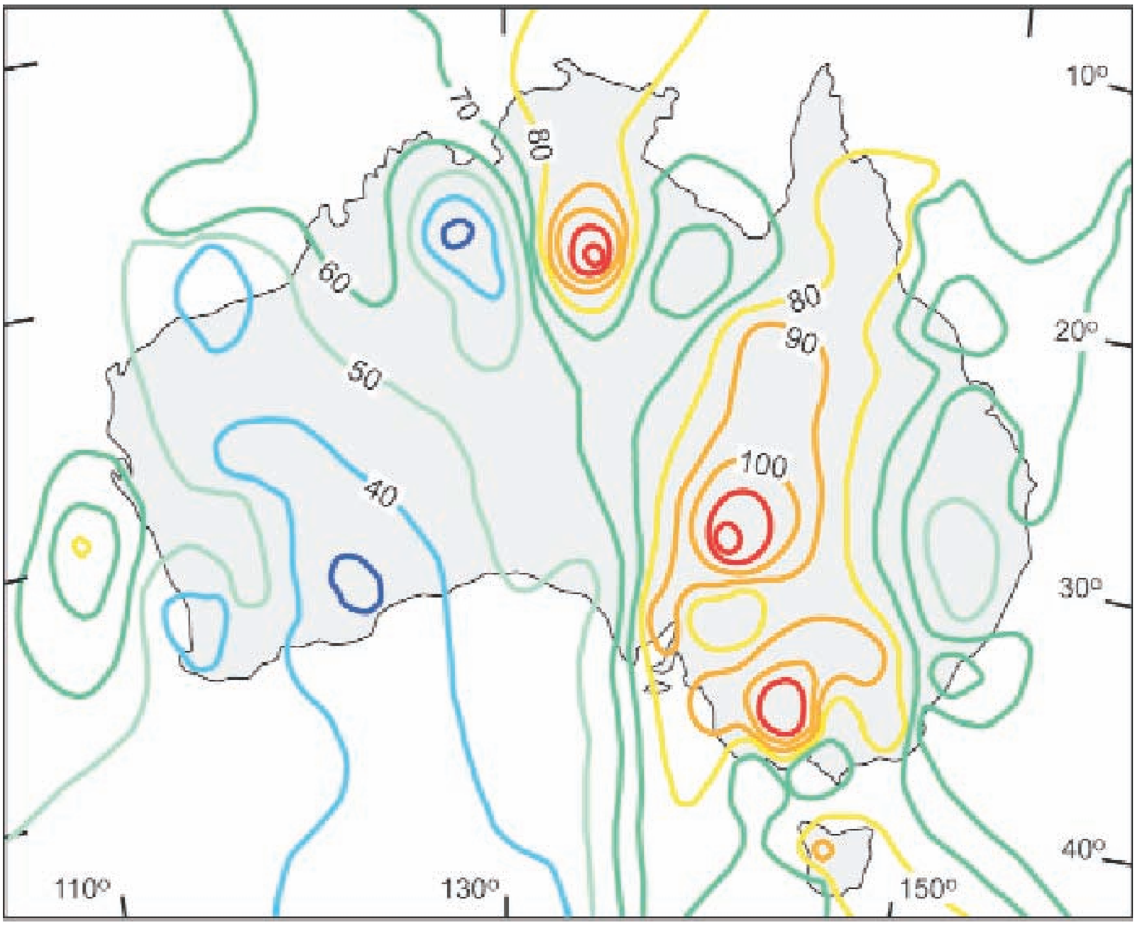

Figure 2. Surface heat flow map of Australia from McLaren et al. (2003). Approximately 150 onshore measurements were used (Cull, 1982).

This is significant because it provides another constraint on geothermal prospectivity of a region. If calculations show that the HPEs in the crust are concentrated in the upper few kilometres, then the geotherm is much more likely to be steep enough to reach hotter temperatures, shallower.

NEXT STEPS

The next step is to use mantle temperatures from seismic velocities (e.g. from McKenzie and Priestley, 2008; Faul and Jackson, 2005 and Goes et al., 2005) with estimates of thermal conductivity (Jaupart and Mareschal, 1999) to calculate mantle heat flow. These calculations will be used in conjunction with existing heat flow measurements (Figure 2) and new heat flow measurements, to be made by Geoscience Australia, geothermal energy companies doing exploration, myself and other students at the University of Melbourne. Using these new data, I will begin to assemble a map of mantle heat flow and a map of HPE differentiation, both of which will assist in choosing prospective fields for geothermal exploration.

FURTHER RESEARCH

There are two key areas which would benefit greatly from further research in Australian geothermics. Firstly, a study of advective – especially hydrological – processes is needed to ensure that heat flow measurements are not assumed to be only the sum of mantle heat flow and crustal radioactive decay. A better understanding of these processes will aid in exploration, exploitation and study of Australia's geothermal reserves. Secondly, the origin of Australia's enrichment in HPEs, particularly in the SAHFA, remains unknown. One attempt has been made to trace the source of the uranium and thorium using lead isotopes (Gordon, 2007) however this approach was unsuccessful due to the low diffusion temperature of lead in K-feldspar. A new approach is needed to identify the cause of the anomaly in South Australia, and whether it might be repeated in other parts of the world.

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Lessons Learnt from the Deep Heat Mining EGS Project in Basel, Switzerland

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ABSTRACT

The Kanton of Basel-Stadt in partnership with a number of Swiss utility companies is endeavouring to develop a geothermal co-generation plant from an enhanced geothermal system. The project is developed and operated by Geothermal Explorers Ltd.

Prior to drilling the 5009 m deep Basel-1 well, a reconnaissance well was drilled to 2,755 m and a refined microseismic monitoring system with five additional shallower wells was set up. The monitoring array was not only for visualising microseismic activity during hydraulic stimulation, but also to observe the natural seismicity in this area, which is characterised by sparse, sometimes destructive seismicity, as shown by the historic Basel earthquake in 1356 with an estimated MW of 6.9.

The hydraulic stimulation process in the Basel-1 well was stopped after six days of injection when the induced seismicity gradually built up with magnitudes of up to ML 2.7. Four hours after shut-in a seismic event of ML 3.4 occurred, coinciding with the start of bleeding off the well to hydrostatic conditions. The short jolt, which was accompanied by a loud bang, scared the local population. The event exceeded the officially accepted threshold of ML 2.9 and led to a suspension of the project for the time being. Within 55 days after stimulation three aftershocks with ML >3 were recorded.

The detailed data analysis of the reservoir growth and the analysis of fault plane solutions of induced events suggest that the excessive induced seismicity is not the result of a rupture process along a single, critically stressed fault plane, but the result of multiple shearing on oblique oriented fractures in a structurally weakened zone.

The second lesson learnt is that communication, preparing the population for felt induced seismicity, cannot start early enough and thoroughly enough. Poorly informed media called people repeatedly to report damages. These public calls triggered a flood of complaints about questionable cracks in plastered walls, whereas well informed house owners in the vicinity of the drilling rig hardly filed any complaints. A verification of the reported damages to be caused by the induced events is yet outstanding.

Madrid Basin District Heating Potential

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The area surrounding Madrid City constitutes one of the most favourable medium-low temperature geothermal environments identified to date in Spain.

Madrid Basin geothermal potential was discovered in 1980 when an oil well drilled by Shell demonstrated temperatures of 88 ºC and 150 ºC at 1,700 m and 3,400 m depth respectively. Petratherm EspaZa applied in 2006 for a geothermal exploration license of 290 km^2 over the most prospective areas. The tenement was awarded in November 2007.

Geologically, the Madrid basin occupies the northern part of the Tajo sedimentary basin, and is filled with fluvial and lacustrine tertiary deposits. Next to the northern margin of this basin, the thickness of sediments reaches 4,000 m. Sediments are thrust against crystalline basement rocks, mainly granites and gneisses which delineate the North Madrid Sierras (Central System). These thrust structures are deep parallel faults trending SSW-NNE.

The low temperature geothermal reservoir was defined by four exploratory wells drilled in the 1980s at four locations namely, Pradillo (the original Shell oil well), San Sebastian de los Reyes, Tres Cantos and Geomadrid 1, these wells have identified a dependable geothermal resource, hosted in a tertiary, clastic, consolidated sandstone reservoir consisting of a thick multilayered sequence (200-800m) with temperatures ranging from 70 º to 90 ºC, overlying a Mesozoic sequence. The reservoir is located under the city of Madrid and Petratherm EspaZa intends to feed partially the heat demand of the City with the development of geothermal district heating technology (GDH).

The lower, medium temperature reservoir is located along the contact between the Mesozoic Cretaceous limestone and the fractured granite that constitutes the basement. A reservoir temperature of 156 ºC was measured at 3,400 m. This lower reservoir is being investigated for combined power and heat production (CPH).

In-Situ Stress in Australia and Subsurface Fluid Flow

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IN-SITU STRESS IN AUSTRALIA

The *in-situ* stress field is a key variable in any geothermal development, principally because of its control on the direction of subsurface fluid flow. Data on the *in-situ* stress field of Australia have been derived from a variety of sources including relatively shallow engineering methods often associated within mining activities (sampling up to a few hundred metres depth); from deeper petroleum wellbores (sampling up to a few kilometres depth); and from earthquake focal mechanism solutions (sampling up to seismogenic depths, typically up to 20 km in Australia). Data on stress orientations within Australia have been compiled within the public domain Australian Stress Map database (www.asp.adelaide.edu.au/asm).

The Australian Stress Map comprises 331 reliable (A-C quality) indicators of horizontal stress orientation within the Australian continent (Figure 1). The map reveals distinct stress provinces

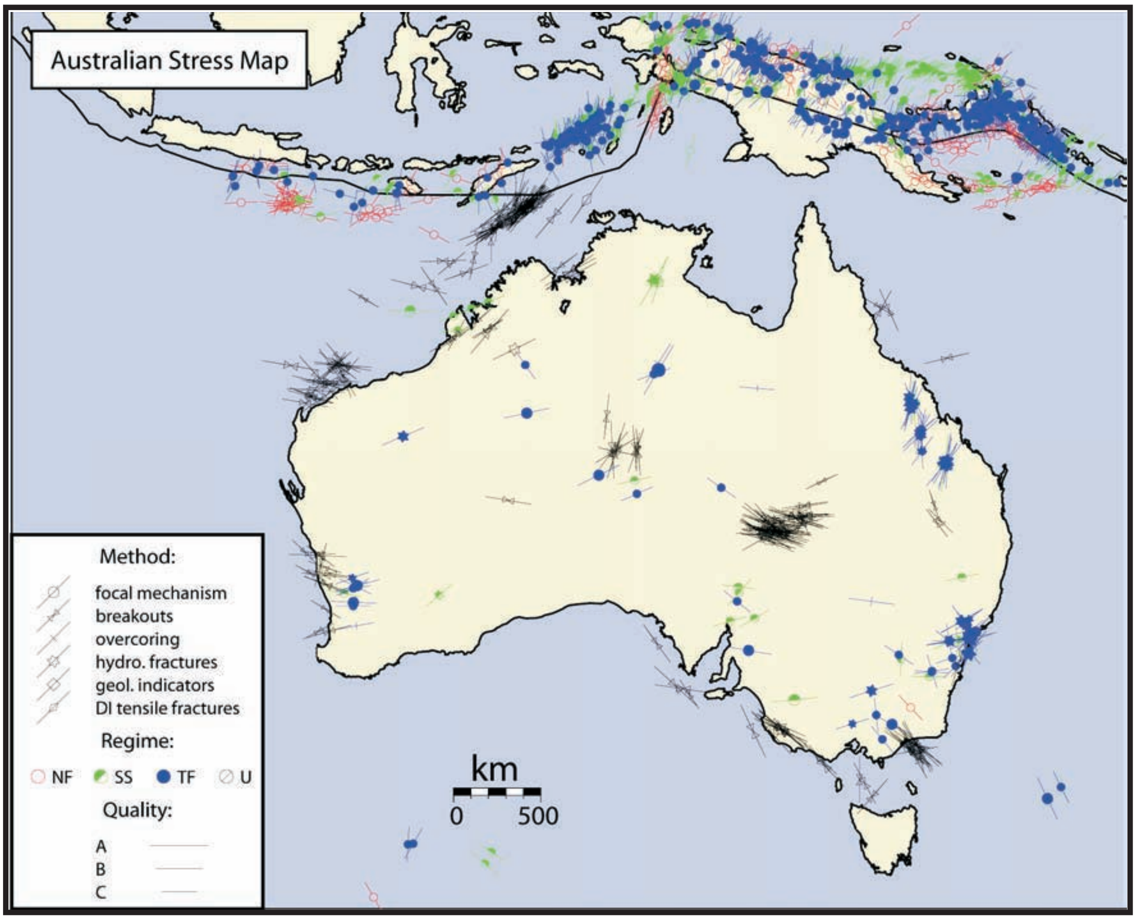

Figure 1. Australian Stress Map (A-C quality data).

(~500 km-scale) within which stress orientations are consistent. However, unlike in many other continental areas, stress directions within Australia change significantly between different provinces and do not parallel the direction of absolute plate motion. The Australian Stress Map data also reveal that stress orientations are generally consistent with depth, i.e. different techniques, sampling different depths in nearby locations yield consistent stress orientations.

The Australian Stress Map data do not support the often-made assertion that the Australian crust is everywhere one consistent with reverse faulting ($s_H > s_h > s_v$) such that the vertical stress (s_v) is the minimum principal stress. The reverse faulting regime is widely considered favourable to the development of engineered geothermal reservoirs because the stimulation zone is horizontal to sub-horizontal in such an environment and can potentially be exploited using horizontally offset vertical injection and production wells.

Earthquake focal mechanism solutions are approximately evenly divided between those of reverse faulting nature ($s_H > s_h > s_v$) and those of strike-slip nature ($s_H > s_v > s_h$). Extensive measurements of the minimum principal stress in petroleum exploration wells suggests that in sedimentary basins in Australia the minimum principal stress is generally horizontal. Even in the Cooper Basin, where the sub-horizontal orientation of the stimulated zone at Habanero suggests a reverse faulting regime in the granite basement, shallower data from the overlying basin suggest a strike-slip fault regime

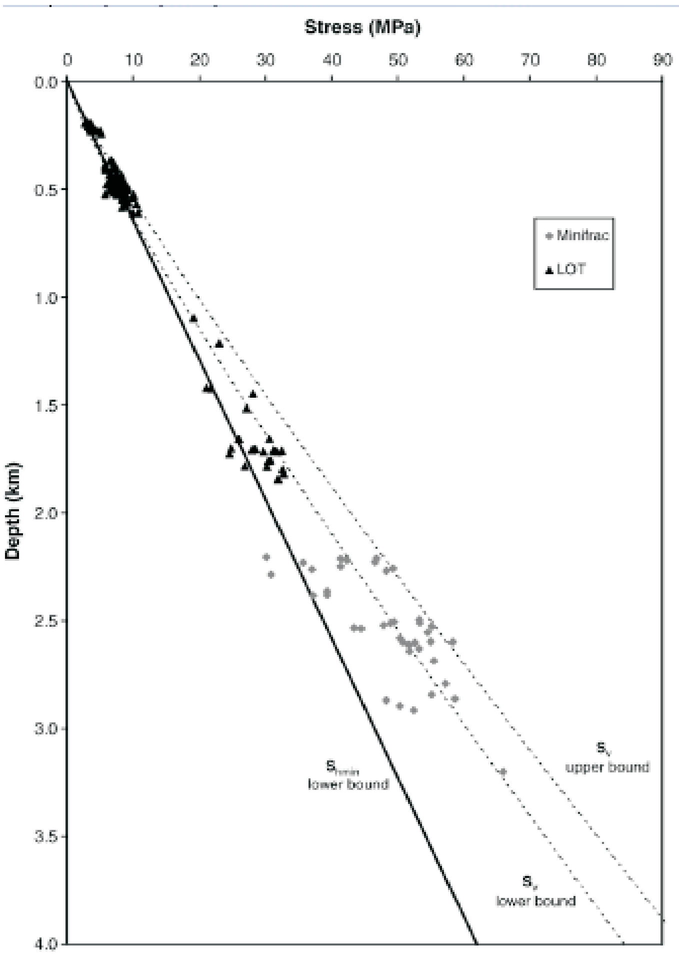

Figure 2. Stress magnitude data from the Cooper-Eromanga Basins. Both leak-off tests (LOT) and minifracs provide estimates of the minimum horizontal stress, the latter generally being more reliable. Note that there is considerable scatter in the magnitude of minimum horizontal stress and only in the minifrac data deeper than 2.5 km does the minimum horizontal stress approach and possibly exceed the vertical stress (from Reynolds et al., 2006).

(Figure 2). It should thus not be assumed that stimulation zones in geothermal reservoirs in Australia will be horizontal, especially within sedimentary basins. In situ stress analysis and measurement is required on a site-by-site basis.

IN-SITU STRESS AND FLUID FLOW IN NATURAL FRACTURES

Numerous field examples illustrate that (unstimulated) fluid flow along natural fractures in the subsurface tends to be focused on fractures that are suitably aligned for failure within the *in-situ* stress field (e.g. Barton et al., 1995). Flow is focused on fractures suitably oriented to be tensile fractures (orthogonal to the minimum principal stress) and/or on those suitably oriented to be conjugate shear fractures (inclined ~30° to the maximum principal stress and intersecting in the intermediate principal stress direction). There is, however, some debate regarding whether tensile or shear fractures play the key role.

It should also be recognised that some fractures are more stress-sensitive than others and partial bridging by cements may lead to fractures remaining open and hydraulically conductive in otherwise unfavourable stress conditions (Laubach et al., 2004). The likelihood of pre-existing fractures being hydraulically conductive within the *in-situ* stress field is best assessed using the fracture susceptibility diagram which can combine information on the orientation and nature of pre-existing natural

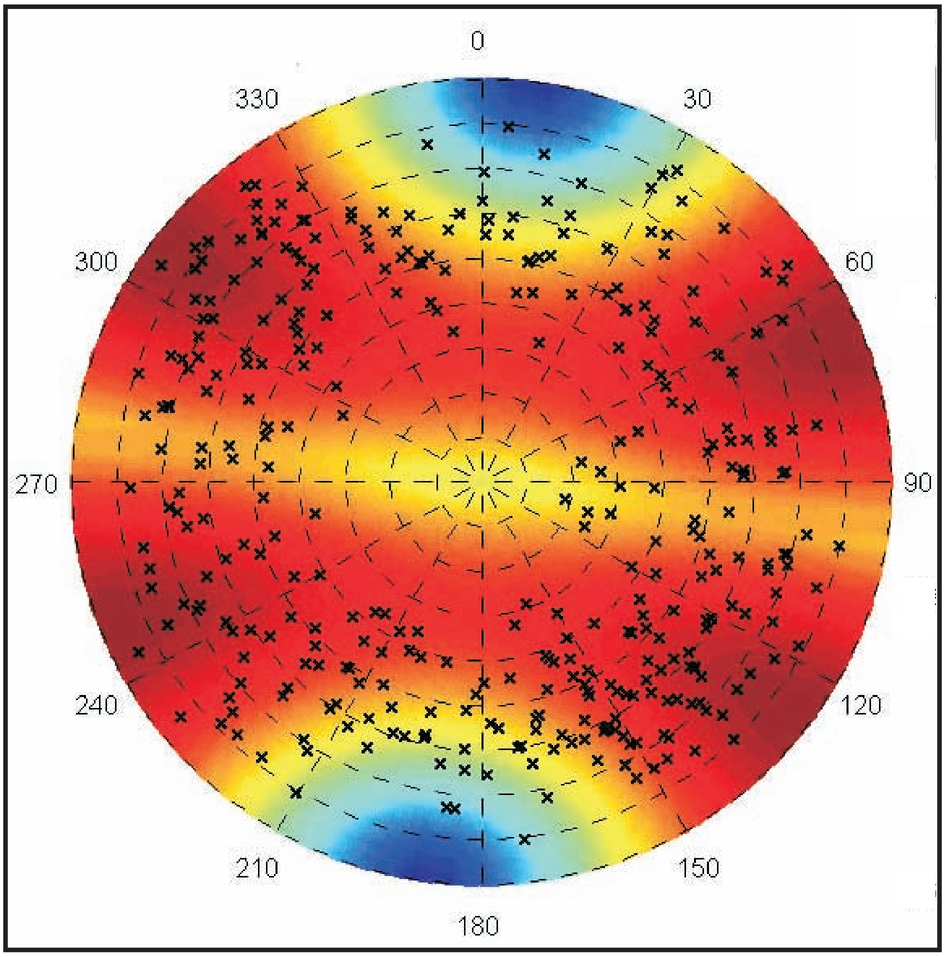

Figure 3. Fracture susceptibility diagram for a strike slip stress regime ($s_H > s_v > s_h$) where s_H is only slightly larger than s_v. The plot is a lower hemisphere projection polar plot of normals to planes. Colours show propensity of a fracture orientation to be open and hydraulically conductive within the in-situ stress field (red most likely to be open) and crosses show the orientation of fractures mapped from image logs.

fractures with information on fracture orientations most likely to be open and hydraulically conductive within the *in-situ* stress field (Figure 3). This presentation will outline the fracture susceptibility methodology.

IN-SITU STRESS AND FLUID FLOW IN STIMULATED FRACTURES

Experience from waterflooding during enhanced oil recovery operations demonstrates the key role of *in-situ* stress on subsurface fluid flow with fluid injection. The influence of *in-situ* stress on fluid flow in stimulated fractures is even stronger than its influence on fluid flow in natural fractures, because new fractures are created and/or pre-existing fractures reactivated dependent on their orientations within the *in-situ* stress field. Figure 4 summarises preferential fluid flow directions of

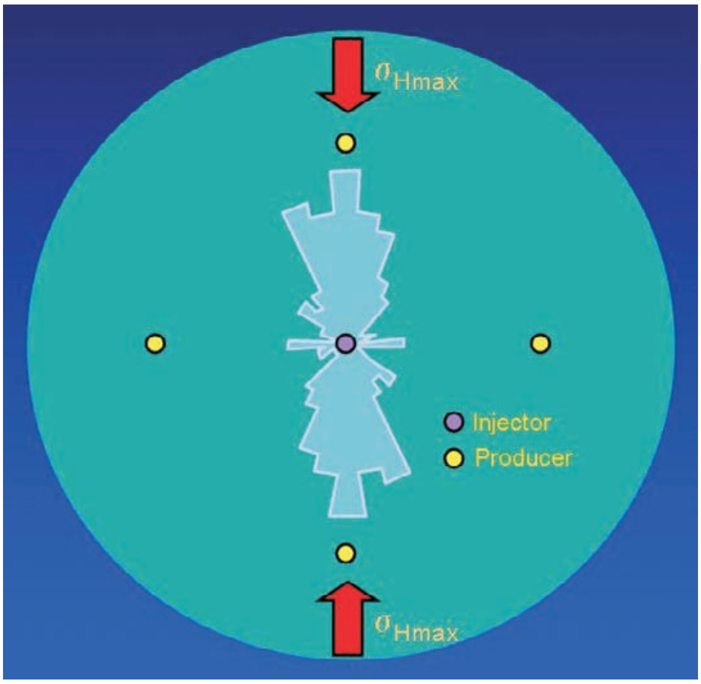

Figure 4: Preferential fluid flow direction in enhanced oil recovery operations in over 80 oil fields. Fluid breakthrough directions from a variety of different injection/production well patterns and a variety of different stress orientations have been normalised to a five spot pattern with maximum horizontal stress as indicated.(from Heffer and Lean, 1993).

injected fluids from over 80 field cases of enhanced oil recovery in North America, North Sea, continental Europe, Middle East & China showing the very strong influence of *in-situ* stress with fluid flow focused in the sH direction. This presentation will present examples of the control of *in-situ* stress on stimulated fluid flow both from oil field and geothermal examples.

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Evidence for Hydrothermal Convection in the Perth Basin, Australia

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ABSTRACT

There is increasing evidence for hydrothermal convection in sedimentary basins, leading to opportunities for exploitation of low temperature geothermal systems. We infer convection in the sediments of the Perth Basin of Western Australia based on two observational arguments and a theoretical one.

Firstly, the fluvial sediments of the Lesueur Sandstone in the southern Perth basin show anomalously low thermal gradients. Logging from the Lake Preston 1 petroleum well shows a thermal gradient of nearly 8.7 °C/km as inferred from unequilibrated temperatures measured in the Lesueur through the depth range from 1,000 m to about 3,300 m (Figure 1). Assuming one dimensional heat conduction, Fourier's Law is $q = -k\, \delta T / \delta z$, where q is vertical heat flux, k is thermal conductivity, T is temperature, and z is depth.

We assess the viability of a conductive explanation for the Lesueur's observed thermal gradient by assuming a low (but credible) value for background heat flux of 30×10^{-3} W/m^2. This yields an estimated minimum thermal conductivity for the Lesueur of 3.45 W/m°C. A more reasonable background value for heat flux is 40×10^{-3} W/m^2, yielding a thermal conductivity estimate of 4.6

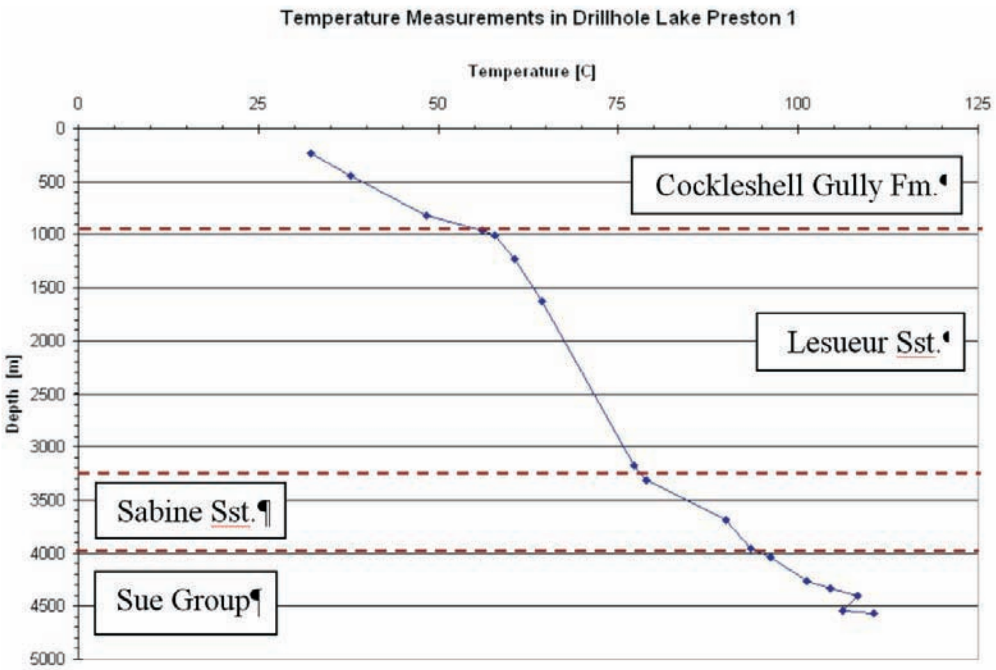

Figure 1. Thermal profile in the Lake Preston 1 petroleum well.

W/m°C. Drawing values for the mean and standard deviations of 1,880 thermal conductivity measurements in 'low porosity' physical sediments from Clauser and Huenges (1995), and assuming a Gaussian distribution, we estimate the probability of finding the required thermal conductivities for heat fluxes of 30 and $40x10^{-3}$ W/m^2 to be 4% and <0.1% respectively. More realistic heat fluxes for the geothermally active Perth basin would drive the probabilities even lower.

We conclude from this first argument that the simplest explanation for the low thermal gradient measured in the Lesueur is that conduction is not the only mechanism of heat transport.

Our second observational argument rests on the measured thermal gradients in several petroleum wells of the northern Perth basin. These gradients are estimated within a region of 55x50 km, have spatially complex patterns, and values ranging from about 28 to 68 °C/km (Figure 2).

There are large variations of thermal gradient in wells that penetrate the same rocks. We argue that convection is a simpler explanation for this observation than the large regional variations in thermal conductivities in the same rocks that would be required to explain this observation using conduction. This agrees with the argument applied to the Upper Rhine Valley, Central Europe, where such patterns are now considered conclusive evidence for convection in the subsurface Rhine graben.

Our third, theoretical argument is based upon an estimate of the Rayleigh number. The critical Rayleigh number for the onset of convection in a porous sedimentary layer is well known to be $4\pi^2$. We assume the following conservative values for the Yarragadee Formation in the north or for the Lesueur in the south Perth Basin: layer thicknesses of 1 km, permeabilities of $0.3 \rightarrow 1x10^{-12}$ m^2 (~0.3 → ~1 Darcy) and a (boundary value) thermal gradient of 20°C/km. We calculate Rayleigh numbers to be in the range of 62 → 186, which are well above the required critical value (Figure 3).

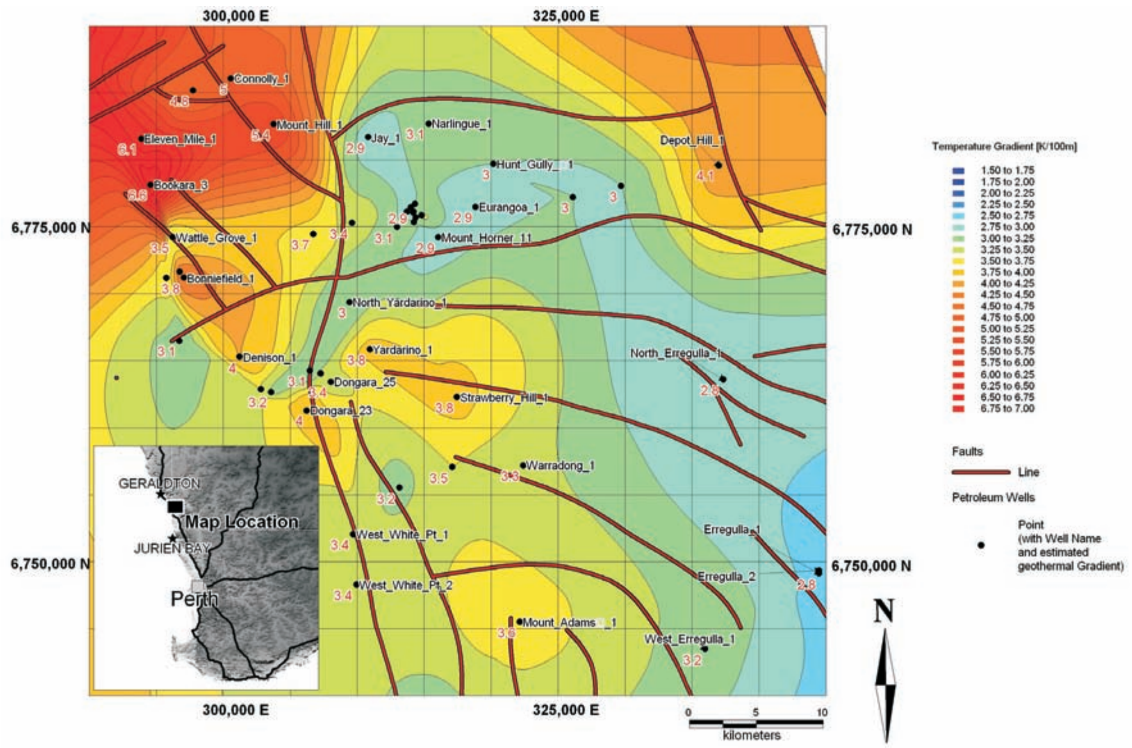

Figure 2. Thermal gradients interpolated from wellbore measurements in the Northern Perth Basin. Data are taken from Mory & Iasky, 1996. Coordinates are in MGA zone 50.

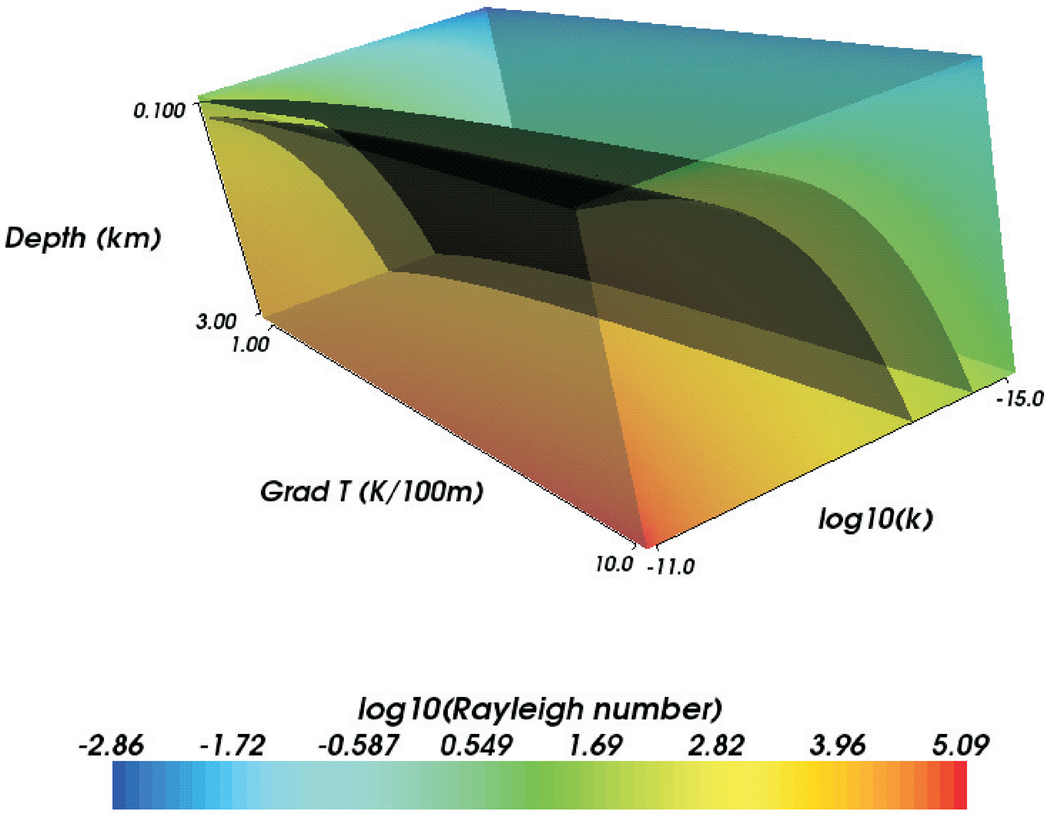

Figure 3. Convection in the Yarragadee aquifer is expected from the principles of basic physics. This plot shows the Rayleigh number (colours) as a function of thickness, thermal gradient and permeability. The critical Rayleigh number for the onset of convection (39.5) is shown as the right-hand iso-surface while the left surface shows a value estimated for the Yarragadee aquifer (186). The Rayleigh number exceeds the critical value for realistic combinations of permeability, thickness and geothermal gradient in the Yarragadee.

Based upon similarities with the measured convecting system in the Soultz-sous-Forêts area in the Rhine graben (Pribnow and Schellschmidt, 2000) and all of the arguments we present above, we infer that these observations are indicative of hydrothermal upwellings and downwellings in the Perth basin.

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Hydraulic Fracturing at the Olympic Dam Geothermal Energy Project

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ABSTRACT

Australia's first mini hydraulic-fracturing program of a hot granite in a slim hole was carried out early this year by Green Rock Energy Limited at its Olympic Dam Engineered Geothermal System (EGS) Project. The viability of EGS projects are critically dependant on being able to establish a sufficient water flow rate through fractures in the hot granites between injection and production wells. Success depends on the capacity to successfully engineer by fracture stimulation a network of sustainable permeable fractures connecting the wells in the granite. The mini hydraulic-fracturing program was undertaken in Blanche No 1 well drilled to a depth of 1.935 km. This was done in order to provide the engineering data and confidence required before undertaking the more expensive drilling and fracture stimulation program to connect the injection and production wells by opening fractures at the greater depths where the granites are hotter.

The mini hydraulic fracturing was undertaken by GEO-Meß-Systeme GmbH of Germany using their crew and specialised equipment in conjunction with Australia's CSIRO. Thirteen hydraulic fracturing stress measurements were carried out in Blanche No 1.

Fractures were successfully opened in the hot granites by the hydraulic fracture tests. Results confirm that the *in-situ* stress regime towards the bottom of Blanche No 1 has high horizontal stresses and the minimum principal stress is the vertical stress. This indicates that the creation of horizontal fractures will be favoured during stimulation operations at production depths, and that the required operating pressures to open the fractures should be in the order of the minimum principal stress. This supports the earlier work undertaken by the CSIRO in which they concluded "…..that hydraulic fracture orientation and fluid flow in a stimulated zone are most likely to be in a sub-horizontal direction. This is an ideal situation for generating an optimal heat exchange reservoir that would allow a maximum distance between injection and production wells.

Data from the mini hydraulic fracturing are being used for design of the deep injection and production wells and the fracture stimulation program.

Progress on the AGEG Code and Lexicon for Geothermal Resources and Reserves Reporting

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Over the past 18 months a Technical Interest Group within AGEG had taken the lead on producing a draft Code and Lexicon for Reporting of Geothermal Reserves and Resources. This has now reached an advanced stage and is under discussion with the JORC Committee and the ASX. It has also been reviewed and accepted by the International Geothermal Association. The need for the Code and key features of the Code and Guidelines are described and discussed, together with an update on progress towards finalisation.

Advection Heat Flow and the 1/F-Noise Fracture Nature of Crustal Rock

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ABSTRACT

Pervasive broadband (cm-Km) 1/*f*-noise power-law fluctuation scaling $S(k) \propto 1/k$ in well-logs and abundant support for poroperm fluctuation relation $\delta\varphi \approx \delta\log(\kappa)$ in clastic-reservoir well-core indicate that crustal rock is nearly everywhere permeable to percolating fluids. Percolating fluids can transport heat in parallel with thermal conduction if formation permeability is sufficiently high. We investigate the level of *in-situ* 1/*f*-noise permeability needed to bring advection of heat to levels comparable to those assumed for thermal conduction. The investigation centres on thermal gradient and neutron porosity well-logs recorded at 5,500-8,500 feet in a tight-gas province in western Colorado, USA. Formation core permeability is of order 10-20 μDarcy. The thermal gradient and porosity logs are 60% spatially correlated at zero lag, but the temperature gradient log has an underlying trend towards higher gradient values with depth/temperature in the well. Well-site core poroperm data are 60% cross-correlated, validating the relation $\delta\varphi \approx \delta\log(\kappa)$ for the tight gas foramtion and providing direct evidence for potential heat advection at all scale lengths. The temperature-gradient trend can be correlated with either a trend towards lower thermal conductivity with increasing depth/temperature, or with an advection term proportional to temperature. For the observed formation permeability, it is entirely possible that thermal advection is comparable to thermal conduction in the tight-gas formation. The tight-gas formation well-log data clearly suggest that higher permeability crustal rock can support advection heat transport where heretofore it has not been considered.

1/F-NOISE FRACTURE NATURE OF CRUSTAL ROCK

The Fourier power spectra of virtually all geophysical well-logs scale inversely with spatial wavenumber k, $S(k) \propto 1/k^{\beta}$, $\beta \approx 1 \pm 0.2$ (Leary 2002). The "1/*f*-noise" scaling law for *in-situ* geophysical fluctuations holds for sonic, resistivity, gamma activity, mass density, neutron scattering and chemical abundances over 5 decades of scale length (~cm to ~ km) in sedimentary and crystalline rock for both horizontal and vertical wells. The power-law nature of *in-situ* geophysical property fluctuations can be understood as arising from long-range spatial-correlation of grain-scale percolation-fracture density fluctuations in analogy with critical-state phenomena such as the organisation of mm-scale domains by Angstrom-scale iron atom magnetic dipoles. In this analogy, grain-scale fracture density plays the role of thermodynamic energy usually associated with temperature; at a critical density n_0 of grain-scale fractures, percolation pathways become effectively infinite in extent, the spatial correlation length goes critical, $\xi \propto 1/\sqrt{|n-n_0|} \rightarrow \infty$, and the spatial correlation function becomes power-law, $\chi(r) \propto 1/r^{P} \exp(-r/\xi) \rightarrow 1/r^{P}$.

The grain-scale percolation-fracture density nature of *in-situ* geophysical fluctuations is further testified to by the well-core poroperm fluctuation relation $\delta\varphi\iota \approx \delta\log(\kappa\iota)$, where $\delta\varphi\iota$ and $\delta\log(\kappa\iota)$ are, respectively, zero-mean-unit-variance fluctuation sequences $\iota = 1,2,3\ldots$ of well-core plug porosity and log(permeability). The poroperm fluctuation relation, observed at 85% ± 8% cross-correlation level for some thousands of well-core plugs from clastic reservoir rock, is physically equivalent to the mathematical statement $\delta n \approx \delta \log(n!)$ for n the number of grain-scale fractures in a unit volume and factorial $n!$ expressing the combinatorial nature of fracture-connectivity for percolation flow via grain-scale fracture populations (Leary & Walter 2008).

