Hot dry rock geothermal exploration in Australia

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Abstract

Hot dry rock (HDR) geothermal energy is obtained by circulating water between injection and production wells through hot subsurface rocks. The recovered hot water should be around 250ºC for efficient electricity generation. South Australia has become a focus for HDR developments due to its exceptionally hot subsurface rocks. Geothermal Exploration Licences have been issued in South Australia following modifications to petroleum legislation. New South Wales has issued geothermal licences after modifications to mining legislation. Renewable Energy Certificates, mandated by the Commonwealth Government, increase the competitiveness of electricity generated from renewable sources such as geothermal energy.

Previous HDR projects have focussed on areas of known high geothermal gradient, based, for example, on experience from petroleum wells such as the European Soultz-sous-Forêts site and Geodynamics' Habanero-1 well in the Cooper Basin. An alternative strategy is to explore for the highest geothermal gradients closest to electricity markets. MNGI/Petratherm holds Geothermal Exploration Licences within the exceptionally hot South Australian Heat Flow Anomaly and will target buried thermally anomalous granites and radiogenic iron oxides therein. Simple thermal calculations indicate that under suitable circumstances temperatures of 250ºC may be attained at depths <4 km within the licences. The thermal conductivity of the cover rocks is as important a factor as the heat-generating potential of the basement. There exists a continuum of geothermal energy sources from hot, shallow, high-permeability aquifers to deeper, tighter aquifers, to hot fractured basement, to basement hot dry rocks. Indeed end-member HDR-type targets may be relatively rare and commercial HDR exploration may also target conventional geothermal resources.

Keywords: hot dry rock; geothermal energy; geothermal exploration; South Australian Heat Flow Anomaly

Introduction

Australia is a minor player in world geothermal energy production with a nominal 150 kW plant at Birdsville, Queensland, powered by approximately 98ºC water from the town's water bore. This well has flowed for 45 years and produces water at about 30 litres per second from the aquifers of the Great Artesian Basin at 1,173–1,220 m depth (Burns et al. 2000). New Zealand, in contrast to Australia, has an installed capacity of some 437 MWe of geothermally-fuelled electricity. The Philippines and the United States each have installed capacities of approximately 2 GWe, together equalling half the world's capacity of 8 GWe of geothermally-fuelled electricity (Huttrer 2001).

Conventional geothermal (hydrothermal) energy is generally produced from hot water from relatively shallow, hot aquifers in volcanic regions. Cooled geothermal brines may be re-injected back into the source aquifer both to dispose of the cooled brines and to maintain reservoir pressure. Given that geothermal electricity must be produced on site, there is a requirement for shallow, hot, permeable aquifers in the vicinity of markets for electricity. Australia's potential for such conventional geothermal energy production is generally perceived to be low.

Recently, however, Australia has had a high profile in geothermal energy. Geodynamics Ltd drilled a 4,420 m deep well into the basement of the Cooper Basin during 2003 in the first

Figure 1. Location of Cooper Basin, Great Artesian Basin (known to geologists as Eromanga Basin) and South Australian Heat Flow Anomaly. As indicated by Neumann et al. (2000), and Figure 5, the extent of the SAHFA is not precisely constrained, but it is centred on the western margin of the Adelaide Fold Belt. It may extend in a northerly direction, passing into the basement of the thermally anomalous Cooper Basin system.

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stage of an attempt to engineer a hot dry rock (HDR) geothermal reservoir. The Cooper Basin underlies the Great Artesian (or Eromanga) Basin (Fig. 1). Another paper in this volume describes the Geodynamics project (Wyborn et al. this volume).

Hot dry rock geothermal reservoirs contrast with conventional geothermal reservoirs in that the rocks are generally deep, impermeable and with little or no porosity/fluid content. Hence a geothermal reservoir must be engineered by pumping cool water down an injection well and recovering hot water from a nearby production well(s), with flow between the two wells stimulated by the pressure of injected fluids.

The HDR resource is larger and more widespread than the conventional geothermal resource and, for example, is considered likely to be the future of geothermal energy in the United States (US Department of Energy, 2004), where the term 'Enhanced Geothermal Systems' or 'EGS' is used as a more general term describing HDR. The potential for HDR-generated electricity in Australia was recognised from Somerville et al.'s (1994) map of estimated temperature at 5 km depth in the Australian crust based on temperatures measured in 3,291 wellbores. In large areas of Australia the temperature at 5 km is >250ºC. Significantly for HDR development, around 250ºC is considered optimal for electricity generation from hot water. The largest area of hot subsurface rock recognised by Somerville et al. (1994) underlies the Great Artesian Basin. This explains the presence of the hot aquifers of the Great Artesian Basin (Burns et al. 2000) and the targeting by Geodynamics Ltd of the underlying basement. Temperatures in the Cooper Basin sector of the Great Artesian Basin are well constrained by borehole data due to hydrocarbon exploration.

Thermal modelling of the South Australian Heat Flow Anomaly (SAHFA; Neumann et al. 2000; Fig. 1), which is only sparsely sampled by relatively shallow boreholes in Somerville et al.'s (1994) map, indicates that geothermal gradients there may be in excess of those in the Cooper Basin given circumstances outlined in the thermal modelling presented herein. Furthermore, anomalously hot regions within the SAHFA are in reasonable proximity (approx. 100 km) to the national electricity grid and to major minesite clients, such as Olympic Dam and Prominent Hill. The recognition of the SAHFA as a potential geothermal source has led to an alternative geothermal energy strategy in South Australia, which has been proposed by Petratherm Ltd. This alternative strategy involves exploration for the highest geothermal gradients in proximity to electricity markets and optimal exploitation of those hot rocks either as engineered HDR systems and/or enhanced Hot Wet Rock (HWR) and/or conventional geothermal systems. The key rationale of Green Rock Energy/Perilya in applying for licences in the vicinity of Olympic Dam has similarly been to seek the highest geothermal gradients in proximity to electricity markets (Adrian Larking and Simon Ashton, pers. comm. Green Rock Energy Pty Ltd 2004). Pacific Power and Geodynamics have also undertaken such a strategy in identifying a potential HDR resource in the Hunter Valley, New South Wales.

