QGECE research on delineation of Australian geothermal resources

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The geology/reservoir program of the Queensland Geothermal Energy Centre of Excellence (QGECE) has the mission to improve the existing knowledge and develop new innovative scientific approaches for the identification of geothermal resources in Australia, with a particular focus on Queensland. Specifically, the QGECE geology/reservoir program is currently (1) producing a comprehensive geochemical dataset for high heat producing rocks, (2) conducting detailed mineralogical and geochronological studies of granites and hydrothermal alteration minerals, and (3) investigating the Cooper Basin representing a superb natural laboratory for understanding of radiogenic heat enrichment process and possible involvement of mantle heat flow. Seven research projects have been established, which are being conducted largely as PhD studies. In the preliminary studies, high quality and valuable results were obtained to address the research topics of understanding the causes and timing of heat producing element enrichment.

Keywords: Queensland, HHP granite, geochemistry, isotope, geochronology, hydrothermal alteration

Research topics of the QGECE geology/reservoir program

The current research projects of the QGECE geology/reservoir program include: (1) Petrological, geochemical and geochronological studies for characterisation and identification of high heat-producing granites (HHPG) in Queensland; (2) Generation of regional high crustal heat flow zones in relation to tectono-magmatic evolution of Queensland; (3) Geochemistry and geochronology of fluid flow events in high heat producing granitic rocks; (4) Origin and evolution of deep fluids and water-rock interactions in the Cooper Basin; (5) Evolution of the Cooper Basin and the origin of the geothermal energy; (6) CO_2 degassing in seismically active geothermal systems; (7) Trace element geochemistry of near-surface quartz deposits in the Drummond Basin as an exploration tool for geothermal systems.

Petrological, geochemical and geochronological studies for characterisation and identification of heat-producing granites in Queensland

The ongoing PhD studies of Vicki Marshall, Coralie Siegel and Jaco Van Zyl are obtaining new age data on HHP granites from Queensland, South Australia and Europe along with chemical information on the accessory U & Th-bearing zircons (e.g., Marshall et al. 2011). The preliminary observations indicate that strong U and Th enrichments in the granites examined so far may be derived through strong fractional crystallisation. While post-magmatic alteration may locally and variably redistribute U in some of the granites (e.g., Carnmenellis, UK), it is probably not responsible for the underlying enrichment in heat-producing elements. Thus it appears that magmatic differentiation must be called upon to produce the observed enrichments. The question that then arises is what factors lead to (and govern) this enrichment through fractional crystallisation. These studies will ultimately place important new constraints on the timing and spatial associations of accessory- and major-mineral precipitation and the influence this has on granite chemical evolution and ultimate HPE architecture. One important implication that emerges from preliminary analyses is that for S-type granites, the most fractionated (e.g., Rb-rich) do not necessarily represent those that are the most enriched in U and Th. This will have important consequences for the heat production through contrasting vertical and lateral distributions of HPE in zoned and composite plutons.

Understanding the spatial-temporal-compositional distribution of HHPG in Queensland

Queensland has >175,000 km^2 of exposed igneous rock; the potential for EGS is thus huge in the state. >15,000 analyses of granitic rocks that include geochemistry, age, lithology and distribution information have been compiled by Coralie Siegel from federal and state geological surveys with additional published and unpublished datasets. The data indicate the significant presence of HHPG in Queensland: approximately ~15% and ~22% of the analysed igneous rock and granitic rocks samples in the database have heat production values >5 μW/m^3, respectively.

However, there is a limited understanding of these HHPG in Queensland in terms of their distribution in the subsurface, dimensions, ages, and controlling factors in their genesis. Compounding this problem is that although high concentrations of radiogenic elements and therefore high heat production is exclusively found in igneous rocks with high silica contents (>70% SiO_2), not all high-silica igneous rocks are high heat producing; and show a spectrum of heat production values from 0 to 18 µW/m^3.The observed extreme variation in calculated heat production for igneous rocks in Queensland and globally, thus raises a number of questions that will be addressed by Coralie Siegel through her PhD study.

Geochemistry and geochronology of fluid flow events in high heat producing granitic rocks

Alex Middleton (PhD student) has presented preliminary results on the petrology and chemistry of secondary accessory minerals from the best-known European HHP granites and some examples from Queensland (Hodgkinson and Gallilee Basin target areas) (see Middleton et al., 2011). He showed that Th (generally considered as an immobile element) could be mobilised and stored in newly formed accessory minerals along with U and some rare earth elements. Electron microscopic studies combined with geochemistry of the Galilee Basin basement rocks (a possible source of HHP in this basin) show that pervasive hydrothermal alteration may have been responsible for secondary precipitation of monazite-cheralite as the predominant REY- and Th-bearing metastable phase. Vitrinite reflectance (VR) and recent temperature data from existing deep petroleum holes indicated that the Galilee Basin has geothermal potential in Queensland. Recent VR data of the Origin Energy show irregular distributions with depth indicating that hydrothermal fluid circulations may have affected the thermal history of the Galilee Basin (personal commun. with Richard Suttill, 2011).