WELL-LOG POROSITY FLUCTUATIONS AND THE WELL-BORE THERMAL GRADIENT

Figure 1 illustrates the close association between neutron porosity and thermal gradient recorded in a well in the tight-gas formations of western Colorado, USA. The well was drilled and logged during a tight-gas production stimulation hydrofrac project (Branagan et al. 1996). Fluctuations in temperature gradient (red) are superposed on fluctuations in neutron porosity (blue). Apart from the trend toward increasing temperature gradient with depth, a close correspondence exists between variations in thermal gradient and porosity for 5,000 data points over 2,500 feet of formation. The two logs have a 60% cross-correlation coefficient at zero lag (with fluctuation standard deviation of 8%, a 60% cross-correlation peak is 8 standard deviations from being a chance occurrence).

Figure 1 establishes that porosity can be closely associated with *in-situ* thermal gradients. Because water and gas are poor conductors compared with mineral grains (0.02 and 0.6 $Wm^{-1}K^{-1}$ for gas and water versus 2-8 $Wm^{-1}K^{-1}$ for minerals, Clauser & Huenges, 1995), positive porosity fluctuations are associated with negative thermal conductivity fluctuations. Expressing thermal conductivity as $K \approx K_0 - K_1\varphi$, with $K_0 \approx 3$ and $K_1 \approx 10$ for $0.0 < \varphi < 0.1$ (Clauser & Huenges 1995), positive porosity fluctuations yield negative conductivity $\delta K = -K_1\delta\varphi$. For steady-state conduction heat flow $Q =$

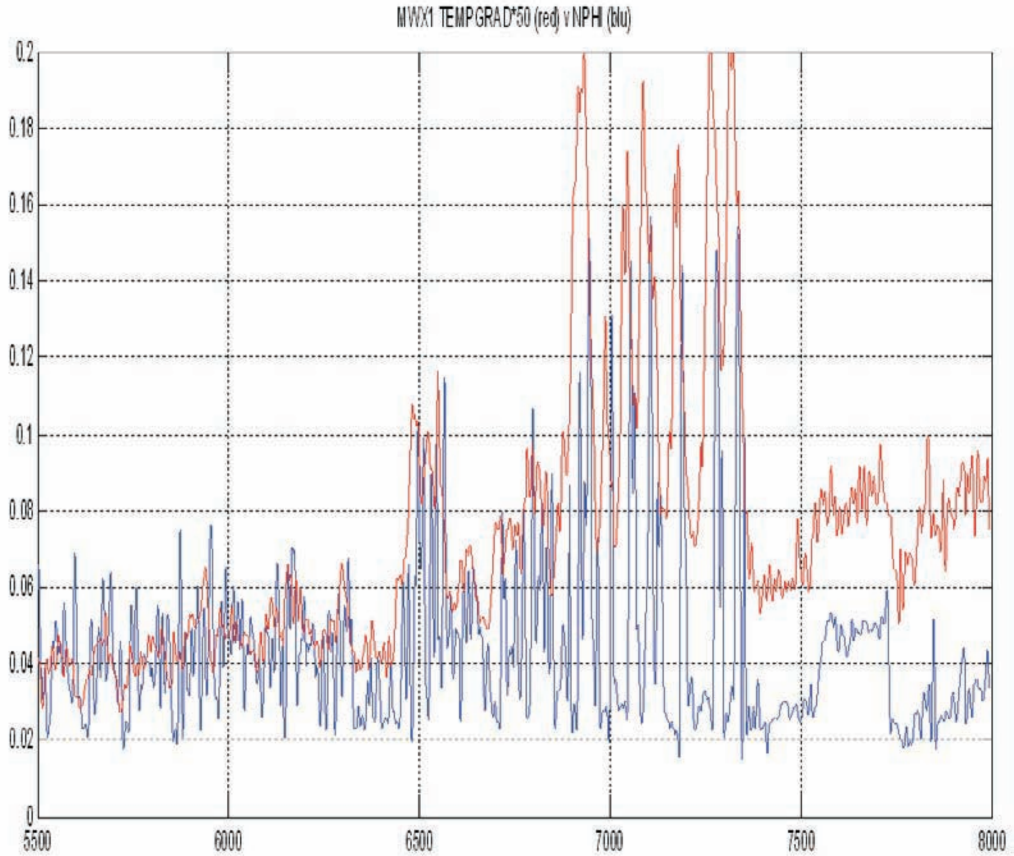

Figure 1. Well-log neutron porosity (blue) and thermal gradient (red) fluctuations recorded in a tight gas formation at the MWX hydrofrac gas production stimulation experimental site in western CO, USA (Branagan et. al. 1996). Horizontal axis: 5500:500:8000 ft; vertical scale for porosity: 0:0.02:0.2; temperature gradient data scaled for visual purposes.

const = $K\nabla T$, positive gradient fluctuations are associated with positive porosity fluctuations. From $\delta\nabla T/\nabla T + \delta K/K \approx 0$,

$$\delta\nabla T/\nabla T \approx \delta\nabla T/\underline{\nabla T} \approx -\,\delta K/K \approx K_1\delta\varphi/K_0 \qquad (1)$$

where $\underline{\nabla T}$ is the mean temperature gradient. Equation 1 shows, however, that Figure 1 porosity can not alone account for the observed upward trend in thermal gradient fluctuations. We can introduce a rising trend into the porosity dependence by giving thermal conductivity a temperature dependence. Again from Clauser & Huenges (1995), temperature dependence of thermal conductivity is of order $K_0(T) \approx K_0(0)\ (1 - 5\ 10^{-3}\ T)$ for $0 < T < 100$ °C, hence

$$\delta\nabla \approx \underline{\nabla T}\,\delta\varphi(1 + 5\ 10^{-3}\ T)\ K_1/K_0 \approx 3\ \underline{\nabla T}\,(1 + 5\ 10^{-3}\ T)\delta\varphi \qquad (2)$$

Alternatively, site well-log evidence indicates that porosity is strongly associated with permeability via grain-scale fracture percolation pathways throughout crustal rock. Advection introduces a temperature trend that can, in principle, also explain the divergence of Figure 1 curves. For largely vertical groundwater flow of rate ν, $[\nu]$ = m/s, steady-state advection heat transport is governed (Carslaw & Jaeger 1959) by $K\partial_z^2 T \approx C\rho\nu\partial_z T$, $C\rho$ = volume heat capacity of water. The combined advection and conduction heat flow Q is given by

$$Q \approx K\partial_z T - C\rho\nu\ (T - T_0), \qquad (3)$$

Where T_0 is an integration constant. With groundwater diffusion flow forced by topography, $\nu \approx \kappa/\eta\nabla P \approx \kappa\rho g/\eta$, (3) gives thermal gradient ∇T in terms of advection and conduction (Jessop 1990),

$$\nabla T \approx C\rho^2 g\kappa/\eta K\ (T - T_0) + Q/K \qquad (4)$$

Assuming for convenience a constant thermal conduction K, fluctuations in permeability generate fluctuations in thermal gradient proportional to fluctuations in porosity, $\delta\kappa \approx \kappa_0\delta\exp(\varphi) = \kappa_0\exp(\varphi)\delta\varphi = \kappa\delta\varphi$,

$$\delta\nabla T \approx C\rho^2 g/\eta K\ (T - T_0)\delta\kappa \approx C\rho^2 g\kappa/\eta K\ (T - T_0)\delta\varphi \qquad (5)$$

Equation 5 is given a vertical scale length h in terms of the dimensionless Peclet number $Pe = C\rho^2 g\kappa\eta/\eta K$,

$$\delta\nabla T \approx Pe\ (T - T_0)/\eta\ \delta\varphi \qquad (6)$$

The natural value for scale dimension h is the length of the temperature gradient log, h = 2500ft ≈ 756m. Integrating the thermal gradient field ∇T to get the temperature distribution, $T = \int\nabla T dz$, over the log length h fixes all parameters in equation 6 except for mean formation permeability κ_0. If κ_0 is large enough, the Peclet number will be large enough for advection (equation 6) to account for the thermal gradient fluctuations. If κ_0 is small, the advection process (equation 6) will not account for the thermal gradient fluctuations.

The terms of the Peclet number are:

- volume heat capacity of water $C\rho \approx$ 4MJ/kg-°C 1000kg/m^3 = 4GJ/m^3-°C;
- pressure gradient of gravity ρg = 1000kg/m^3 10m/s^2 = 104 Nt/m^3;
- dynamic viscosity of water η = 0.1kg/m-s;
- thermal conductivity K = 3Wm^{-1}K^{-1};
- mean formation permeability κ_0 in m^2; 1 μDarcy = 10^{-18}m^2;
- scale length h = 756m.

For $\kappa_0 \approx 1$ μDarcy, $Pe \approx 0.1$. However, well-site core permeability data indicate that tight-gas formation permeabilities have mean and median values in the range 10 to 20 μDarcy, hence the effective Peclet number is potentially of order unity $Pe \approx 1$ in the 5,500-8,000ft depth range surveyed for thermal gradient. Values of order $Pe \approx 1$ indicate that advection (equation 6) as well as conduction (equation 2) can plausibly account for the 60% thermal-gradient/neutron-porosity cross-correlation in Figure 1.

SUMMARY AND CONCLUSIONS

While heat flow in the crust is almost everywhere thought of in terms of thermal conduction, the broadband $1/f$-noise phenomenology of well-log spectra and well-attested poroperm fluctuation relation $\delta\varphi \approx \delta\log(\kappa)$ in clastic reservoir core suggest that fluid percolation at scale lengths from cm to km is a viable means of heat transport heat in crustal rock. Evidence for possible advection heat flow is seen in well-logs of highly correlated thermal gradient and neutron porosity fluctuations recorded over 750m in a tight-gas formation. Well core evidence for formation permeability returns a Peclet number $Pe \approx 1\text{-}2$ in a volume of 750m scale dimension. In these circumstances, both the trend and the fluctuations in the thermal gradient well-log data can be directly explained by fluctuations in formation porosity in the presence of an overall temperature trend. The potential for heat advection in more permeable rock is proportionately stronger. If heat flow inferred from well temperature data is more dependent on crustal percolation permeability than on thermal conduction, there may be a need to reassess existing heat flow maps.

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New Heat Flow Data From Tasmania and the Emergence of Eastern Tasmania as a New EGS Province

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INTRODUCTION

Most published maps of Australian 'hot rock' plays or estimated temperature of basement at about 5,000 m show Tasmania as relatively cool and hence perhaps geothermally unprospective at those depths (eg Holgate and Chopra, 2004). This situation is an artefact of several things, including a) the dataset being largely compiled from hydrocarbon exploration and other sources which did not have geothermal mapping as their primary purpose, b) incorrect assumptions being made on the estimate of depth to geothermal basement in Tasmania and c) the use of temperature gradients as a primary tool for estimation of basement temperature.

New, systematic surface heat flow and thermal conductivity data presented here build on isolated values published over a considerable time and when combined with a new gravity model of the depth to geothermal basement, produce a strong technical argument for eastern Tasmania to be recognised as a new Engineered Geothermal Systems (EGS) or 'hot rocks' province.

Clues concerning the prospectivity of Tasmania for hot rocks first emerged over a half century ago. Heat flows of between 85 mW/m^2 and 105 mW/m^2 were reported from boreholes principally drilled for hydro-electric dam engineering investigations (Jaeger and Sass, 1963; Newstead and Beck, 1953). In the 1960s the Department of Mines calculated the heat flow from a hole drilled into the Devonian granite at Storeys Creek in north-eastern Tasmania and a value of 159 mW/m^2 was reported (Jaeger and Sass, 1963). This remains one of Australia's highest recorded borehole heat flow values.

In the 1970s and 1980s, further drilling by the Department of Mines and others continued to produce scattered high heat flow and encouraging thermal gradient values in Tasmania. The Devonian Coles Bay Granite in the far east returned 102 mW/m^2 from a borehole (Green, 1989) and this finding of a high heat production granite was re-enforced by publication of scintillometer readings for outcropping Devonian granitoids in Tasmania which showed the Coles Bay and Storeys Creek/Rossarden granitoids to be anomalously radioactive (Collins et al., 1981). Boreholes into the Tasmania Basin sediments at Glenorchy and Tunbridge, where there is no known granite at depth or laterally for many kilometres, returned values of 87mW/m^2 for the former and thermal gradients of about 40 °C/km for both (Green, 1969; Wronski, 1977).

Hence to the year 2000, anomalous to high heat flow (i.e. >85mW/m^2) and thermal gradient (i.e. >40 °C/km) values had been recorded from most areas of Tasmania and from environments both above and laterally distant from known granites. The single unambiguously cool area was in the Proterozoic metamorphic terrane of the south-west (57 mW/m^2 heat flow and 18 °C/km thermal gradient at Olga Ridge) (Wronski, 1977).

Situation in the early 2000s

In the early 2000s, the prospectivity of the Cooper Basin and some other parts of South Australia had been clearly recognised and investment capital was being mobilised to begin exploring those areas for EGS project development. The publication of a map of Australia showing 'estimated temperatures at 5 km depth' re-inforced the work published in the mid 1990s and continued to show Tasmania as relatively cool at those depths and hence possibly unprospective for EGS.

The first systematic compilation of geothermal-related data and analysis of the potential of Tasmania for geothermal energy was undertaken by Lewis (Lewis, 2005). This report synthesised the existing heat flow, temperature gradient, gravity and granite sub-surface distribution data and recognised that the published estimates of temperature at 5 km notwithstanding, all the components required for a successful 'hot rocks' or EGS play were present in eastern Tasmania. Four areas were highlighted:

- An interpreted granite cupola under the Tamar River;
- An area east of the hot Storeys Creek granite, where the granitoid extension was interpreted to lie about 4 km deep;
- An area south of Storeys Creek and west of Coles Bay, again in an area of favourable granitoid burial depth; and
- A large area of the Tasmania Basin from the Great Lake in central Tasmania to Bruny Island in the south-east, incorporating the City of Hobart. This area was recognised mainly for the potential for non-granite related hot aquifers.

The 2005 report then developed a range of thermal models for eastern Tasmania, with varying granite and overlying stratigraphic characteristics producing a range of possible thermal outcomes at 5 km depth. Finally, economic criteria were superimposed on the thermal models and key areas identified for follow-up.

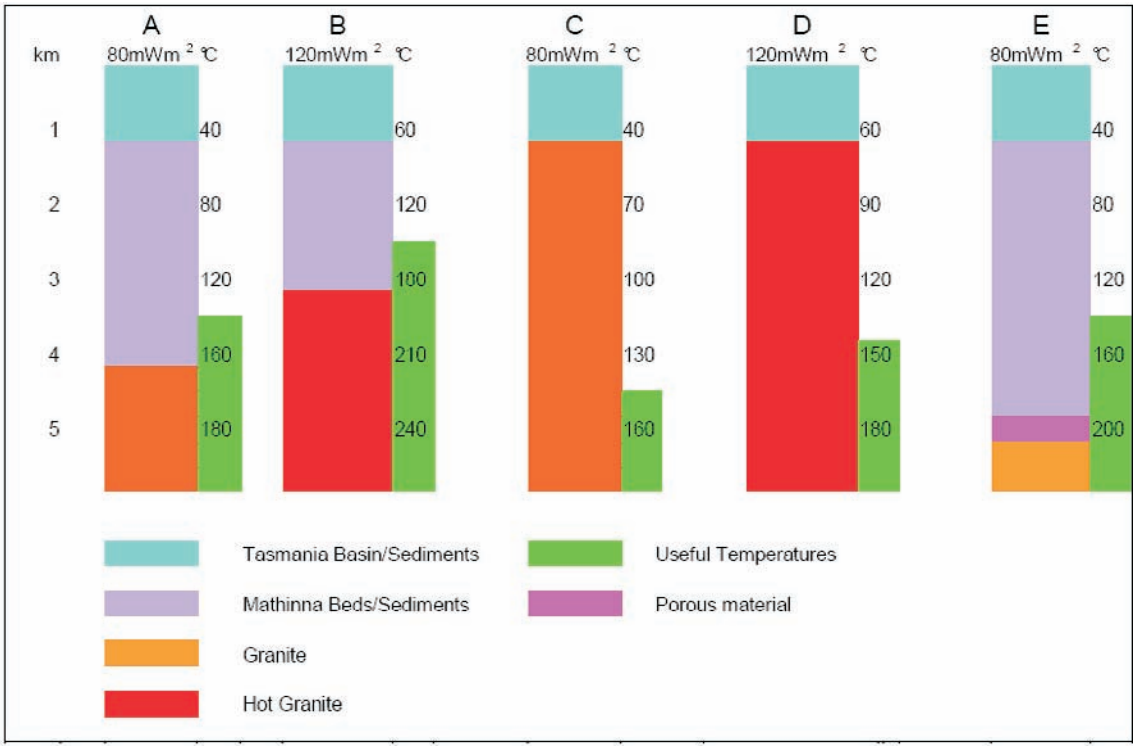

Figure 1. Thermal scenarios for eastern Tasmania from Lewis (2005).

Progress since 2005

In 2006, Tasmania's first tenement for exploration for geothermal substances was awarded to KUTh Exploration Pty Ltd. The *Mineral Resources Development Act* of 1995 already accommodated the issuing of a licence for geothermal and no legislative modifications were required, unlike nearly every other State in Australia. The tenement, Special Exploration Licence 26/2005 was 12,360 km^2 in area and included not only most of eastern Tasmania and EGS prospective areas but also metropolitan Hobart and Launceston, targeting 'direct use' heating and drying geothermal applications.

Since the grant of the first tenement, a further tenement of 1,811 km^2 has been granted to KUTh Exploration. Three tenements totalling almost 8,500 km^2 have been awarded to Geothermal Energy Tasmania Exploration Pty Ltd (GET) and one tenement of 4,892 km^2 is under application by GeoPower Pty Ltd.

NEW RESULTS

A systematic thermal drilling programme in eastern Tasmania which began in late 2007 has continued through 2008. Approximately 40 holes will be drilled by the time the programme is completed. The key parameters of the drilling programme are as follows:

- Holes vertical and on an approximate 20 km x 20 km grid, drilled into Jurassic dolerite where possible, (competent formation with low aquifer quality and flow);
- Percussion drilling to approximately 100 m depth, then HQ cored to approximately 250 m deep;
- Precollar cased with 100 mm PVC and aquifers cemented off; 40 mm PVC from the collar to end of hole;
- Holes left to achieve thermal equilibrium for at least 3 months after drilling;
- Temperature measured every 1.0 m down-hole using resistivity (thermistor);
- Thermal conductivity of core samples measured using a steady-state divided bar apparatus.

The surface heat flow results received to 1 July 2008 are shown in Table 1.

Table 1. New surface heat flow values for eastern Tasmania.

Hole ID	**Location**		**Dominant lithology**	**Equilibrated surface heat flow#**
	Northing	Easting		mW/m²
Snow	5,358,389	572,873	Jd	92.0
Lake Leake	5,338,586	568,510	Jd	92.0
Elizabeth	5,356,701	549,501	Jd	94.0
Tooms	5,319,894	567,354	Jd	96.0
Temple Bar	5,402,059	530,426	Jd	87.0
Ben Lomond	5,402,059	546,613	Sm	97.0
Tower Hill	5,399,699	573,964	Sm	83.0
Epping	5,382,606	533,251	Jd	62.0§
	Lithologies: Jd = Jurassic dolerite; Sm = Silurian Mathinna Group sediments All holes are vertical and equilibrated for 3 months after drilling # Values have an average error margin of < 2.5 mW/m² § Heat flow in base of hole (268m) 92.0 mW/m²			

Thermal conductivities were measured on core samples to derive the heat flow values. Typically five samples were taken from each cored interval and conductivities measured at a standard temperature of 30 °C using a calibrated steady-state divided bar apparatus by contractor Hot Dry Rocks Pty Ltd. Typically three samples were prepared from each specimen to investigate variation over short distance scales and to determine mean conductivity and uncertainty. Results for the above holes are presented in Table 2.

Table 2. New thermal conductivity values for drill holes in eastern Tasmania

Hole ID	Thermal conductivity#		Lithology
	Maximum w/mK	Minimum W/mK	
Snow	1.99	2.25	Jd
Lake Leake	1.96	2.18	Jd
Elizabeth	1.99	2.27	Jd
Tooms	1.82	2.07	Jd
Temple Bar	2.28	2.49	Jd
Ben Lomond	3.87	4.41	Sm
Tower Hill	4.06	5.23	Sm
Epping	1.87	2.18	Jd

Lithologies: Jd = Jurassic dolerite; Sm = Silurian Mathinna Group sediments
\# Values have an average error margin of up to +/-10%
Note: Mathinna Group sediments strongly foliated at low angle to axis of core (direction of measurement); see text for discussion

DISCUSSION

Most of the new reported surface heat flow values are anomalously high. South of the Rossarden and Storeys Creek granites, the values are consistent and within the range commonly reported from the Cooper Basin, regarded as Australia's leading EGS play to this point. In Tasmania, the strong heat flows already represent an area of about 1,200 km^2 which is open on three sides. The values also lie where the buried granite is between approximately 3 km and 5 km below the surface, reinforcing the technical model (Leaman and Richardson, 2003; Leaman, 2007).

Figure 2 shows the co-incidence of the anomalous surface heat flow with the area where the basement granites are interpreted to be between 3 km and 5 km below the surface.

North of the Storys Creek granite, the values to date are less consistent, but still relatively high on a national scale, ranging from 83 mW/m^2 to 97 mW/m^2. The subsurface distribution of the granites is less well constrained in this area. The surface value of 62 mW/m^2 at Epping, west of Rossarden appears to result from heat subtraction within the measured drill hole, as a base of hole value of 92 mW/m^2 was estimated.

In respect of thermal conductivities, the values for the Jurassic dolerite are considered typical for that rock type (Beardsmore and Cull, 2001). The values for the Silurian 'Mathinna Group' sediments are comparatively high, although consistent with Palaeozoic basement in other parts of Tasmania and mainland Australia (Jaegar and Sass, 1963; Wronski, 1977). Elevated rock thermal conductivity results for the Mathinna Group samples reflect a strong foliation, which is steeply dipping with respect to the long axis of the core and is therefore at a low angle to the direction of conductivity measurement. A predominance of quartz wackes and silicification of the particular samples measured has also influenced the measured conductivity.

Laboratory work presently being undertaken by Hot Dry Rocks Pty Ltd suggests that when measured perpendicular to foliation, thermal conductivities for the same sediments are much lower, in the order of 1.43 W/mK for one sample from the Tower Hill well, representing a decrease of

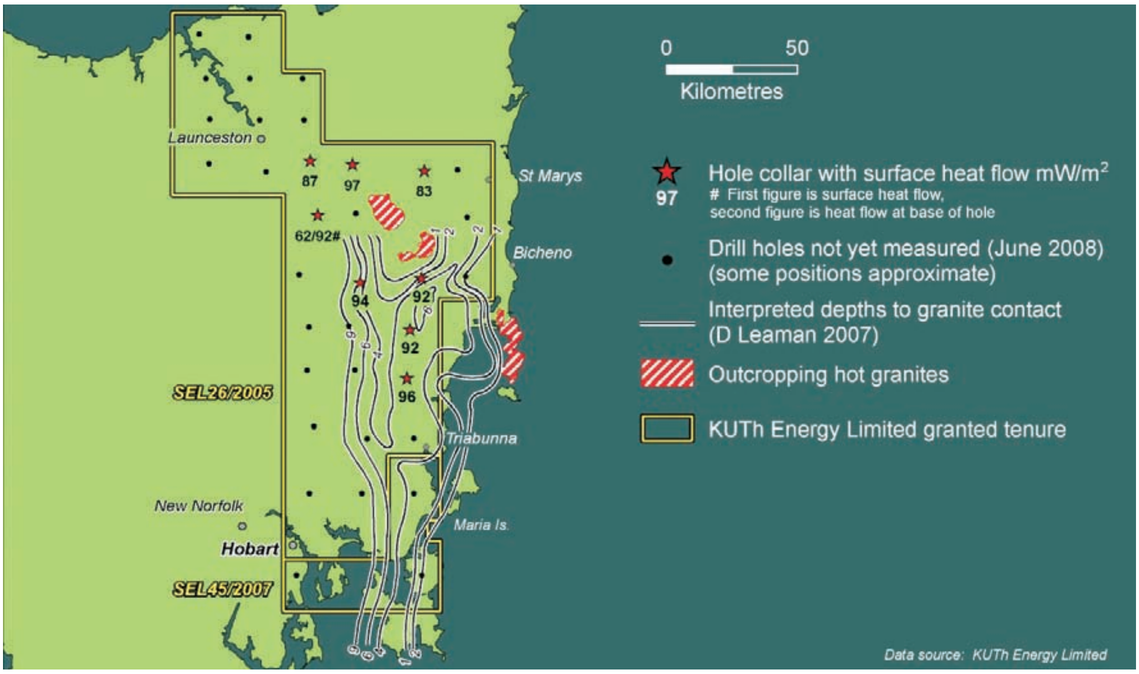

Figure 2. New surface heat flow values for eastern Tasmania set against interpreted depths to granite basement.

about 66.5% from the standard rock thermal conductivity measurement (harmonic mean) for the same sample. The Mathinna Group sediments in central eastern Tasmania are relatively poorly known and how typical these results are for the formation as a whole is unknown. Certainly parts of the Mathinna Group are carbonaceous mudstones which are expected to have a lower thermal conductivity and foliation directions in the sedimentary package will vary. This is supported on one Ordovician mudstone sample from Olga Ridge, Tasmania, which has a document thermal conductivity of 2.8 W/mK (Wronski, 1977).

CONCLUSIONS

This paper has presented new equilibrated surface heat flow and thermal conductivity values for eastern Tasmania. Of the eight new heat flow values reported, five lie between 92 and 97 mW/m^2 and a further two between 83 and 87 mW/m^2. These anomalous values were calculated from a systematic shallow drilling programme, designed to map the thermal characteristics of eastern Tasmania and build upon earlier isolated but still anomalous values reported in the previous decades. Put together with improved knowledge of the distribution of buried granites in eastern Tasmania, a strong case is emerging for eastern Tasmania to be recognised as a new thermally anomalous province in Australia. The depth and characteristics of the granites and the size of the thermally anomalous area are such that there is strong potential for Engineered Geothermal Systems type power generation in Eastern Tasmania.

We thank KUTh Energy Limited for their permission to present this paper, and Hot Dry Rocks Pty Ltd for permission to present the results of foliation/conductivity testing and for related comments.

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Big Boom in Basel: is Oz next?

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ABSTRACT

We deployed a 6 station borehole microearthquake network around an Engineered Geothermal System stimulation-site beneath the city of Basel Switzerland. The borehole stations ranged in depth between 400 m to 2,700 m. During the stimulation several thousand accurately-locatable microearthquakes were generated, culminating in an M~3.4 event late in this man-made tremor sequence. This event exceeded the license limits for the stimulation, shutting down the associated Hot/Dry Rock power venture. Using standard source parameter analysis procedures and theory we have plotted the radiated energy versus seismic moment of the EGS sequence. The results suggest that the bulk of the stimulated events do not follow standard source scaling relations, with only a small fraction of small events and event larger than about M~1, falling along a constant stress drop line. Among the possible explanations for this break down are continued near source attenuation and scattering effects, which could be hiding the critical high frequency portions of the borehole seismic data. It could also be that the stimulation events actually follow different source physics than standard double couple events, owing to their origin in hydraulic fracturing. If so, then it might be possible to use this type of analysis to forecast the likely distribution of induced event magnitudes prior to licence exceeding induced earthquakes.

INTRODUCTION

We present a case history of a (somewhat) unexpected outcome of a geothermal investment of many millions of Euros by the city of Basel, Switzerland. The objective of the investment was to obtain clean geothermal power from hot rocks beneath this medieval-age city. The reason for the investment was the growing conflict between an electricity starved city and heavy air pollution from fossil fuel power plants. The idea was to "crack" the hot, but dry rocks under a very small portion of the city (under its main power distribution station) and pull heat up by circulating water into the cracks – i.e. create an Engineered Geothermal System in downtown Basel.

The main stimulation commenced on December 2, 2006. To monitor the anticipated seismic activity a small network of borehole seismographs were deployed in the vicinity of the injection well, but all within the city. Despite heavy cultural noise, the net could detect and locate M<0 microearthquakes from the drill site. On December 8, 2006 a magnitude 3.4 was induced, raising a civil alarm. The entire EGS effort was shut down shortly thereafter and is still being debated in Swiss court.

Could this same scenario take place in Australia?

To avoid a repeat of this very costly and embarrassing situation we have been studying the sequence and source parameters of the microearthquakes induced by the Basel stimulation. Even before the main stimulation, at the time of cementing of the well casing, it was possible to observe and locate the induction of very small events with the borehole seismic array. Standard source parameter analysis of the borehole seismic data after the sequence of events was more-or-less over shows that there was a breakdown in source scaling. This observed change in scaling related to the difference between very much fewer, but unfortunately larger, events and the bulk of the induced seismicity. Larger events appear to lie along curves of constant apparent stress, while the much more numerous small events fall along a significantly different curve. Perhaps careful real time monitoring of the induced seismicity could thus have been used to avoid this transition ahead of time by adjusting the stimulation factors that control it?

Observing the Big Boom with borehole seismology

Switzerland is powered by hydroelectric and nuclear power. Additional power could be supplied by geothermal sources. Basel sits at the southeast end of the Rhine Graben and at the northern front of the Jura Mountains, a young section of the Alps; the combination of the two leads to mild seismic activity. In fact, Basel has experienced several major quakes, the worst in 1356 has been analyzed to have been of magnitude 6.5 to 7.0 (Weidmann, 2002). Most quakes are rather shallow, some occurring within 5 km of the surface. The heat flow in the region is between 100 and 130 mW/m^2 (Medici and Rybach, 1995) compared to a globally averaged value of about 50 mW/m^2. This suggests that the region near Basel would have a strong potential to be a source of geothermal energy that could be efficiently mined. (see: Kahn, 2008, PhD Dissertation, Duke University.)

The main stimulation of the Basel Switzerland Hot Dry Rock geothermal experiment commenced on December 2, 2006. The primary purpose of the stimulation was to create a hydro-fractured reservoir, using an injection well bored to 5,000 m that could be used for heat exchange in the Basel Deep-Heat Mining Project.

To monitor the seismic activity we deployed 6 sondes each with 3 velocity sensors (5 also having 3 accelerometers) in the vicinity of the injection well at depths ranging from 317 to 2,740 meters below the ground surface. On December 8, 2006 a magnitude 3.4 was induced. This main event occurred after the injection flow had been "shut-off", in response to increased seismic activity. During the surrounding period, data from over 13,000 events were recorded with approximately

Figure 1. Air photo showing location of induced earthquake beneath the Basel HDR site.

3,300 of those events being locatable and nearly one hundred of them of magnitude one or greater (Figure 1).

Source scaling: a key to avoiding limit exceeding HDR earthquakes?

An important topic in seismology is the question of scaling relations of earthquakes. Are small quakes (magnitude ~< 2) simply large quakes scaled down? If so, then perhaps there exists a simple relationship to "forecast" what might happen during a stimulation by simply monitoring the size of the fracture being created and stopping short of the local "large" scale size. Numerous studies have examined this question with mixed results (see for example: Ide et al. (2003)). There are several reasons that might explain the disagreement (see: https://eed.llnl.gov/scaling-workshop/overview.php); these include 1) large uncertainties in the seismic energy; 2) large energy variability for different earthquakes with the same moments within the same study; 3) lack of common events between studies, making comparisons of the different scaling difficult; and 4) few studies using a single consistent technique covering a wide range of sizes (e.g. M~-1 - M~3).

Other than energy, one of the variables that we examined is the standard description of stress drop, the change in stress before and after the quake. The stress drop, which is a ratio of seismic moment and source dimension cubed is hypothesised to be constant over many magnitudes (0 to 7). However, because of the difficulty in separating the effects of source, path, and site, it is difficult to verify the scaling relationships below magnitude 3. Below this magnitude, using standard data collection and analysis techniques, the source dimension appears to have a constant value of about 100m; therefore, the stress drop decreases with decreasing moment.

While there are arguments that support this dimension (typical width of a fault zone), it has also been suggested that the attenuation seen in surface stations is responsible for the breakdown. This attenuation is particularly important for high frequencies (>50 Hz), because the absence of short wavelength observations could severely restrict the resolution of small source sizes. As a result studies are using relatively deep (~3 km) sites to eliminate near-surface attenuation and determine whether the scaling relations hold. In our Basel study, we used the borehole seismic data acquired during the hydro-fracture stimulation to examine the source scaling parameters for the ~3000 events that were recorded in one week, the borehole data significantly reducing attenuation.

We find that the standard plot of radiated energy versus seismic moment differs significantly from the standard scaled models (e.g. Ide and Beroza, 2001; Figure 2). The nearly linear plot of data is significantly different from the expected values. Rather than being proportional to M, which is the commonly stated relation for events of constant apparent stress, the radiated energy appears to go as ER ~ M*1.74. Using the standard model results, apparent stress for smaller Basel stimulation events increases with increasing moment, up to a point. However, larger events, and a small fraction of smaller ones, do seem to track along the constant τA=0.2MPa line. In particular, the results could be taken as suggesting that scaling is valid for events of moment greater than approximately M~1 or so.

SUMMARY AND CONCLUSIONS

The result of the Basel HDR stimulation was that the operators working on behalf of the city exceeded the allowable limit of ground shaking and the project was shut down pending a public hearing on what happened. Given the several hundred thousand Euro cost of the drilling operation each day, several millions were lost in the confusion resulting from the M~3.4 event. The whole sequence of subsequent "political events" illustrates how a very good idea can go badly wrong without a great deal of care by both private investors and public officials. While geothermal conditions in Australia are significantly different than in Switzerland, there is much to be learned

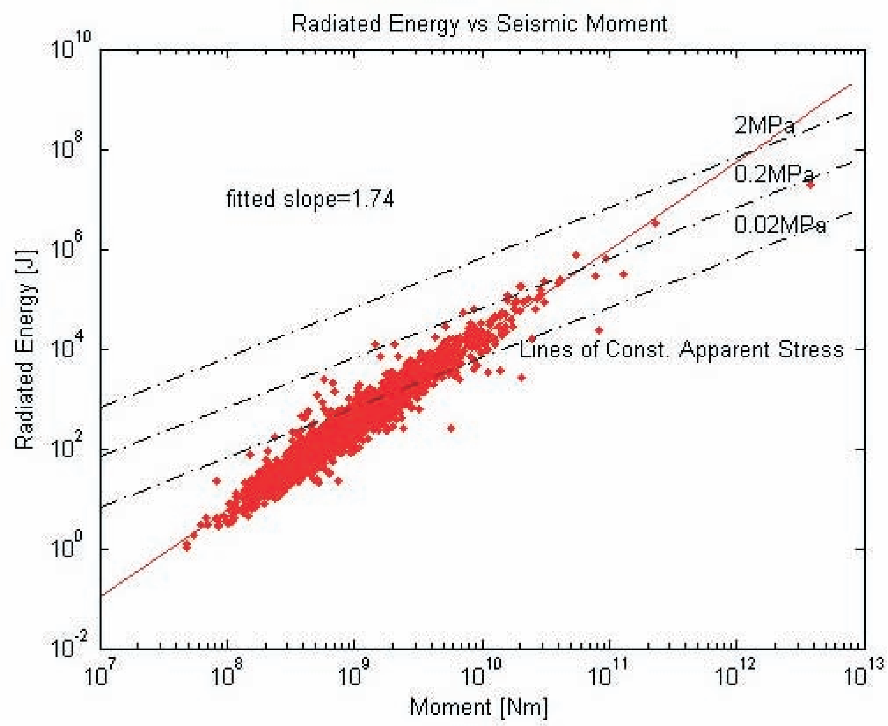

*Figure 2. Radiated energy versus seismic moment for the P-wave in the full cluster. Lines of constant apparent stress are given by the -.-. curves. The red line is the least squares fit of log(E_R)=a*log(M)+b, with a=1.74. While the overall fit is not consistent with constant apparent stress, those events with larger moment seem to lie along a constant apparent stress of =0.2 MPa (Kahn, 2008, PhD Dissertation, Duke University). It may be that, in the case of Basel, beyond the intersection of this line with the observed curve one can expect larger events to occur.*

from the Big Boom in Basel even here. Given Australia's thrust forward in geothermal development, this case should give pause for both sectors, private and public, and spur significant efforts in both research and human relations so as to avoid similar losses in time and resources.

We have used the very high quality borehole seismic data from Basel to test to see if the standard energy-stress-scaling relationships of these events might yield a way to forecast the potential occurrence of a "license-exceeding" earthquake during HDR stimulation (Kahn, 2008, PhD Dissertation, Duke University). Using standard analysis and scaling relations we conclude from this study that:

- Scaling does not appear to be valid for stimulated events over the full range of moments.
- Scaling is approximately obeyed for the larger events and a small fraction of smaller events.
- It maybe possible to track the energy – moment relations of fracture stimulation to a point beyond which larger events can be expected. These events appear to follow a more standard scaling relation.

Thus we suggest it may be possible to develop an empirical method for monitoring the progress of a HDR stimulation and forecast the potential for a licence exceeding event. It is also possible that this relationship holds only for a given configuration of observation stations and induced events, with near source attenuation and other propagation effects such as scattering still obscuring the true scaling. However, given that the induced microearthquakes could include mechanisms fundamentally different from natural, double couple events, our results do not preclude the development of such a monitoring system. So there is still hope that Australia can be saved from the embarrassment and expense of a Basel while trying to develop alternatives to fossil fuel energy.

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Applying Lessons Learned in Borehole Seismology to the Paralana Geothermal Development in South Australia

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ABSTRACT

The Institute of Earth Science and Engineering (IESE), at The University of Auckland, will be applying borehole seismology for a variety of investigations in Australia, including geothermal exploration. In the development discussed here, working with Petratherm Ltd of Adelaide, IESE will provide both seismic monitoring and advanced data analysis for the Paralana Geothermal Development. The objective is to monitor and analyse the seismicity produced by the hydrofracturing program in order to create a tomography of the fracture zone. The project will proceed in 3 phases. The initial phase was begun in June 2008 with the deployment of a preliminary shallow "post-hole" microearthquake net. This net is aimed at establishing the local background seismicity for comparison to induced events, and we expect the first data from it to be available at the AGEC meeting. The subsequent phases will focus on monitoring the geothermal development, with initial EGS drilling and, hopefully, power production.

Introduction: Improvements in geothermal exploration and monitoring using borehole seismology

The primary advantage of placing seismographs underground in borehole is summarised in Figure 1. As this plot shows, surface and shallow seismograph network have both a cut off in high-frequency signal detection and a significant loss in Signal-to-Noise ratio with decreasing sensor depth. These affects result from strong near surface attenuation and trapped wave noise. The result is that surface nets miss the much more numerous small earthquakes because much of their energy is contained in the higher frequencies. Yet these events can be used to tell much about the surface conditions and their changes during geothermal exploration and monitoring.

In this presentation we will cover the first results of our efforts to begin geothermal development in the Paralana area in the right way, seismologically speaking. This way is to establish the background seismicity before any development takes place so natural events can be separated from those induced by geothermal production. We also describe the plans for developing the monitoring array that will be installed once the best configuration for observing the background and induced events has been established.

These phases are described below, along with mention of advanced data analysis techniques that will be applied to assist both the well targeting and field management aspects of the Paralana development.

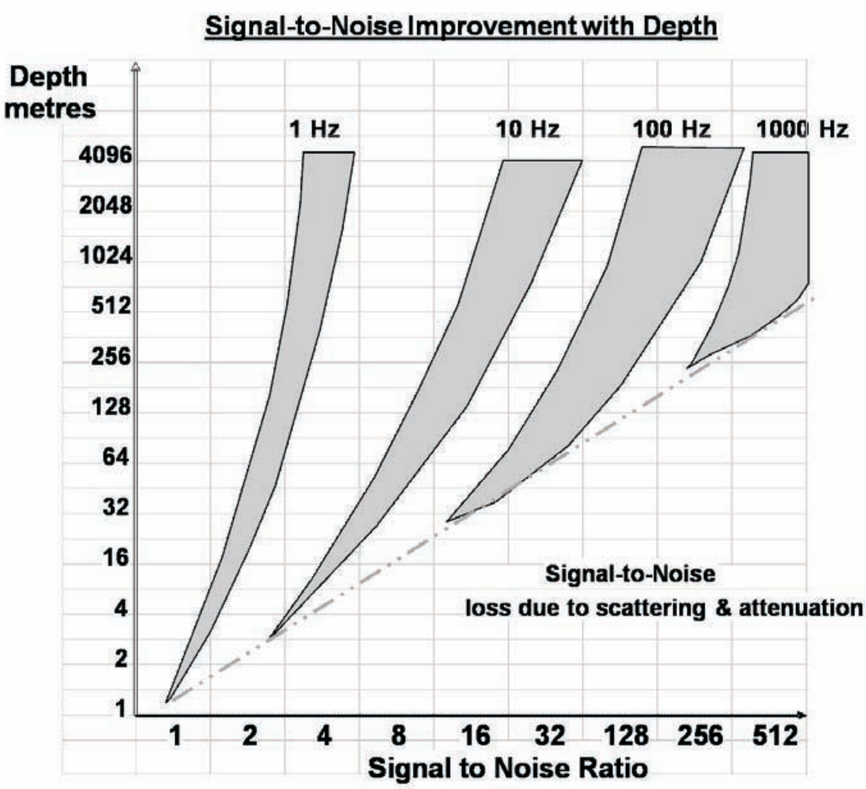

Figure 1. Signal-to-Noise improvement with depth of seismograph, showing cut-off in high frequency detection and loss of high frequency signal with decreasing depth.