This paper briefly reviews the HDR process and the experience of major HDR developments worldwide to date. It then summarises the licencing and political framework for geothermal exploration in Australia, focussing on South Australia which has become the focus for geothermal exploration in Australia, both because of its exceptionally hot rocks and because of its licencing framework. Finally, the paper summarises Petratherm's approach to geothermal energy exploration. A companion paper discusses techniques for optimising the subsurface fluid flow between injection and production wells, recognising the influence of pre-existing natural fractures and of the in situ stress field on hydraulic stimulation of the thermal reservoir (Reynolds et al. this volume).

Hot dry rock geothermal energy: the process

We recognise three distinct stages to HDR geothermal electricity production. The first stage involves exploration for and discovery of rocks in excess of 200ºC at the shallowest possible depth in the subsurface. In the second stage, below-ground engineering of the HDR reservoir is carried out. Cool water flows from injection wells through the subsurface, where it is heated by contact with the hot rock, to production wells. In an HDR system the water is injected, for example, from a shallower aquifer, and flow between the wells is stimulated by the pressure of injected fluids (i.e. the subsurface flow system is engineered). In the third stage a power plant uses heat from the recovered hot water to boil a low boiling point 'working fluid' (e.g. iso-pentane). The vaporised working fluid is expanded across a turbine to drive a generator and produce electricity. After electricity generation the cooled water is reinjected into the subsurface to restart the cycle.

The above-ground engineering aspects of HDR systems are largely identical to conventional commercial binary geothermal electricity plants. The environmental impacts of HDR electricity generation are likely to be less than those associated with conventional geothermal electricity generation (US Department of Energy Efficiency and Renewable Energy Website, 2004). For discussion of the long term behaviour and thermal recovery of HDR reservoirs see, for example, Swenson et al. (2000).

The original concept of engineered HDR reservoirs involved injection of high pressure fluids to create simple, vertical, planar, tensile hydraulic fractures between injection and production wells (Evans et al. 1999). However, it is now recognised that the best hydraulic linkage between boreholes results from enhancing the pre-existing natural fracture system (Evans et al. 1999). Injection of high pressure fluids may cause shear displacement of natural fractures which may remain open due to asperities on the fracture surface.

Seismic recorders in wells surrounding the injection well monitor microseismic events caused by the propagating fracture system as the fluid is injected into the subsurface thermal reservoir. This monitoring is a critical aspect of HDR design as the location of these microseismic events indicates the preferential fracture/flow directions in the subsurface and guides the location and trajectory of the production wells (Brown & Duchane 1999). Experimental HDR systems to date have generally involved one injection and one production well. However, commercial systems are likely to utilise a triplet of deep wells, with production wells on opposite sides of the injection well, in recognition of the ellipsoidal rather than spherical shape of subsurface fluid flow (Brown & Duchane 1999). Numerous waterfloods of both naturally fractured and unfractured petroleum reservoirs have indicated that fluid flow is strongly focussed in the present-day maximum horizontal stress direction on either side of the injection well (Heffer & Lean 1993; Yale et al. 1994).

Hot dry rock geothermal energy was originally considered a resource distinct from conventional geothermal energy (as described in the introduction). However, the results of deep drilling have revealed that fractures may provide permeable pathways even at great depth in the crust (e.g. Fehler 1989; Shapiro et al. 1997). This has been dramatically demonstrated in the Geodynamics Habanero-1 well in the Cooper Basin where mud weights had to be increased to prevent high-pressure fluids in the granite from entering the wellbore (Wyborn et al. this volume). Recognition of the presence of fluids at great depth has led to the concept of engineered hot wet rock (HWR) reservoirs. In the HWR system, hydraulic stimulation is used for permeability enhancement and for sustaining production in reservoirs that exhibit minor flow. The HWR concept recognises a continuum between HDR and conventional geothermal resources.

The authors believe that a resources pyramid of geothermal energy, akin to that recognised for fossil fuels, will be progressively recognised (Fig. 2). The resources pyramid concept suggests that

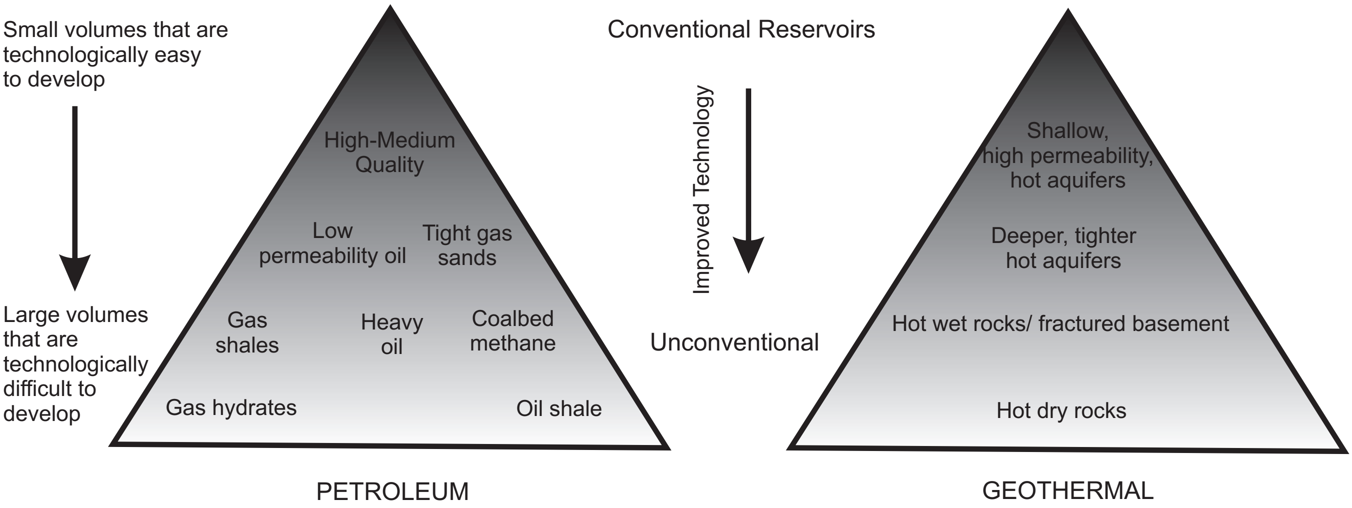

Figure 2. Petroleum and geothermal resource pyramids. The petroleum resource pyramid is from Holditch (2003).

there is a small amount of prime resources that are easy to extract. There is also a much larger volume of resources that are technologically more difficult to extract. Over time, resources near the top of the pyramid are depleted and technological developments lead to resources further down the pyramid being developed cost-effectively. Indeed deep gas in low-permeability reservoirs, long considered a resource below the economic cut-off in the hydrocarbon resources pyramid, now constitutes around 25% of US natural gas reserves (Holditch 2003). If the geothermal industry follows a similar pattern, evolution from hot, shallow, high-permeability aquifers to deeper, tighter aquifers, to hot fractured basement (HWR), to hot dry rocks (HDR) is similarly predicted.

Hot dry rock geothermal energy: historical and international developments

The concept of extracting geothermal energy from HDR by circulating water through an engineered reservoir originated in the United States more than 30 years ago. The original HDR patent, which has now expired, was issued to Los Alamos National Laboratory in 1974 (Brown & Duchane 1999). From 1974, Los Alamos National Laboratory conducted numerous experiments at Fenton Hill (New Mexico) where recent volcanism creates a local hotspot with temperatures reaching 327ºC at the base of a 4.4 km vertical depth well (Brown & Duchane 1999). Tests at Fenton Hill demonstrated that it was possible to drill into hot, impermeable granite and create flow passages that stayed open despite the high earth stresses tending to close fractures. Rather than new fractures being formed, all the evidence pointed towards the opening of an interconnected array of existing joints that had been sealed by hydrothermal processes. The first-opened joints were, as might be expected, oriented in a direction approximately orthogonal to the present-day least principal stress (Brown & Duchane 1999).

The Fenton Hills test plant produced power and conducted stimulation and flow tests for 17 years (1978–1995). Circulation tests were completed at heat extraction rates of up to 10 MW thermal with small pressure losses and water losses as low as 7% of the water injected (Abé et al. 1999). Ultimately the plant was not commercial, but much of our understanding of the potential of HDR geothermal energy derives from this project. The Fenton Hills site has now been decommissioned with the US Department of Energy declaring its intent to pursue future HDR work through the commercial geothermal industry. Australia has recently become the focus for the present-day, commercially-supported HDR industry, as described herein. There is also a commercial HDR venture in El Salvador where Shell is working with Salvadorian firm GESAL in a project to create 2–5 MW of power at a known natural hydrothermal site (Fischer 2004).

The most advanced HDR project is at Soultz-sous-Forêts (France) on the western edge of the Rhine Graben, about 50 km north of Strasbourg. The site is on the former Pechelbronn oil field and was selected because of the high heat flow anomaly observed in oil wells (Baria et al. 1999). Soultz-sous-Forêts is the principal European HDR site and exhibits temperatures of 168ºC at 3.5 km. The Soultz project commenced as a research project (funded by France, Germany and the European Commission) but the project is now being commercialised by an industry consortium, ‘EEIG Heat Mining’ that includes Shell International and utilities such as Electricité de France.

Two wells, 450 m apart, were drilled to a depth of 3.6 km at Soultz between 1987 and1997. During 1997 a circulation test demonstrated the feasibility of the HDR concept. Water circulated between the two wells at a rate of 25 litres per second for a period of 4 months without any water losses. The water reached the surface at a temperature of 140ºC and maintained its temperature during the test. Following this successful test, one of the wells was deepened to 5 km, and rock temperatures of 200ºC. This well was stimulated creating a reservoir 1500 m long and 500 m wide. A second well has been drilled into this reservoir 650 m away and water successfully circulated between the two wells. The planned scientific pilot plant will be a triplet of wells with a second producer recently completed on the other side of the injector. All the wells are started from a single platform. The project has shown that the fracture network in the basement at Soultz-sous-Forêts is well developed with a degree of permeability and this project is perhaps closer to an HWR development than an end-member HDR project (Baria et al. 1999; Brown & Duchane 1999).

There are several additional HDR/HWR projects worldwide. However, it is beyond the scope of this paper to summarise all of these and the reader is referred to the following:

- Rosemanowes, UK (Parker 1999)
- Fjällbacka, Sweden (Wallroth et al. 1999)
- Hijiori, Japan (Kuriyagawa & Tenma 1999 www.nedo.go.jp/chinetsu/hdr/hijiorinow.htm)
- Ogachi, Japan (Hori et al. 1999)
- Deep Heat Mining, Basel, Switzerland (www.dhm.ch)
- Stadtwerke Bad Urach, Germany (www.geothermie.de/bad_urach2.htm)
- Geodynamics Habanero-1 project, Cooper Basin, South Australia (Wyborn et al. this volume; www.geodynamics.com.au).

The Australian regulatory framework: Geothermal Exploration Licences

As an onshore resource, the regulatory framework for HDR developments in Australia lies in the remit of the State Governments. New South Wales was the first state in Australia to develop legislation specifically for geothermal energy. In 1992 New South Wales modified regulations under the Mining Act to define 'geothermal substances' as a mineral. This allowed the issue of mineral licences for the exploration for and production of 'geothermal substances'. 'Geothermal substances' were initially defined as any underground substance that was not already specifically defined as a mineral, and 'that occurs, because of the natural heating processes of the earth, at temperatures exceeding 80 degrees Celsius'. In 1998 this definition was modified to include substances artificially introduced underground (as well as those naturally occurring) heated to temperatures exceeding 100ºC. This modification was made to ensure that water injected to extract heat from hot dry rocks was covered by the Act. The modified definition also increased the temperature cutoff from 80–100ºC to exclude local use of warm groundwaters (e.g. spas, aquaculture). Royalty is payable at 4% of the geothermal substance value. Pacific Power subsequently won a tender for an area in the Hunter Valley, but has since withdrawn from the licence, which was taken over and extended by Geodynamics (Table 1; Fig. 3).