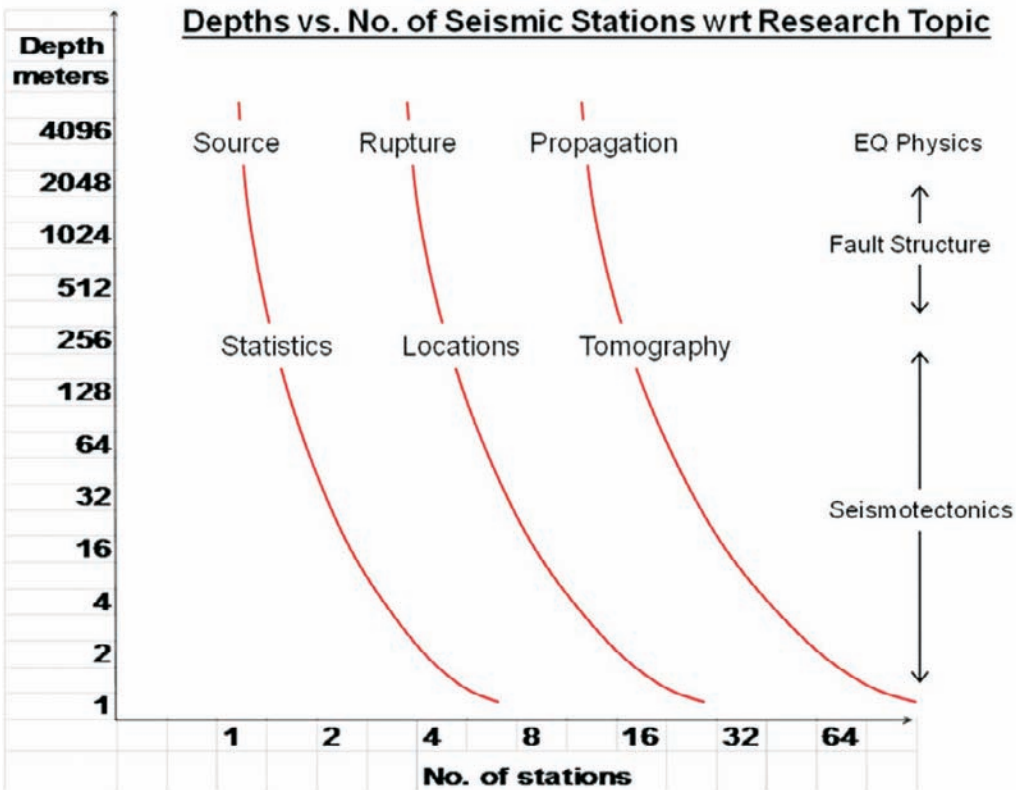

Figure 2. Engineering diagram summarising Number of Stations vs. Depth. The deeper and greater number of stations gets us closer to understanding the physics of the rupture process.

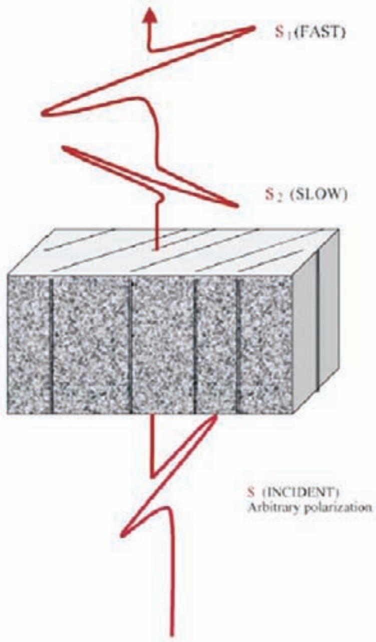

Figure 3. Shear wave propagation in a fractured medium. From Rial et al. (2005).

Phase 1: Initial data monitoring period and preliminary data analysis to ensure optimal network capabilities

The project will begin with the recording of a six month catalogue of background micro-seismicity for the region around the Paralana site. To record the background seismicity a network of four surface sensors, four 30-metre posthole stations and one deep 1,442 m borehole station have been deployed. The advantage of placing seismographs in boreholes to explore geothermal areas is their ability to quickly determine the level of local seismicity, often picking up events several orders of magnitude below the sensitivity of regional networks. Such installations also greatly increase the frequency bandwidth of the microearthquake observations, improving event location and signal analysis. Figures 1 and 2 summarise these advantages.

Phase 2: Re-locate individual stations or network as advised from Phase 1. Additional stations and telemetry links maybe added to the network during this phase

During the hydro-frac program, scheduled for early 2009, 4 to 6 additional surface stations will be installed and the network will be upgraded with real-time telemetry, and linked to a remote data acquisition and analysis computer system in the field. The 30 m deep stations may also be redeployed into 250 m boreholes to provide higher resolution data. Real-time data analysis will be performed on the waveforms to determine event locations during the fracturing program, and to monitor the directional "move-out" of the fracture front in real-time so as to provide feedback to the operators.

Phase 3: Continued monitoring and Analysis of data and summary report

The primary technique IESE will apply is shear-wave splitting analysis. These methods are based on the principle that shear-waves travelling along fractures travel at a different velocity to those travelling perpendicular to the factures (Figure 3). Facture densities and orientations can be calculated from maps of travel-time delays (Figure 4). After the completion of the hydro-fracturing program, the data will undergo a detailed analysis focused on the pre- and post-seismic travel times in order to detect shear-wave splitting events. These results will be used to create a map of the fracture density and direction. A detailed tomographic velocity inversion of the data will be created

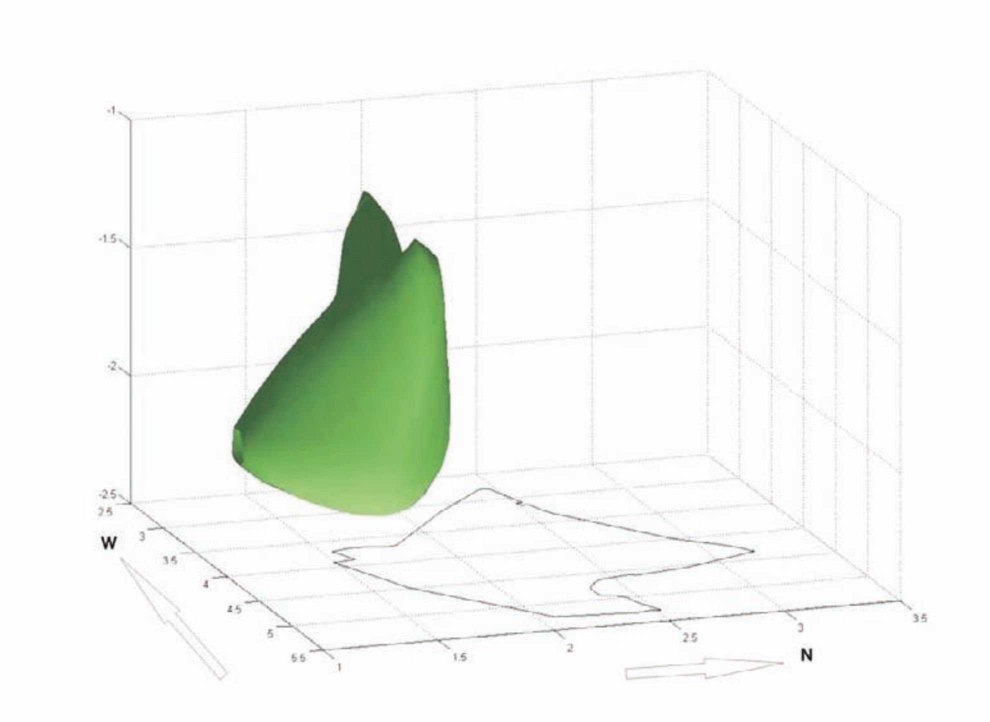

Figure 4. 3-D crack density map produced as a result of passive seismic monitoring of an Example Geothermal Field. The green area represents the area most likely to have high fracture density and permeability. The lease boundary is plotted at the bottom for orientation. Scale is in km. (From unpublished consultancy report).

to develop a high-resolution map of the velocity field and detect any changes that may take place as a result of hydro-fracturing. Furthermore, a double-difference event location will be performed for each of the events in the data set to develop a better image of the fracture patterns created by the hydro-fracturing.

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Analysis and Management of Seismic Risks Associated With Engineered Geothermal System Operations in South Australia

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ABSTRACT

In 2005, the Petroleum and Geothermal Group (PG) of the Division of Minerals and Energy Resources, Department of Primary Industries and Resources SA funded a report into evaluation of the seismic hazard generated at Geodynamics' engineered geothermal system (EGS) site in the Cooper Basin (Hunt & Morelli 2006). This report was well received internationally, and in 2007, after the induced seismic events at Basel, Switzerland, a second report was funded (by PG for the land access protocols technical interest group (TIG 1) of the Australian Geothermal Energy Group (AGEG)) to develop protocols for the analysis and management of seismic risks associated with EGS operations in SA (Morelli & Malavazos in progress). This presentation summarises the findings of that report, which outlines the:

- Risk analysis and management processes;
- Risks associated with both natural, and induced seismicity and the monitoring of such events;
- Infrastructure and population within SA's geothermal exploration licences (GEL);
- Geotechnical data that is required for comprehensive risk analysis; and
- Recommendations for the analysis and management of seismic risks associated with EGS operations in SA.

RISK ANALYSIS & MANAGEMENT

Risk analysis is recognised as the core element of the risk management process and along with communication and consultation and monitoring and review, is one of the most important components of the risk management process, as outlined in Figure 1.

Risk Analysis

The EGS seismic risk analysis process used in this study (Figure 2) was developed from the risk analysis process used by Dhu and Jones (2002) (for the analysis of earthquake risk in Newcastle and Lake Macquarie), and that proposed by Hunt and Morelli (2006) (for the analysis of induced seismic risk associated with EGS operations).

Communication & Consultation

Effective communication and consultation is important as it provides a means for all stakeholders, from the organisation in control of the EGS project, to the relevant government and private organisations, through to the general public, to be aware of what may occur. If implemented

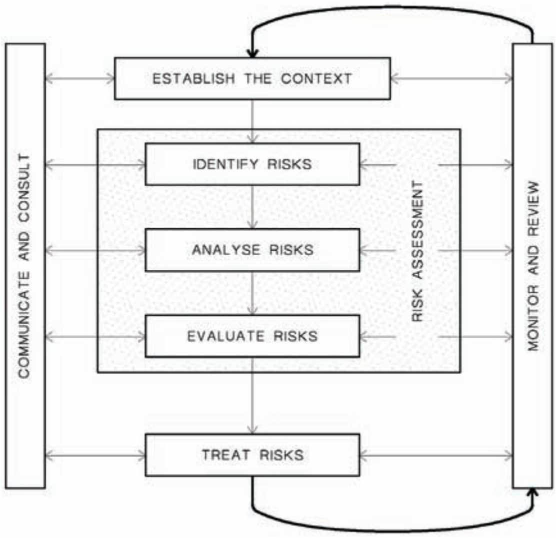

Figure 1. Risk management process (Standards Australia & Standards New Zealand 2004).

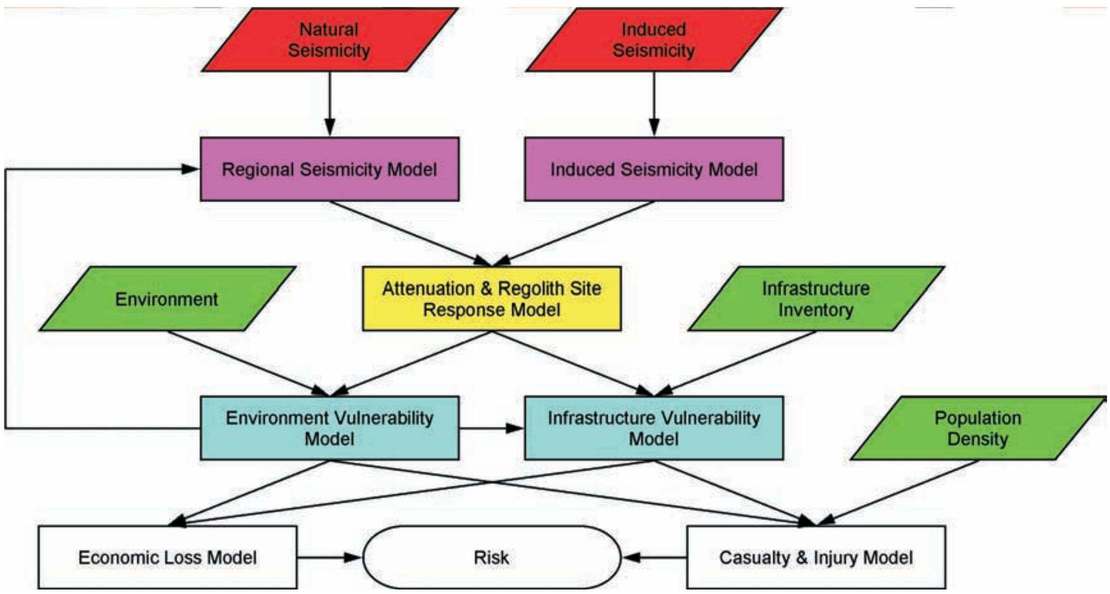

Figure 2. EGS seismic risk analysis process.

effectively, any induced seismicity generated will not come as a complete surprise to most and delays due to public perception of induced seismic events, as have been experienced in Basel due to an extensive, yet ineffective, public notification campaign (Häring, MO 2008, *pers. comm.*, 7 February), can be avoided.

Monitoring & Review

The ongoing monitoring and review of any risk management process is very important from an organisational sense, and essential to making the process as dynamic as possible. Incorporating changes in context, risk, and the effectiveness of risk treatment, as new data and information come to hand, ensures that the management plan remains relevant.

RECOMMENDATIONS

The main recommendation to come from this report is that for the geothermal industry in SA to keep advancing as it has in recent times, and avoid any postponements due to seismicity, there needs to be close interaction between government and industry regarding seismicity associated with EGS operations. This will 'share the load' with regards to research into seismicity from an EGS point of view, and the seismic profile of the state in general.

Protocol

Protocol recommendations were developed from the risk analysis and management processes, while taking into consideration a previously developed protocol (IEA-GIA Annex 1-Subtask D Working Group 2008), and risk evaluation 'traffic light' concepts, as have already been implemented at Basel (Geothermal Explorers Ltd 2007) and Berlín (Bommer et al. 2006). Protocol recommendations are as follows:

- AS/NZS 4360:2004 (Standards Australia & Standards New Zealand 2004) is to be the basis of all EGS seismic risk analysis and management processes;
- EGS seismic risk management is to be a regulatory requirement of any work program once a suitable site is selected for development;
- Once a site is selected for development, the deployment of an appropriate seismic monitoring network for the site, to gather both natural and induced seismicity data that complement existing SA Government and Australian Government networks (i.e. able to detect seismic events less than M 3), should be a priority and remain active throughout the life of the project;
- Seismic risk analysis should be completed before deep exploration drilling commences, to obtain a general indication of the level of risk and reveal any major risk issues for consideration later in the development;
- At least one deep (as is practical and below regolith if possible) seismic monitoring station to be deployed prior to hydraulic stimulation or large scale injections;
- Strong motion accelerometers to be deployed with the seismic monitoring stations, downhole and near surface, to record events that 'clip' the seismometer, and determine regolith amplification;
- Seismic risk analysis to be completed prior to hydraulic stimulation or large scale injection to assess the potential monetary or human consequences of induced seismicity;
- The proponent or licensee must demonstrate to the regulatory authority (PG) that it has adequately assessed and can effectively manage any seismic risk before commencing any hydraulic stimulation or large scale injection. The process should not be static and changes should be made as more information/data become available; and
- There should not be a 'one size fits all' 'traffic light' system employed state-wide as there is far too much diversity within SA's GELs, in terms of population, infrastructure and environment. Seismic risk should be assessed on a case by case basis.

Other

Another recommendation that has come about as a result of this study is:

Old seismic monitoring stations should be updated and new stations deployed as part of the SA Government and Australian Government seismic monitoring networks, so that seismic events greater than M 3 can be located accurately and relevant data obtained for attenuation and regolith site response models at EGS locations.

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Direct-Heat Use for Australia

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ABSTRACT

Direct geothermal heat use is an overlooked sustainable opportunity for displacing large scale electrical consumption. Recent trends for small scale (< 1MW) direct heat use by ground source heat pumps now dominate over historical space heating and bathing applications (Lund, et al., 2005). According to the 2005 review, the global total direct geothermal heat use is estimated at 28 GW. Through the addition of this new trend, direct heat has now overtaken the global geothermal electricity production of close to 10 GW (Bertani, 2005). We propose here that a new wave of utilising direct heat is imminent through the advent of newly attractive megawatt-scale applications. The biggest challenge is to drive them with low temperature (typically around 90 °C) geothermal sources in metropolitan areas. Intermediate temperature deep groundwater systems are widespread around the world. The immediate opportunities stemming from this hitherto neglected resource are in geothermal desalination, and heat driven air conditioning. We present here a pilot study for the case of Western Australia which is an archetypal sedimentary basin. Our proposed direct heat use can significantly extend the classical volcanically driven direct heat use technology. The broader perspective of such direct heat use is that it can displace worldwide peak electricity consumption by 30%.

SEDIMENTARY BASINS IN AUSTRALIA

Sedimentary basins offer an ideal target to push forward new technologies of direct heat use. Sedimentary basins occupy a large proportion of the Australian landmass (Figure 1). The Great Artesian Basin (comprising amongst others the Eromanga and Surat Basin), for instance, is one of the world's largest artesian groundwater basins, underlying one fifth of the Australian continental landmass. Groundwater comes out at wellheads at temperatures up to 100 °C. The natural temperature, porosity and permeability of these sedimentary basins may be sufficient to provide usable geothermal power without the requirement of stimulation. A new technology has emerged in which natural hot water motions are targeted. This technology is particularly suited for direct use of heat from extremely deep sedimentary basins such as the Perth Basin (>10 km thick sedimentary sequences).

THE WESTERN AUSTRALIAN GEOTHERMAL CENTRE OF EXCELLENCE

The Western Australian State Government announced a new $2.3 million WA Geothermal Centre of Excellence focussing on direct heat use (e.g. geothermally powered air conditioning and desalination) in populated centres where there is shallow groundwater of moderate temperature.

By exploring for and utilising low-grade heat in a permeable sedimentary environment we address an overlooked opportunity for broadening the footprint of geothermal energy utilisation. We are particularly focussing on the geological setting of sedimentary basins like the Perth Basin, where exploitable heat is available right where it can be used. The Centre comprises three participants: The

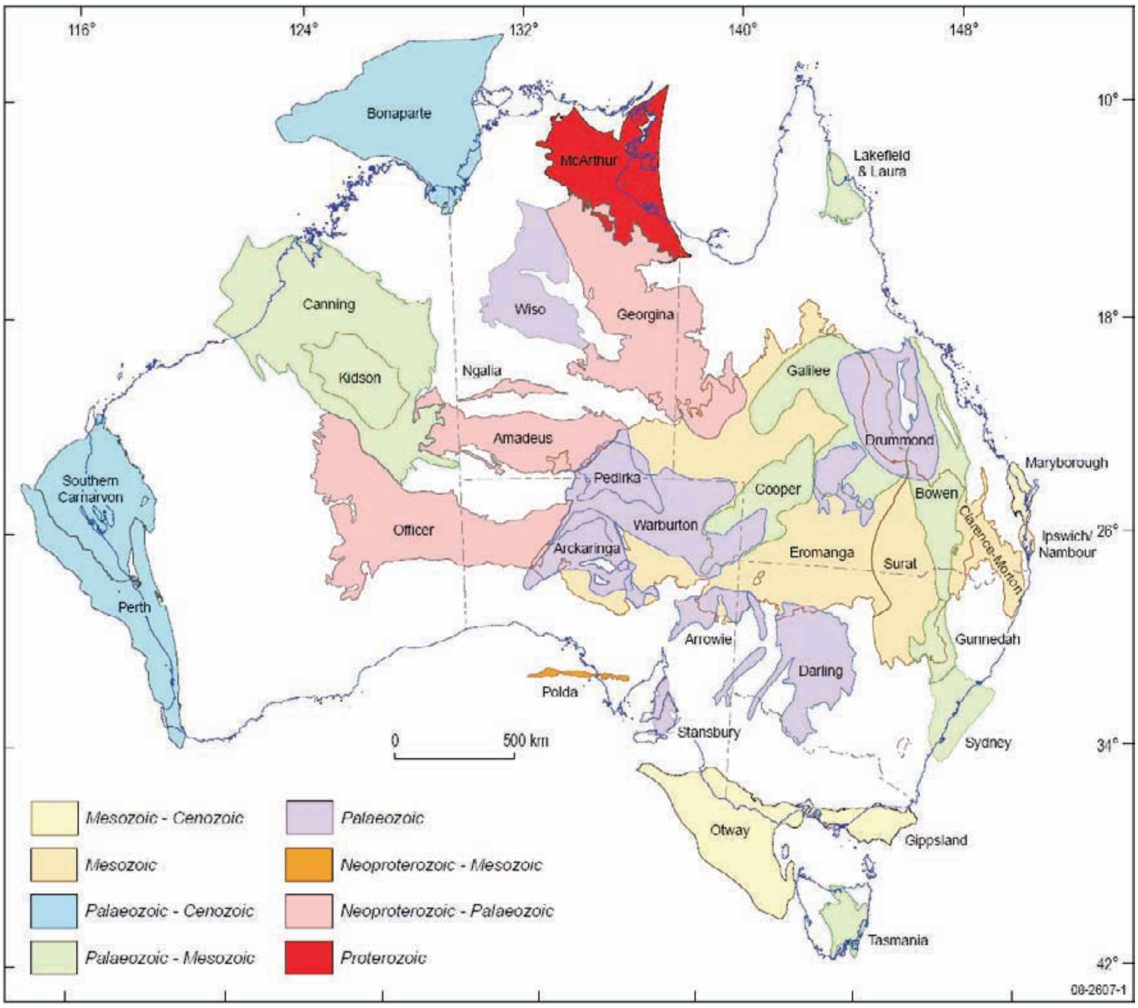

Figure 1. A large portion of the Australian landmass is covered by sedimentary basins.
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University of Western Australia, CSIRO, and Curtin University of Technology. For 3-D modelling of these geothermal systems the Centre will harness the supercomputers now being set up in Perth. This will make it possible to drive geothermal research into computationally intensive directions that had previously been out of reach in Australia. Because reactive flow simulations are classically performed on single processor infrastructure our parallel implementation will also be a focus of research. The research is organised in three interlinked Programs: 1) Assessment of Perth Basin Geothermal Opportunities using presently available data (including the supercomputer modelling program); 2) Optimal use of geothermal resources (this report); 3) Identification of Future Potential by going deeper.

There are challenges and opportunities. The main opportunity is that the drilling costs can be reduced substantially because heat and topography driven upwellings exist that provide natural transfer of heat to shallower levels. Through this effect geothermal power may in the future become more competitive even in areas with normal or only slightly elevated regional heat flow. The main challenges are that natural convective upwelling zones need to be accurately targeted and new methods need to be devised to harness the use of low-grade heat. Shallow geothermal sources may not reach the temperatures necessary for efficient electricity generation but are ideally suited for direct heat-driven desalination, heating and cooling, and dehumidification technologies. In this paper we wish to only present the above ground aspect of this new geothermal opportunity. The engineering challenges of using the heat directly will be addressed. Aspects of targeting these fluid heat sources will be discussed in the companian contribution on "Evidence for hydrothermal convection in the Perth Basin" Horowitz et al. (this volume).

The above-ground engineering aspects will be led from the UWA Mechanical Engineering Department in strong collaboration with Earth Scientists from the other institutions in Australia. We are focussing on novel exploitation technologies for low-grade heat. This is an essential step for broadening the utilisation opportunities of geothermal energy in the metropolitan urban environment.

THE DIRECT HEAT USE PARADIGM

A theoretical upper limit on extractable mechanical work from a heat driven process between a maximum temperature level, T_{max}, and a minimum temperature level, T_{min} is the well known Carnot efficiency, given by

$$\text{Carnot efficiency} = \frac{T_{max} - T_{min}}{T_{max}}$$

Here, an efficiency of 1 defines a full but impossible conversion of heat into work. Note that temperatures are expressed in Kelvin. For illustration of the Carnot principle consider an existing geothermal plant at Mokai in New Zealand which uses an ORMAT Energy Converter binary unit. Mokai uses steam at T_{max} = 219 °C (492.15 K) and cools to the ambient temperature of say T_{min} =20° C (293.15 K) thereby allowing a theoretical Carnot limit - which is of course not achieved in the plant - of 40% work extraction efficiency. Because we are targeting relatively low temperatures for T_{max}, obviously the lower difference between the hot and cold sources limits the theoretical amount of electrical energy we can extract from geothermal heat. We therefore suggest a more practical route - that is the direct use of geothermal heat.

DIRECT HEAT TECHNOLOGIES

For Australia we propose investigating two direct heat use technologies. The technologies are not new in their basic principle. However, their engineering art has advanced significantly and their potential for incorporation into geothermal systems has been mostly overlooked. These are:

- Desalination (65 °C < T_{max} < 90 °C geothermal water)
- Air Conditioning, via sorption cooling (55 °C < T_{max} < 200 °C geothermal water)

Geothermal Desalination

For geothermal desalination Multi-Effect Distillation (MED) Technology is a perfect match because it is driven with a maximum temperature of about 90 °C. Higher temperatures have to be avoided to prevent the precipitation of gypsum which will severely foul the heat exchanger in the distillation plant.

Given a hotter source of geothermal energy, one could drive an organic Rankine cycle (ORC) to produce green electricity which is in turn used to power a Reverse Osmosis (RO) plant or an MED plant.

The principles of geothermal desalination extend the classical design of an MED technology driven by hot groundwater in the first effect (leftmost box of Multi-effect distillation plant in Figure 2). This hot water is supplied at the highest temperature and highest pressure available from ground source. This hot ground water heats and boils the seawater (green line in Figure 2). Having

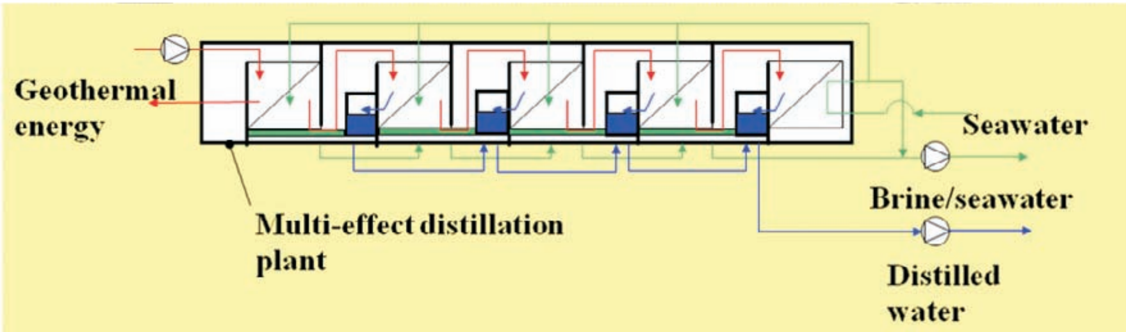

Figure 2. Principle of geothermal desalination.

expended only its thermal energy to the distillation plant the cool ground water will be pumped back into the aquifer so that there is no environmental impact of the MED plant. The steam from the seawater is then condensed and the resulting latent heat released is used at the next effect (the second leftmost box of the MED plant in Figure 2) which is at a lower temperature and pressure. The steam thus condensed becomes the first stream of fresh water (blue line in Figure 2). The same condensation transfer of latent thermal energy to the next effect is then repeated downstream to the other cascading effects at lower temperatures and pressures. When steam temperature is sufficiently close to the incoming seawater temperature the remaining heat is rejected to preheat the incoming seawater. The concentrated brine (green line in Figure 2) can be collected in evaporation ponds for extraction of minerals out of the seawater. This cannot be efficiently done with a reverse osmosis (RO) technology because the rejected brine is not as concentrated and is much lower in temperature.

The MED technology is commercially available in sizes from 1 m^3 a day (see Figure 3) to 25,000 m^3 a day.

Figure 3. Alfa Laval Freshwater Generator (document No.PD2037-en0109 www.alfalaval.com).

Air Conditioning (Sorption Chillers)

For air conditioning we can utilise geothermal water as low as 55 °C. For reference a Perth swimming pool heating system (Christ Church Grammar School) extracts 41.6 °C water at 738 m

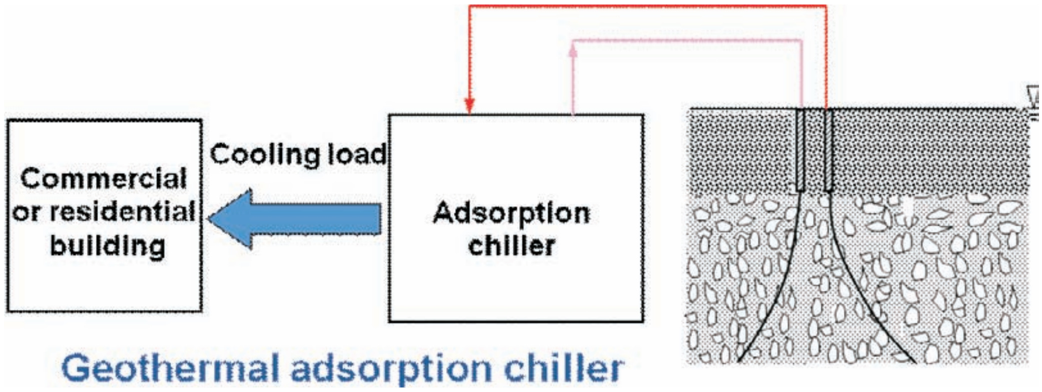

Figure 4. Principle of geothermal air conditioning.

depth from the Yarragadee aquifer and reinjects the cooled groundwater without contamination. We believe this to be a strong indication that the economics will be viable for air conditioning via these systems.

Essentially sorption chillers are very similar to vapour compression chillers, the latter technology being the dominant technology in air conditioning. However they are currently electricity driven. Just as with vapour compression chillers, sorption chillers can supply chilled water at the same temperature to a commercial or residential building (see Figures 4, 5). We propose to use heat driven sorption chillers to replace the vapour compression chillers so that geothermal heat instead of electricity is the driving energy source. Air conditioning constitutes the bulk of the peak load

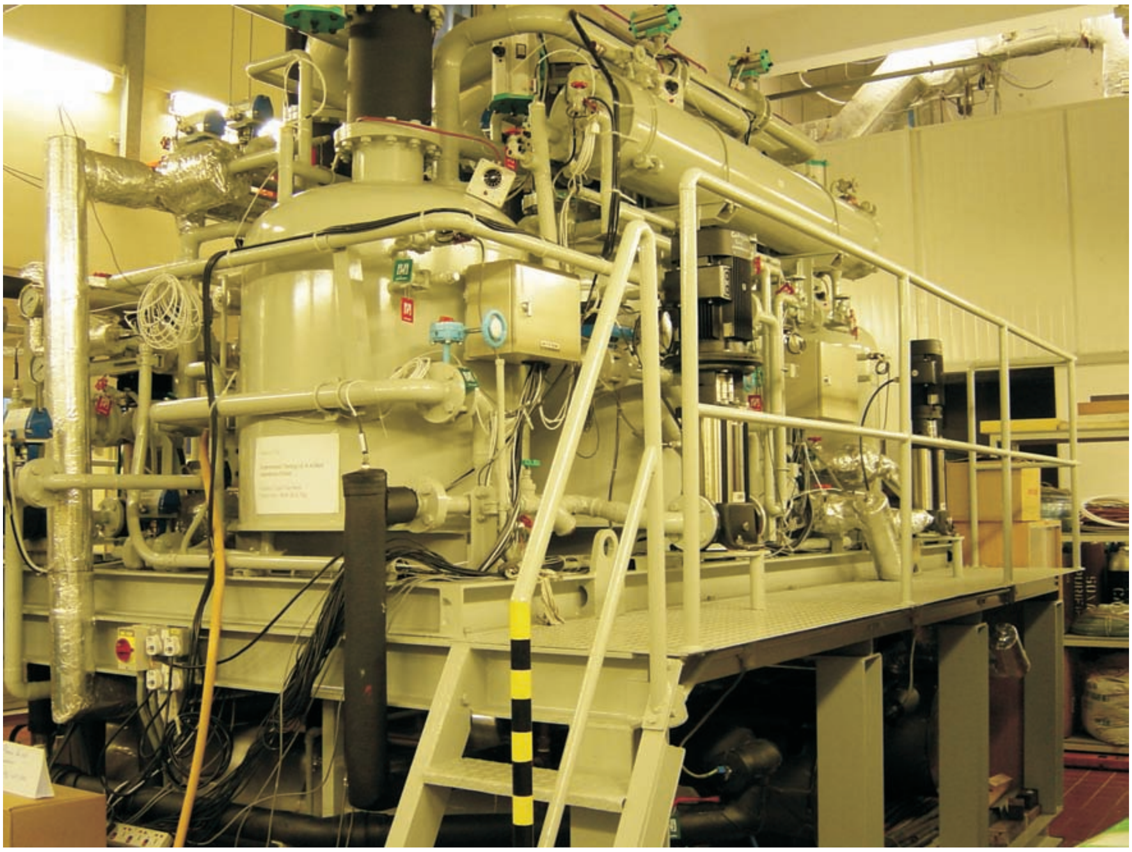

Figure 5. A prototype lab-scale multi-bed adsorption chiller (designed by Assoc. Prof. Hui Tong Chua and Dr. Xiaolin Wang).

electricity use in modern Australian cities. Major buildings like hospitals, malls, hotels, office and government buildings can use this exciting technology to replace their existing chillers. In such buildings chilled water from the chillers located in the central chilling plant is piped around the sprawling complexes into the individual air handling units. Therefore, the air conditioning infrastructure is already in place and we propose to simply replace the central vapour compression chiller by a sorption chilling unit hooked to a central geothermal bore which should be sufficient to service a large complex or several customers (Figure 4). Unlike ground source heat pumps this technology is powered by heat directly and not electricity. It is also currently commercially available in up to about 10 MW cooling capacity per unit. It is therefore an order of magnitude larger in cooling capacity than ground source heat pumps. To put this opportunity into perspective we give the potential CO_2 savings for one example building using this technology.

As an example, the Australian Resources Research Centre (ARRC) in Perth currently has approximately 2.1 MW cooling capacity of electrically powered vapour compression chillers installed. Over the fiscal years 04/05 and 05/06 the ARRC consumed 5.1 GWh electrical energy and an estimated 3.2 GWh equivalent of natural gas. The ARRC's facilities manager estimated 65% of the electricity and 75 % of the natural gas went towards space cooling and heating activities during that period. At Western Power's estimated 2004 greenhouse gas emissions rate of 0.85 tonnes CO_{2e}/megawatt-hour, and assuming no electrical transmission infrastructure energy losses, that corresponds to approximately 1400 tonnes CO_{2e} per annum emitted from air conditioning the ARRC. The natural gas component adds about another 70 tonnes CO_{2e} per annum. Those are the potential CO_{2e} savings for one example building using this technology.

SUMMARY

We have described two new archetypal examples for exploitation of the direct heat opportunity. The components interact amongst themselves in a fashion that both advances present day real world needs of the exploitation system and lays the groundwork for a strong Western Australian contribution to a future cooperation with the broader geothermal community in Australia and worldwide. We are particularly excited by the opportunity of intermediate to low temperature geothermal systems to contribute towards a zero emission energy supply.

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Optimisation of Geothermal Resource Economics

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INTRODUCTION

This talk covers optimisation of the cost of electric power from Hot Dry Rock (HDR) systems, otherwise known as Enhanced Geothermal Systems (EGS). These systems are hydraulically tight reservoirs whose permeability has been enhanced by hydraulic stimulation. An EGS "unit" in this talk refers to an injection well and the neighbouring production wells that derive fluid from it; for example, a doublet, triplet, five-spot, etc. The reservoir is assumed to be developed in the basement rock rather than in any sedimentary overburden. Most of the parameters in this exercise reflect the conditions encountered at the U.S.A. Desert Peak EGS project and the costs reflect 2006 U.S. dollars, but the conclusions reached here regarding optimisation should be applicable, at least qualitatively, to any EGS project today.

Optimisation of geothermal resource economics calls for minimising the levelised cost of power (¢ per kilowatt-hour) over the project life. Minimising the levelised cost, in turn, requires minimising the capital cost of project development ($ per kilowatt-hour installed) as well as the operations-and-maintenance (O&M) cost (¢ per kilowatt-hour generated). The approach taken here is as follows: (a) using numerical simulation of an idealised reservoir to estimate power generation over time for various system configurations (number and spacing of wells, assumptions about stimulation effectiveness, etc.); (b) estimating the levelised power cost for each configuration, based on capital cost, O&M cost, cost of money and inflation rate; (c) determining the sensitivity of levelised cost to the cost components, interest and inflation rates, and resource characteristics (pumping rate, reservoir properties, depth to the reservoir, etc.); and (d) based on this sensitivity analysis and certain issues of site characteristics, identifying the practical steps that could be taken towards economic optimisation.

LESSONS FROM RESERVOIR MODELLING

From the forecast of the production rate and temperature from the reservoir model, the net power generation versus time was calculated, for each well geometry, after subtracting the parasitic power needed by injection and production pumps. For each combination of assumed geometry, injector-producer spacing, stimulated thickness, enhancement level (fracture spacing and permeability) and production rate, three criteria of performance were computed: (a) net generation profile (net generation versus time over project life), (b) net power produced per unit injection rate, and (c) fraction of in-place heat energy recovered.

This numerical simulation study led to the following conclusions relevant to optimisation of resource economics:

- Cooling rate at production wells is not an adequate criterion for measuring the effectiveness of an EGS power project; net generation profile and reservoir heat recovery factor are more appropriate criteria;
- Improving permeability, without improving the matrix-to-fracture heat transfer area (that is, reducing the fracture spacing), has little benefit in heat recovery or net generation;

- The net generation profile can be improved (that is, the decline rate can be reduced) by curtailing the throughput without significantly affecting average generation over the project life;
- Increasing the stimulated volume increases the generation level without significantly affecting the shape of the generation profile; and
- For a given state of stimulation (that is, fracture spacing and permeability) average net generation increases linearly with stimulated volume and is nearly independent of well geometry.

LESSONS FROM ECONOMIC MODELLING

We have estimated the drilling cost based on a statistical correlation with depth, and the stimulation cost based on the experience of the European EGS project at Soultz-sous-Forêts and Geodynamic Ltds' EGS project at Cooper Basin, Australia. For the power plant and surface facilities cost and the O&M cost, we have used the typical range of values in the geothermal industry. The uncertain variables in this analysis (capital costs of drilling, stimulation, power plant and surface facilities, O&M cost, interest rate and inflation rate) were subjected to Monte Carlo sampling and used in a probabilistic assessment of the levelised power cost. The capital cost was amortised over the project life at the interest rate, and O&M cost was increased at the inflation rate over the project life. The annual capital-plus-interest payment and O&M cost were discounted to their present value using the inflation rate. The mean levelised power cost versus stimulated volume per EGS unit was thus estimated for all configurations and stimulated volumes considered.

The economic analysis resulted in the following conclusions relevant to economic optimisation:

- Levelised power cost declines with increasing stimulated volume, and for any configuration, with the repeating of contiguous EGS units;
- The lowest possible cost of power at Desert Peak was estimated at 5.43¢ per kWh, ignoring certain uniquely site-specific and/or atypical costs of exploration, infrastructure development (such as roads and the transmission line), regulatory compliance, environmental impact mitigation, royalties, and taxes;
- Levelised power cost is most sensitive to O&M cost, followed by power plant/surface facilities cost, drilling cost per well and interest/inflation rates, in that order. It is insensitive to stimulation cost but very sensitive to the effectiveness of stimulation;
- Improvements in geothermal pump technology in the future could allow increasing the maximum practicable pumping rate from a well (currently 200 ℓ/s), thus reducing the levelised power cost; a plausible 50% improvement in the pumping rate can reduce the levelised cost to 5¢/kWh;
- The effectiveness of stimulation in creating closely-spaced fractures and the desired reservoir characteristics (uniform, isotropic and sub-horizontal) reduces the risk of cooling of the produced fluid. The levelised power cost is sensitive to cooling rate (approximately 0.5¢/kWh increase per °C cooling per year); and
- Reservoir depth determines drilling cost, energy reserves and well productivity, while the effectiveness of stimulation, which is dependent on the lithology and in-situ stress condition at this site, determines cooling. Therefore, the levelised cost can be very sensitive to site characteristics.