The approach taken in South Australia differed from that of New South Wales. South Australia began a review of the Petroleum

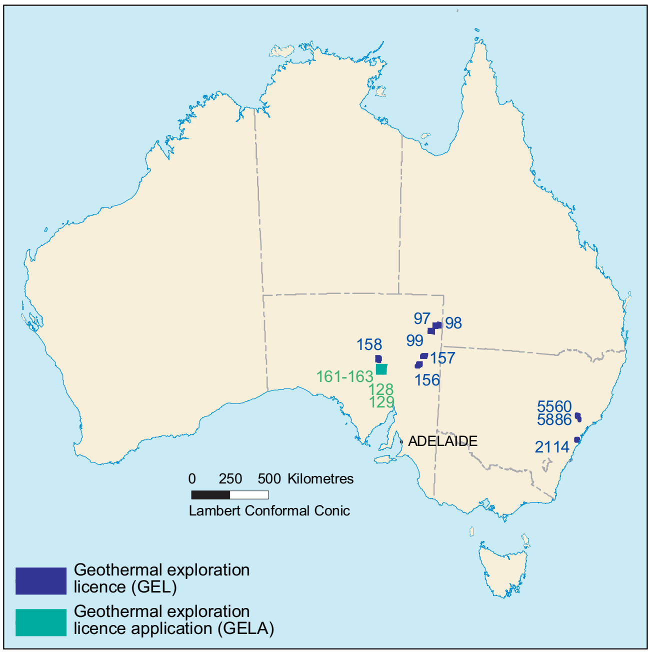

Figure 3. Geothermal Exploration Licences in Australia.

Table 1. Current HDR Licences in Australia.

Licence	Company	State	Area (km^2)	Target Temp. (°C)	Target Depth (m)	Status
GEL 97, 98	Geodynamics	SA	991	250	4,000–4,500	First deep well (Habanero-1) drilled to 4.4kms and successfully stimulated in 2003. Planning to drill 2nd well in 2004 to establish circulation.
GEL 99	Scopenergy	SA	496	235–265	3,000–4,000	Capital raising to undertake initial 5 well program
GEL 156	MNGI/Petratherm	SA	498	>200	3,000–4,000	Reviewing data and developing hot rock exploration models. Petratherm initial public offering (IPO) at time of writing.
GEL 157	MNGI/Petratherm	SA	496	>200	3,000–4,000	
GEL 158	MNGI/Petratherm	SA	499	>200	3,000–4,000	
GELA 128, 129, 161, 162, 163	Perilya/Green Rock Energy	SA	2456	>200	4,000–5,000	Licences offered (except areas covering WMC operations), awaiting acceptance
EL 5560, 5886	Geodynamics	NSW	490	200–250	4,000–5,000	Planning to drill two shallow holes for the determination of the temperature gradients in the centre of the Bulga gravity low.
EL 2114	Longreach Oil/ Hot Rock Energy	NSW	5500	Unknown	Unknown	Undertaking initial evaluation of area

Act, 1940 in 1996, as part of a general initiative to bring the petroleum regulatory regime in South Australia up to modern regulatory practice. Coincidently in 1996, Ashton Energy attempted to apply for exploration licences for geothermal energy in the Olympic Dam area under the Petroleum Act. However, these could not be granted, as the Petroleum Act at that time did not include such rights. The area has recently been offered to a joint venture between Perilya and Green Rock Energy, with the consent of Ashton (Table 1; Fig. 4). Representations were also made from other parties, as part of the review process seeking a legislative framework for HDR exploration in South Australia. Given that the most prospective area for HDR in South Australia was perceived to be granites underlying the Cooper Basin oil and gas fields, it was felt that the Petroleum Act was the most appropriate way to regulate geothermal energy. Furthermore, the drilling and production technology (i.e. fluids under pressure) to be applied was petroleum-based, and there was potential for conflict with coincident petroleum rights. A specific set of licences was developed for geothermal exploration and production (GELs – Geothermal Exploration Licences and GPLs –Geothermal Production Licences), with a limit of 500 km^2 for a single exploration licence. This size limit allowed three separate licences to be offered in the Cooper Basin area and was chosen to allow multiple parties to be involved and to encourage innovation in the development of the resource. The definition of geothermal energy in the Petroleum Act, 2000 differed from that in New South Wales, in that it is exclusively for HDR and excludes conventional geothermal resources (hot groundwater). Conventional geothermal resources are regulated via the Water Resources Act.

The South Australian legislation defined a source of geothermal energy as a ‘regulated resource’ (i.e. the emphasis was on the heat in rocks rather than on hot water as the resource) and defined it as ‘thermal energy contained in subsurface rock or other subterranean substances which is extracted or released by means other than as part of the production of a naturally occurring underground accumulation of a substance’. In October 2000, shortly after the Petroleum Act, 2000 was enacted, three areas were offered for competitive tender (work program bidding) and three consortia responded. Since then two consortia have combined, leaving GELs 97 and 98 with Geodynamics and GEL 99 with Scopenergy (Table 1; Fig. 4). Subsequently, a number of other areas in the state have been the subject of GELs by MNGI/Petratherm and Perilya/Green Rock Energy (Table 1; Fig. 4). Royalty is payable on geothermal energy at the rate of 2.5% of value. It is the South Australian Government’s belief that geothermal exploration is not ‘mining’ under the Commonwealth Native Title Act, and therefore GELs can be issued without the right-to-negotiate process.

Currently, Queensland has no legislative basis to allow or regulate the exploration for potential geothermal energy resources, although it may have high-temperature resources similar to South Australia, in addition to current conventional geothermal exploitation (the Birdsville plant). During 2003, the Queensland Department of Natural Resources, Mines and Energy drafted a Geothermal Exploration Bill to enable commencement of geothermal exploration in Queensland, largely in response to interest shown by Geodynamics for an area of the Cooper Basin in southwest Queensland. Specific targeted consultation has occurred on this Bill. The Bill allows Geothermal Exploration Licences up to 600 km^2 to be offered by competitive tender. All geothermal resources (HDR and conventional) are covered, but minor local users will be excluded. The legislation to cover production is still to be finalised, but it is anticipated that a royalty will apply, based on a cents-per-gigajoule basis. The Queensland Minister for Natural Resources, Mines and Energy introduced the Geothermal Exploration Bill 2004 to State Parliament on 20 April 2004.

Victoria is considered to have relatively low-temperature geothermal resources, occurring as warm groundwater, although there is potential for HDR. Warm groundwater has been utilised to a limited extent since 1983, particularly in Portland for heating public buildings. Proponents are also considering its use for electricity generation using low flashpoint technology. The Victorian government is reviewing legislation for geothermal resources, driven by a petroleum licensee who has shown interest in acquiring rights to geothermal resources in eastern Victoria. Geothermal energy resources are currently provided for under the Water Act, 1989. However, this legislation does not currently address some significant issues in relation to geothermal energy, such as a definition of geothermal energy, security of tenure, or ownership of the resources. At this stage it is not clear if separate legislation is to be enacted, or if the existing Petroleum Act is to be amended, or if in fact no legislative changes are to be made.

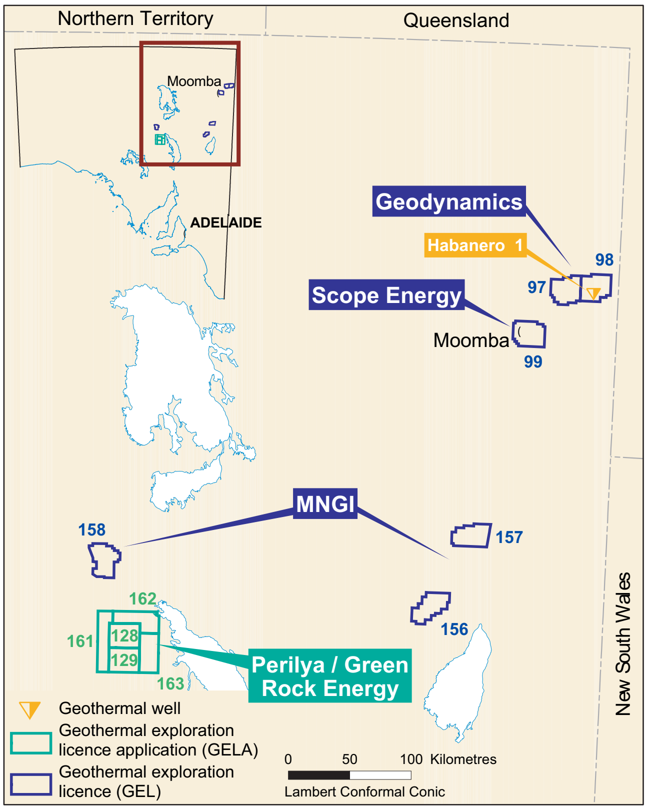

Figure 4. Geothermal Exploration Licences in South Australia.

The Northern Territory, Western Australia and Tasmania have no specific legislative framework for geothermal energy, and have no plans to develop such legislation in the short term, given that no interest has been expressed in exploring for geothermal energy in these areas.

The political framework: Renewable Energy Certificates

The Commonwealth Government introduced the Renewable Energy (Electricity) Act, 2000 to encourage the use of renewable energy. One of the initiatives introduced by this act is the Mandatory Renewable Energy Target (MRET). The aim is to achieve an additional 2% of Australia’s electricity from renewable sources. The objectives of this act are:

- to encourage the additional generation of electricity from renewable sources
- to reduce emissions of greenhouse gases
- to ensure the renewable energy sources are ecologically sustainable.

The renewable generation targets are assigned to electricity retailers on the basis of how much electricity they sell. The task, as mandated by the Renewable Energy (Electricity) Act, 2000, is to generate 9,500 GWh of electricity per annum from renewable means by 2010. The Electricity Supply Association of Australia estimates that an additional 3,000 MWe of renewable capacity will need to be brought on-line to generate the required amount of renewable electricity.

Generators of electricity from renewable sources may register with the Office of the Renewable Energy Regulator and receive Renewable Energy Certificates (RECs) for the renewable energy that they generate. These certificates can be traded with electricity retailers, which are required to obtain and surrender a certain amount of RECs per year. There is a non tax-deductible penalty of $40 per MWh for retailers who fail to surrender the correct number of certificates. This price is anticipated to encourage new renewable electricity generation projects and has a major impact on the commercial competitiveness of HDR-generated electricity.

The MRET Review Panel was established in September 2003 and its report recommends that after 2010 the $40 penalty should be indexed and that RECs should have a 15 year period applicable to all projects commenced after 2005. The panel also recommended that the renewable energy target should be increased to 20,000 GWh by 2020.

Petratherm's geothermal energy exploration program

Currently, MNGI, a wholly-owned subsidiary of Minotaur Resources, holds GELs 156, 157 and 158 in South Australia (Table 1; Fig. 4). At the time of writing an IPO (initial public offering) is planned for geothermal energy company, Petratherm Ltd. Petratherm will purchase MNGI, and its ownership and analysis of GELs 156, 157 and 158, from Minotaur Resources in exchange for a shareholding in Petratherm.

The Petratherm geothermal energy exploration programme is based around the key cost parameters for HDR geothermal energy, which are:

- temperature of the hot rock reservoir and thus of the recovered water
- flow rate of the recovered water
- drilling costs (hence depth of the hot rock reservoir)
- location with respect to market (electricity grid or customer)
- above-ground plant costs and efficiency.

Petratherm has developed a programme to minimise these costs that differs from previous HDR projects. The Cooper Basin is a current focus for HDR activity because previous petroleum wells in the area encountered anomalously high geothermal gradients. Likewise the Soultz-sous-Forêts site is on the former Pechelbronn oil field and was selected because of the temperatures experienced in petroleum wells. However, discounting volcanic areas, it is possible that the Cooper Basin and the Soultz site may not exhibit the highest geothermal gradients in Australia or Europe respectively.