CONSIDERATION OF CERTAIN SITE CHARACTERISTICS

It is obvious that the higher the temperature gradient at a site the more attractive the resource economics is likely to be. Site selection is often based on regional heat flow distribution and drilling of relatively shallow exploration wells. However, the temperature gradient measured at relatively shallow depths cannot necessarily be extrapolated downward indefinitely because of intervening geological issues such as the thickness of sediment cover on the basement, radioactive heat generation rate in the basement or the presence of natural convection cells. These issues are reviewed in this talk.

While energy reserves per unit area at any site increases with depth, net MW production capacity per well does not necessarily increase with depth. This issue arises from the fact that up to the depth where the temperature reaches 190 °C, which is the temperature limit for pumps available today, the capacity of a pumped well would increase with depth. Below this depth a well will have to be self-flowed and its capacity would actually be less; this would be true up to the depth where the temperature reaches about 220 °C. Above this temperature level no generalisation is possible about well capacity. Considering the well capacity and cost of drilling versus well depth, an optimum drilling depth may be defined at a site; this optimum drilling depth can be either the depth at which the well capacity is maximised or the drilling cost per MW well capacity minimised.

CONCLUSIONS

Based on numerical modelling of an idealised reservoir, economic analysis, and practical considerations of certain site characteristics, we conclude that the following steps can be taken towards optimising the economics of an EGS project; the steps are presented below in decreasing order of their importance:

- Reduce the operations and maintenance cost;
- Reduce the power plant cost;
- Choose the site with the highest possible vertical temperature gradient and/or the thickest possible sedimentary cover on the basement;
- Choose the drilling depth that maximises MW well capacity per unit drilling cost rather than reaches the hottest resource;
- Create the largest possible stimulated volume per well;
- Improve stimulation effectiveness, and in particular, reduce the fracture spacing and heterogeneity in the hydraulic characteristics of the stimulated volume;
- Pump the production wells, if possible, taking advantage of the evolving improvements in pump technology;
- Develop multiple contiguous EGS units to benefit from the economy of scale; and
- Through reservoir modelling optimise well spacing and injection rates that minimise the rate of decline in net generation with time.

Geothermal District Heating Development

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ABSTRACT

The first U.S. geothermal district heating system, built in Boise, Idaho in 1892, is still running strong and currently serves about 275 customers. Yet its early start up did not lead to the kind of growth one might expect in a country with such high demand for heating homes and buildings. Currently in the U.S., after over a century of development in the sector, there are only 21 operating Geothermal District Heating Systems (GDHS) providing about 100 MWt. The systems were developed in the 1980s or earlier with the exception of three systems developed in the last five years. The slow growth of the U.S. GDHS sector has been in sharp contrast to what happened in Iceland where the first GDHS was built in the 1930s and now about 90% of the country's space heating needs are supplied by geothermal energy (Icelandic National Energy Authority, 2006).

This presentation will describe the results of an analysis aimed at understanding why growth in the U.S. GDHS sector has been so slow after a successful start early on. There are several potential reasons for this slow expansion – in part because other low cost fuels such as natural gas and fuel oil were readily available and because energy efficiency and use of renewable energy has not been consistently supported with government policies or incentives. Through interviews with current U.S. geothermal district heating systems operators, data were collected that provide a good overview of the status and market environment of U.S. GDHS. As a part of this study, recent cost experience in this sector was evaluated and the total cost of large scale deployment was estimated. To assess why the Icelandic GDHS sector developed much faster than then American one, the Icelandic experience was compared with U.S. experience and differences in government policies reviewed. Finally the GDHS opportunity presented by Engineered Geothermal System (EGS) was briefly explored. Analysis of the data collected was used to identify barriers and enablers of GDHS development in the U.S. to develop recommendations of how to encourage growth in the sector.

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Discrete Element Simulation of Hydraulic Fracturing and Induced Seismicity in Engineered Geothermal Systems

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ABSTRACT

In this paper the Discrete Element Model (DEM) 'ESyS_Particle', previously used to model fracture of brittle rocks and earthquake processes, is further developed to be able to be applied to the hydraulic fracturing process in Engineered Geothermal Systems (EGS). The advantage of DEM is that large deformations and dynamic process can be modelled easily. ESyS_Particle has been used to successfully model fracture of brittle rocks and earthquake processes in the past 15 years. Currently it incorporates thermal-hydro-mechanical coupling based on Darcy's Law and Biot theory. A simple simulation of a hydraulic fracture is provided, which reproduces the most basic features of hydraulic fracture. I hope to model induced seismicity in the future.

INTRODUCTION

Australia has a unique hot rock geothermal resource which can provide clean, reliable and cost-effective energy for centuries to come. A type of geothermal energy extraction process involves the injection of high pressure fluid to exchange heat from granite situated at depths near 5 km and temperatures up to 250 °C. Although hydraulic fracturing is a mature technique in the oil industry, there remain some issues which are not fully understood. The challenge in this process is how to stimulate and sustain the flow of fluid through the geothermal field and how to generate an efficient hydraulic subsurface heat exchanger system. Great effort is required to offer some explanations of types of fracturing and flow rates that occur under different conditions such as the fluid viscosity, propellants used, pump rates etc. This is a crucial step in understanding and quantifying the flow aspects of the heat exchanger, and can then be used to give some confidence to the viability and sustainability for such a system.

Another concern is the risk of fluid injection generating induced seismicity. One example is injection-induced earthquakes in Basel, Switzerland which occurred between December, 2006 and January, 2007. Although no severe damage was reported, the pumping operation was terminated and the project remains in suspension. The possible societal and economic impact of induced earthquakes associated with geothermal pumping can not be ignored in Australia. While monitoring seismic events provides valuable information with respect to spatial and temporal reservoir growth, a numerical model which has the capability of simulating the process is also helpful. Such a numerical model should include full coupling between thermal-, hydro- and mechanical- processes. A DEM is a good candidate because it is suitable for modelling brittle fractures and seismic events thanks to its discrete nature.

In this study, ESyS_Particle is developed to include thermal-hydro-mechanical coupling based on Darcy's Law and Biot poroelastic theory. The model is introduced briefly below, followed by an example of a hydraulic fracture simulation. It is intended that ESyS_Particle is further developed to be able to model induced seismicity in the future.

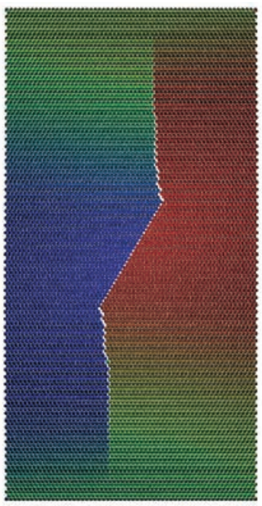
INTRODUCTION TO THE ESYS_PARTICLE MODEL

ESyS_Particle is a Discrete Element Model (DEM) developed by ESSCC, University of Queensland. It has been applied to the study of physical processes such as rock fracture, stick-slip friction behavior, earthquake processes and frictional behaviour of granular materials (Mora et al. 1993, 1994; Place et al. 2002). At its current state, ESyS_Particle is able to conduct simulations in parallel utilising the Message Passing Interface (MPI).

ESyS_Particle has been recently extended to include single particle rotation and a full set of interactions between particles. Some of the more important features that distinguishes ESyS_Particle from existing DEM's are the explicit representation of particle orientations using unit quaternion. Complete interactions (six kinds of independent relative movements are transmitted between two 3-D interacting particles) and a way of decomposing the relative rotations between two rigid bodies in such a way that the torques and forces caused by such relative rotations can be uniquely determined (Wang et al. 2006; Wang et al. 2008a). In most existing DEM codes, the incremental method is used to update the interactions between particles. However, results show that when dealing with finite rotations of particles, the incremental method is not as stable and accurate as the method used in ESyS-Particle (Wang et al. 2008a).

Figure 1 shows two examples of the ESyS_Particle Model. On the left is a simulation of a 2-D wing crack extension. Wing cracks are frequently observed in uniaxial compression of brittle materials with a pre-existing crack. It is found that tensile cracks nucleate at the tips of the flaw, grow in a stable manner with increasing compression, then tend to align with the direction of axial loads. It can be shown that these observations are well reproduced using our model (Wang et al. 2008b).

The right side of Figure 1 shows the 3D fracture pattern of a brittle rock-like material. In this example, the sample is subjected to slow uniaxial compression in the vertical direction. The colours represent vertical displacements. Discontinuities in colours show the formation of fractures which are difficult to capture in laboratory experiments because of the rapid nature of this process. When the main faults are formed, two intact blocks can be observed with more fragile parts shattering



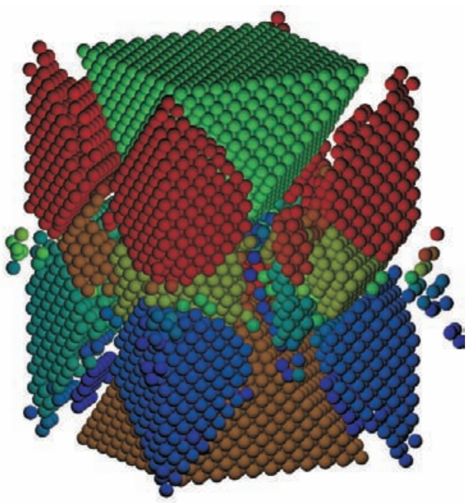


Figure 1. Simulation of 2-D wing crack extensions(left) and of the fracture pattern of a 3-D brittle rock-like material under uniaxial compression (right).

away from the four sides. This kind of pattern can be shown to occur in rock fracture experiments (Andreev, 1995).

Currently ESys_Particle has included thermal effects (which include heat transfer, thermal expansion and friction generated heat) and Darcy flow. The algorithm for hydro- and mechanical-coupling is outlined below.

Incorporation of pore flow within ESyS_Particle

Generally, movement of particles, or change of mechanical pressures will cause a change in pore pressure. On the other hand, Fluid pressure gives rise to extra forces on the particles, which in turn affects the movement of the particles. In the model presented, a two-way coupling between hydro- and mechanical- processes is realised using Darcy's Law and Biot poroelasticity theory.

Darcy's Law

Unlike the similar DEMs, volume space between particles is not viewed as pore voids in this study. Instead, the assumption is made that the voids inside rock are much smaller than the particle sizes; therefore the porosity is just an average concept for each particle. There is an average and uniform pore pressure p_i for each particle *i*. For two contacted particles *i* and *j*, the fluid exchange is

$$\Delta V_f = C(p_i - p_j)\Delta t \qquad (1)$$

where *C* is the conductance of the link, which is related to local permeability and geometry of the material.

Biot linear poroelastic theory

According to Biot's linear poro-elastic theory, the constitutive equations of a porous medium can be written as (Detournay and Cheng, 1993)

$$\varepsilon = -(P-\alpha p)/K_m \qquad (2a)$$

$$\zeta = -\alpha(P-p/B)/K_m \qquad (2b)$$

where p is pore pressure, $P=-\sigma_{kk}/3$ is the mean or total mechanical pressure (isotropic compressive stress), $\varepsilon = \varepsilon_{kk} = \Delta V/V$ is the volumetric strain (positive for extension), $\zeta = V_f/V$ is the variation of fluid content (positive corresponds to a "gain" fluid), α is Biot coefficient, B is the Skempton pore pressure coefficient and K_m is the drained bulk modulus of the material. V and V_f are the volume of the material and fluid respectively. From Equation 2a and 2b, the following equation is obtained

$$p = BP + K'\zeta \qquad (3)$$

where $K' = BK_m/\alpha$.

The pore pressure for particle *i* is updated according to:

$$p_i(t+\Delta t) = p_i(t) + B\Delta P_i + K'\Delta\zeta_i \qquad (4)$$

where $\Delta P_i = P_i(t+\Delta t) - P_i(t)$ and $\Delta\zeta_i(t+\Delta t) - \zeta_i(t) = C\Delta t\Sigma_j(p_j-p_i)/V$. The summation j goes though all the neighbouring particles of particle *i*.

Tunnel interaction

When a crack develops, the bond between two particles will break, and there exists a small separation of the particles. This increases the local permeability and fluid is allowed to flow into the crack, thereby increasing pore pressure and causing the crack to open wider.

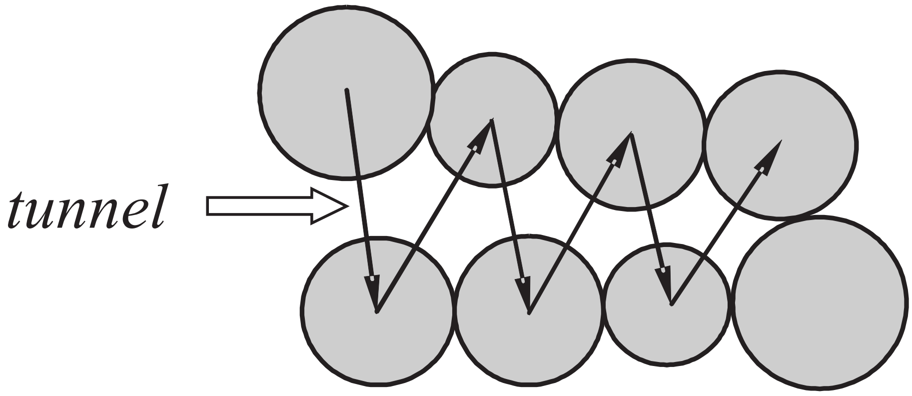


Figure 2. Schematic illustration of an zigzag simulation of fluid along a crack.

In the model presented, this process is taken into account. Besides the bonded interaction and elastic (or frictional) interaction, another kind of interaction, tunnel interaction, is introduced. In case of the tunnel interaction, particles do not come in contact with each other, but remain in close proximity from one another. Fluid flow between particles occurs in a zigzag route (Figure 2). This route is a good representation of the flow along the crack. In this case, the tunnel conductance is empirically set 20 to 100 times larger than normal. However this has the effect of slowing down calculations as smaller time steps are required to compute the problem.

Forces caused by pore pressure

Fluid pressure will give rise to forces acting on the particles. This mechanism has been included through the use of equation 2a which implies that when there is no volume change ($\varepsilon=0$) a mechanical pressure $P=\alpha p$ is required to balance the pore pressure, otherwise the volume will increase. This also suggest that a repulsive force $F_{ij} = \lambda A(p_i+p_j)/2$ is needed between the particles i and j, where A represents the contact area, and λ is a factor which depends on the geometry of particle packing and dimension of the problem. In 2-D regular packing is used.

Preliminary simulation of hydraulic fracture

Figure 3 shows snapshots from a 2-D simulation of hydraulic fracture. The model consists of 5301 particles of different sizes ranging from 0.1 to 1. A small and constant confining pressure is applied on the four boundaries. The image on the left shows the initial state of the simulation, the hole in the middle of the sample represents the location of where liquid is to be injected through increasing pressure. The middle image of Figure 3 shows the appearance of some cracks, once fluid flows into the cracks it will cause them to propagate as shown on the right hand side of Figure 3. Although the simulation remains predominantly un-calibrated against laboratory and *in-situ* testing, it can be shown to reproduce the basic features of hydraulic fracture. It is believed that a more realistic boundary conditions will be able to produce better results.

Simulation of induced seismicity by geothermal reservoir

Fluid extraction and injection can induce seismicity (Majer, 2006). Both fluid extraction and injection are undertaken in geothermal operations. In the case of water injection, pore pressure near the well increases.

The role of pore pressure in earthquake generation is that it can push apart the fault surfaces, reducing the "effective strength" of the fault. It is known that several factors control the

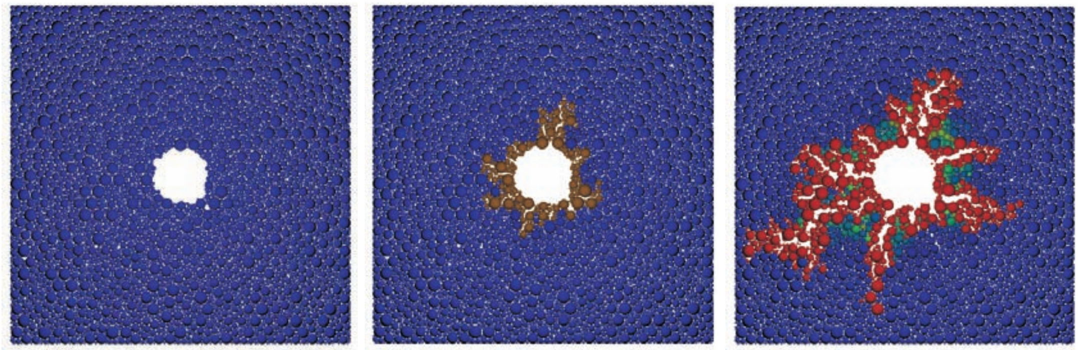


Figure 3. 2-D simulation of hydraulic fractures. The colours represent pore pressure (blue for low and red for high).

magnitudes, spatial and temporal distribution of induced seismicity. Using the model mentioned above, it is a future goal to investigate numerically the following aspects:

1) The impact of rate of fluid injection on induced seismicity.
2) The effect of permeability, strength of rocks.
3) The effect of sizes, orientations and distances of faults.
4) What controls the time lag (or delay) observed between induced events and the injection.

It is hoped this study will be helpful in understanding the dynamics of the physical processes of geothermal energy extraction and the mechanisms causing the seismicity.

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Recent Developments in the Measurement of Down-Hole Temperatures and Thermal Conductivity for Heat Flow Determination: a Review

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ABSTRACT

Heat flow data are fundamental to almost every Enhanced Geothermal System (EGS) exploration program in Australia. In the absence of direct temperature data from deep petroleum wells, the extrapolation of heat flow data provides one of the only techniques that is able to remotely sense the presence of buried anomalous heat.

Collecting heat flow data can be expensive with bores drilled specifically for heat flow determination (typically 300 m to 1000 m in depth) having a total drilling cost of between AUD$100,000 and AUD$1,000,000.

Exploration boreholes are typically slim 'minerals style' holes with a combination of open-hole and coring techniques used to obtain desired rock samples. Thermal conductivity of the intersected geological section is estimated using laboratory measurements of core or cuttings or by analysis of wireline proxies. Temperature data are collected down-hole using a wireline probe and are either manually recorded at regular intervals (typically every metre) or continuously recorded with a digital data logger. Temperature and thermal conductivity data are used to calculate a single heat flow value or to identify and quantify variations in heat flow with depth. Heat flow data and downward-modelled thermal conductivity values are then used to extrapolate temperature models to target EGS temperatures (typically around 200 °C) at between 3 km and 6 km depth. This large extrapolation is sensitive to the accuracy and inherent uncertainties of heat flow estimates.

Borehole heat flow determinations equate to the regional heat flow if the following assumptions are met:

- Temperatures measured in the bore are only a function of the surface temperature, the basal heat flow and the thermal conductivity of the rock mass under investigation;
- Modelled thermal conductivity accurately reflects the actual thermal conductivity of the rock mass; and
- Heat flows along a path normal to the Earth's surface.

In practice all three of these assumptions are likely to be invalid to varying degrees. Numerous factors influence both temperature and thermal conductivity measurement that must be taken into consideration when calculating heat flow. In recent years there have been a number of significant investigations concerned with improving estimates of crustal temperatures (e.g. Cermak et al., 2007; Vosteen et al., 2006), thermal conductivities of rocks (e.g. Popov et al., 1999a; Vosteen and Schellschmidt 2003; Goutorbe et al., 2006; Mattsson, 2007) and heat flow (e.g. Popov et al., 1999b;

Zschocke et al., 2005b). A selection of the findings from these studies are discussed with respect to EGS exploration objectives.

TEMPERATURE PROFILES

Inherent instability

Temperatures were continuously monitored in two boreholes in Kamchatka (Russia) by Cermak et al. (2007). The authors noted that the temperature intermittently oscillated by several hundredths of a degree over all observable timescales (from a few minutes to several days; Figure 1). This oscillation was attributed to inherent instability in the borehole due to the temperature gradient (i.e. intra-borehole convection) and thermo-structural complexity of the rocks surrounding the bore

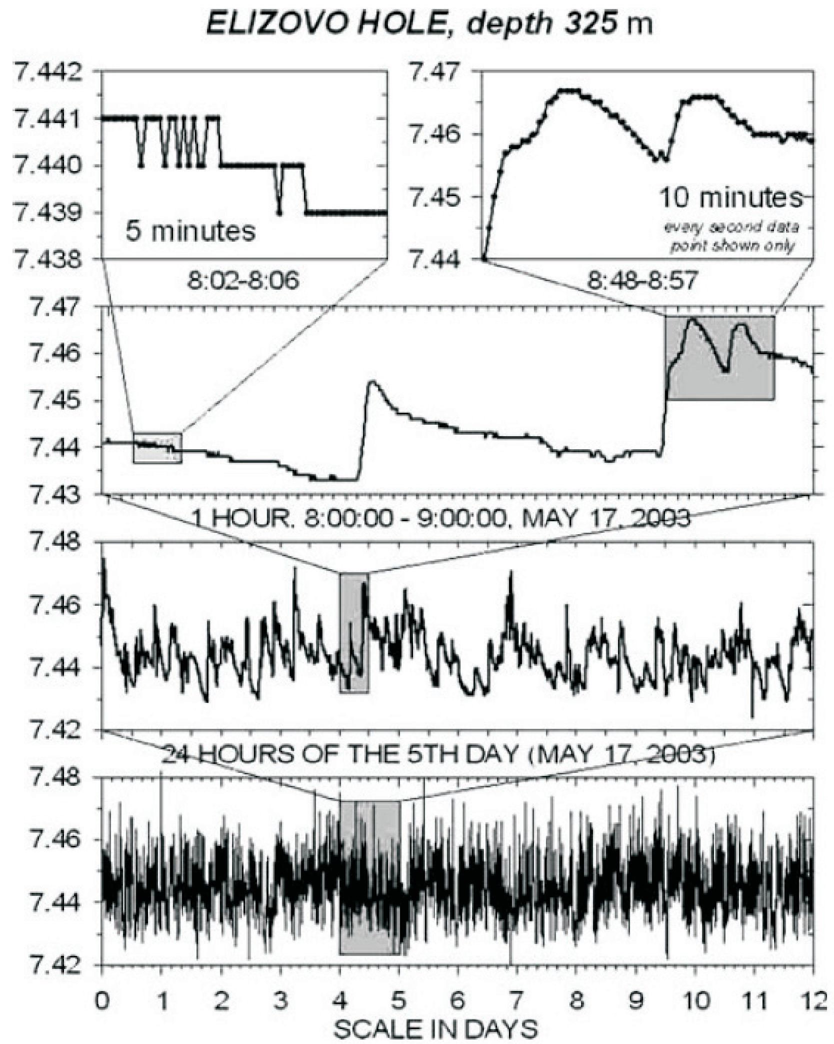

Figure 1. Time series temperature data from Cermak et al. (2007) showing variations in measured temperature of several hundredths of a degree over several timescales.

wall. These findings suggest that care should be taken when measuring borehole temperatures with high resolution temperature sensors and that longer measurement times (>5 minutes) may remove the effect of inherent instability in the temperature profile.

Surface and Palaeoclimatic Effects

Variations in surface temperature due to seasonal and palaeoclimatic change have the potential to cause significant deviations in measured temperature profiles with respect to the steady-state geothermal gradient. The effect of transient palaeotemperatures on temperature profiles in the

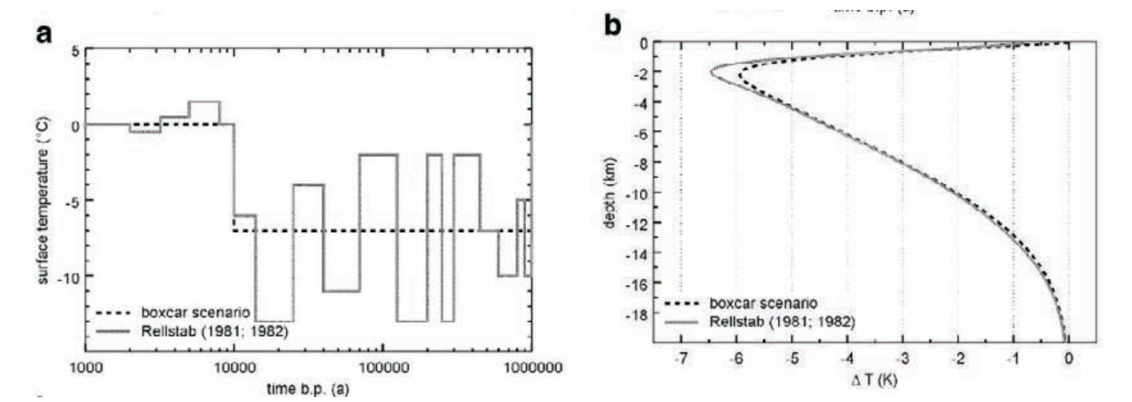

Figure 2. Palaeoclimatic signal calculated from two palaeoclimatic models for the central Alps (Vosteen et al., 2005).

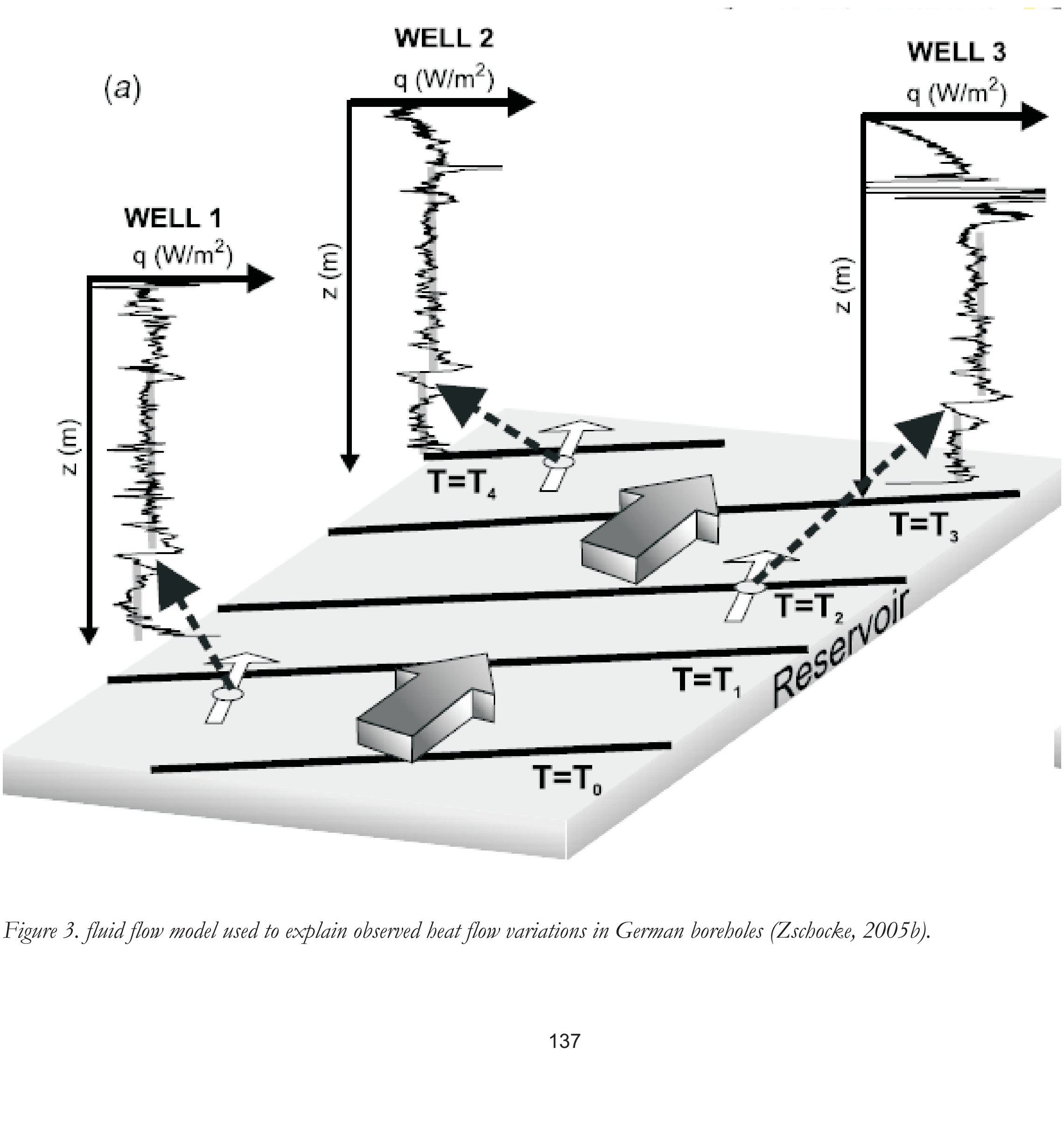

Figure 3. fluid flow model used to explain observed heat flow variations in German boreholes (Zschocke, 2005b).

Tauern Window of the Central Alps has been modelled by Vosteen et al. (2006; Figure 2). The results of a 1D finite difference model, where surface temperatures were 7°C cooler between 10,000 and 1,000,000 years B.P., indicated a maximum perturbation of the steady-state geotherm at 2,000 m depth. The perturbation diminished downwards and could be effectively neglected at 20 km depth. This result implies that temperatures that are uncorrected with respect to variations in paleoclimate may significantly underestimate the steady-state geothermal gradient used for heat flow determinations and temperature extrapolations.

Heat advection

Heat advection due to fluid flow within permeable rocks can also cause significant excursions in the temperature profile and geothermal gradient measured in boreholes. The effect of fluid flow on the steady-state geotherm can be analysed with respect to the Péclet number (the ratio of conductive heat transfer). For large Péclet numbers there is a large positive increase in the observed temperature profile (Zschocke, 2005b). Variations in calculated down-hole heat flow density have been interpreted by several authors as evidence of fluid flow (e.g. Zschocke et al., 2005b; Mottaghy, 2005). For example, Zschocke et al. (2005b) correlated vertical heat flow anomalies across a series for three wells from the Alpine Molasse Basin to estimate the rates of fluid flow within a sub-horizontal aquifer (Figure 3). Variation in down-hole heat flow density had a consistent signature between three wells and could be related to a known dipping aquifer. The thermal conductivity of the sediments was known from laboratory analysis. This allowed the authors to determine that the heat flow perturbation was too large to be due to changes in the thermal conductivity alone and advection of heat was a likely source of the anomalously low values at depth (Zschocke et al., 2005b).

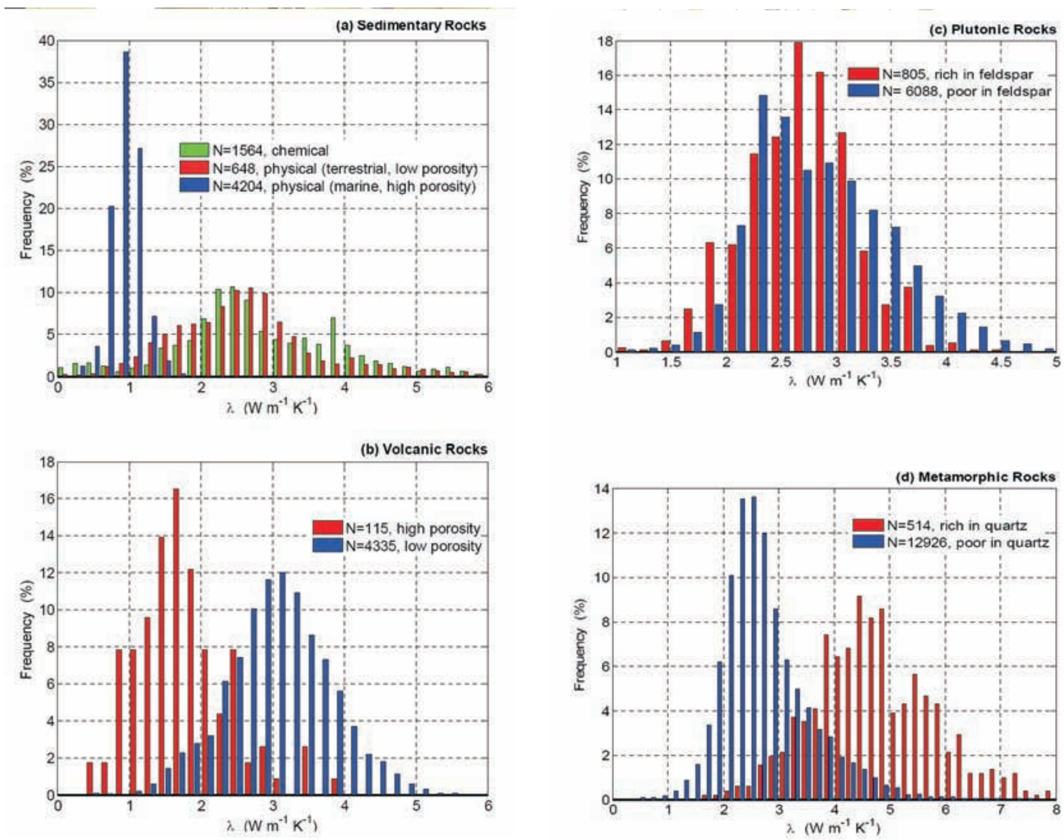

Figure 4. Frequency histograms of thermal conductivity values for various rock types (Data from Hartmann cited in Clauser, 2006).

Time Series Temperature Measurement

Multi-sensor thermistor arrays (e.g. the Seistronix TL-300 Borehole Temperature Logger) can be used to instantaneously measure the down hole temperature over a useful depth range (e.g. 200 m). Measurements can be made periodically permitting time series analysis of temperature variations. Thermal diffusivity, thermal conductivity, the effect of advection and palaeotemperatures can all be modelled by analysing the rates of change of the temperature field following a thermal perturbation (e.g. circulation during drilling; Zschocke, 2005a).

THERMAL CONDUCTIVITY

A detailed review of the thermal conductivity of rocks and minerals can be found in Clauser and Huenges (1995) and more recently in Clauser (2006). Figure 4 shows measured thermal conductivities for a range of rock types.

Wireline proxies

Cores are usually taken to provide laboratory thermal conductivity samples. However, coring is expensive (approximately 30 % to 50 % of drilling cost). Rock cuttings are cheaper to procure and may be used to determine matrix thermal conductivity and then corrected if rock porosity data are available (Clauser, 2006 and references therein). Due to drilling processes (e.g. abrasion during drilling and transport) it is common for particular lithologies (e.g. mudstones, coals, and shales) to be poorly represented in recovered core and cuttings (Williams and Anderson, 1990). Furthermore, there is often significant uncertainty as the exact depth of sampled drill cuttings due to lag times of the circulating drill mud. In such situations, wireline measurements (where available) may provide the best source of lithological and down-hole ambient data.

Several empirical methods have been suggested that use petrophysical wire line proxies to estimate thermal conductivity. Most methods use some combination of sonic, gamma, bulk density, and neutron density and use multi-component mixing laws to determine the thermal conductivity models (comprehensively discussed in Hartmann et al., 2005 and Clauser, 2006). Many of these methods have shown good correlation with laboratory measured thermal conductivity values for similar geological samples; however, due to the empirical derivation of these studies no method has yet been developed that is applicable to global datasets (Clauser, 2006).

Artificial Neural Networks

Goutorbe et al. (2006) developed a protocol for using neural networks to predict thermal conductivities from wireline logs. The authors compared their neural network protocol to a conventional mixing law proxy (described in Hartmann et al., 2005) and found that they achieved better correlation for ODP site863B. They quoted an accuracy of around 15 % which is comparable to other empirical methods (Clauser, 2006). The authors argued that their neural network method is more robust and objective than conventional mixing law calculations and should be applicable to a diverse range of geological materials (Goutorbe et al., 2006).

Optical scanning technology

Optical scanning of rock slabs and core is a novel, non-destructive method for determining the thermal conductivity (and thermal diffusivity) of geological samples (Popov et al., 1999a and 1999b). The method uses a constant laser heat source combined with two infra-red sensors (one in series and one parallel to the source) that track at uniform speed along the desired sample profile (Figure 5). This versatile method can be applied to the three dimensional study of sample anisotropy. The results of optical scanning show good correlation with both line-source and divided

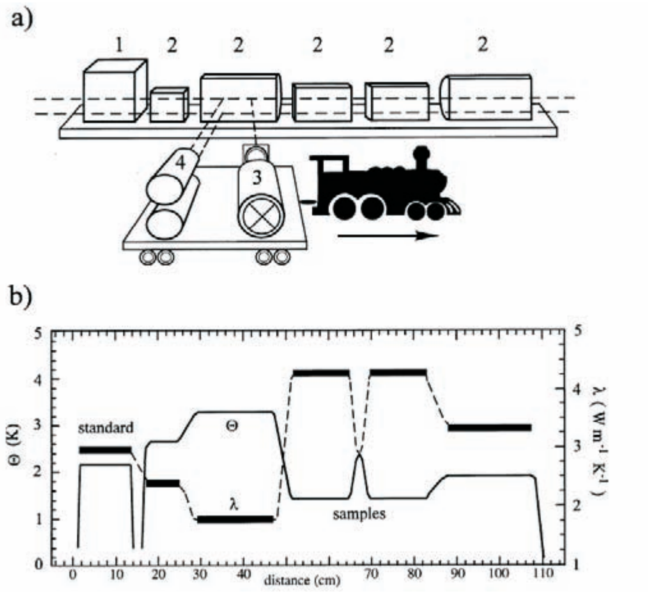

Figure 5. Analytical setup for optical scanning analysis of various samples (Popov et al., 1999a).

bar thermal conductivity determinations (Popov et al., 1999a). Yuri Popov is currently working on a device that will reliably measure smaller samples and possibly cuttings (*pers. comm.*).

Thin section analysis

Analyses of cores and crushed samples from the 4 km deep KTB hole (Germany) by Pribnow and Umsonst (1993) indicated strong links between thermal conductivity, mineralogy and fabric development. These authors found that in metamorphic rocks quartz had an overriding control on the magnitude of thermal conductivity while sheet silicates were largely responsible for measured anisotropy. Previous work on thin section determination of thermal conductivity is reviewed in Drury and Jessop (1983). They found models that used aggregate values derived from known mineral thermal conductivities yielded results that were within ±15 % of laboratory-measured values. The results of Pribnow and Umsonst (1993) and Drury and Jessop (1983; and authors discussed therein) allow the possibility that mineral volume data combined with porosity data and fabric analysis of samples (via thin section analysis) may be used to make estimates of the thermal conductivity of core (and possibly cuttings) from exploration drill holes.

In-Situ Thermal Response Testing

In-situ thermal response testing is used to characterise the averaged thermal properties of boreholes. A fluid of known elevated temperature is pumped through a coupled u-tube heat exchanger that is inserted into the entire length of the bore hole (Mattsson, 2007). The temperature of the outgoing fluid is then measured as is the amount of heat required to maintain the injection temperature. These tests yield an average value of thermal conductivity along the entire length of the hole. Thermal response testing has been developed to service the needs of the direct use geothermal industry (Mattsson, 2007), but the technology could easily be scaled up for use in EGS exploration.

Portable Divide Bar Apparatus

A drawback of convention steady-state thermal conductivity measurement has been that the equipment required has been too heavy and power intensive to be used in the field. A new highly portable divided bar apparatus has been developed by Hot Dry Rocks Pty Ltd for use in the field

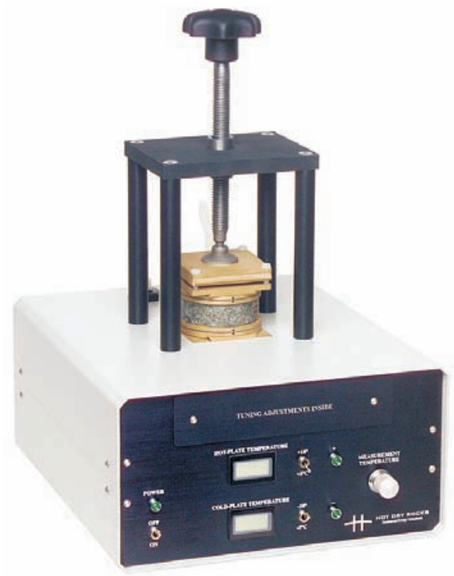

Figure 6. Portable divided bar apparatus from Hot Dry Rocks Pty Ltd.

(Figure 6). This device has the advantage that the samples can be analysed for thermal conductivity at the drill site shortly after sampling, so long as some basic core preparation facilities are at hand. Field measurement of this kind could potentially reduce the magnitude of errors which may occur as a result of dehydration (and rehydration) of the sample (as is common practice for laboratory analysis).