Rather than relying on high temperatures previously encountered in petroleum provinces, Petratherm has developed a programme of exploration for the highest geothermal gradients in proximity to electricity markets. This is also the philosophy of Green Rock Energy/Perilya in applying for licences in the vicinity of Olympic Dam (Adrian Larking and Simon Ashton, pers. comm., Green Rock Energy Pty Ltd 2004). Furthermore, sophisticated analysis of natural fracture patterns and in-situ stresses will be undertaken in order to optimise fluid flow through the subsurface geothermal reservoir (as described in a companion paper by Reynolds et al. this volume). The Petratherm programme will enable optimisation of all four of the subsurface cost parameters with respect to HDR developments.

The potential risks and rewards of a hot rock exploration programme are apparent. The potential rewards are hotter rocks at shallower depth and closer proximity to electricity markets. The risks are those associated with exploration (i.e. unlike in areas of previous petroleum exploration, only drilling will confirm the unusually high geothermal gradients sought). Petratherm have developed a programme of thermal modelling and shallow drilling to minimise this exploration-related risk. Thermal models will be developed for all geothermal targets and these will be tested with relatively shallow, 750 m, slimline holes. Deeper drilling will then focus on the targets displaying the highest geothermal gradients.

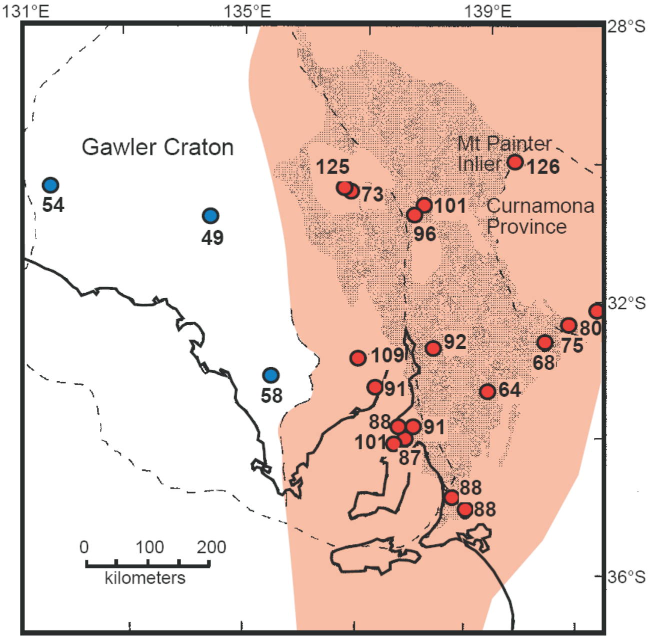

Figure 5. South Australian Heat Flow Anomaly (shaded area, amended from Cull, 1982; Neumann et al., 2000). Figures are heat flow in mWm^{-2}. Darker shading within SAHFA represents extent of Neoproterozoic metasediments. Dashed lines represent inferred boundaries of Gawler and Curnamona Cratons.

GELs 156, 157 and 158 were obtained within the South Australian Heat Flow Anomaly (SAHFA; Neumann et al. 2000; Fig. 5) because it is an exceptional target for exploration of geothermal energy. The average heat flow in the SAHFA is almost twice that of typical Proterozoic crust (e.g. McLaren et al. 2003). While the dataset is sparse, the average heat flow in the SAHFA is around 90 mWm^{-2} (Cull 1982; Houseman et al. 1989; Fig. 5). The global average heat flow from Proterozoic continental crust is around 50 mWm^{-2} (e.g. Morgan 1984; Nyblade & Pollack 1993). Outcropping felsic rocks within the SAHFA (including the Mt Painter Inlier; Curnamona Province and eastern Gawler Craton) contain anomalously elevated uranium and thorium contents, which result in the very high heat production rates.

Heat flow is high throughout the SAHFA, reaching almost 130 mWm^{-2}, in the northern part of the SAHFA (Fig. 5). In order to encounter the unusually high geothermal gradients sought by Petratherm, areas with high heat flow and low thermal-conductivity cover sediments are required (as further discussed in the following section on thermal modelling). There are three distinct geothermal styles within GELs 156, 157 and 158 that have the potential to satisfy these requirements:

- thermally anomalous granites (TAGs) buried by younger, insulating cover
- radiogenic iron oxides (RIOs) buried by younger, insulating cover
- enhanced natural thermal systems (ENTs).

Granites in general generate anomalously high heat flows compared to other rock types due to their relatively high content of radiogenic potassium, uranium and/or thorium. However, many of the granites within the SAHFA are thermally anomalous compared