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Habanero Circulation Test – Connection Between Two Wells in Granite at 4,200 m Depth

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ABSTRACT

Geodynamics carried out open loop (venting to atmosphere) flow testing between its two geothermal wells Habanero 1 and 3 in March and April 2008. The wells are located in basement granites beneath the Cooper Basin in NE South Australia and are 550 m apart. The temperature in the reservoir which is mostly contained in what is known as the main fracture zone is 245-250°C. The testing was designed (i) to demonstrate communication between the wells along the fracture zone which was stimulated from Habanero 1 in 2003 and 2005 and (ii) to determine the impedance or friction loss associated with circulation between these wells. The impedance would govern the pumping requirement for closed loop operation which in turn dictated the operability of the pump that had been purchased for this phase. If the impedance was too high the pump would not be suitable and a number of remediations would need to be effected.

During the drilling of Habanero 3 the intersection of the main fracture zone was clearly indicated by a sudden increase in flow rate (influx) through the flow line choke, and the fracture pressure was estimated at 76.4 MPa (11,080 psi). By analyzing the response it was calculated that the productivity of the fracture zone was approximately 2.7 l/sec/MPa draw-down. The influx resulted in a small pressure decline in the Habanero 1 wellhead pressure indicating that the influx was from the reservoir connected to Habanero 1. This response was required before the well could be declared as achieving its target.

Open loop circulation testing

The testing can be divided into a number of phases as shown in the Table below:

Operation	Date	Comment
Flow testing from Habanero 3 with Habanero 1 shut-in	14 to 21 March	A stable flow of 16 kg/sec at a flowing pressure of 27 MPa was achieved with a 14mm fixed choke. Wellhead temperature reached 209°C
Main circulation	22 to 25 March	Injection 18.5 kg/sec at 51.7 MPa (7,500 psi), production of 20 kg/sec at 27.5 MPa, an increase of 4 kg/sec over the earlier test with Habanero 1 shut-in. Temperature reached 212°C
HDC injection	26 March	Slow injection of HDC barite dissolving agent in Habanero 1 to increase injectivity
Post HDC injection	26 March	Injection at 18.5 kg/sec at 50.3 MPa (7,300 psi), an improvement of 1.4 MPa. Expect further improvements with longer injection during closed loop operation.
Stimulation of Habanero 3	18-19 April	Injection of 2,173m3 of water at injection pressures up to 64 MPa, resulting in 276 microseismic events close to Habanero 3. Expected increase in productivity

Based on the testing the circulating impedance at a flow rate of about 12 kg/second will be in the vicinity of 10 MPa. This rate is expected to be high enough to operate the 1 megawatt pilot power station and re-injection pump both of which have already been purchased. Consequently, in early April 2008, the company commenced construction of a high pressure pipeline between the two wells to connect in the equipment for long term closed loop operation.

Further testing in the closed loop will be reported with operations expected to commence in early June including the introduction of chemical tracers.

Towards High Performance Simulation of Geothermal Reservoir Systems

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ABSTRACT

Australia has a unique Hot Fractured Rock (HFR) geothermal resource that could potentially provide enough green energy to meet all its energy needs. Geodynamics Limited, an Australian company that is leading the nation in developing HFR geothermal energy, is presently conducting Australia's first HFR field test. Supported by an ARC linkage grant, a novel supercomputer simulation tool is being developed with collaboration of Geodynamics Limited for simulating the highly coupled geomechanical fluid-flow thermal systems involving heterogeneously fractured geomaterials. It addresses the key scientific and technological challenge in developing HFR energy. Namely, it is targeting a new predictive modelling capacity with the potential to yield breakthroughs in understanding how to enhance the flow of water through the geothermal field and how to sustain it over decades such that the trapped heat energy can be extracted.

PANDAS - Parallel Adaptive static/dynamic Nonlinear Deformation Analysis System - is a finite element based software being developed for simulating the geothermal reservoir system. It is built on the long term and ongoing efforts on the software infrastructure construction for the ACcESS Major National Research Facility previously (http://www.access.edu.au) and the AuScope (http://www.auscope.org.au) currently in simulation of crustal dynamics at ESSCC led by the first author. Currently, PANDAS includes the following five key components: PANDAS/Pre, ESyS_Crustal, PANDAS/Thermo, PANDAS/Fluid and PANDAS/Post as detailed in the following:

- PANDAS/Pre is developed to visualise the microseismicity events recorded during the hydraulic stimulation process to further evaluate the fracture location and evolution and geological setting of a certain reservoir, and then generate the mesh by it and/or other commercial graphics software (such as Patran) for the further finite element analysis of various cases; The Delaunay algorithm is applied as a suitable method for mesh generation using such a point set;
- ESyS_Crustal is a finite element method based module developed for the interacting fault system simulation, which employs the adaptive static/dynamic algorithm to simulate the dynamics and evolution of interacting fault systems and processes that are relevant on short to mediate time scales in which several dynamic phenomena related with stick-slip instability along the faults need to be taken into account, i.e. (a). slow quasi-static stress accumulation, (b) rapid dynamic rupture, (c) wave propagation and (d) corresponding stress redistribution due to the energy release along the multiple fault boundaries; those are needed to better describe ruputure/microseimicity/earthquake related phenomena with applications in earthquake forecasting, reservoir engineering, hazard quantification, exploration, and environmental problems. It has been verified with various available results (e.g. see Xing 2006a and references thereafter);
- PANDAS/Thermo is a finite element method based module for the thermal analysis of the metals and the fractured porous media; the temperature distribution is calculated from the heat transfer

induced by the thermal boundary conditions without/with the coupled fluid flow effects in the fractured porous media and the geomechanical energy conversion for the individual/coupled thermal analysis;

- PANDAS/Fluid is a finite element method based module for simulating the fluid flow in the fractured porous media; the fluid flow velocity and pressure are calculated from energy equilibrium equations without/with the coupling effects of the thermal and solid rock deformation for the individual/coupled fluid flow analysis; and
- PANDAS/Post is to visualise the simulation results through the integration of VTK and/or Patran.

All the above modules can be used independently or together to simulate individual or coupled phenomena (such as interacting fault system dynamics, heat flow and fluid flow) without/with coupling effects. PANDAS has been applied to the following issues related with geothermal reservoir systems:

- visualisation of the microseismic events, such as that recorded during the hydraulic stimulation process of Harbanero #1 in the Cooper Basin by Geodynamics Limited, to monitor and determine where/how the underground rupture proceeds during a hydraulic stimulation, to generate the mesh using the recorded data for determining the domain of the ruptured zone and to evaluate the material parameters (i.e. the permeability) for further numerical analysis;
- interacting fault system simulation to determine the relevant complicated dynamic rupture process for both the intraplate and interplate fault systems, such as to simulate the stress/velocity variations of the Southern California (CA) and Southern Australian (SA) fault systems over a long period of time in discrete models with 500,000 nodes constructed using the practical fault data (Xing et al., 2006b and 2007), and to calculate the stress evolution and dynamic rupture process along the faults within a fracture dominated gas reservoir and their potential effects on the fluid flow. This is the first effort in the world to successfully simulate such realistic and complex interacting fault systems using finite-elements efficiently and stably (without any convergence problems);
- geomechanical fluid-flow coupling analysis to investigate the interactions between fluid flow and deformation in the fractured porous media under different loading conditions. A new finite element based numerical modeling of the deformation and fluid flow through fractured porous media is proposed with the special attention to the FEM mesh generation of the fractured media. Based on the available rock image data, the rock structure information including interfaces/fracture boundaries can be extracted through the converted image data and further applied to mesh generation and material permeability calculation. The numerical tests demonstrated the efficiency and usefulness of the proposed algorithm; and
- thermo-fluid flow coupling analysis of a geothermal reservoir system. A geothermal reservoir model in the Cooper Basin has been analysed to determine how to sustain it over decades through the sensitivity analysis of the effects of permeability. In addition, the finite element based numerical solution has also been verified through the comparison with the analytical results (Xu et al., 2007; Xing 2008).

PANDAS will be further developed for a multiscale simulation of multiphase dynamic behaviour for a certain geothermal reservoir system. More details and additional application examples will be given during the presentation.

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Carbon Dioxide Thermosiphon Optimisation

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Geothermal power has the potential to become a major baseline power source (Tester et al. 2006). Large-scale generation requires the use of Engineered Geothermal Systems (EGS). The standard engineering assumption would be to use water as a heat extraction fluid, however water may not provide the optimum economics. Carbon dioxide is the only cheap, abundant alternative with favourable properties. The characteristics making CO_2 a potential competitor are (Brown, 2000; Pruess, 2006; Gurgenci et al., 2008):

- Abundance
  - as geothermal reservoir flow can involve significant losses of geofluid, a large source of fluid is needed.
- Sequestration potential
  - there are economic benefits involved in loss of CO_2 into the reservoir (providing it is appropriately sealed) through carbon credit schemes.
- No process scaling (deposition of low-solubility minerals on surfaces) issues
  - as CO_2 is a non-polar fluid with low solubility of ionic compounds, a geothermal plant utilising CO_2 will not have the issues with scaling in process equipment often encountered in traditional hydrothermal power generation.
- Buoyancy drive
  - a CO_2-based system would have high-density fluid in the injection well and low-density fluid in the production well, providing additional impetus for flow through the reservoir and decreasing pumping requirements.
- Suitable thermodynamic & transport characteristics
  - while the heat capacity and density of CO_2 are lower than water, the viscosity is also lower, allowing similar flows of thermal energy when utilising CO_2.

The interaction of CO_2 with the reservoir is investigated in a separate project by the Queensland Geothermal Research Centre.

PROJECT AIMS

A PhD project has been commenced to examine the usage of CO_2 in a geothermal power plant design, particularly from an economic point of view. The main goals of the project are to:

- Examine the merits of CO_2, and conduct comparative analysis between CO_2- and H_2O-based power plant designs;
- Identify efficient designs and appropriate modifications for CO_2-based geothermal power plants;
- Construct a model for the economic optimisation of CO_2-based geothermal plant designs; and
- Utilise model to examine the impacts of key parameters (such as process pressures, heat exchanger sizes, well spacing and depth), and how they can be optimised for site constraints.

CURRENT PROGRESS

Current work has been focussed on a thermodynamic study comparing a number of basic plant designs. The purpose of this comparative study is not to give definitive analytical results but to validate CO_2-based designs as viable alternatives to H_2O, and indicate appropriate directions of further research. The plant designs examined are:

- CO_2 thermosiphon;
- Binary water/isopentane;
- Binary water/CO_2;
- Binary CO_2/isopentane; and
- Air thermosiphon.

The additional binary alternatives are used to examine the benefits gained from utilising CO_2 in different parts of the plant. Air is included as a comparative indicator of how the non-ideal gas properties of CO_2 make a significant difference to design viability.

Plant Design and Model Setup

The design of the plants for comparative analysis differs as required for the different styles of plant (as shown in Figure 1). All plants include an injection wellbore, a reservoir model, a production wellbore, a turbine, and condenser. The plants utilising water as a heat extraction fluid include a water pump, and binary plants include an additional heat exchanger and working fluid pump/compressor.

The plants have been modelled using MATLAB, utilising Helmholtz free energy-based equations of state (IAPWS, 1996; IAPWS, 2007; Lemmon and Span, 2006; Lemmon et al., 2000; Span and Wagner, 1996). Most components in the system have been considered ideal – compression, expansion, and wellbore flows have been considered isentropic. Heat exchange operations have been considered as isobaric processes, except in the case of the reservoir. The reservoir has been modelled as a single channel of Darcy flow, with linear temperature increase with distance between

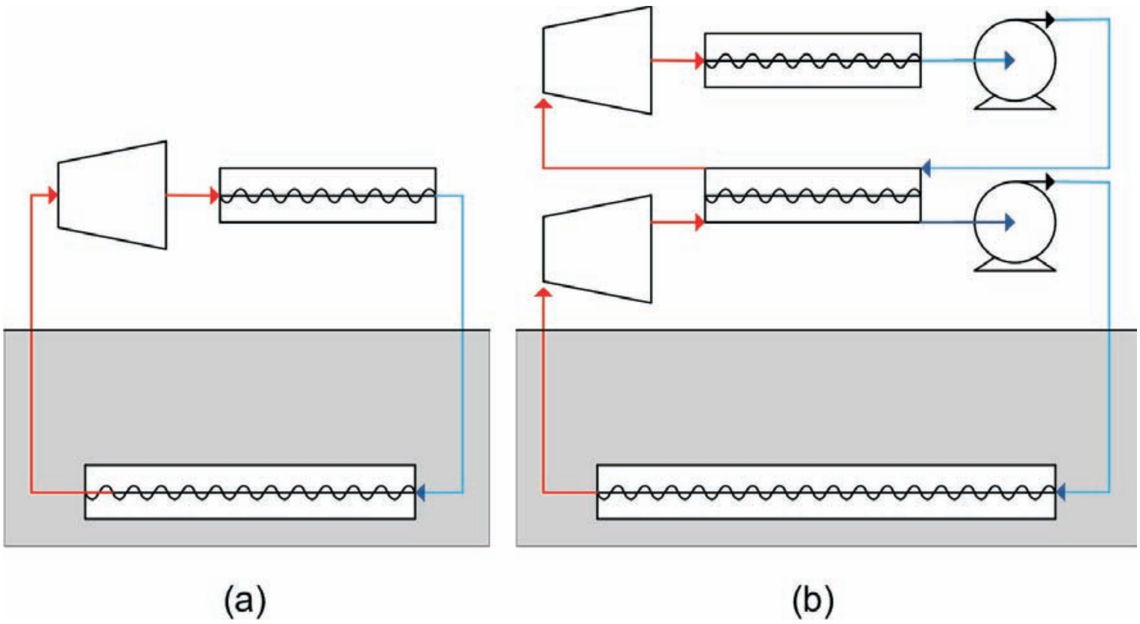

Figure 1. Geothermal (a) thermosiphon plant design, and (b) H_2O-based binary plant design.

injection and production wells. Preliminary calculations indicate that the buoyancy of CO_2 results in a net gain of ~12MPa through the subsurface section of the design. The effect of this on the viability of the power generation system is being examined. Examination of transport properties of CO_2 indicates that the average ratio of viscosity to density (the critical factor for reservoir pressure drop) is about 1/3 of that of water.

FUTURE DIRECTION

Planned directions of additional future research include both assessment of a range of design modifications, and design of an economically optimised plant.

Plant Design Alternatives

There are a number of interesting options that may be explored for increased thermodynamic and economic optimisation of the process, such as:

- Thermosiphon design vs. compressor usage
  - Higher cycle pressures generally increase power generation efficiency, with the drawback of increased equipment cost.
- Intermediate heat exchange transfer fluid
  - Removal of the significant amounts of waste heat from geothermal plants is a significant obstacle. If a CO_2 thermosiphon design is used coupled with air cooling (as is likely the case in arid climates), there is an opportunity to examine using an intermediate heat exchange fluid flowing in a cycle between different pressures to remove the need for very thick heat exchanger piping (due to the high pressures of CO_2 used).
- Solar heating
  - As Australian sites with large geothermal temperature gradients generally also have a high influx of solar radiation, there is the potential to include solar heating in the power plant design for improved efficiency, in a role of superheating or reheating.

Design alternatives such as these require cost-benefit analysis to assess their suitability for inclusion in a power plant design.

Plant Optimisation

The eventual goal is a system for optimising a design for maximising economic benefit. There are a number of key system parameters that must be selected, based on the constraints of the plant location. The purpose of plant optimisation should not only be to determine the parameters for an economic maximum, but also examine how the constraints affect both the economics of the design, and the way in which the parameters must be changed in response.

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Preliminary Assessment of the Effect of Ambient Temperature on the Performance of Air-Cooled Geothermal Power Plants at a Typical Site in South Australia

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ABSTRACT

The paper aims to undertake a relative comparison of the performance and mechanical systems required to extract power from a geothermal site under typical conditions that are expected to apply in South Australia. A distinguishing feature of this assessment is the combination of high day-time ambient temperatures, the use of an air-cooled system due to the assumed requirement to reinject all of the geothermal liquid, and the lack of any alternative water source from which to facilitate a cooling tower. The investigation considers a site at which the geoliquid reaches the surface at a temperature of 210 °C, and the effect of variations in ambient temperature from 15 - 45 °C. A single stage flash cycle, an Organic Rankine Cycle (ORC) and Kalina cycle are chosen for this preliminary assessment, since the trends are likely to apply for more advanced cycles, although with lower absolute performance.

The calculations are performed using standard analytical approaches. It is assumed that the geo-liquid is maintained at sufficient pressure to be in a liquid state throughout the pipes and aquifer, and that there is no leakage. Hence, a leakage of 5 - 10 %, which is often assumed for such systems, would increase parasitic pumping requirements by the square of the additional flow-rate. It is also assumed that no non-condensable gases (NCG's) are present, which represents a best-case scenario. The isentropic efficiency of the turbine was calculated based on the vapour quality. The ORC is calculated assuming Pentane as the working fluid, and only basic optimisation is performed for the Kalina cycle, so the calculations will somewhat under-predict what is possible for this cycle.

The low thermal efficiency of geothermal systems makes the condenser a highly capital intensive item. Hence a detailed model of an air-cooled condenser was developed. The ambient air has been assumed to be completely dry (0 % humidity) and no fouling factors have been included for the condenser. The design procedure was based on established procedures. The Overall Heat Transfer Coefficient (OHTC), fan power and the Log-Mean Temperature Difference (LMTD) between the cooling air and the condensate are not independent variables. A sensitivity study was used to determine that a LMTD of around 15 to 20 °C degrees is the most suitable. At smaller LMTD's the condenser size required increases dramatically. Similarly, the cooling air temperature rise that is most suitable is 19-25 °C. The combination of these two variables gives a moderate approach velocity of 4-5 m/s, high enough for a good OHTC and low enough so that the pressure drop (and hence fan power) are moderate (less than 10 % of the net power generated before re-injection). The resulting size of air coolers is large, with a typical size calculated to be 10 m tall x 8.48 m long x 0.182 m thick per MW for the pentane ORC.

Figure 1 presents the effect on subnet power (before pumping losses), of variations in ambient temperature. It is evident that increasing the ambient temperature from 15 to 45 °C is calculated to

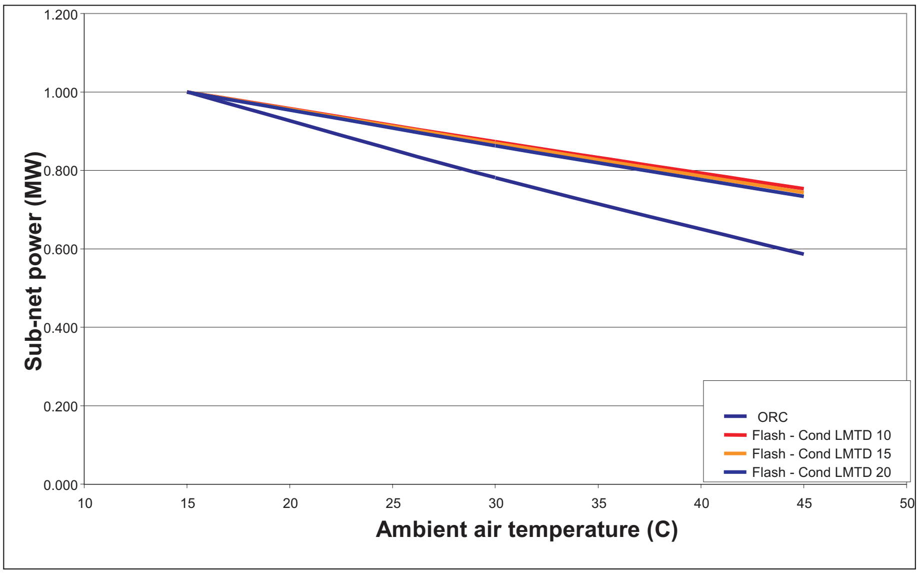

Figure 1. The relative sub-net power production of the ORC and flash systems as a function of the ambient air temperature.

cause a drop in output of subnet power of 30% for the flash cycle, and 40% for the pentane ORC. This is particularly significant because it causes a significant mis-match between the output power and the demand cycle, with peak demand typically being well correlated with peak ambient temperature.

The investigation also assessed the impact of pumping power as a parasitic loss. Figure 2 compares the influence on sub-net power of the reinjection pressure needed to over-come net pumping losses (i.e. after the thermo-syphon has been accounted for) through pipes and reservoir. These calculations all assume that the geothermal liquid reaches the surface at approximately ambient pressure and that the ambient temperature is 15 °C. It is evident that there are slight differences between the three cycles, and that losses become significant. For example, pumping losses of 10 MPa results in a reduction in net power of about 25 % for all cycles. The paper will also compare

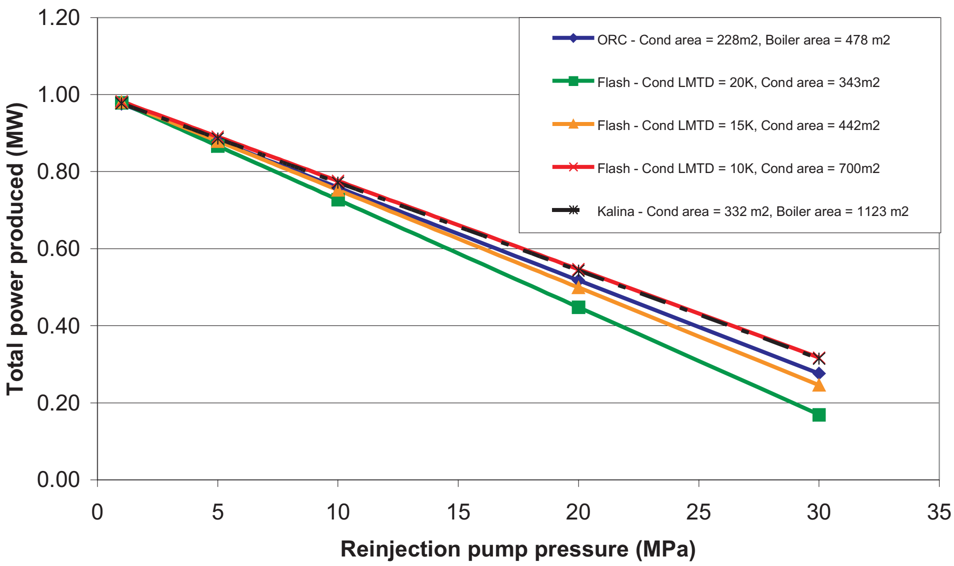

Figure 2. The effect of net re-injection pump pressure required to overcome parasitic pumping losses on all three cycles, based on an ambient temperature of 15 °C.

the sizes of key components for the three cycles, discuss key differences between them, and comment on the role of NCG's.

Improving the Performance of Geothermal Heat Pumps through Borehole Grout Materials

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ABSTRACT

The performance of Geothermal Heat Pump (GHP) systems depends on the efficiency of the heat transfer process in the ground heat exchangers. Much of the interest by the geothermal industry has focused on how to reduce the cost and increase the efficiency of GHPs. A critical issue that needed to be addressed in response to such interest is the material used to fill the boreholes in vertical loop systems. The boreholes in GHP installations were traditionally filled with bentonite grout. Such grout is a relatively poor thermal conductor and also prone to severe cracking and shrinkage under drying conditions. Water table fluctuation has an adverse effect on the ability of the ground heat exchanger to perform its function in boreholes filled with such materials. Long-term effects with shrinking grouts can be assessed by considering that the heat exchanger loop within the borehole has a reduced contact with the surrounding formation. An improved cement-sand grout material (Mix 111) was developed in the laboratory to address shortcomings in conventional grouts and subsequently was subjected to field validation tests in different geologic environments. This paper describes the grout properties, field performance and commercial use.

Enhancing Material Behaviour

Much of the research performed concentrated on how to increase the thermal conductivity of the grouts used to backfill the heat exchanger loops in the boreholes. Thermal conductivities up to three times higher than bentonite and neat cement grouts were achieved through appropriate selection of grout ingredients and mix design. The developed grout consists of cement, water, silica sand and small amounts of superplasticiser and bentonite. The mix proportions are given in Table 1. Its behaviour was investigated by a series of rigorous laboratory tests including: thermal conductivity, permeability, shrinkage, coefficient of thermal expansion, bond strength, sulfate resistance, durability under wet-dry cycling, compressive strength, splitting tensile strength, flexural strength, elastic modulus and Poisson's ratio, thermal resistance, ultrasonic pulse velocity, freeze-thaw durability and infiltration rate. Graphical comparison of Mix 111 cement-sand grout thermal conductivity with other grouts of interest is presented in Figure 1. This shows the significant increase in thermal conductivity achieved when silica sand filler is incorporated in grout and the retention of conductivity under drying conditions. Table 2 presents a summary of properties for the developed grout. Further details of the grout development and properties are given in Allan (1997), Allan and Philippacopoulos (1998; 1999) and Allan (2000). The impact of grout thermal conductivity on required bore length is discussed in Allan and Kavanaugh (1999) and Kavanaugh and Allan (1999).

Material	Proportion
Cement (kg/m^3)	587.7
Water (l/m^3)	323.3
Sand (kg/m^3)	1251.8
Bentonite (kg/m^3)	6.5
Superplasticiser (l/m^3)	8.8

Table 1. Mix Proportions of Superplasticised Cement-Sand Grout (Mix 111).

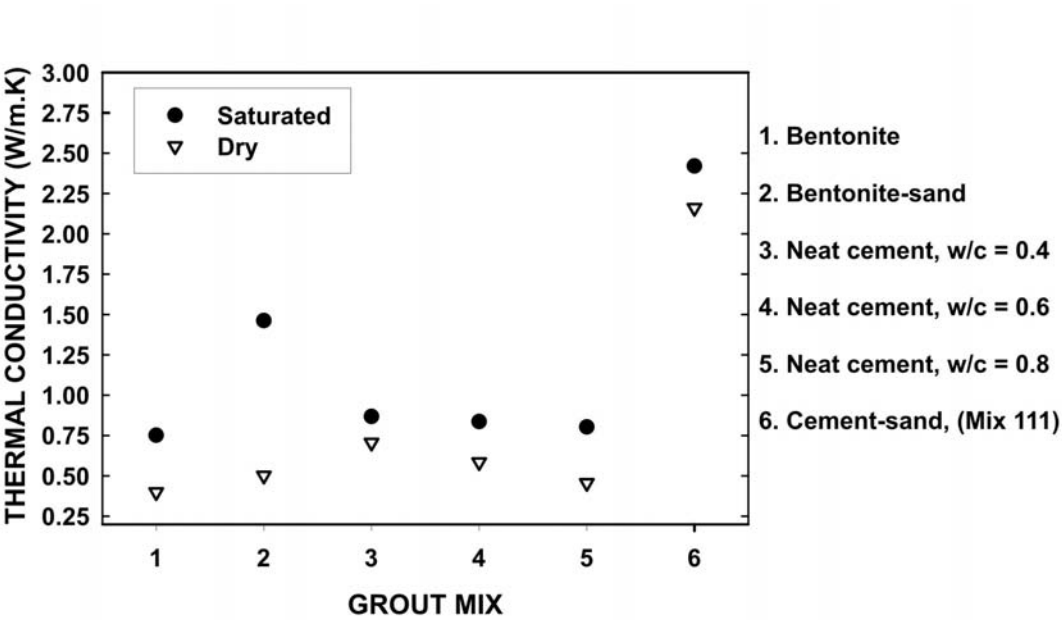

Figure 1. Thermal Conductivities of Superplasticised Cement-Sand Grouts (Mix 111), Neat Cement Grouts with Water/Cement Ratios (w/c) of 0.4-0.8 and Bentonite Grouts.

Thermal Conductivity, Saturated (W/mK)	2.42
Thermal Conductivity, Dried (W/mK)	2.16
Coefficient of Permeability (cm/s)	1.6×10^{-10}
28 Day Compressive Strength (MPa)	36.7 ± 4.2
28 Day Splitting Tensile Strength (MPa)	6.01 ± 0.48
Static Elastic Modulus (GPa)	13.8 ± 0.9
Poisson's Ratio	0.21 ± 0.02
Bond Strength to HDPE (kPa)	150 ± 20.5
Specific Gravity	2.18

Table 2. Summary of Properties for Superplasticised Cement-Sand Grout (Mix 111).

Numerical Studies

Phenomenological analysis reveals that the stress regime in ground heat exchangers is complex. This was confirmed by numerical modeling which demonstrated the presence of tensile stresses in the grouted borehole. Grouts are required to withstand such stresses without cracking which reduces the heat transfer between the exchanger loops and surrounding media. The developed cement-sand grout has high stress capacities which were demonstrated in laboratory as well as in field tests. The heat transfer in vertical heat exchanger loops was evaluated using finite element analysis. The models incorporated sections of vertical ground closed loops of typical GHP configurations and material properties from laboratory tests.

The thermal conductivities of the pipes, grout and surrounding formation were: 0.40, 2.42 and 1.73 W/m.K, respectively. The entering (EWT) and leaving water temperatures (LWT) were: EWT=5 °C and LWT=2 °C for the heating mode. The corresponding values for the cooling mode were: EWT=30 °C and LWT=36 °C. These values were taken as worst case averages considering their variation with depth. Additional boundary conditions were imposed for the thermal stress analysis models so that they are adequately constrained. Thermoelastic properties considered for each of the materials were: a) HDPE pipe: E=1.4 GPa, ν=0.45, α=2.16x10^{-4} m/m°C; b) grout: E=13.8 GPa, ν=0.21, α=1.65x10^{-5} m/m°C; and c) formation: E=2.0 to 5.5 GPa, ν=0.33, α=1.65x10^{-5} m/m°C (E=elastic modulus, ν=Poisson's ratio and α=coefficient of thermal expansion). The results were obtained with the ANSYS code.

The steady state temperature distributions for heating and cooling modes are shown in Figure 2. Since the response inside the borehole is of primary interest, only results within the borehole are

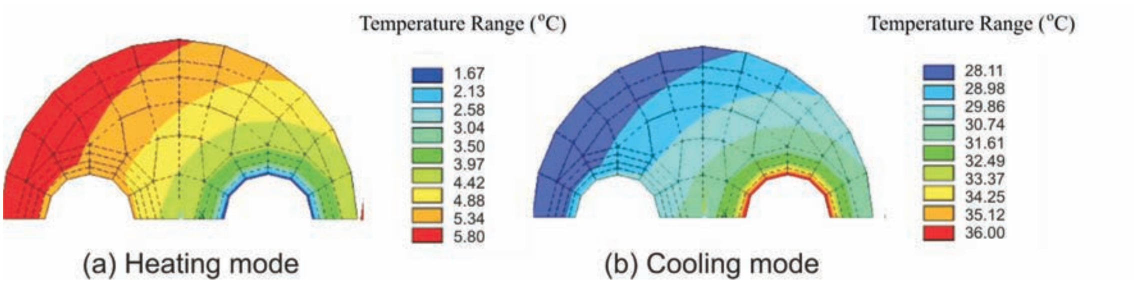

Figure 2. Temperature Distribution in Grouted Borehole.

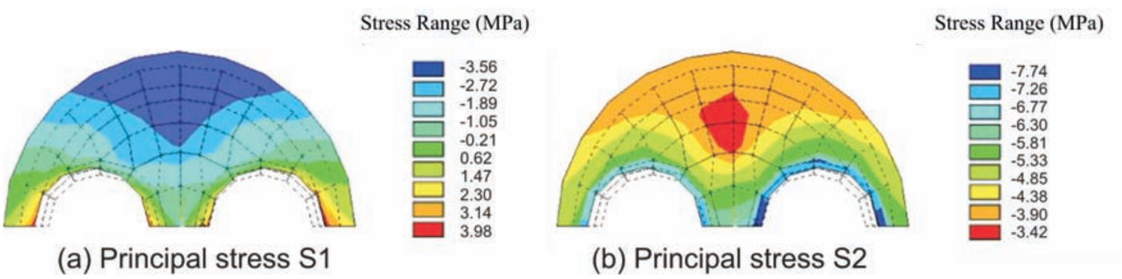

Figure 3. Thermal Stresses for Cooling Mode of Operation.

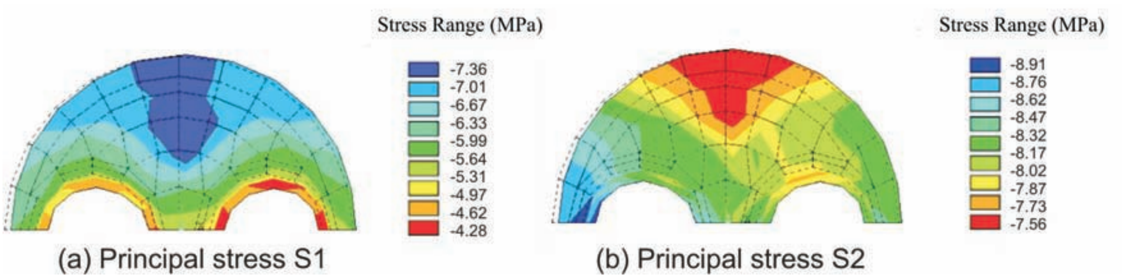

Figure 4. Thermal Stresses for Heating Mode of Operation.

displayed. Similarly, thermal stresses for the cooling and heating mode of operations are shown in Figures 3 and 4, respectively. Comparison of Figures 3 and 4 with Figure 2 leads to the conclusion that the stress fields are consistent with those of the temperature. Stresses are especially higher in the grout near the axis of symmetry in the exterior area. The modelling results show that the stresses are predominantly compressive for the conditions considered and that cracking of the grout due to thermal stresses is unlikely.

Field Verification Tests

The cement-sand grout was tested in the field and its performance was measured and compared to that of other grouts. Field tests were performed by Oklahoma State University and Sandia National Laboratories. The objective was to test the grout at different climates as well as geologic conditions. With completely instrumented boreholes, thermal resistance was recorded at different depths thus enabling monitoring of the heat transfer along the exchanger loop.

Tests were also performed at several boreholes filled with a variety of grouts including bentonite as well as thermally enhanced bentonites. Field data obtained from both tests clearly demonstrated that the developed grout had a decreased thermal resistance as compared to other grouts. Its resistance was 29 % and 35 % less compared with bentonite grouts for the two sites, respectively. Figures 5 and 6 depict the field test results. Further details are available in Allan and Philippacopoulos (1999).

Regulatory Approval and Field Use

The developed grout was successfully used to resolve environmental regulatory concerns in New Jersey. The New Jersey Department of Environmental Protection (NJDEP) had raised concerns

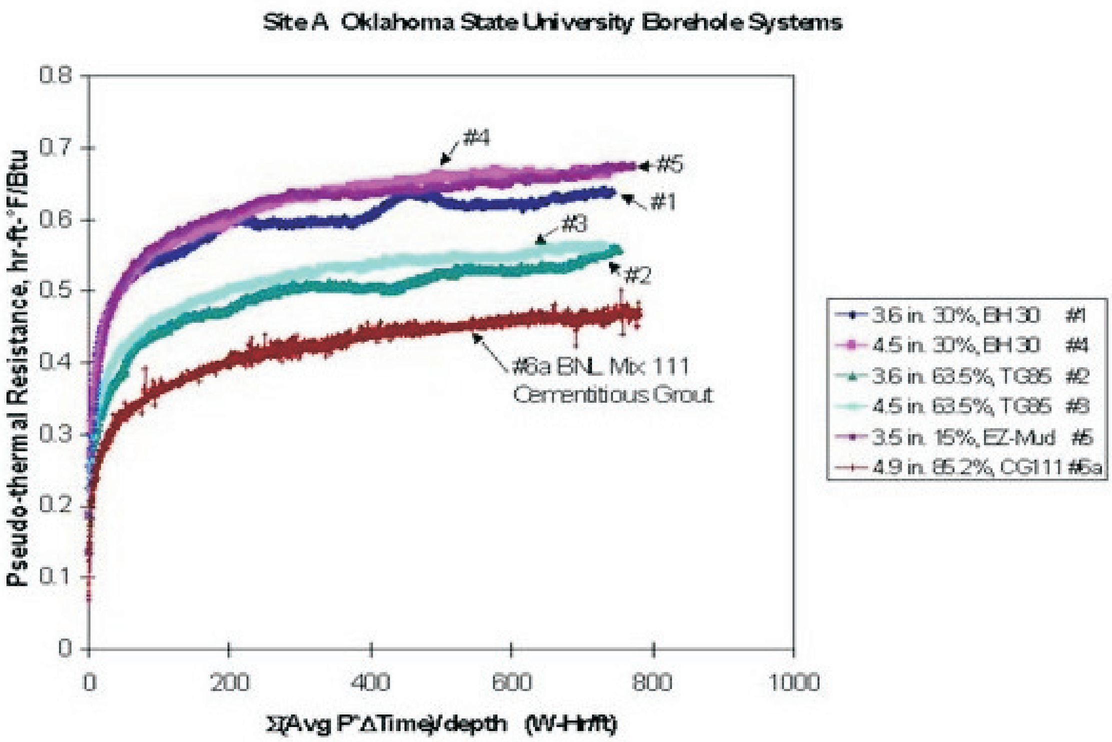

Figure 5. Results of Thermal Resistance Field Tests at Oklahoma State University.

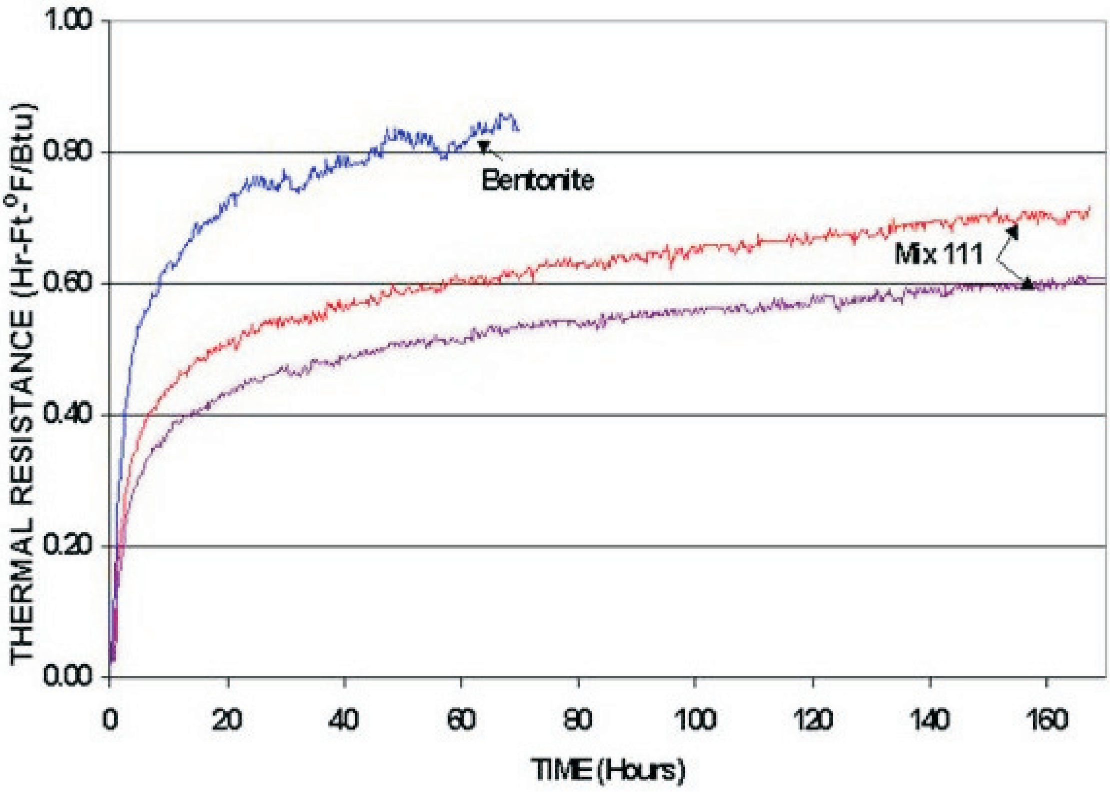

Figure 6. Thermal Resistance Field Test Results from Sandia National Laboratories.

regarding the questionable bond integrity between neat cement grout and U-loop and the possibility of aquifer contamination. The superior performance of the grout included characteristics such as: (a) reduced coefficient of permeability (b) lower infiltration rate (c) shrinkage resistance and (d) good bond strength to U-loop. Such characteristics convinced NJDEP that the environmental risk would be minimised by using Mix 111. Furthermore, numerical modelling by finite element analysis of the thermal stresses developed in the grouted borehole alleviated concerns of cracking induced by expansion of the U-loop. Based on such performance assessments, the grout was approved for use in both consolidated and unconsolidated formations. The State of New Jersey well permit conditions include specifications for mixing and pumping the grout and the grout is also approved by the Tennessee Department of Environment and Conservation for use with geothermal boreholes. The developed grout is currently used throughout the US and other countries. The properties of the grout make it suitable for use in Australian conditions. It has also been used successfully with Deep Well Direct Exchange (DWDX) systems that use copper rather than HDPE pipe by Earth to Air Systems LLC.

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Feasibility of Underground Cooling for Geothermal Power Plant Applications

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ABSTRACT

The efficiency of any thermal cycle depends on the temperature differential of the working fluid in the boiler and the condenser. As such, it depends not only on the temperatures of the geo-liquid, but also on the temperature of the condenser. Most of Australia's geothermal energy resources are found in arid or semi-arid regions where day-time ambient temperatures are high, and where limited access to water will almost certainly prevent the use of cooling towers. This leaves air cooling through large fin and tube heat exchangers (analogous to large automotive "radiators") as the only established alternative option for cooling. However, air cooling in the desert will lead to degraded performance when ambient temperatures are high. The extent of this degradation is illustrated by way of example, based on a flash cycle with a re-injection pressure for the geoliquid of 10MPa and a geo-liquid temperature of 210 °C. It is estimates that a change in ambient temperature from 15 °C to 45 °C, will reduce the output power of this cycle by 44 %, and that this percentage reduction increases with re-injection pressure (Langman et al., this volume). While the magnitude of this effect will depend on the type of cycle and local conditions, it will be significant for all geothermal cycles. Furthermore, the degradation will be most significant during the period of peak summer demand, at precisely the time when the price of electricity is greatest. As such, it could have a significant adverse impact on the commercial return of the plant. To address this problem it is proposed to undertake a preliminary assessment of the potential to use under-ground cooling for the plant.

The broad principles of utilising the thermally cool and stable layer of the soil for cooling are well known (DiPoppo , 2005; Hewit et al., 1994). Underground houses have been used for centuries in desert environments to maintain cool living, and this principal has been extended to provide underground cooling and heating in some modern buildings. This shallow geothermal energy exchange and storage capitalises on the large thermal mass of the soil to damp out temperature fluctuations, provide a semi-uniform thermal reservoir and provide a time lag to avoid the coincidence of peak temperature with peak electricity demand. While the potential to exploit this principle in the cooling of a condenser is therefore evident, some challenges can also be anticipated.

It is well established that below 2 m depth the temperature of the soil is almost constant during the day and changes slightly across the year (Sanner, 2001; Nowak and Satchel, 2005; Hillel, 1998). Both heat conduction and latent heat convection contribute to the transfer of heat in the soil. The thermal properties of the soil depend on its constituents and vary substantially with moisture content. At locations of interest in Australia the likelihood is that a well weathered sandy soil will exist for more than 10 m depth. A sandy soil has a thermal conductivity of 0.55 W/mK (dry) and 2.5 W/mK (wet), porosity of ~40% and thermal heat capacity of ~1.3E6 J/m^{3}K which varies with the compactness of the soil and its density. These characteristics point to a large potential for energy storage, albeit at a moderate transfer rate.

As most sites identified with high potential for geothermal energy have dry weather and hardly any rain the issue of water content need not be considered in a preliminary assessment. Although water drastically improves thermal conductivity it also can cause swelling of the soil (up to 100 times) and introduce substantial directional mechanical stresses. In addition water can enhance the reactivity of the soil and its salts which can cause slow degradation of the buried tubes and heat exchangers.

From the above it is clear that such an underground cooling system can be expected to involve a large network of pipes, and to require significant capital cost. It is also clear that there will be significant potential to reduce this cost by careful design and optimisation. Further, there is significant potential that they may be cost-competitive with air-cooled systems, considering both the capital cost of using fin and tube heat exchangers and the ongoing operational cost of large fans. However, at present, little information is available of the details of such a system, or of the soil and temperature fluctuations on which to base reasonable estimates of its potential. This work aims to address this need.

Although the thermal mass available for storage is large this method relies on temporary storage of the heat during the day for release during the night. The differential temperature during a typical summer day allows for the majority of the heat dissipated from the underground pipes to be released into the atmosphere during the night. Innovative night time cooling methods are being considered to enhance energy release.

A preliminary assessment of a single pipe buried 1m deep receiving liquid at 90 °C has been completed. The average daily temperature for January taken at outback South Australia was estimated to be similar to that at Oodnadatta Airport. At steady state operation it was found that the buried pipe loses 0.25 of the heat compared to a similar pipe in an air-cooled heat exchanger above ground. Considering that no fan power is required and that flexible pipes with moderate heat conduction characteristics can be used in this application, to reduce installation cost, substantial savings in the on-running cost can be achieved through the underground cooling system.

In this talk details of one and two dimensional analysis will be presented highlighting the feasibility of this concept when applied to areas in the outback. In addition a preliminary cost benefit assessment of this concept when compared to air cooling will be presented.

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A Comparative Study on Dry Cooling of Different Working Fluids for Geothermal Applications

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ABSTRACT

Air cooled heat exchangers have been designed, manufactured, and supplied worldwide for over forty years. Forced or inducted air draft are mainly used as the main coolant in chemical, petrochemical, oil and gas, process, and power generation industries. Scarcity of water in Australia is the main reason for such heat exchangers to replace the wet cooling counterparts albeit at lower efficiencies. In this study we have considered CO_2 and C_5H_{12} for possible application, as the working fluid, in geothermal power plant cycles. Besides applying the commercially available engineering software B-Jac, we have studied the main design parameters including size, efficiencies, outlet temperatures, and the required air flow rates. Moreover, mechanical properties of the heat exchanger are investigated on top of the thermal counterparts. Finally, in view of the above, recommendations are put forward for the application of these two fluids as the working fluid in the air cooled power plants.

PROBLEM DESCRIPTION

Making use of the thermal energy stored in the hot rocks, the thermal energy can be used in the boiler (heating stage of the power cycle). Using either of CO_2 or C_5H_{12} as the working fluid, there is a need to cool the working fluid when it leaves the turbine. As mentioned above, due to scarcity of water, air cooled heat exchangers should replace the conventional condensers (cooling stages). Figures 1 and 2 are presented to show the side and top views, respectively, of an induced industrial air cooler in the 5th Olefine Plant in Assaluyeh port-Iran as a part of our previous investigation for a fairly similar problem (Ejali 2007). This work, not necessarily an extension to our previous report, aims at introducing the same techniques in a different plant.

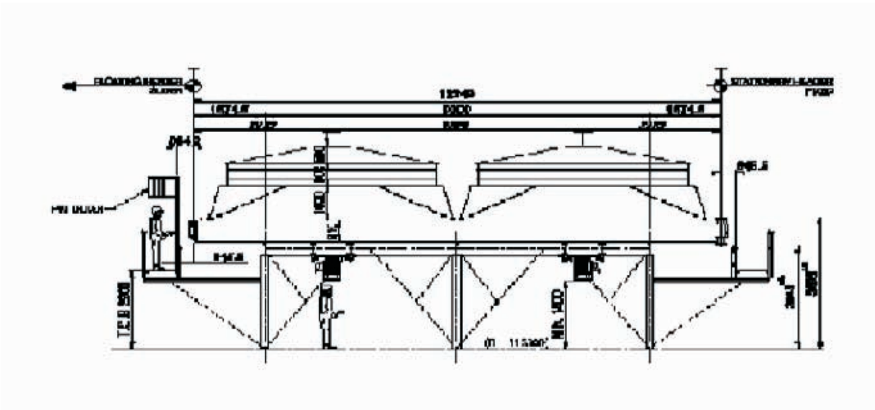

Figure 1. A sample of industrial Air Cooler Heat Exchanger (Side View).

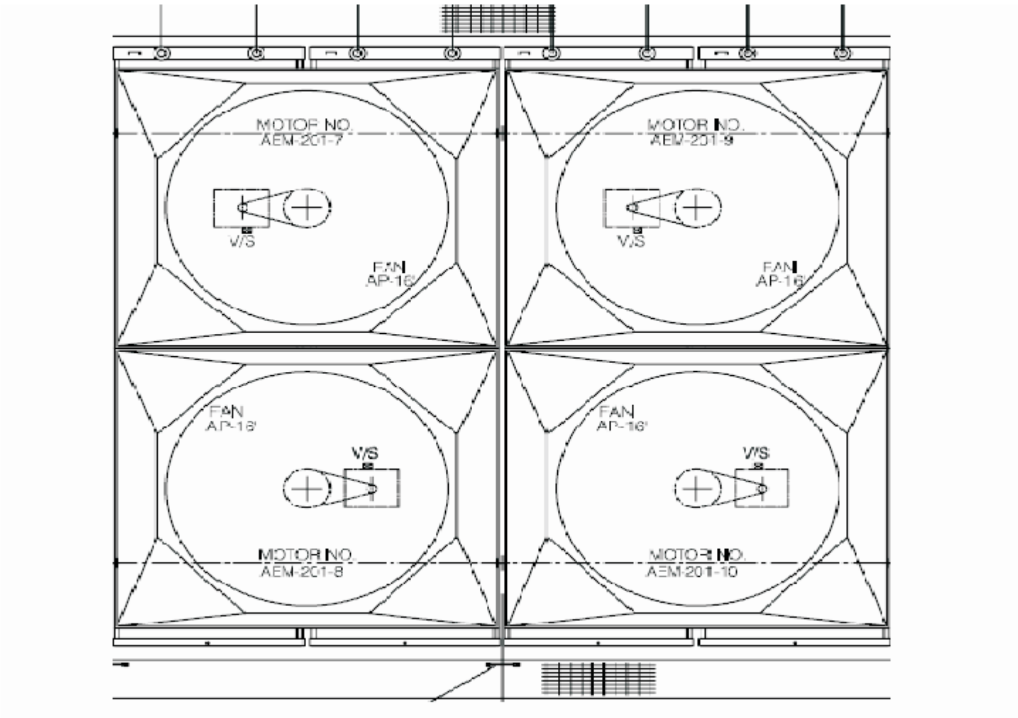

Figure 2. A sample of industrial Air Cooler Heat Exchanger (Top View).

Depending on the mass flow rate and entrance condition of the working fluid, air dry bulb temperature and flow rate (which can be varied via fan lovers), the heat exchanger size should vary. In air-cooled heat exchangers heat is transferred from the process fluid to the cooling air stream via extended surfaces or finned tubes. While the performance of the wet cooling system is dependent on the ambient wet bulb temperature, the performance of the air cooled heat exchangers is determined by the dry bulb temperature. Due to different thermo-hydraulic properties of CO_2 and C_5H_{12}, they will behave differently under similar cooling conditions. Another feature of considerable interest is that the above-mentioned fluids, as opposed to water and air as the most popular working fluids, are showing different thermodynamic behaviours under similar operating conditions, see Mills (1992). The problem becomes even more complicated with supercritical conditions where there are very sharp changes in the thermodynamic properties of the fluid. Hence, there is a need for a parametric study to account for different operating conditions. Based on our previous experience in similar industries, B-Jac engineering software HTFS-AspenTech (2007) (see also API 661) can produce reliable results for the thermo-mechanical analysis of the system. Hence, it is used in this study to investigate the performance of a geothermal power plant with both CO_2 and C_5H_{12} as the working fluids.

The following two Tables are presented to show a sample of our results for cooling C_5H_{12} in a shell and tube air-cooled heat exchanger for two different mass flow rates of 40 and 400 kg/s. Details of mechanical and thermal design are readily available but are not presented here for brevity.

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API 661, ASME SEC VIII, Div 1

Air-Cooled Heat Exchanger Specification Sheet

1	Company:					
2	Location:					
3	Service of Unit:		Our Reference:			
4	Item No.:		Your Reference:			
5	Date:	Rev No.:	Job No.:			
6	Size & Type	7524 / 2036.62 Type	Induced	Number of Bays 1		
7	Surf/Unit-Finned Tube	1877.8 m^2		Bare Tube	174.2 m^2	
8	Heat exchanged	W		MTD, Eff	°C	
9	Transfer Rate-Finned	Bare, Service		Clean	W/(m^2 K)	
10	PERFORMANCE DATA - TUBE SIDE					
11	Fluid Circulated					In/Out
12	Total Fluid Entering	kg/s	40	Density, Liq	kg/m^3	540.87/540.87
13			In/Out	Density, Vap	kg/m^3	14.51/14.51
14	Temperature	°C	86.85/86.85	Specific Heat, Liq	kJ/(kg K)	2.496/2.496
15	Liquid	kg/s	/	Specific Heat, Vap	kJ/(kg K)	2.044/2.044
16	Vapor	kg/s	40/40	Therm. Cond, Liq	W/(m K)	0.082/0.082
17	Noncondensable	kg/s	/	Therm. Cond, Vap	W/(m K)	0.022/0.022
18	Steam	kg/s	/	Freeze Point	°C	
19	Water	kg/s	/	Bubble / Dew point	°C	/ 81.85
20	Molecular wt, Vap		/	Latent heat	kJ/kg	292.2
21	Molecular wt, NC			Inlet pressure (abs)	bar	5.3
22	Viscosity, Liq	mPa s	0.105/0.105	Pres Drop, Allow/Calc		0.48/
23	Viscosity, Vap		0.011/0.011	Fouling Resistance	m^2 K/W	
24	PERFORMANCE DATA - AIR SIDE					
25	Air Quantity, Total	40	kg/s	Altitude		m
26	Air Quantity/Fan	12.184	m^3/s	Temperature In	45	°C
27	Static Pressure	21.71	mmH^{2}O	Temperature Out	45	°C
28	Face Velocity 3.18 m/s	Bundle velocity	6.9 kg/s/m^2	Design Ambient		°C
29	DESIGN-MATERIALS-CONSTRUCTION					
30	Design pressure	7.929 bar	Test Pressure	Code	Design temperature	138.89 °C
31	TUBE BUNDLE		Header		Tube	
32	Size	7524	Type	Plug	Material	CS
33	Number/bay	1	Material		Specifications	Welded
34	Tube Rows	11	Passes	1	OD 30 Min Thk.	1.65 mm
35	Arrangement		Plug Mat.		No./Bun 308 Lng	6 m
36	Bundles	1 par 1 ser	Gasket Mat.		Pitch 68.35 / 59.19	Staggered
37	Bays	1 par 1 ser	Corr. Allow.	3.18 mm	FIN	
38	Bundle frame	Galvanized steel	Inlet Nozzle (2)	355.6 mm	Type	Embedded
39	MISCELLANEOUS		Outlet Nozzle(2)	508 mm	Material	CS
40	Struct. Mount.		Special Nozzles		OD 62 Tks	0.58 mm
41	Surf.Prep		Rating		No. 197 #/m Des Temp	°C
42	Louvers		TI	PI	Code	
43	Vibration Switches		Chem Cleaning		Stamp	Specs API 661
44	MECHANICAL EQUIPMENT					
45	Fan,Mfr., Model		Driver, Type		Speed Reducer, Type	
46	No./Bay 3	RPM 287.99	Mfr.		Mfr.&Model	
47	Dia. mm 1981.2	Blade(s) 8	No./Bay		No./Bay	
48	Pitch 1.1	Angle	RPM		Rating	hp
49	Blade(s) 1981.2	Hub 1016	Enclosure		Ratio	
50	hp/Fan 3.962	Min Amb	V/Phase/Hz	/ /	Support	
51	Control Action on Air Failure-				Louvers	
52	Degree Control of Outlet Process Temperature					
53	Recirculation				Steam Coil	
54	Plot Area	m^2	Drawing No.	Wt.Bundle	9982.7 Wt.Bay	11326 kg
55	Notes:					
56						
57						
58						

Table 1. API sheet for mass flow rate of 40 kg/s (total price~ 92,000 AUD from HTFS-AspenTech).

Air-Cooled Heat Exchanger Specification Sheet

No.			
1	Company:		
2	Location:		
3	Service of Unit:	Our Reference:	
4	Item No.:	Your Reference:	
5	Date: Rev No.:	Job No.:	
6	Size & Type 5286 / 7498.1	Type Induced	Number of Bays 2
7	Surf/Unit-Finned Tube	9511 m^2	Bare Tube 882.2 m^2
8	Heat exchanged	W	MTD, Eff °C
9	Transfer Rate-Finned	Bare, Service	Clean W/(m^2 K)
10	PERFORMANCE DATA - TUBE SIDE		
11	Fluid Circulated		In/Out
12	Total Fluid Entering kg/s 400		Density, Liq kg/m^3 540.87 / 540.87
13		In/Out	Density, Vap kg/m^3 14.51 / 14.51
14	Temperature °C	86.85 / 86.85	Specific Heat, Liq kJ/(kg K) 2.496 / 2.496
15	Liquid kg/s	/	Specific Heat, Vap kJ/(kg K) 2.044 / 2.044
16	Vapor kg/s	400 / 400	Therm. Cond, Liq W/(m K) 0.082 / 0.082
17	Noncondensable kg/s	/	Therm. Cond, Vap W/(m K) 0.022 / 0.022
18	Steam kg/s	/	Freeze Point °C
19	Water kg/s	/	Bubble / Dew point °C / 81.85
20	Molecular wt, Vap	/	Latent heat kJ/kg 292.2
21	Molecular wt, NC		Inlet pressure (abs) bar 5.3
22	Viscosity, Liq mPa s	0.105 / 0.105	Pres Drop, Allow/Calc 0.48/
23	Viscosity, Vap	0.011 / 0.011	Fouling Resistance m^2 K/W
24	PERFORMANCE DATA - AIR SIDE		
25	Air Quantity, Total	40 kg/s	Altitude m
26	Air Quantity/Fan	18.276 m^3/s	Temperature In 45 °C
27	Static Pressure	19.98 mmH^{2}O	Temperature Out 45 °C
28	Face Velocity 1.71 m/s	Bundle velocity 3.7 kg/s/m^2	Design Ambient °C
29	DESIGN-MATERIALS-CONSTRUCTION		
30	Design pressure 7.929 bar	Test Pressure Code	Design temperature 138.89 °C
31	TUBE BUNDLE	Header	Tube
32	Size 5286	Type Plug	Material CS
33	Number/bay 4	Material	Specifications Welded
34	Tube Rows 15	Passes 0.5	OD 30 Min Thk. 1.65 mm
35	Arrangement	Plug Mat.	No./Bun 390 Lng 3 m
36	Bundles 2 par 2 ser	Gasket Mat.	Pitch 68.35 / 59.19 Staggered
37	Bays 2 par 1 ser	Corr. Allow. 3.18 mm	FIN
38	Bundle frame Galvanized steel	Inlet Nozzle (2) 558.8 mm	Type Embedded
39	MISCELLANEOUS	Outlet Nozzle(2) 762 mm	Material CS
40	Struct. Mount.	Special Nozzles	OD 62 Tks 0.58 mm
41	Surf.Prep	Rating	No. 197 #/m Des Temp °C
42	Louvers	TI PI	Code
43	Vibration Switches	Chem Cleaning	Stamp Specs API 661
44	MECHANICAL EQUIPMENT		
45	Fan,Mfr., Model	Driver, Type	Speed Reducer, Type
46	No./Bay 1 RPM 186.32	Mfr.	Mfr.&Model
47	Dia. mm 2895.6 Blade(s) 12	No./Bay	No./Bay
48	Pitch 0.81 Angle	RPM	Rating hp
49	Blade(s) 2895.6 Hub 1524	Enclosure	Ratio
50	hp/Fan 6.086 Min Amb	V/Phase/Hz / /	Support
51	Control Action on Air Failure-		Louvers
52	Degree Control of Outlet Process Temperature		
53	Recirculation		Steam Coil
54	Plot Area m^2	Drawing No.	Wt.Bundle 38758.4 Wt.Bay 171001.5 kg
55	Notes:		
56			
57			
58			

Table 2. API sheet for mass flow rate of 400 kg/s (total price~ 450,000 AUD from HTFS-AspenTech).

Air Cooled Porous Matrix Heat Exchangers for Geothermal Applications

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ABSTRACT

Power plants are voracious water users. For example, the 1400 MW Stanwell Power plant used 19.4 Gigalitres in 2004-05. Due to their lower thermal efficiencies, the cooling needs of geothermal plants are higher. Unfortunately, the best prospects for the geothermal energy utilisation in Australia appear to be in places where water is already scarce. Evaporative cooling with water is no longer acceptable, not even in the general Australian power supply context and certainly would not be possible in the Cooper Basin due to lack of water. Cooling systems using air as the coolant have attracted no significant advances in scores of years, with scientific literature in the last 10 years limited to parametric optimisation studies (Conradie et al., 1998) and (Conradie and Kroger, 1996). Unfortunately, air-cooling is the only option if the geothermal energy is to become a reality in the hot and arid environment of the Australian interior.

This work explores a new cooling concept by numerically investigating heat removal from condensers by mixed convection flow of air over the tubes and through a vertical chimney-shaped cooling section where the tube bundle is modeled as a porous medium. Phase changing flow of water inside the tubes allows for a uniform wall temperature assumption on the tube wall which is well above that of the ambient. Geometrical constraints are looked into. Among them are the height and shape of the cooling section as well as the porosity and permeability of the tube bundle.

PROBLEM DESCRIPTION

Figure 1 shows a schematic diagram of the problem under consideration. As the flow field is symmetric about the tower centerline, only half of the domain is considered to reduce the required time and computer recourses. Air flow through the entrance (at the bottom left) is mainly due to wind. Hence, there is a need to parametrically change this inlet velocity. Moreover, due to temperature difference between the condenser and the ambient, buoyant forces will emerge leading to upward motion of the air through the tower. Finally, air at a temperature higher than that of ambient exits the tower from top. We systematically altered the temperature difference, which is the driving force for free convection, the key geometrical parameters, and the entrance length. Then we investigated the effects of these variations on the system performance.

GOVERNING EQUATIONS

Generic form of the governing equations

$$\frac{\delta(u^*\varphi)}{\delta x^*}+\frac{\delta(v^*\varphi)}{\delta y^*}=\frac{\delta}{\delta x^*}\left(\Gamma_\varphi\frac{\delta\varphi}{\delta x^*}\right)+\frac{\delta}{\delta y^*}\left(\Gamma_\varphi\frac{\delta\varphi}{\delta y^*}\right)+S\varphi \tag{1}$$

is used in this study as indicated by our Table 1. For the non-porous regions, one simply sets $\varepsilon=1$ and $K\to\infty$ where the effective thermal conductivity reduces to a fluid property, see (Nield and Bejan 2006). Interface boundary conditions are taken from (Alazmi and Vafai 2001) and the problem is solved for steady-state condition. Undertaking the volume-averaging techniques,

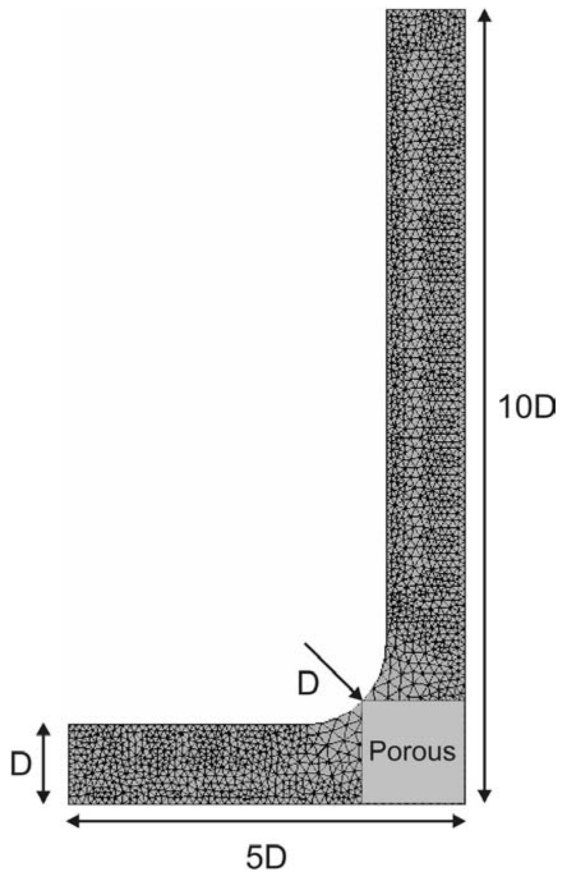

Figure 1. Schematic description of the problem under consideration.

following (Bejan, 2004) and (Vafai and Tien, 1981), values of porosity and permeability are selected to be in agreement with physical constraints.

Extensive checks on the accuracy of our numerical solver have been performed including grid-independence and code validation, similar to our previous reports, see for example (Hooman and Gurgenci, 2007) or (Hooman et al., 2007). Figure 2 shows a sample of our numerical results for vertical and horizontal components of velocity as well as the temperature distribution in the condenser.

Table 1: Summary of the Governing Equations

Equations	φ	Γ_φ	S_φ
Continuity	1	0	0
x*-momentum	u^*/ε^2	ν/ε	$-\frac{1}{\rho}\frac{\delta p^*}{\delta x^*}-\frac{\nu u^*}{K}-\frac{C_F u^*\lvert U^*\rvert}{\sqrt{K}}$
y*-momentum	v^*/ε^2	ν/ε	$-\frac{1}{\rho}\frac{\delta p^*}{\delta y^*}-\frac{\nu v^*}{K}-\frac{C_F v^*\lvert U^*\rvert}{\sqrt{K}}+g\beta\left(T-T_{ref}\right)$
Energy	T^*	α	0

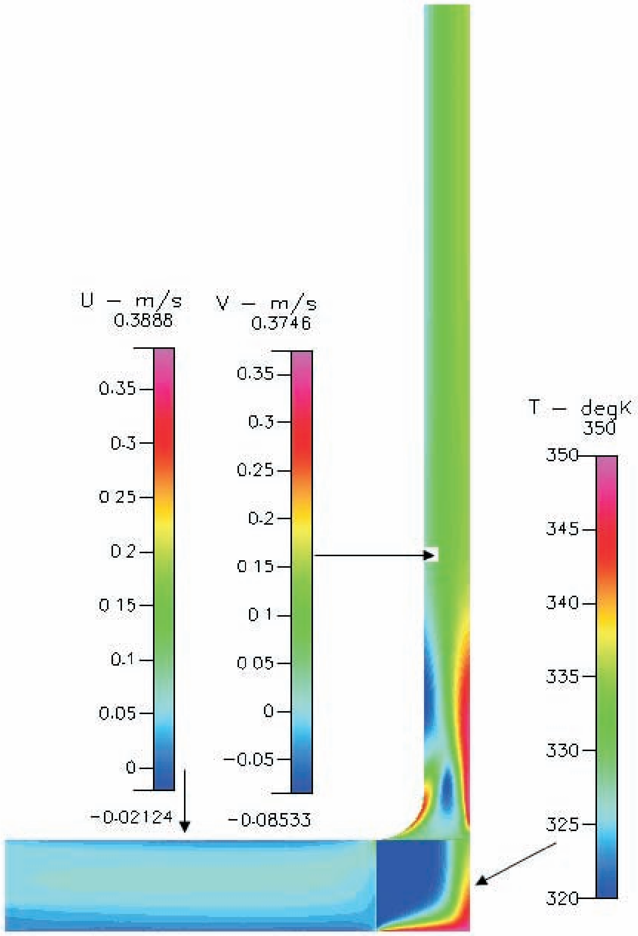

Figure 2. A sample of numerical results for u, T, and v in horizontal, condenser, and vertical sections.

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A Small Turbomachinery Laboratory for Geothermal Energy

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INTRODUCTION

Over the next few years, the Queensland Geothermal Energy Centre will be developing technology to assist with the exploitation of the hot-rock thermal reservoirs in western Queensland. It is hoped that, if the geothermal power systems can use carbon dioxide as the working fluid, we can obtain electric power at the same time as sequestering significant amounts of the carbon dioxide produced by traditional coal-fired power stations in other parts of the state. Within the new centre, we are establishing a small laboratory for the development of suitable turbomachinery.

Geothermal Power Cycle

As discussed by Gurgenci et al. (2008), one option for the power-generation cycle is a "geothermal siphon" with turbine, using supercritical carbon dioxide as the working fluid. Figure 1 shows the arrangement of the major components of such a system.

The keys to getting this cycle to work are (1) the use of carbon dioxide as the working fluid as suggested by Brown (2000) and (2) that, over the 5 km descent to the hot-rock thermal reservoir, gravity does approximately 49 kJ/kg of work compressing the carbon dioxide. The relative buoyancy of the heated fluid in the production well drives the mass flow around the cycle.

The ambient conditions in western Queensland are such that, with an air cooled low-temperature heat exchanger, we estimate the minimum temperature in the cycle to be 47 °C. If we set a pressure

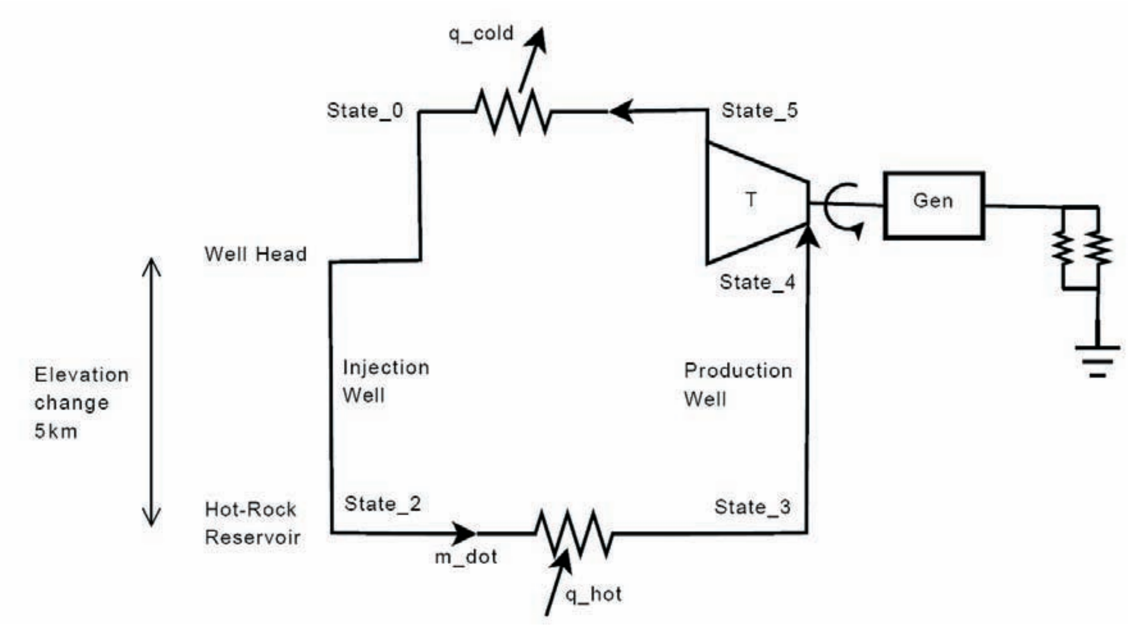

Figure 1. The geothermal siphon with carbon dioxide as the working fluid.

of 8 MPa leaving the cooler (State_0) and entering the injection well, the carbon dioxide is expected to maintain supercritical conditions throughout the cycle. The key states (labelled in Figure 1) are shown in Table 1. These have been calculated using the equation of state developed by Reynolds (1979).

Table 1. Key states in the thermodynamic cycles. Note that the undashed states are for the ideal cycles while the dashed states are for compressor and turbine efficiencies of 70%.

State	Pressure	Temperature	Enthalpy	Entropy
	(Mpa)	(Degree K)	(KJ/kg)	(KJ/K.kg)
0	8.00	320.0	348.1	1.219
1	13.39	359.7	367.4	1.219
1’	13.39	363.3	375.7	1.241
2	25.01	408.4	396.9	1.219
3	25.01	508.0	553.4	1.563
4	13.39	444.0	504.1	1.563
5	8.00	395.3	469.3	1.563
5’	8.00	403.8	479.8	1.599

In this idealised geothermal cycle, the process going down the injection well is considered to be isentropic and the end state can be determined by integration (Gurgenci et al., 2008). The heat is added to the working fluid as it flows through the hot-rock reservoir in a constant pressure process, that is, assuming no viscous losses. As the carbon dioxide flows up the production well, the work associated with gravity again causes a significant change in enthalpy. The fluid arrives at the turbine (State_4) with a pressure of 13.39 MPa and a temperature of 171 °C. Expanding the carbon dioxide through the turbine to 8 MPa makes available 34.8 kJ/kg of work and gives this idealised cycle a thermal efficiency of 22%.

Laboratory Cycle

For the laboratory-scale experiments, we will concentrate on the above-ground components and replace the wells and hot-rock reservoir with a compressor and an electrical heater, q_hot, as shown

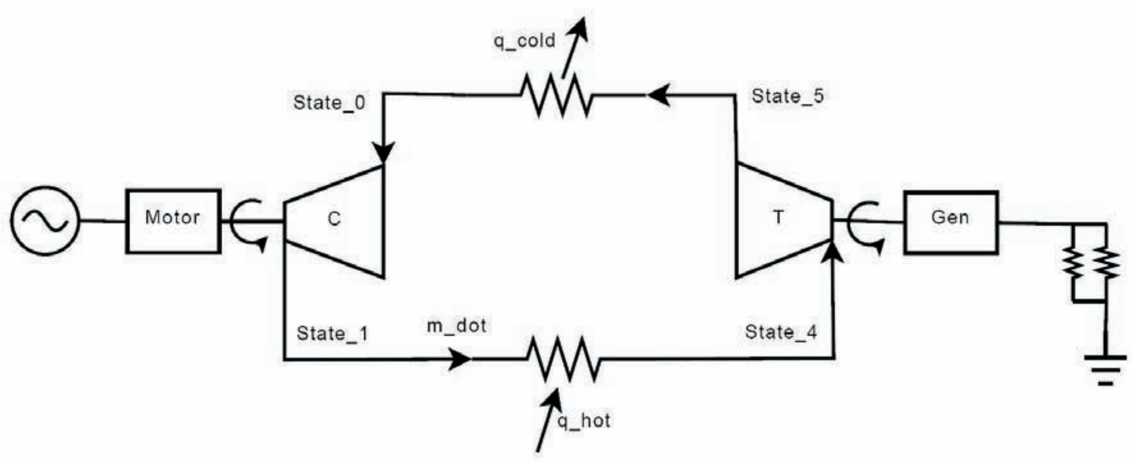

Figure 2. Thermodynamic loop proposed for the laboratory tests.

in Figure 2. Our interest is in developing efficient turbines for use with carbon dioxide as the working fluid.

The compressor and turbine are not mechanically coupled but are driven (or loaded) independently by electric motor and generator. This arrangement is now a simple Brayton cycle with heat being added at a pressure of only 13.39 MPa. Although the thermal efficiency of the ideal laboratory cycle quite low (11 %), our concern is really in providing an operating environment for the turbine that is similar to the full geothermal siphon.

In sizing the equipment for the laboratory, we have chosen the (somewhat arbitrary) value of 5 kW for the turbine output power. This leads to a mass flow of 0.144 kg/s within the loop, a compressor input power of 2.8 kW and a heat input of 19.7 kW at 171 °C. Presently, we are looking at modified automotive turbochargers as a cheap source of rotors for our initial exploration. It seems that typical turbochargers have efficiencies of about 70% for both the turbine and compressor so we show the laboratory cycle states assuming that level of performance. As compared to the cycle with ideal turbomachinery, the work from the turbine drops to 24.3 kJ/kg while the work required by the compressor rises to 27.5 kJ/kg. This highlights the importance of developing a very efficient turbine.

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Experimental Study on CO_2 Injection Into HDR Geothermal Reservoir

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ABSTRACT

The purpose of this research is to study sequestering CO_2 in solid carbonate minerals. CO_2 dissolved in water was injected into an open hole interval of a 1,100 m depth well which was drilled into a Hot Dry Rock (HDR) geothermal reservoir. The bottom hole temperature was measured around 230 °C. Ca concentration of the water sampled at 1,030 m depth increased in a few hours after CO_2 dissolved water injection. Calcite precipitation on calcite crystals set in CO_2 dissolved water at 850 m in the well was observed within a few hours.

INTRODUCTION

In Japan there are many active volcanic areas. There is a possibility that CO_2 injected into high temperature rock reacts faster than normal temperature rock allowing CO_2 to be sequestered in the formation as solid carbonate minerals such as calcite as shown in Figure 1 (Ueda et al., 2005). We conducted some field experiments to study CO_2 sequestration in solid minerals by injecting CO_2 dissolved in water into high temperature a borehole drilled into granitic rocks.

EXPERIMENT PROCEDURE AND RESULTS

The test site is located at Ogachi, northern Japan. At Ogachi there are three 1,000 m class wells (OGC-1, 2, 3) which were drilled into granodiorite. These wells were drilled for basic experiments for Hot Dry Rock geothermal energy development (Kaieda et al., 2005). The temperature of the wells at 1,000 m depth was measured at around 230 °C. OGC-2 was used for this research. OGC-2 was completed with casing from the ground surface to a depth of 700 m and below 700 m to the bottom of the well of 1,100 m was left uncased (open-hole).

Chemical reaction of CO_2 dissolved in water with rock

For the first experiment, neutralised river water was injected into OGC-2 following which water was recovered from the 1,030 m level of OGC-2 using a water sampler. Six samples per day were taken for 12 days. The results of chemical components analysis of the sampled water are shown in the upper part of Figure 2. Ca concentration in the sampled water does not change very much. In the second experiment, 1 wt % CO_2 dissolved in river water was injected into OGC-2 and again water at 1,030 m depth in OGC-2 was sampled, 4 times for 12 days. The chemical components results were shown in the lower left part of Figure 2. In this Figure, we can see that Ca

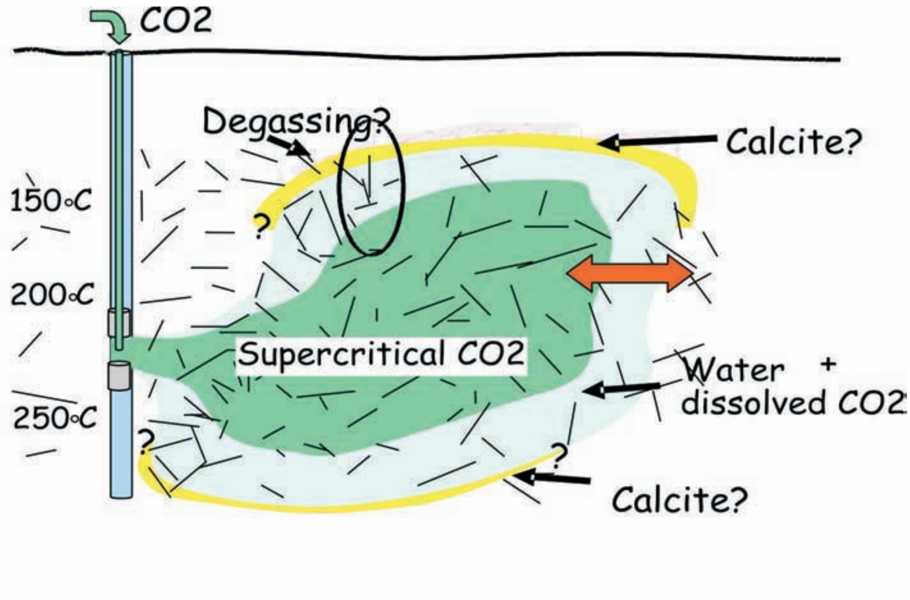

Figure 1. Concept of CO_2 injection into geothermal reservoir.

concentration of the sampled water increased up to 21 mg/kg at 16 hours after CO_2 dissolved water injection was stopped. Then Ca concentration decreased to original level. In the third experiment, 3 wt % CO_2 dissolved in river water was injected, whereafter water at 1,030 m depth in OGC-2 was sampled 6 times for 8 days. The chemical components results are shown in the lower right part of Figure 2. In this figure we can see Ca concentration of the sampled water from OGC-2 increased to 85.2 mg/kg in one hour and decreased to the original level for some days.

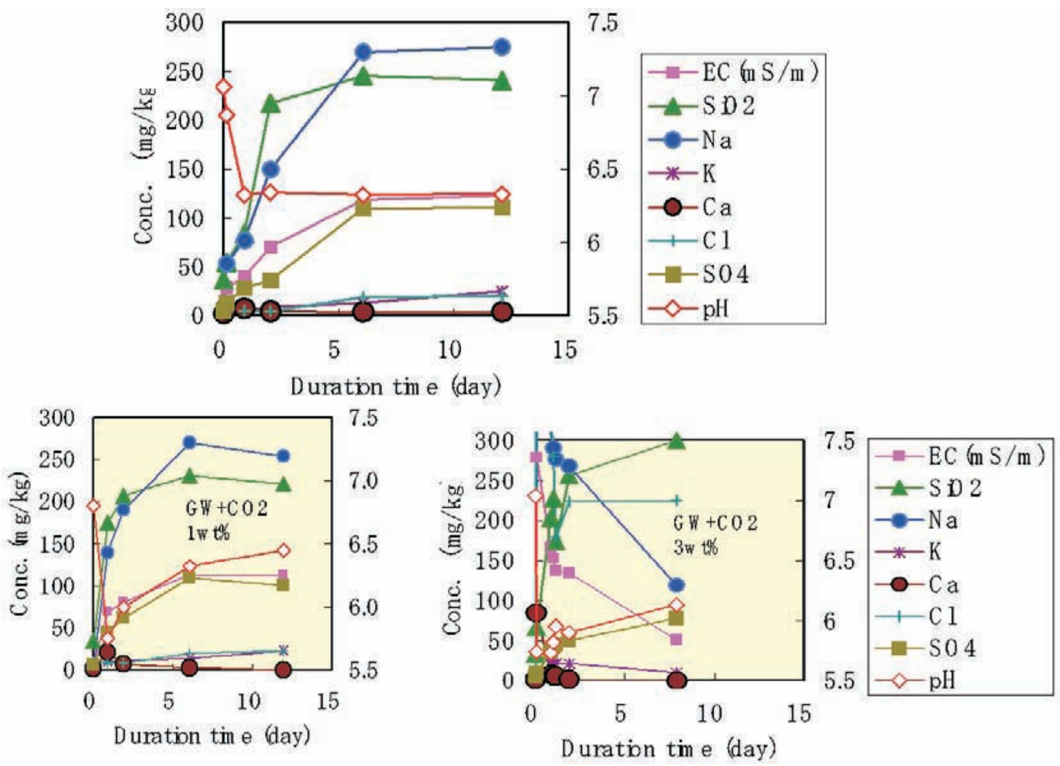

Figure 2. Chemical components concentration after CO_2-charged water injection.