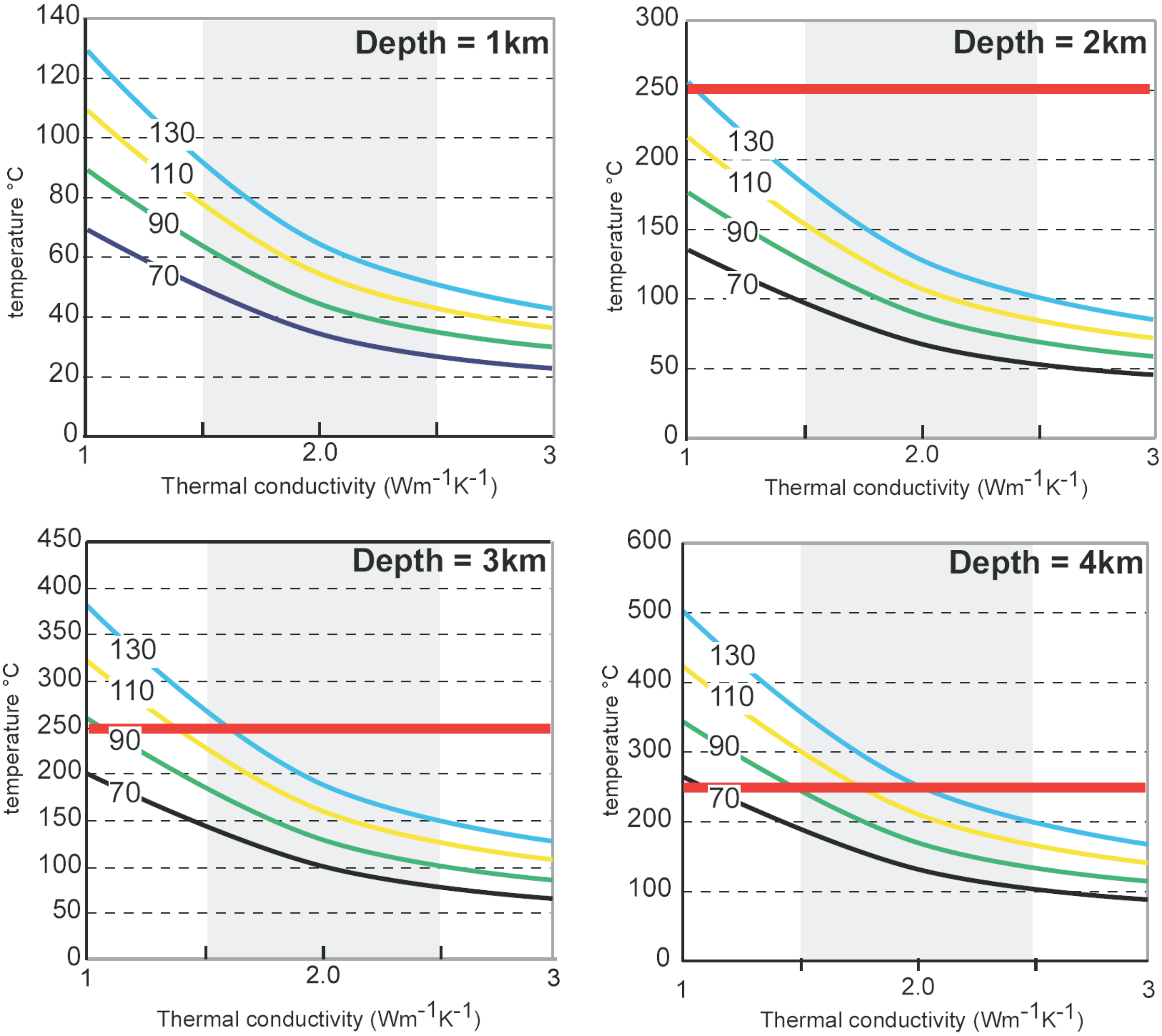

Figure 6. Relationship between thermal conductivity of a cover sequence, depth of burial of heat-producing basement and temperature. The values on the curves are the heat flow (mWm^{-2}) The average heat flow in the SAHFA is around 90 mWm^{-2} (pink curve). The red line allows rapid evaluation of the parameter ranges required to generate temperatures >250ºC. Generating temperatures >250ºC at <4km, for the average heat flow in the SAHFA, would require exceptionally low thermal conductivities. However for a heat flow similar to the Mt Painter region (~130 mWm-^{2}), temperatures >250ºC at <4 km can be attained with cover or average thermal conductivity.

to normal granites. For example, the average heat production rate in the Mt Painter Inlier is 10 μWm^{-3} (Neumann et al. 2000), which is around four times the rate of average granite (McLennan & Taylor 1996). The granites of the SAHFA are amongst the most thermally anomalous granites in the world. GEL 156 includes the partially outcropping and partially covered Mt Painter granites. Only younger cover rocks outcrop within GEL 157, but gravity data indicate a large buried granite that we term the Callabonna Granite, about 50 km northeast of Mt Painter and possibly part of the same suite of TAGs. Petratherm will use gravity data to determine the depth to the top of the granites within its permits and thermal modelling (as discussed in the following section) to then determine the optimum geothermal targets.

Granites have been a key focus in HDR projects worldwide, but radiogenic iron oxides (RIOs), such as those known in South Australia at Olympic Dam and Prominent Hill, also have the potential to generate exceptionally high geothermal gradients given circumstances outlined in the thermal modelling herein. Measured heat production rates in RIOs may be as much as 50 times greater than those in average granites (Houseman et al. 1989). The gravity and magnetic signatures of the Ferguson Hill prospect within GEL 158 is the same as that of known RIOs. A mineral exploration test hole to 1,500 m did not encounter the top of this body and geophysical modelling suggests that its top is at approximately 2 km. No temperature measurements are available for the hole, but such will be sought as part of the exploration programme. Although RIOs are much hotter than TAGs, they are smaller in volume, thus their thermal footprint is smaller and geophysical and thermal modelling and test drilling must be suitably focussed.

As discussed earlier, we recognise a resources pyramid for geothermal energy from hot, shallow high-permeability aquifers to deeper, tighter aquifers, to hot fractured basement (HWR) to hot dry rocks (HDR). There is a continuum through these geothermal resource types. The third geothermal style mentioned above

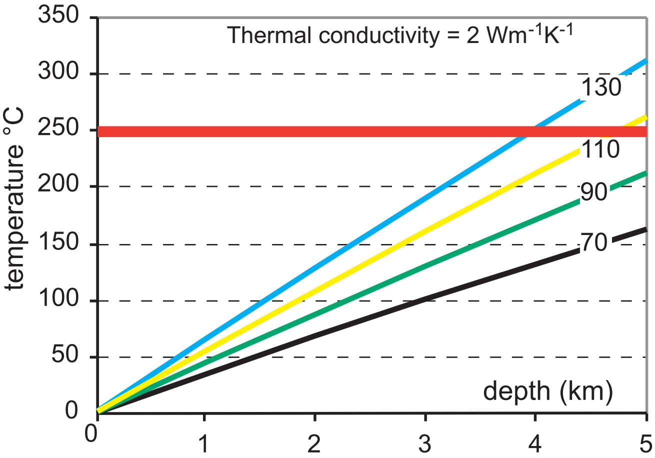

Figure 7. Relationship between depth of burial and temperature for a range of heat flows, and assuming a constant thermal conductivity of a cover sequence.

comprises enhanced natural thermal systems (ENTs). In the anomalously hot environment of the SAHFA, pre-existing faults may focus natural superheated groundwater flow. For example, the Paralana Hot Springs occur along a major fault zone at the eastern margin of the Flinders Ranges within GEL 156. Surface water temperatures at Paralana have been measured at 62ºC. The springs have only low flow rates (i.e. groundwater may cool while coming to the surface) and there is evidence of near-surface mixing with cool groundwaters. Hence the groundwater temperature may be significantly higher at shallow depths. Many faults similar to that at Paralana can be recognised on aeromagnetic data and represent potential HWR or even conventional geothermal targets. Efficient circulation between injection and production wells is a critical issue for HDR systems (see also Reynolds et al. this volume) and we believe that augmenting an existing flow system increases the probability of obtaining efficient subsurface fluid circulation compared to an entirely engineered system. Furthermore, such natural thermal systems may provide convective heat flow into the reservoir during its exploitation, potentially improving its thermal behaviour beyond that which would be predicted if heat transfer into the reservoir were purely conductive.