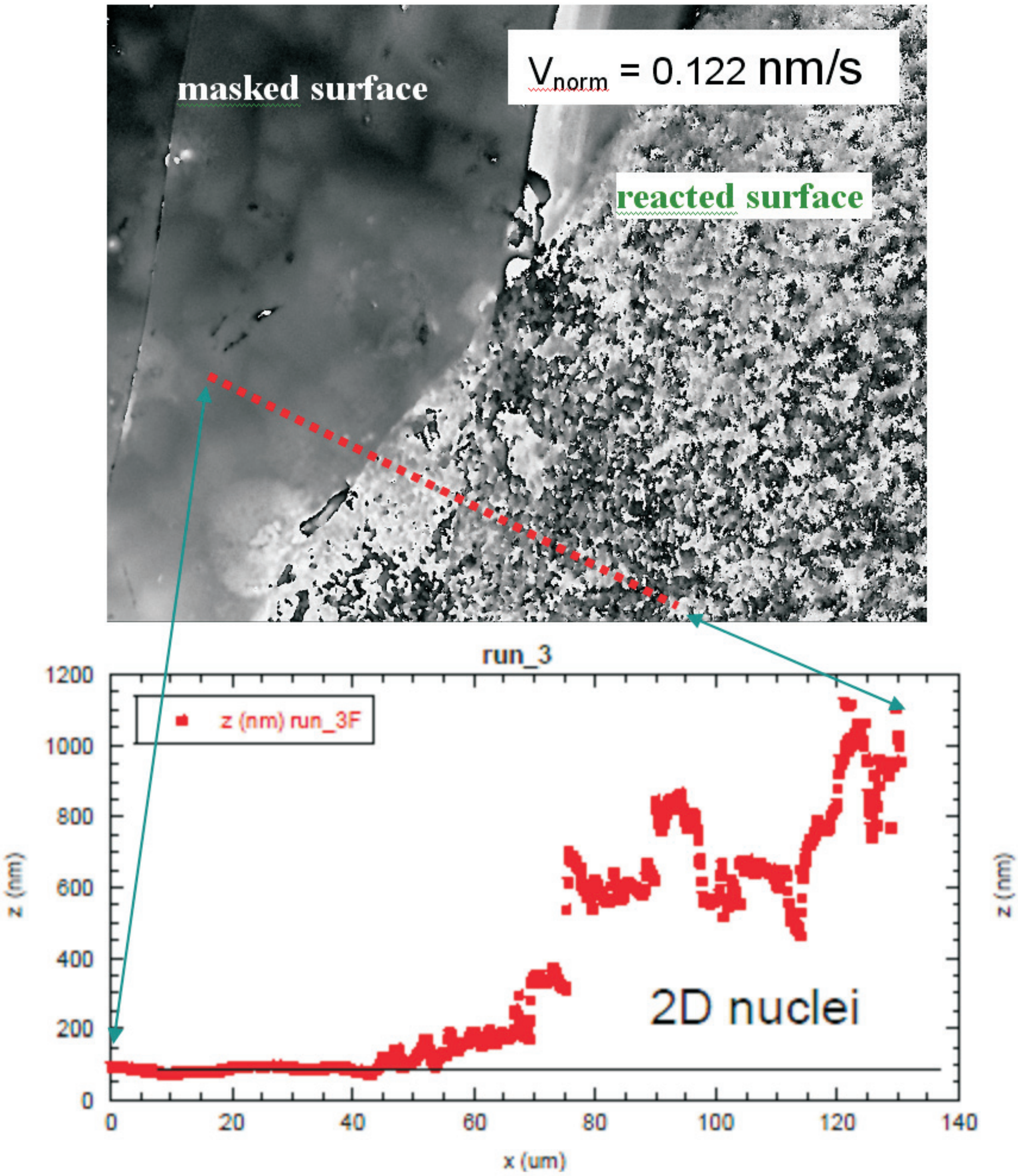

Figure 3. $CaCO_3$ precipitation in CO_2 dissolved water.

From these results, we considered that the reaction of CO_2 dissolved river water with rock is very fast. Ca concentration after injection of CO_2 dissolved in river water increased in a few hours. The ratio of the concentration increasing depends on dissolved CO_2 percent. After increasing Ca concentration, the concentration decreased to the original level for some days. The Ca concentration decrease may be caused by water flow in and/or out between OGC-2 and surrounding rock, or by precipitation as $CaCO_3$. We considered that Ca was supplied from Ca-feldspar in granodiorite.

Calcite precipitation in water with dissolved CO_2 at high temperature

In the previous experiment, we confirmed that Ca concentration increased by injecting CO_2 containing water into high temperature granitic rock. In this experiment we intended to study the possibility for CO_2 sequestration as calcite. Calcite crystals partially covered with Au film was held in a sonde. The sonde was put into OGC-2 to a depth of 850 m where CO_2 containing water was injected. The sonde was recovered after one hour and the calcite crystal surface was observed by a phase shift interferometer.

Figure 3 shows an example of a picture of the calcite crystal surface by a stereo microscope (upper picture) and roughness of the crystal surface along the red dashed line observed by the phase shift interferometer (lower figure). The masked surface means the area covered with Au film. In this masked area, no change occurred, but other area shown as reacted area calcite crystal grew to a maximum height of about 1,100 nm. From the results we can calculate the calcite precipitation rate of order of 0.1 nm/s. This means calcite precipitate crystals of 0.1 mm in 12 days.

CONCLUSION

CO_2 dissolved in water was injected into an open hole interval between 700 m to 1,100 m depths of OGC-2 at Ogachi which was drilled into a Hot Dry Rock (HDR) geothermal reservoir. The bottom hole temperature was measured around 230 °C. Ca concentration of the water sampled at 1,030 m depth increased in a few hours after CO_2 dissolved water injection then decreased in a few days. For the Ca increase it was considered that Ca was supplied from Ca-feldspar in granodiorite. Calcite precipitation on calcite crystals was observed for CO_2 dissolved in water at 850 m in the well, within a few hours.

ACKNOWLEDGEMENTS

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Efficiencies, Availabilities, Reliabilities and Environmental Impact of Commercial Geothermal Power Plants

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The economy of a geothermal power plant is only one of the conditions to be fulfilled in the development of a geothermal resource. In many cases it is only secondary. The developer should often give precedence to the environmental impact, to the sustainability of the resource, to the safety of the operation, to strength, and durability of the equipment, to small cost of operation etc. This paper will discuss the challenges and advantages of geothermal power generation when compared to wind, solar and biomass and draw a clear line between the available commercial technologies and some pilot development as Kalina on the other side.

Among the commercial technologies the single and in particular the double flash system will be compared with the different binary technologies and in particular with the Geothermal Combined Cycle system. The theoretical and practical advantages of the each system will be evaluated and compared to examples from existing projects.

The State of the Art in Geothermal Power Plant

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ABSTRACT

This paper provides a technology assessment of current and future technologies for power generation from geothermal resources. A particular attention will be given to power cycles suitable for electricity generation from fractured hot-dry-rock which dominates the Australian geothermal resources.

By and large geothermal energy is an untapped energy resource despite its potential and clear environmental advantages (e.g. minimal CO_2 emissions) over other sources of energy, such as fossil fuels and nuclear energy. Although according to the IEA geothermal power production is expected to steadily increase at a rate of 4.3% per year reaching a share of 0.6% of the global electricity production by the year 2030, the growth clearly falls short of expectations. The contribution of the geothermal energy to the world's electricity production by 2030 can be potentially one order of magnitude higher than the IEA's estimate, should the technical problems associated with the use of geothermal energy be resolved.

Within this context, the study of geothermal power cycles is regarded as one of the key areas for major technological improvements since many of the problems associated with the geothermal power technology are underpinned by inefficient and often unsuitable heat exchange processes within power cycles. That is partly due to the fact that most power cycles currently employed in geothermal applications were originally designed for large-scale power production from fossil fuels where higher temperature sources are available for heat exchange.

Geothermal power cycles can be generally classified into following groups: (1) non-condensing direct steam cycles, (2) condensing direct steam cycles such as single- and double flash, (3) binary cycles, and (4) combined cycles. The choice of one power cycle over another depends on a number of parameters most importantly the reservoir temperature and the type of geothermal fluid (i.e. vapour or liquid). For example, in the case of relatively high temperature ($T > 235$ °C) steam dominated reservoirs, the steam from the geothermal well can be used directly to run a turbine/generator and hence the most suitable power cycle is a non-condensing direct steam cycle.

Steam dominated reservoirs are unfortunately quite rare and most common geothermal sources are of either water dominated or hot-dry rock nature. Depending on the temperature of the reservoir, various hydrothermal power cycles can be used to generate electricity from both water dominated and hot-dry rock geothermal reservoirs. Typically, at temperatures between 150-200 °C, the preferred cycles are the so called "Flash Steam" power cycles in which some of the water from the production well is flashed into steam in a separator and then powers the turbines/ generator unit. Flashing of the geothermal fluid can be carried out in either single- or double-flash configurations where the fluid is flashed into steam in two different separators each operating at different pressures. The cycles associated with flashing systems are often referred to as condensing "direct steam" cycles.

For lower temperature reservoirs (100-150 °C) the preferred options are "Binary" power cycles where the geothermal fluid is passed through a heat exchanger to heat a secondary working fluid that runs the actual power cycle. The secondary working fluid is usually an organic fluid which vaporises at a lower temperature than water. Two examples of more novel and efficient binary power cycles which have been purposely developed for geothermal applications are Kalina and Regenerative Supercritical (RGSC) cycles which are discussed in more details during the presentation.

Flash and binary cycles can be hybridised to improve the conversion of geothermal energy to electrical power. In such systems some of the geothermal fluid from the production well is first used in a flash cycle to run a primary turbine/generator unit. The condensate from the turbine outlet is then mixed with the remaining hot geothermal fluid and passed through a binary cycle for further generation of electricity. The cycles associated with such hybrid power plants are referred to as "combined cycles".

With the exception of Kalina and RGSC cycles, the major limitation of other geothermal power cycles is the fact that similar to Rankine cycle they have been designed to operate under or near the saturation dome of the working fluid's phase diagram. As a result, the evaporation and condensation of the working fluid both happen at constant temperatures. This, however, implies that there are great temperature mismatches between the working fluid and heat source / sink during the heat addition or rejection processes. For a binary cycle, for example, the temperature difference between the working and geothermal fluids in the primary heat exchanger unit could be as high as 80-100 °C. From a thermodynamics point of view, greater temperature differences associated with a particular power cycle increase the generation of entropy and, thereby, reduce the efficiency of the heat exchange processes. This thermal inefficiency which is underpinned by the thermodynamics of a given power cycle may lead to significant revenue loss.

The major advantage of the Kalina cycle over other conventional geothermal power cycles is the fact that the multi-component working fluid employed in the cycle has a variable phase change temperature. As a result, unlike other conventional cycles the evaporation of the working fluid occurs over a range of temperatures and, hence, the mixture temperature can track that of the geothermal fluid from the production well. The amount of thermal energy recovered from the geothermal sink is, therefore, greatly enhanced helping to minimise the entropy generation and improve the efficiency of the heat exchange unit. Similarly, the condensation of the working fluid takes place over a temperature range permitting additional heat recovery to be made in the condenser. Although the Kalina cycle with its multi-component working fluid has indeed shown improved thermal efficiency, it is at the expense of absorption and distillation equipment added to the cycle. It is this complexity which significantly increases the cost of a Kalina plant as opposed to other types of power plants. The added complexity and, in particular the high sensitivity of the cycle towards pressure and composition of the ammonia-water mixture, also limits the application of the cycle over a wider range of reservoir temperatures. The RGSC cycle avoids this complexity by using a single-component working fluid. The necessary variable phase change temperature is achieved by operating under supercritical conditions.

Controlled Pressure Drilling Applications for Engineered Geothermal Systems in Australia

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ABSTRACT

The adaptation, analysis, and testing of new technologies are required to reduce well costs associated with deep Engineered Geothermal Systems (EGS). One of the advanced technologies already in use in the oil and gas industry that can be utilised to improve the economics of EGS is Controlled Pressure Drilling (CPD). CPD methods are an aggregation of techniques that utilise a closed and pressurised wellbore instead of the conventional practice of drilling with the hole open to the atmosphere. These methods utilise a Rotating Control Device (RCD) to close the well at surface, thereby allowing for greater and more precise control over the pressure profile of the well, which translates to more effective and efficient drilling operations. The three main types of CPD methods are Air Drilling (AD), Managed Pressure Drilling (MPD) and Under-Balanced Drilling (UBD). AD is mainly geared towards increasing the rate of penetration, MPD is for reducing rig non-performance time, while UBD is for minimising reservoir damage and increasing productivity.

In Australia, all the CPD methods hold promise for greatly improving the economics of EGS projects. However, of the three CPD types, only UBD and MPD have so far been used to drill EGS systems in the country. AD methods, which according to studies have the potential to cut drilling costs by 15% to 20% by maximising the penetration rate, have not yet been utilised. Recent advances in AD technology have included the development of RCDs, air hammers, foam systems, and corrosion control chemicals that are able to withstand high temperatures and pressures, making them uniquely applicable to EGS systems. The varying nature and geology of the EGS systems in the country as well as the different approaches that have been taken by the companies pursuing their development, however, will require the customisation of CPD methods based on the applications required.

This paper provides an introduction to CPD methods and a background as to how these methods have been used to improve drilling operations in other countries. It then narrows down its focus on the applicability of CPD methods in drilling EGS systems in Australia. It assesses the feasibility of utilising these methods in light of recent advances in CPD technology and provides how it can improve the economics of drilling EGS systems. Recommendations for the application of CPD methods in Australia are also provided.

INTRODUCTION

CPD methods utilise a closed and pressurised wellbore instead of the conventional practice of drilling with the hole open to the atmosphere. These methods utilise a RCD to close the well at surface, thereby allowing for greater and more precise control over the pressure profile of the well, which translates to more effective and efficient drilling operations. The three main types of CPD methods are AD, MPD and UBD. AD is mainly geared towards increasing the rate of penetration, MPD is for reducing rig non-performance time, while UBD is for minimising reservoir damage and increasing productivity. Additional information about the three CPD types is provided in the Weatherford CPD Wheel shown in Figure 1.

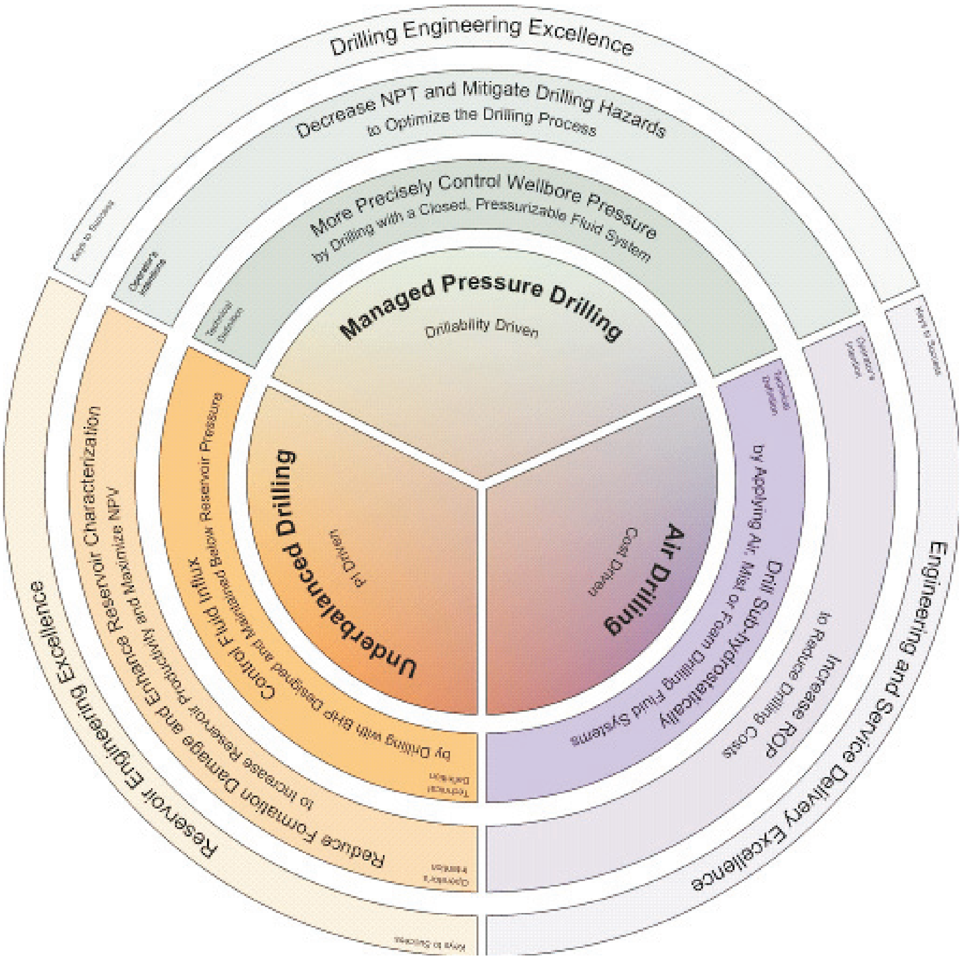

Figure 1. The Weatherford Controlled Pressure Drilling Wheel.

Air Drilling, the application of air, mist, aerated liquid or foam fluid systems to lower the density of the drilling fluid, is mainly intended at reducing costs by drilling faster. It is a widely accepted technique for drilling geothermal wells for a variety of reasons, which include but are not limited to, minimisation of circulation losses, increase in penetration rate, material savings, elimination of differential sticking, lesser water requirements, the ability to discharge during drilling, and the prevention of formation damage. The technique and the four different types of fluid systems (air, mist, aerated liquid and foam) it involves have been proven to produce positive results in geothermal applications all over the world. Figure 2 shows the four types of drilling fluid systems (air, mist, aerated liquid and foam) commonly used for aerated fluids drilling.

The International Association of Drilling Contractors (IADC) defines MPD as an adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile accordingly. MPD is intended to avoid continuous influx of formation fluids to the surface. Any influx incidental to the operation will be safely contained using an appropriate process.

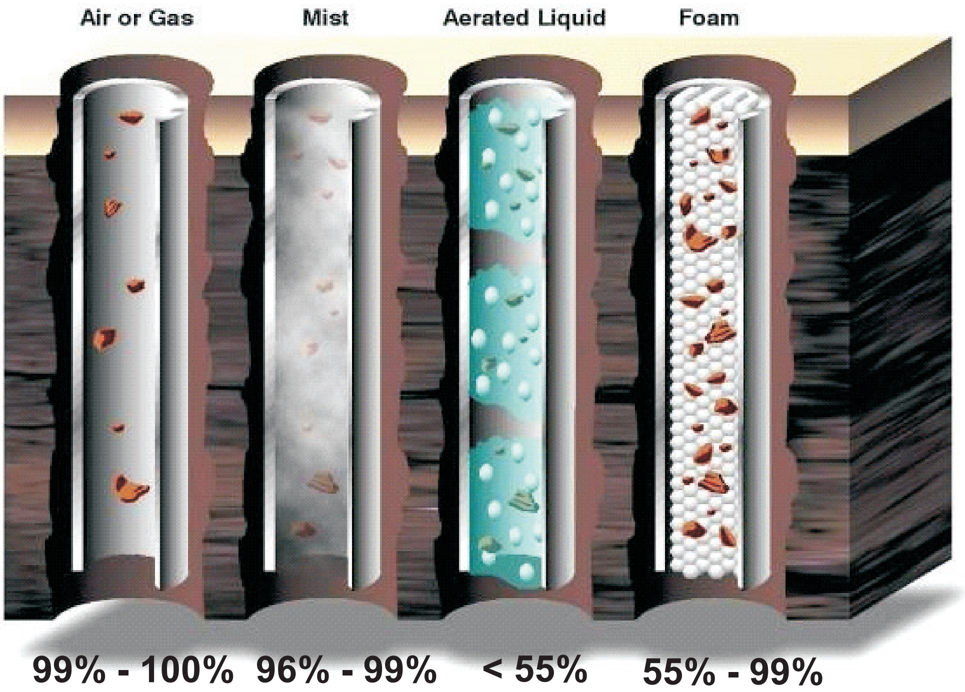

Figure 2. The different types of Aerated Drilling Fluid Systems and the percentage of air involved.

The same organisation defines UBD as a drilling activity employing appropriate equipment and controls where the pressure exerted in the wellbore is intentionally less than the pore pressure in any part of the exposed formations with the intention of bringing formation fluids to the surface.

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Electricity Generation using Enhanced Geothermal Systems with CO_2 as Heat Transmission Fluid

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INTRODUCTION

Harnessing clean geothermal energy from Hot Rocks or Enhanced Geothermal Systems (EGS) using water /superheated steam for electricity generation is progressing well in Australia and worldwide.

This paper investigates the feasibility of using carbon dioxide (CO_2) instead of water as EGS heat transmission fluid which has the potential additional benefit of CO_2 geosequestration of significant scale.

Background

Hot rocks /EGS are defined as subsurface reservoirs that have been enhanced to extract geothermal energy. The thermal energy is recovered by creating or accessing a system of open, connected subsurface reservoirs through which water can be circulated down injection wells, heated by contact with the subsurface hot rocks, and returned to the surface in production wells as superheated water/steam used to drive a turbine to generate electricity (Figures 1 and 2).

Given the need to reduce carbon dioxide emissions, the use of CO_2 as the heat transfer fluid has some distinct advantages (improved heat transfer efficiency/sequestration). If successful, this approach could establish a significant CO_2 geosequestration province with capacity to manage the majority of total CO_2 emissions from Eastern Australia.

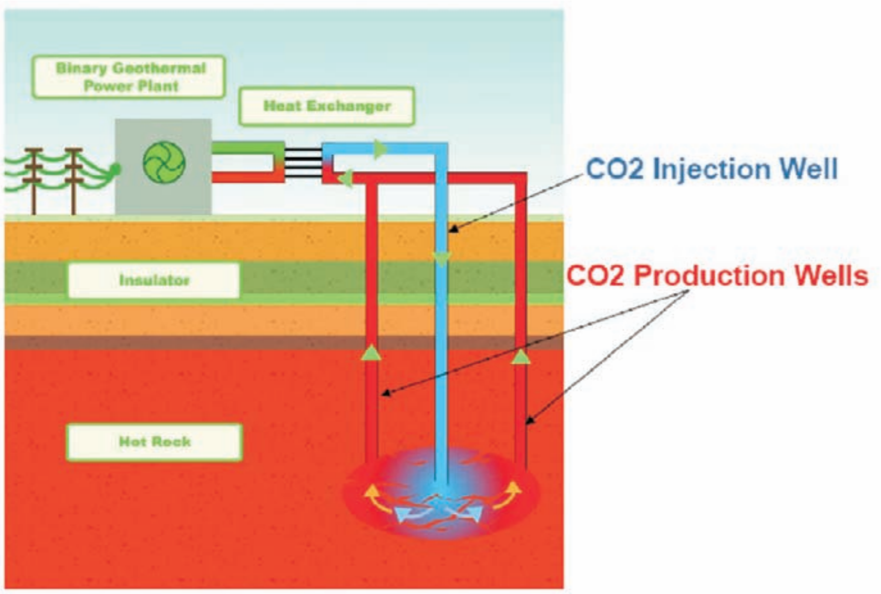

Figure 1. EGS geothermal power generation using CO_2.

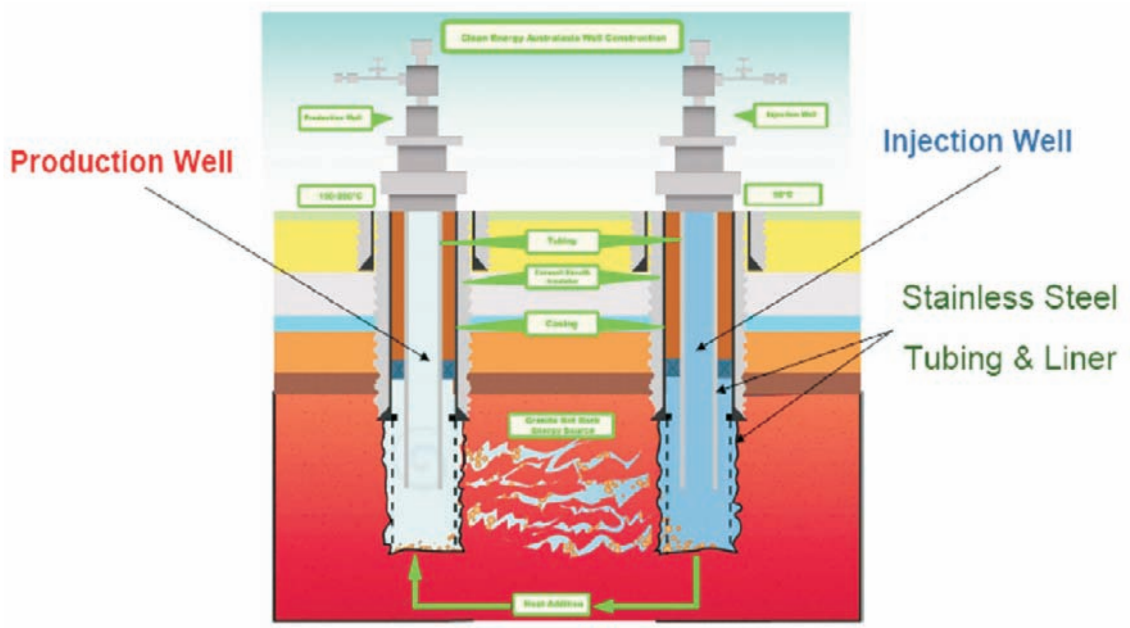

Figure 2. EGS geothermal wells construction using CO_2 as the heat transmission fluid.

Benefits

Previous work has indicated that CO_2 may be technically superior to water or steam in transferring natural heat from hot rocks due to:

- Lower viscosity therefore greater subsurface mobility (Figures 3a & b) [3];
- Heat extraction rate is greater than water at lower temperatures and pressures (Figure 4);
- Increase in efficiency due to lower parasitic power consumption through improved wellbore hydraulics due to greater compressibility and expansivity (Figure 3c);
- Sequestration of CO_2 resulting in negative emission of greenhouse gas (Figure 5); and
- Geothermal energy produce zero emissions.

Technical and Commercial Challenges

However there are a number of challenges, including:

- The infrastructure required to capture and to transport CO_2 over long distance pipelines (Figure 6 Santos MCS);
- The potentially corrosive nature of CO_2 with associated water;
- Compression requirements to transport and store CO_2;
- Capital Requirements to enable the infrastructure; and
- Emissions Trading Scheme (structure of scheme yet to be finalised/announced).

Hot Rocks/ EGS Locations

Australia is estimated to have 22,000 EJ or 5,000 times its annual energy consumption stored in EGS resources [1]. 'Over 80% of the resource was found to be concentrated in central Australia, extending over the north-eastern corner of South Australia and the south-western corner of Queensland. Much of this region is essentially coincident with the Cooper Basin, an infrabasin below the Great Artesian Basin (GAB)' [1].

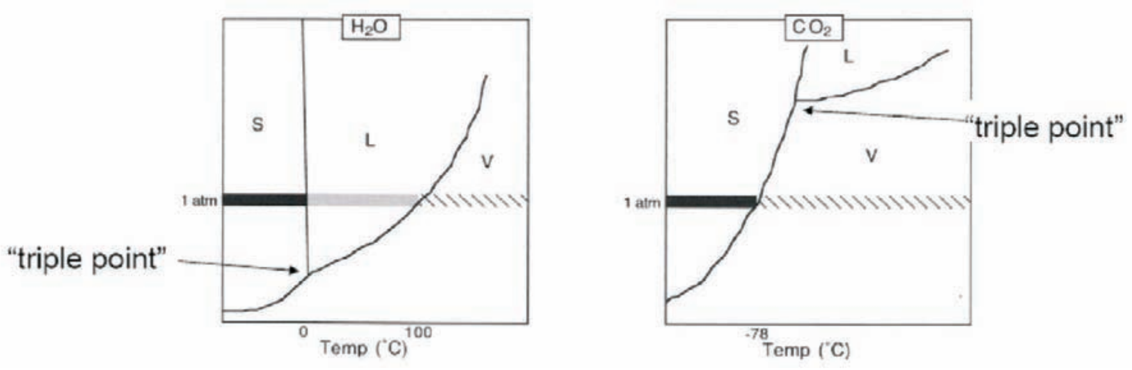

Figure 3(a). Water and Carbon Dioxide properties: phase diagrams.

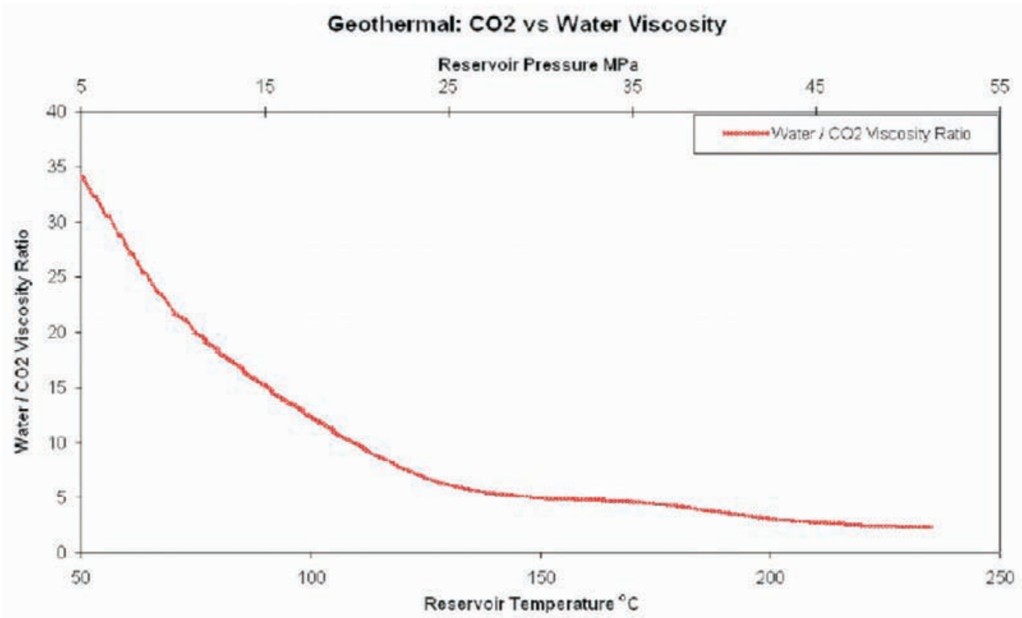

Figure 3(b). Water and Carbon Dioxide properties: viscosity ratio.

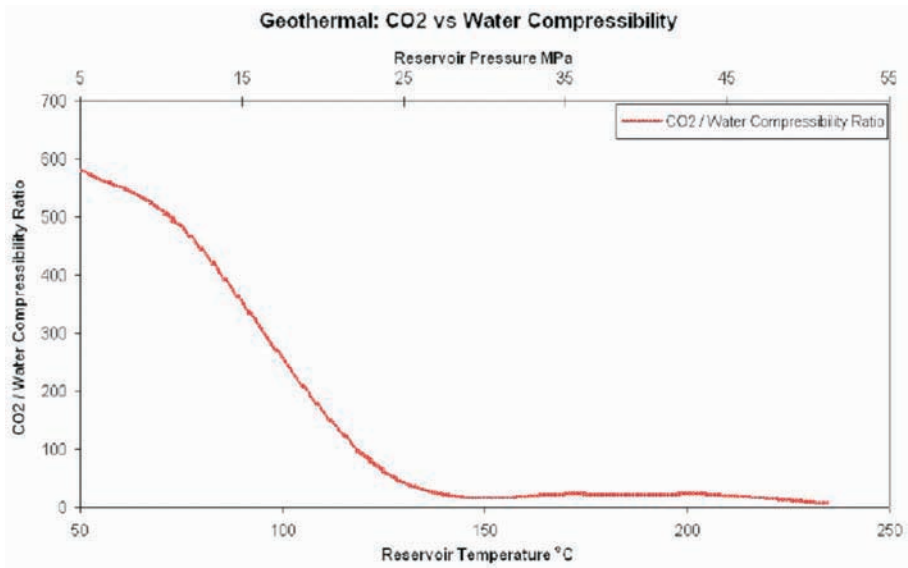

Figure 3(c). Water and Carbon Dioxide properties: compressibility ratio.

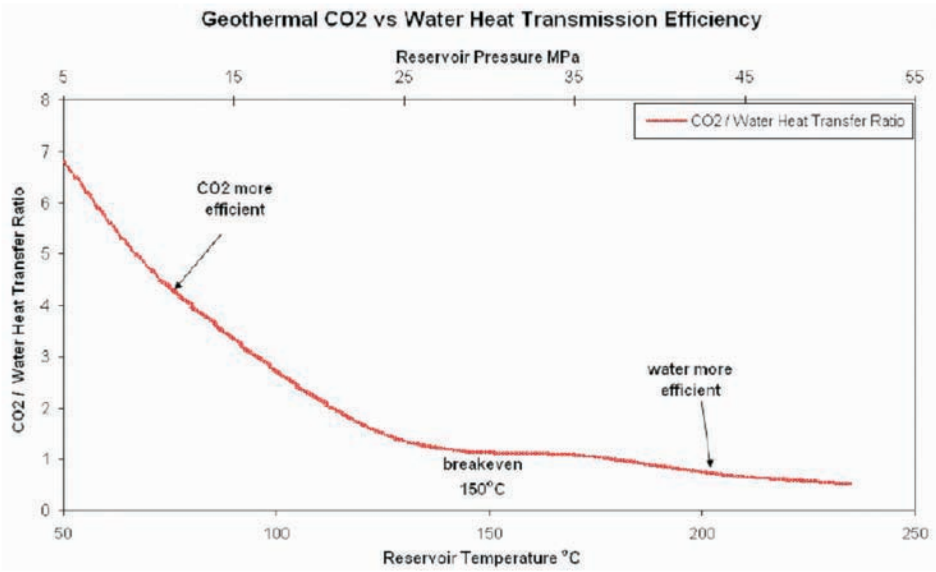

Figure 4. Carbon Dioxide vs water heat transfer efficieny.

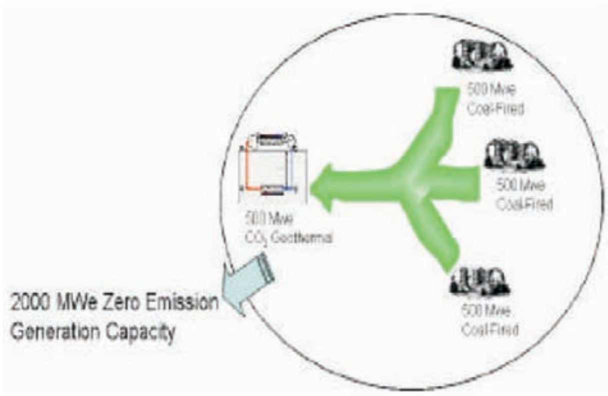

Figure 5. Geothermal power - CO_2 sequestration model (courtesy of UQ Geothermal School of Excellence).

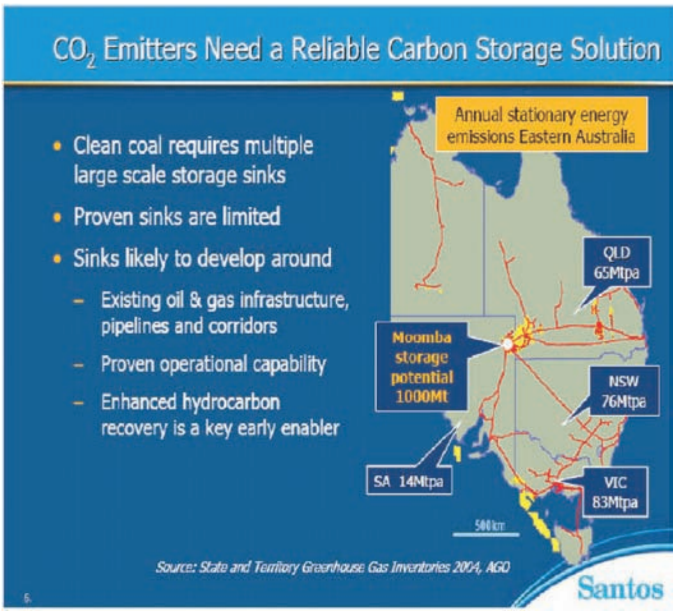

Figure 6. Santos Moomba carbon storage (courtesy Santos Ltd).

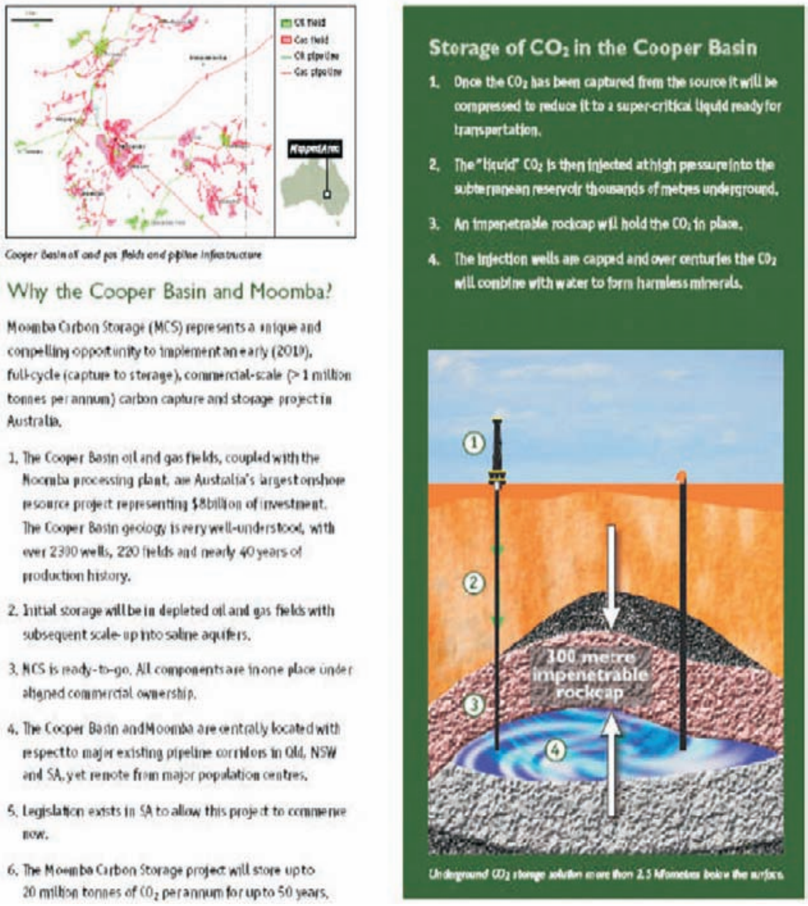

Figure 7. Santos Moomba carbon storage (courtesy Santos Ltd).

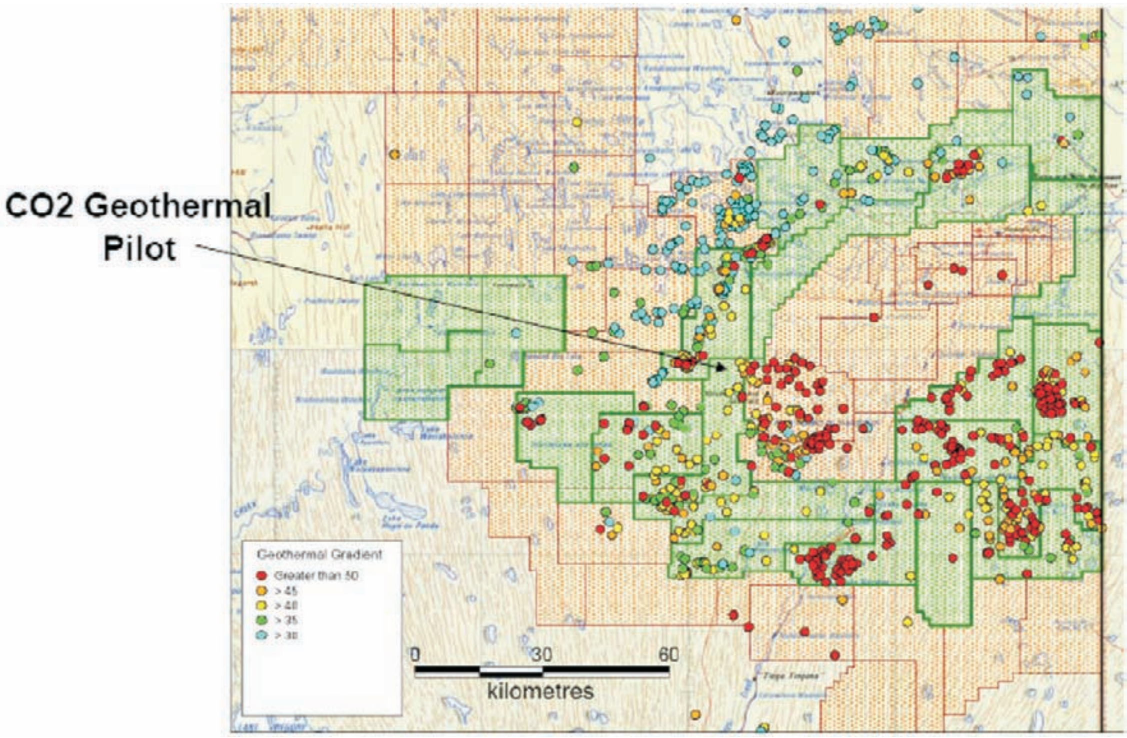

Figure 8. CEA geothermal tenements - Cooper Basin.

CO_2 Source Locations

Coal fired power stations on Australia's eastern seaboard are considered to be the most likely source of CO_2 for potential capture and geosequestration ('clean coal' technology), as well as potential use in EGS projects in the Cooper Basin. Relatively small volumes of CO_2 are extracted from Cooper Basin natural gas processing plant at Moomba, which could be captured and utilised *in-situ* for a small scale EGS / CO_2 pilot.

Project potential

In June 2007 Santos Ltd announced the Moomba Carbon Storage (MCS) project [2] concept to store CO_2 in depleted petroleum reservoirs in the Cooper Basin with the potential to become the world's largest CO_2 storage facility (Figure 7). Initial injection using CO_2 captured from the Moomba plant will commence at approximately 1 million tonnes per annum. Subject to the success of the demonstration phase, MCS would then be scaled up to serve as a regional, multi-user carbon storage hub serving eastern Queensland and NSW's Hunter Valley coal fired power stations. It is projected that these volumes could exceed 20 million tonnes per annum of CO_2 for over 50 years.

Coal fired power plants currently emit nearly 200 million tonnes per annum, approximately 30 % of Australia's total greenhouse gas emissions [3]. The Australian Greenhouse office has forecast that under 'business as usual' , by 2020, Australia will be emitting 837 million tones of which stationary emissions will account for over half (423 million tonnes).

It is estimated that EGS using CO_2 as heat transmission fluid, assuming losses of 5 % or more of the CO_2 circulation, has the potential to sequester the majority if not all of the projected CO_2 emissions from coal fired power stations, on an on-going basis.

In addition, the electricity generation from EGS geothermal would be estimated to add 1 MW of geothermal zero emission electricity generation per 3 MW of 'clean coal' sequestered electricity [3].

Project delivery

Clean Energy Australasia Pty Ltd (CEA) holds geothermal tenements in the SA Cooper Basin (10,950 km^2) and in the GAB in Queensland (3,600 km^2), suitable for large scale EGS electricity generation (Figure 8).

In the Cooper Basin, synergy exists between the MCS and EGS using CO_2 as heat transmission fluid, in sharing the capacity to support potentially large scale 'clean coal' projects in Eastern Australia, in addition to potentially large scale zero emission geothermal electricity generation.

As a first step, the feasibility of a Cooper Basin EGS / CO_2 pilot using CO_2 captured by the Moomba plant is being considered by CEA (Figure 9).

Pilot Project

The proposed Cooper Basin pilot would be a small scale demonstration plant, initially to match local CO_2 availability. Future major expansion is feasible once large quantities of CO_2 from coal fired power stations are transported to the MCS project (Figure 6)

Located near the Moomba plant, the pilot would consist of one injection well and one or more production wells. The wells would be drilled through sedimentary rocks to granitic basement, and then drilled a further 500 metres through basement. The temperature at total depth is estimated at 150-200 °C, based on temperature gradient is ~50 °C/km. The project parameters are estimated as follows;

Resource properties		
Thickness to 5km	1000 - 2000	metres
Thickness - wellbore	500	metres
Fracture height	100	metres
Porosity	2-5	%
Permeability	10-100	md
Well Depth	3000-4000	metres
Initial Conditions		
Water Saturation	100	%
Temperature	150-200	°C
Pressure	300-450	bar
Residual Saturation	5-30%	%
Temperature - 5km	200-250	°C
Temperature Average	~200	°C
Production/Injection		
Area	1	km^2
Injector-Producer Distance	0.7	km
Injection Temperature	25-50	°C
Rock grain density	2650	kg/m^3
Rock specific heat	1000	J/kg/ °C
Rock thermal conductivity	2.1	W/m/°C
Resource thickness	1-3	km

The expectation is that the basement rock will be water saturated. Initially the producing wells would produce of 100% water. Gradually over time increasing amounts of CO_2 would be produced (Figure 10). While theoretically 100% CO_2 production is possible, this is unlikely to occur for several years, if at all, due to migration of CO_2 to surrounding areas, reservoir rock heterogeneities,

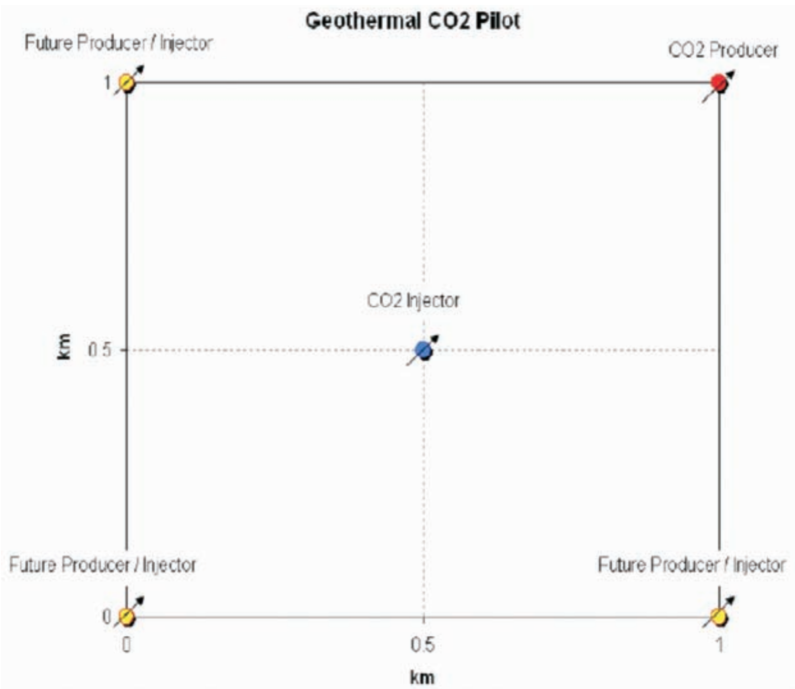

Figure 9. Geothermal using CO_2 pilot.

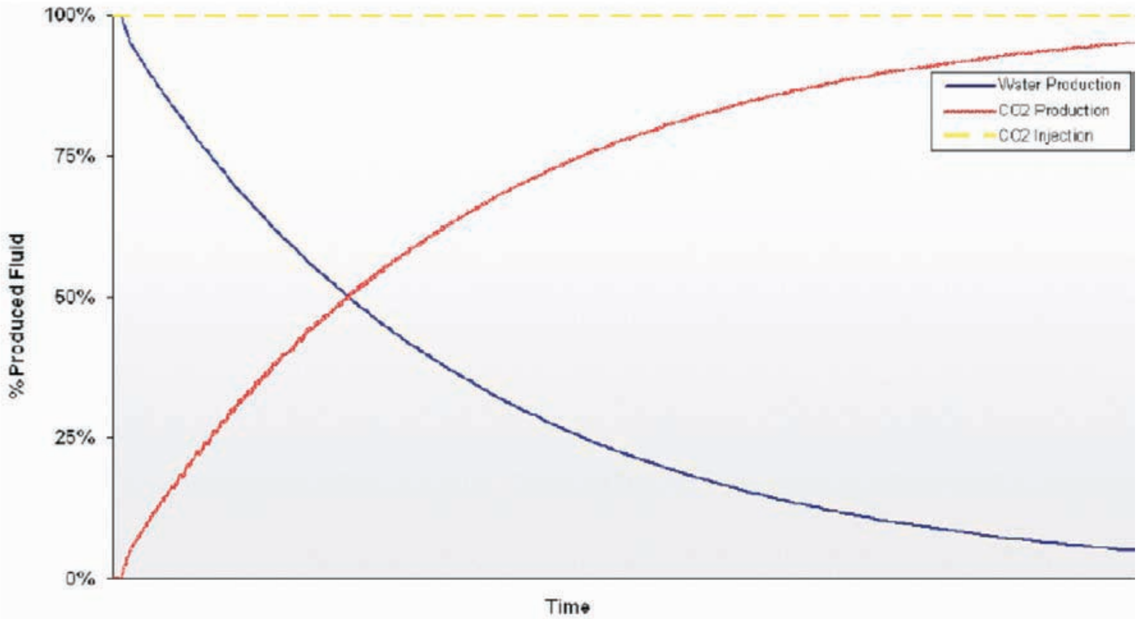

Figure 10. Geothermal CO_2 production / injection expected profiles using CO_2 as heat transmission fluid.

build up of residual CO_2 saturation, etc. Gradually, as the reservoir becomes saturated with CO_2, losses/sequestration are expected reduce to and remain at 5-10%, in line with experience with water based EGS systems.

Given the corrosive nature of CO_2 – water mix, the wellbore tubulars, as well the surface facilities in contact with reservoir fluids, would need to be constructed of corrosion resistant materials (Figure 2).

Project Expansion

The power generation could be readily expanded by adding more wells and increasing CO_2 injection volumes. CEAs 22 Cooper Basin geothermal tenements, covering an area of some 10,950 km^2 have the potential to sequester a significant proportion of Australia's greenhouse gas emissions in the medium to longer term. A single tenement of 500 km^2 could potentially generate 1000 MW using CO_2 as a heat transmission fluid and sequester 50 million tonnes of CO_2 per annum – approximately 25% of current CO_2 emissions from east coast coal fired power stations.

CONCLUSIONS

- CO_2 offers benefits as a geothermal heat transfer fluid to generate zero emission electricity.
- Significant CO_2 sequestration as part of this process results in negative emissions.
- CEA is actively pursuing a proof of concept pilot using CO_2 for geothermal.
- CO_2 geothermal could enhance the viability of 'clean coal' technology.

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The Impact Of Drilling Costs on Determining Optimal Well Depth for Geothermal Exploitation

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ABSTRACT

If we are to transition our global energy system and have geothermal energy play a significant role, it will be necessary to exploit the Engineered Geothermal Systems (EGS) resource on a large scale. To economically utilise low-grade geothermal energy for electricity generation from low gradient, conduction-dominated EGS resources, deep drilling will be required to depths of 6 km or more in most regions of the world. Even in mid- to high gradient regions where drilling depths will be less, drilling costs are still significant and inherently linked to reservoir productivity and reservoir temperature. Regardless of the fluid temperature or its enthalpy content, the lower the fluid productivity of the reservoir system per well, the greater the number of wells that are needed for a given energy production rate. Likewise, given the inherent limitations of thermodynamic conversion efficiencies, lower temperature reservoirs will require a greater number of wells for a given energy production rate. As well productivity or reservoir temperature decreases, individual well costs become increasingly important in terms of determining economic feasibility.

In general, higher reservoir temperatures are achieved with deeper wells. Higher geothermal fluid temperatures decrease per-kW-capacity surface plant costs. However, because drilling costs increase non-linearly with depth, a point is reached where the benefit of drilling deeper to reach higher reservoir temperatures is offset by the increased cost of drilling the wells. Our presentation reviews cost trends and limitations of conventional drilling and stimulation methods to identify a range of optimum drilling depths for developing an EGS resource. The sensitivity of optimum depth is explored as a function of resource parameters, including temperature gradient and well productivity. Our analysis illustrates that advanced technologies for drilling and reservoir stimulation are needed if we are to universally and economically utilise geothermal energy at levels that could make a difference in meeting national and international energy supply and environmental objectives.

Engaging Stakeholders in the Formation of Policy for Geothermal Developments

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ABSTRACT

The confluence of legislative tenure, renewable energy policy drivers, supportive equity markets and recognition of Engineered Hot Rock and Hot Subterranean Aquifer geothermal energy potential for Australia has seen the development of a nascent Australian geothermal industry with some 33 companies holding licences for exploration and or heat extraction from these reserves. It is estimated that there are sufficient energy in the Australian crust to provide renewable, clean, base load power to meet Australia's energy demand several times over.

While some forms of geothermal energy are mature and commercial, Australian reserves, geology and characteristics are different to existing developments and therefore unproven. Hence, significant development in drilling and stimulation technologies, resource assessment and transmission interconnection are required to prove these resources to be viable and practicable. Thus industry faces a number of challenges: technical, environmental, regulatory, financial (institutional capability approvals) and legislative. These include different treatment of permitting across the different states, different treatment of indigenous community rights, high cost of project finance capital (due to the 'unproven' nature of the technology as a whole), tightening labour markets and equipment shortages and remoteness.

This paper explores the processes developed and undertaken to engage all potential stakeholders in this new industry: industry players; related industries (such as oil and gas explorers); financial institutions; law firms; community groups; government and government officials, to identify raise and discuss issues that might impede the rapid development of the industry. As well as to identify and adopt/adapt solutions and expertise that already exists in other industries to avoid the industry "re-inventing the wheel". The result being a series of key and fully auditable recommendations that will aid informed, co-ordinated policy making within government across the areas of:

- Technology;
- Research, training and skills development;
- Legislative and regulatory framework;
- Private and public financing structures; and
- Community concerns.

As well as outlining the processes developed, we report on the success of the methodology in gaining input from all relevant sources, in increasing the 'knowledge base' amongst stakeholders and in identifying key recommendations to support the development of a sustainable and sizeable geothermal industry in Australia. Finally, we outline possible improvements to the methodology and discuss other potential areas for its application in overcoming barriers to implementation of sustainable energy technologies.

Geothermal Energy Regulation

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INTRODUCTION

The paper will examine regulation which affects the geothermal industry on a national basis.

The examination will cover 5 primary fields:

- the capacity to regulate the geothermal industry nationally;
- the lack of consistency in current State based geothermal legislation;
- the regulation of simultaneous geothermal and mining or petroleum operations
- the lack of a consistent approach across jurisdictions to application of other legislation to the geothermal sector
- the adequacy of other legislation which affects the geothermal sector.

Each of these fields will be considered by reference to actual examples.

In relation to the 4th area of focus, particular attention will be given to the question of land access and the application of the right to negotiate procedure under the Native Title Act to geothermal operations.

NATIONAL REGULATION

There is a natural desire from the sector for consistency of legislation nationally.

The paper will consider the constitutional capacity for the Commonwealth to legislate for the sector, a voluntary referral of powers to do so by the States or a co-operative legislative scheme.

It will be argued that this is a remote possibility even in an environment where the Labor Party is in power federally and in all States and the Northern Territory.

It will be concluded that the sector would better use its energies on seeking greater consistency between State based legislation than seeking a national legislative scheme.

STATE BASED LEGISLATION

The legislative picture is characterised by different approaches in each jurisdiction.

There is a significant lack of consistency in approach.

Three primary examples of this will be noted:

- the legislative framework within which geothermal regulation has been placed
- the definition of geothermal energy
- the degree to which geothermal sector activities are regulated in each jurisdiction

It will be argued that inter-jurisdictional consistency is unlikely to be achieved.

The analogy of other resources industry legislation will be applied to support this proposition.

Nevertheless it will be submitted that the AGEA should lobby for a greater level of consistency in key concepts in the legislation of each jurisdiction.

SIMULTANEOUS OBLIGATIONS

Geothermal operations run the risk that they are conducted or proposed to be conducted in the same area as already existing or subsequently commenced activities by other resources sectors – minerals or gas/petroleum exploratory or production operations.

The paper will examine the inadequacies of current geothermal and related resources legislation in dealing with this issue.

The paper will also propose more adequate means by which this issue can be more effectively regulated.

INCONSISTENT APPLICATION OF OTHER LEGISLATION

The most topical area in this regard is the application of Sub-Division P of Part 2 of the *Native Title Act* to geothermal operations.

The paper will note the different approach in this regard of the various State geothermal regulators.

The paper will examine the requirements of this Sub-Division and, in particular, the definition in section 253 of the *Native Title Act* of "mine" and consider whether "mine" applies to geothermal operations.

The paper will also consider the various definitions of geothermal energy in State geothermal legislation and assess whether there are any differences in these definitions which give rise to these different regulatory approaches.

The paper will examine the circumstances in which the "right to negotiate" process was introduced when the *Native Title Act* was enacted in 1994, will argue that it would be a retrogressive step to extend the application of the process to the geothermal sector and that this should be opposed by the sector.

The paper will note that, even if the "right to negotiate" process were not to apply, the sector still needs to deal with native title issues, particularly at the production stage. The implications of these requirements will be examined and the conclusion drawn that ultimately the geothermal sector will need to deal with native title even if the "right to negotiate" process does not apply.

ADEQUACY OF OTHER LEGISLATION

In a number of areas legislation which affects the geothermal industry does not adequately take account of the requirements of the industry.

Whilst mention will be made of other areas, water resources legislation will be used as an example to illustrate this issue.

The paper will argue that this in an area of primary focus for AGEA in lobbying for legislative change affecting the geothermal sector.

Advancing Geothermal Energy — Opportunities, Options and Strategies

A PRELIMINARY DISCUSSION ON MAXIMISING SUCCESS IN AN ENVIRONMENT OF HIGH UNCERTAINTY AND RAPID CHANGE

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ABSTRACT

With energy security and climate change as the backdrop, there is an urgent need to diversify national and international energy portfolios to include renewable and near-zero emission generating energy sources and technologies. This paper provides a preliminary concept and discussion on a current project, "Advancing Geothermal Energy – Opportunities, Options and Strategies". The project is due for completion in June 2008.

In this paper we attempt to provide a clear description of the project. This includes key theoretical frameworks and concepts being used within the project and commentary on preliminary project findings. These findings include the emerging major factors and uncertainties facing the geothermal industry.

We propose that the combined use of new theoretical frameworks and leading-edge concepts that incorporate uncertainty and dynamism can yield significant insight for parties interested in geothermal energy, in particular energy players and geothermal players. This insight holds the potential for players to make significantly enhanced strategic decisions, undertake an enlightened management of options and understand the relevant uncertainties and shaping factors within which the options are contextualised. In summary, by moving beyond technical focus and traditional strategic approaches, geothermal companies can advance their commercial interests and maximise the likelihood of success in an environment of high uncertainty and rapid change.

About the Project

NEGOTIACTION is undertaking this research and analysis project through our cross-disciplinary, innovative NEGOTIACTION Challenge project model (see Appendix 1.0). With energy security and climate change as the backdrop, there is an urgent need to diversify national and international energy portfolios to include renewable and near-zero emission generating energy sources and technologies.

Different challenges and opportunities for deployment and diffusion are associated with each technology, and these influences may vary significantly across and within different states [1], different time horizons and in light of different plausible scenarios and environmental outcomes. Some key issues for consideration include:

- Poorly defined economic costs, market share and technology improvements in the emerging carbon economy;
- Some remaining uncertainty about technological feasibility;
- The rate at which alternative energy sources can be diffused; and

- Community perceptions about each technology (that may or may not be soundly or objectively based) [5].

In Australia, geothermal energy is one such potential energy source and there are a number of drivers and uncertainties that are informing the decision making agenda and shaping the risks and opportunities for different types of energy players. To date a variety of perspectives and expectations have been posited about geothermal energy in Australia, in particular pertaining to hot dry rocks.

This initiative is focused on two commercial perspectives. One perspective covers energy players seeking to understand potential plays[1], shaping factors, uncertainties and the design of options in taking an interest within the geothermal industry. The other perspective covers the perspective of geothermal energy companies seeking to understand potential plays, shaping factors, uncertainties and options in enhancing the likelihood of their success through better managing uncertainty and the design and implementation of market strategy.

We intend to generate insight and provide enhancements in the use of critical futures, strategy and energy frameworks in advancing emerging geothermal technologies under significant uncertainty. This project will have a number of potential avenues through which the geothermal industry and those interested in participating in it could stand to benefit. The four outcomes that we are seeking to generate through this project are:

- An outlook on the extent to which geothermal energy could shape Australia's energy future.
- Identification of plays available to be advanced by energy players either today or in the near future.
- Evaluation of the attractiveness of these plays using qualitative and quantitative criteria, assessed over several time-horizons.
- An appreciation of the significant factors driving the value of these plays and the extent to which these factors may be controllable, influenceable, or predictable by business, community or government.

As a result of this project we hope to make a significant contribution to the advancement of the geothermal industry.

This initiative will be contextualised within existing and developing policy frameworks and major national and international studies such as *The Heat is On – The Future of Energy in Australia* undertaken by CSIRO, the upcoming Geothermal Industry Development Framework commissioned by DRET and ABARE's Energy in Australia 2008.

UNDERPINNING THEORETICAL FRAMEWORKS AND KEY CONCEPTS

In the geothermal industry advances will not come easily. Accordingly, all players will need to work hard simply to stay in the game. But unlike their losing cousins the winners will be those companies that work hard and think smart. At the core of smart thinking is the confidence to view options from a strategic perspective and the ability to consider prospective futures, to execute enlightened strategy and plays, and to apply futures thinking, uncertainty concepts and real options logic.

By assuming this approach the geothermal winners will be able to identify with increasing confidence the pathways that could lead to attractive prospective futures. Smart thinking also enables the winners to act with agility. In this way they will be able to shape the game and respond to events as they unfold. It is of concern to us that many geothermal companies are unlikely to be equipped to take this approach. They could be wedded to reactive tactics rather than proactive

[1] Plays are courses of action involving one or more entities and can be identified and exercised now or in the near future.

strategies. Or they could be grounded in basing their decisions on past experiences and their current situation. Or worse yet, they could suffer from both limitations.

Futures Thinking and Uncertainty

Success in the competitive and dynamically changing business environment is often measured by management's flexibility and ability to adapt to changes [9]. Incorporating futures thinking enables us to reframe our analysis, move away from narrow or familiar perspectives and to consider the many futures that could unfold: what is possible, what is plausible and what is preferable. By looking at these alternatives and thinking in broader perspectives we can gain multiple benefits including better identifying the relative attractiveness of strategies.

Uncertainty

Uncertainty could be a source of value creation [6] and could also be a source of value deterioration. To make better strategy choices under uncertainty, the uncertainty must be understood.

Traditional approaches to decision-making assume a static, relatively linear processes with fixed outcomes [9]. The typical strategic-planning and decision-making process is built around describing the strategic action in great detail and a fact-based case to estimate expected economic return. In generating point-forecast assumptions, managers are encouraged to ignore whatever uncertainties they may find. This business case approach assumes that a deep analytical understanding of today is the key to developing foresight about the future [2].

The use of traditional strategy processes in the context of non-traditional environments characterised by significant uncertainty lead to strategies that fail to either manage risks or take advantage of opportunities [2]. Futures thinking and concepts are non-traditional tools that assist in dealing with different types of uncertainty and complexity. Concepts that are of particular significance are drivers and indicators.

Drivers

Drivers are the key factors that underpin and effect change. Defining the drivers of major trends enables us to understand change dynamics, anticipate discontinuities and gain a stronger appreciation for alternative futures.

Indicators

Indicators come in two types – events and variables. It is through identifying relevant, significant indicators that geothermal players can undertake effective monitoring and therefore more effectively execute strategies and plays within highly uncertain and complex environments.

Events are discrete occurrences that either happen or don't. Examples of events include securing a geothermal tenement, gaining project finance, accessing a drilling rig and executing a contract with complementary geothermal companies within a formal consortium.

Variables are continuous quantities that vary over time and can be a part of trends and long-term changes. Demand for electricity, economic growth, interest rates, price of carbon, geothermal source temperature and steam flow rates are examples of variables. Variables can act in a number of ways. They can be constant or change, and can change at varying rates or in varying directions. Any one of those movements could be an indicator that one or another scenario is developing [7].

The time horizons that are relevant, the time horizons that are considered and the role that time plays in changing industry landscapes is a critical factor of consideration.

IN FOCUS: REAL OPTIONS AND OPTIONS LOGIC

One particularly compelling play logic is the integration of real options reasoning and analysis in the design and execution of strategic and operational commitments. This is applicable in several ways in the energy industry.

Real options are defined as "investments in real capital, relationships, capabilities, and other tangible or intangible assets that offer the asymmetric payoff profiles associated with financial options"[2]. Such investments are option-like, because they create or potentially create a decision right available to be exercised in the future, importantly allowing for further learning about the potential payoff before the future decision is made.

Flexibility to change direction can reduce investment risk and expand potential value creation in environments of significant uncertainty, unpredictability or rapid change. This is the key benefit to a staged, option-like resource commitment as opposed to an irreversible commitment.

On a business strategy level, real options reasoning involves framing decisions in such a way that major opportunities and choices for learning and commitment are rigorously identified and evaluated in light of their potential contribution to achieving a strategic objective such as future growth or hedged risk.

It is important to note that not every option created is destined to be exercised and thus some resources committed may be seen in hindsight as yielding little payoff. Thus, a key insight of real options reasoning is to structure both highly leveraged options, where the payoff is significant relative to its cost and following through with the larger commitment that is usually required to realise the option value created.

Contingent road maps or option management frameworks are examples of practical strategy tools that can be created – linking indicators (events and shifts in variables) with implications on strategic decisions [2].

A simple example of a strategic real option play in the energy industry could be a player's staged entry into the geothermal market, in which the energy player, perhaps through joint venture, locks in a future contractual right but not an obligation with a smaller geothermal player, to provide full production phase investment should technical uncertainties (e.g. temperature and flow rates) and environmental uncertainties (e.g. the emission trading scheme's indirect effect on energy prices), both affecting the variability in future cumulative revenue from the production lifetime, be resolved. Given the scarce nature of geothermal projects underway, an energy player securing this kind of option, in a single instance, or with several projects, may necessarily lock out their competitors from similar option-like or irreversible commitment opportunities.

Real options analysis can also play a valuable role in many operational investment decisions, as seen in the oil industry. This industry is characterised by large investments in time, money and technology. Decisions are based on imperfect information and under typically significant uncertainty. In order to manage a project under a scenario of future uncertainty, coupled with investment irreversibility, the manager needs managerial flexibilities (real options) to adapt the project to new market conditions [10].

While qualitative and quantitative modelling of decisions using real options techniques can be highly complex it can be used to model serious decisions and overcome the shortcomings of traditional net present value (NPV) project valuation. This does not factor in the flexibility of decision-making and inherent option value.

Examples of decisions which could be analysed in the geothermal area using real options techniques during exploration and appraisal phases include the level of investment that should be spent in acquiring geological data, and how much risk should be ideally shared with a collaborator; as well as the number and location of wells to be drilled, and the size of the power plant in the development and production phases.

Using real options reasoning and analysis in certain strategic and operational decisions allows organisations to enhance their management of risk and uncertainty. For organisations with interests or prospective interests within the geothermal industry, incorporating qualitative and quantitative elements serves to position and monitor for new value creation and capture opportunities.

COMMENTARY ON PRELIMINARY PROJECT FINDINGS

In the geothermal industry there will be winners and there will be losers. One thing is clear from the official releases of publicly listed geothermal companies and the comments made through reputable media channels by privately held geothermal companies. This thing, simply put, is obsession. These companies are obsessed with their energy sources, their geology, their tenements, their drilling technologies, their power generation technologies, their drilling programs and their ability to connect via existing or planned infrastructure to the all-important power grid. But the obsession with these hard-core technical factors is simply not enough.

In fact, we argue that this obsession is counterproductive and will probably lead to the demise of many geothermal companies. In our view some geothermal companies are going to succeed in attracting the relatively large tranches of capital they so desperately require and transform vision into reality to become big winners in the emerging clean energy game. These companies understand things that the others do not.

They understand that their success depends on moving beyond technical models and purely technical considerations to adopting advanced commercial thinking and doing.

One such element of advanced commercial thinking is the understanding that success depends on a handful of critical relationships within and beyond the geothermal industry. By working collaboratively with well-chosen organisations geothermal companies can create greater value. Furthermore, fair shares of value can be captured by designing and executing in an environment where uncertainty is managed and futures thinking is built into organisational process and culture.

At this stage of the project we provide preliminary views on a select few drivers and factors for change affecting geothermal energy's diffusion in Australia. These drivers and factors have been identified based on their prospective role in shaping the geothermal industry and in particular the strategic plays – and the attractiveness of these plays – that energy players could pursue.

Selected key factors and drivers will be explored in detail through the next phase of our project, in particular where drivers and indicators will be connected by a vision of the future, enabling the analysis and profiling of key strategic plays. Given the project is still underway and a layered process of verification is not yet complete these are subject to refinement and change.

Selected key drivers for change affecting geothermal energy (in no particular order):

1. Carbon Constrained Future

Refers to the eventual outcomes that systems such as an Emissions Trading Scheme (ETS) will produce around the globe and the consequences for Australia. Geothermal will need to compete with, and provide cost savings over, other technologies to win the market mandate. The strength of a domestic target and international linkages are likely to see an EU-style carbon price emerging. Auction revenues may provide additional support for overcoming first mover disadvantage and transmission connection [11]. Many uncertainties remain about the design and implementation of Australia's ETS, and how the dynamics will play out to produce intended and unintended consequences in the energy sector broadly and the geothermal industry specifically. This is seen to be a factor that will continue over the long term.

2. Social Attitudes

Refers to how people are responding to climate change and associated sustainability issues. The speed and coverage of climate change communications by geothermal companies and other stakeholders is relevant. It refers not only to awareness but also acceptance of the issues so as to affect behaviours related to energy demand. This encompasses demand for renewable energy generally and geothermal energy specifically. This is seen to be a factor operating over the long term.

3. Renewables Portfolio

Refers to the mix of existing and potential renewable technologies (wedges) that will be eventually adopted and diffused. While it seems evident that many forms of renewable technologies will have to be implemented in order to have a positive impact on greenhouse gas emissions and global warming, it is the exact mix of technologies chosen that remains uncertain. Early successes in one renewables technology with possible consequent heavier investments may reduce investments in other technologies. Many uncertainties are collectively contributing making commitment decisions difficult at this moment. This factor may have a shorter timeframe than other two.

See Appendix 3.0 for a more detailed snapshot of some factors included within project analysis.

CONCLUSIONS

With energy security and climate change as the backdrop, there is an urgent need to diversify national and international energy portfolios to include renewable and near-zero emission generating energy sources and technologies.

Preliminary project findings propose the major drivers for change affecting geothermal energy (in no particular order) as: carbon constrained future, social attitudes and renewables portfolio.

In the geothermal industry there will be winners and there will be losers.

We propose that the combined use of relatively new theoretical frameworks and leading-edge concepts that incorporate uncertainty and dynamism can yield significant insight for parties interested in geothermal energy, in particular energy players and geothermal players.

This insight holds the potential for players to make significantly enhanced strategic decisions and undertake enlightened strategic management of options and the relevant uncertainties and shaping factors within which the options are contextualised.

In summary, by moving beyond technical focus and traditional strategic approaches, geothermal companies can become more commercially advanced, and maximise the likelihood of success in an environment of high uncertainty and rapid change.

As a result of this project we hope to make a significant contribution to the advancement of the geothermal energy industry.

ACKNOWLEDGEMENTS

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Appendix 1.0

About NEGOTIACTION Challenge

To date we have engaged dozens of leading thinkers from major Australian Universities through the vehicle of NEGOTIACTION Challenge and made significant contributions to their growth and development and the field into which Challenge is being applied.

Each round of Challenge is unique, and involves the serious input of one or more teams in "solving" a nominated client project, internally-driven research initiative or opportunity realisation. As a result of our interactions some of our Challenge Alumni have joined our team, some have assumed greater prominence within academia and others are confidently contributing within our business community and government.

This is a unique opportunity for academics and students and an effective vehicle for working on major challenges in a way that drives innovation and forms a successful nexus between academic theory and commercial application. NEGOTIACTION places a high value on disciplined collaborative endeavours.

The transdisciplinary team with academic-commercial crossover creates effective and exciting innovation within projects.

"We have begun to appreciate more fully how the world's dazzling know-how can solve the seemingly unsolvable when we view our problems through the right perspective." – Ban Ki Moon, Secretary-General United Nations on solving Climate Change, TIME Magazine

Appendix 2.0

NEGOTIACTION Challenge Project Team:

NEGOTIACTION Project Team

David La Ferla, Managing Director, Stakeholder Relationship Manager

Wendy Miller, Initiative Project Manager

Jonathan Gomez, Project Lead Architect & Challenge Team Leader

Shiraj De Silva, NEGOTIACTION Research and Project Support

Project Panel

Dr Graham Mitchell AO, Principal, Foursight

Charles Brass, Founder and Chair, The Futures Foundation

Dr Graeme Beardsmore, Senior Research Fellow (Hons), School of Geosciences Monash Univeristy; Technical Director, Hot Dry Rocks

Guest Speakers

Justin Hillford, Director of Corporate Strategy, Telstra

Amir Kordvani, Associate Director, Centre for Resources, Energy and Environmental Law University of Melbourne

Julian Turecek, Investment Manager, Cleantech Ventures

Cate Turner, Consultant, RMCG

Project Team

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Oscar McLennan, Project Strategist

Vivek Prasad, Project Strategy & Finance, Real Options Valuation

Zhi Hao Yao, Project Strategist

Appendix 3.0

Table 1: A snapshot of some factors included within project analysis

Technical

Geographical Location / site (sources of energy, proximity)
Potential availability of drilling rigs and personnel
Training, skills base, personnel availability
Research base - exploration modelling, tools e.g. remote sensing, techniques, geological understanding
Geological suitability - temperature, flow rates, depth, fluids, hydraulic stimulation behaviour, stress regimes
Project development Timeframes
Transmission (capital cost, infrastructure availability, operating cost, maintenance, efficiency)
Project life-cycles - exploration, appraisal, development, production & divestment, and respective (and relative) certainty of outcomes from each phase.
Position of geothermal on technical and technological innovation curve - Degree of HFR technology development
Importance of success of key geothermal demonstration plants, proof-of-concept
Unknown technical implication resulting from AETS

Political /Government/ Regulatory

Licensing Policy - Exploration, Production & Retention Licenses
Ownership of assets and transmission lines - regulation
Likelihood of tax incentives to invest and the nature of these investments
Geothermal regulations being modelled on natural resource tenements and the variations in these regulations across the states
State policy convergence or divergence
Targets in emissions
Conflict resolution and Management/Reduction of Regulation Complexity and Duplication between and within resource types and elements of industry value chains
Emissions Trading Scheme (e.g carbon prices, caps and the implications for the economic viability of incumbent and emerging industries)
Measures for transitioning to the ETS
Federalism in shaping the relative positions and interests of federal, state and territory governments
Political inertia and/or resistance
Government measures (e.g. grants, rebates and innovation funding)
The calibre and wider acceptance of the Geothermal Industry Development Framework and the associated roadmaps
The parameters of construction codes and standards deployed - residential and commercial

Social

Consumer attitudes - demand for "green" energy
Consumer behaviour - e.g. ETS ethical offset - increasing demand/guilt factor/ cap
Citizenship (e.g. national participation, activism, voting power)
Ramifications of major events such as energy-related events
Role of education - energy management/efficiency
Siting - NIMBY
Social inertia and/or resistance
Shifts in perspectives on timeframes from short-term to long term
Design of global management systems - holistic nature
Native title

Environmental

Surface impact of plant infrastructure and transmission lines - impacts
Potential surface expressions of induced seismic events
Interaction between 'power-up' (renewable) and 'power-down' (efficiency) to reduce CO2

Emissions from stationary energy sector - largest in relative and absolute terms, therefore prime target for mitigation

Catastrophes - susceptibility to weather changes and consequences of catastrophes

Potential loss of water deep underground - effects on farming and communities

Inevitable climate change

Loss of heat at surface negligible

Loss of heat deep underground - leading to thermal contraction

Transient design and construction impacts

Shifting climatic and seasonal conditions - impacts on current land utilisation

Economic

Degree of foreign entity interest - foreign investment

Foreign entity interest - expertise - affecting rates of development, timeframes

Skills availability - Technical and Implementation

Location assets vs Intellectual property

Likelihood of skills transfer from oil industry

Geothermal companies - revenue generation difficulties

Capital constraints

De-stabilisation and shifts from conventional global energy models

Transparency and liquidity provided by ASX Coal Futures market

Relative cost of other renewable energies - shifts in demand and supply

Shifts in competitiveness of energy types

Export/import industry

Rural and urban economic development

Cost of electricity and industry cost structure

Design/construction benefits and operation benefits

Business / Industry / Commercial

Private investment interest and frameworks (ethical investment schemes)

Intra-industry and cross-industry collaboration - research and sharing lessons to reduce critical uncertainties

Business risk management (hedging, strategy, taxation, shifting between subsidiary, fee transfer)

Degree of collaboration with research bodies (research funding directed towards green)

Importing and exporting geothermal expertise (skills)

Entrepreneurial climate

Ease of market entry, competitive forces

Business relocation or takeover possibilities - CO_2 mitigation strategies

Early successes and early failures in geothermal may affect the way geothermal energy is used - electricity/direct use

Early successes and early failures in geothermal may affect the way people perceive geothermal (addresses doubt, investment interest)

Revenue challenges

Disciplined investment by players with stakes in the largest geothermal companies

Influence by and involvement of AGEA and AGEG

Industry expectations regarding funding (antagonism in the market and continuing need for investment)

Path dependence (huge funds available for coal mining research and relatively few for geothermal)

Heavy dependence of success of demonstration plants

Challenges for a Future Australian Electricity Network Dominated by a Geothermal Hub

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ABSTRACT

When a large power plant is located far away from major load centres and also from the high voltage transmission grid, a number of significant issues need to be investigated. In the context of huge potential for geothermal energy in the area of Cooper Basin, electricity transmission issues will provide some key challenges and opportunities for a future secured power network for the Australian national electricity grid. The Cooper Basin does not have electricity consumers next to it, so the power would have to be transmitted quite a long distance over costly transmission facilities. For example, the Innamincka power plant, which plans to produce 50 MW in 2012, will send electricity over 110 kms of transmission lines to the Moomba oil and gas field. It is understood that a 500 MW plant will be built by 2016, which is expected to supply power through a 500 km high-voltage transmission line to the national electricity grid in Port Augusta, and a transmission line to BHP Billiton's Olympic Dam mine, 490 kms away.

By 2030, Australia electricity usage will increase by 66%, with one third of this growth in Queensland. Hence, when large geothermal power plants will be built in the future, power will possibly be transmitted to the Queensland electricity network, which is further away compared to the South Australian grid locations. When the transmission lines are long and the lines carry AC power the reactive power loss at peak load, line charging at off peak load and hence voltage stability issues becomes extremely important to maintain power grid security. In addition, the possibility of inter-area frequency oscillation can't be ignored when power is transmitted through AC transmission lines and the use of flexible AC transmission systems or high voltage (HV) DC transmission systems needs to be examined. There are proven technologies in HVDC converters/inverters, but interaction with HVAC lines and related costs versus technical advantages need to be investigated in an optimum way. The Australian grid in general is weakly meshed and is almost a radial network. Hence any outage of a key transmission facility can create a catastrophic imbalance between generation and demand. This can also create cascaded blackouts. To better understand the consequences of such events, a comprehensive power systems analysis of the national electricity grid is required with possible combinations of geothermal power plants and their connections to the grid. In a deregulated electricity market with a foreseeable carbon trading scheme a number of relevant economic issues also need to be investigated.

This presentation will focus on some key challenges relating to building new transmission facilities for transmitting large amounts of electricity over long distances. Some of them are:

- HVAC versus HVDC, regarding cost and network security;
- HVAC and HVDC interactions;
- Grid stability: thermal, reactive power, harmonics, voltage limits and inter-area frequency oscillation; and
- Overall grid security.