It is important to recognise the continuum between geothermal resource types. Although TAGs or RIOs may be the ultimate source of heat, subsurface geothermal circulation systems need not target the heat-producing basement rocks themselves and can target immediately overlying cover rocks if they are sufficiently hot. Such cover rocks may be Great Artesian Basin aquifers, such as those already exploited at Birdsville's conventional geothermal plant, or the deeper, tighter, Cooper Basin rocks that are exploited for oil and gas. Hence commercial exploration for basement HDR geothermal resources should not neglect the conventional geothermal potential of overlying aquifers or indeed HWR opportunities. Multi-target wells testing multiple geothermal resource types present an important exploration opportunity.

The South Australian heat flow anomaly and thermal modelling

This section of the paper demonstrates that temperatures of 250ºC may be developed under suitable circumstances within the South Australian Heat Flow Anomaly (SAHFA) at depths <4 km, providing very high heat-producing basement (such as TAGs and RIOs) and thermally insulating cover rocks can be located. Thermal modelling is the first stage in the exploration for exceptional geothermal gradients and has been undertaken for likely subsurface thermal parameters within the SAHFA. If we neglect the role of fluid flow in modifying the near surface thermal field, the basic control on the near surface geothermal gradient is the interplay between the insulating properties of the uppermost crust and the heat flow field. For the SAHFA, surface heat flows lie in the range 70–130 mWm^{-2} (e.g. Cull 1982; Houseman et al. 1989). Figure 6 shows the thermal implications of burying a basement complex that generates anomalous heat flow in the range 70–130 mWm^{-2} with varying thicknesses of cover of varying thermal conductivity, assuming:

- typical mantle heat flow of 25 mWm^{-2} in accord with the seismic shear wave velocities pointing to thermally 'normal' mantle (e.g. Zielhuis & Van der Hilst 1996; Debayle & Kennett 2003)
- a granitic layer 5 km thick with a heat production rate of 9 μWm^{-3} (typical of many of the TAGs in the SAHFA) at the base of the insulating cover sequence
- a cover sequence generating 1 μWm^{-3}

The grey-shaded region in Figure 6 is the range of typical thermal conductivities of cover sedimentary rocks (i.e. 1.5–2.5 $Wm^{-1}K^{-1}$). Temperatures of 250ºC (the thick horizontal line) at 3 km, require high heat-flow and low thermal-conductivity cover rocks, both at the extreme of accepted parameter ranges. It is apparent that temperatures >250ºC at 3 km are very unlikely. Conversely, temperatures of 200ºC at 3 km within the SAHFA are entirely plausible. Figure 7 is effectively a slice through Figure 6, and shows the relationship between depth of burial to a heat-producing source such as a TAG or RIO and temperature for a thermal conductivity of 2 $Wm^{-1}K^{-1}$ in the cover rocks. For such average thermal-conductivity cover rocks, a high heat flow of ~130 mWm^{-2} is associated with temperatures of approximately 200ºC at 3 km and 250ºC at 4 km. Conditions such as these may be present in the Mt Painter region.

The above calculations suggest that for temperatures >200ºC the cover rocks must exhibit low thermal conductivity, heat flows must be high and depths must be at least 3 km. It is apparent from Figure 7, that the thermal conductivity of the cover rocks is as important as the heat generation rate in the basement. This highlights that exploration for geothermal energy must focus significant attention on the thermal conductivity of the cover rocks. The thermal conductivity of cover rocks in the shallow test holes, as well as temperatures, will be measured in order to refine the thermal models and select the optimum targets for deeper drilling.

Conclusions

The EEIG Heat Mining industry consortium operating the Soultz-sous-Forêts site, Shell's involvement in an HDR project in El Salvador, Geodynamics' Habanero-1 well in the Cooper Basin and the current IPO for Petratherm Ltd. all indicate that HDR projects are moving from the research to the commercial realm. Furthermore, in contrast to the conventional geothermal energy industry, in which Australia is a very minor player, Australia is playing a key role in current HDR developments. Geothermal Exploration Licences have been issued in two States: New South Wales and South Australia, in the former under mining legislation and in the latter under petroleum legislation.

Hot dry rock projects to date have largely focussed on areas of known high geothermal gradient, such as those in volcanic regions and those where high gradients have been demonstrated in petroleum exploration. Given that attaining high temperatures at shallow depth and the location of such with respect to the electricity market are critical to the commercial viability of geothermally-generated electricity, Petratherm is undertaking a programme of exploration for the highest geothermal gradients closest to electricity markets. It holds tenements within the exceptionally hot South Australian Heat Flow Anomaly and will target buried thermally anomalous granites (TAGs) and radiogenic iron oxides (RIOs) as well as enhanced natural thermal systems (ENTs, essentially HWR systems) within the SAHFA. Thermal modelling indicates that, under suitable circumstances, temperatures of 250ºC may be attained at depths <4 km in association with such targets.

There exists a resources pyramid for geothermal energy, akin to that recognised for petroleum resources, from hot, shallow, high-permeability aquifers to deeper, tighter aquifers, to hot fractured basement (HWR) to hot dry rocks (HDR). There is a continuum through these geothermal resource types. Hence commercial exploration for basement HDR-type geothermal resources in Australia should not neglect the conventional geothermal potential of overlying aquifers or indeed HWR opportunities. Multi-target wells testing multiple geothermal resource types present an important exploration opportunity.

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