Origin and evolution of deep fluids and water-rock interactions in the Cooper Basin: Geochemical investigation of a geothermal reservoir

Study of fluid-rock interaction in geothermal systems has become one of the major goals. This is mainly because fluids play an important role in heat transfer as well as mineral reactions and precipitations in the reservoir, geothermal loop, from the production casing to the surface tubing, the heat exchanger and the reinjection casing. Chemical and isotopic compositions of geothermal fluids in conventional hydrothermal systems have been studied extensively for reconstruction of the evolution of fluids in space and time, their migration pathways, and their sources (e.g., Pauwels et al., 1993). However, similar studies for understanding the fluid flow process and water-rock interaction process in Hot systems, particularly in the Cooper Basin are virtually missing. The QGECE geology/reservoir program is conducting a project to establish the viability of Sr-O-H isotope, trace and rare earth element geochemistry of deep waters in the granite and waters in the sediments of the Cooper/Eromanga Basin. The studies will provide understanding of mineral scaling in the geothermal system, and help determining the geothermal fluid pathways and evaluation of the potential of shallow waters as a geothermal exploration tool. Previously, we analysed trace element content of the granite of Big Lake Suite and reported that the most altered shallow granites have anomalously high U and Th concentrations (Uysal et al., 20110). We analysed recently trace element chemistry of deep geothermal fluids from the Habanero drill hole provided by Geodynamics. U content is low considering relatively high concentrations and mobility of this element in granitic environments. The low U indicates its extreme immobility and therefore strongly reducing conditions, which is consistent with positive Eu anomaly on the normalised REE diagram (Fig. 1). REE values are extremely low suggesting that fluid element composition comes from interaction with granite, but certainly not a high-heat producing granite. In other words, the chemistry of the deep reservoir water does not indicate interaction with HHPG. Our future research will include the investigation of more samples from Habanero holes as well as water samples from Cooper/Eromanga Basin sediments.

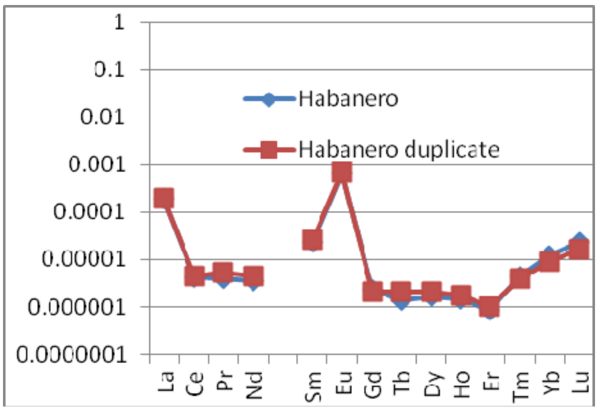

Figure 1. REE pattern of Habanero geothermal water

Evolution of the Cooper Basin and the origin of the heat production

We investigated trace element (analysed by ICP-MS) and stable isotope (Oxygen and hydrogen) geochemistry of whole rock granite samples and hydrothermal phyllosilicate alteration minerals separated from the granite and overlying sandstones and mudstones of the Cooper Basin. Granite core samples from shallow depths in the Moomba 1, Big Lake 1 and Mcleod 1 wells are strongly altered with pervasive sericite (illite) and

Table 1. Trace element data for Habanero geothermal water

Sample (ppb)	Habanero 03-1	Habanero 03-2
Li	68219	50856
Mg	116	94
Ca	6039	5487
As	607	416
Rb	6326	5749
Sr	1008	1030
Cs	11435	10357
Ba	847	959
La	0.0463	0.0464
Ce	0.0026	0.0028
Pr	0.0004	0.0005
Nd	0.0017	0.0020
Sm	0.0035	0.0040
Eu	0.0387	0.0399
Tb	5.02427E-05	7.91647E-05
Gd	0.000	0.000
Dy	0.000	0.001
Ho	8.25232E-05	9.75189E-05
Er	0.0001	0.0002
Tm	0.0001	0.0001
Yb	0.0020	0.0016
Lu	0.0006	0.0004
W	303	403
Pb	0.0011	0.0014
Th	0.0003	0.0004
U	0.0001	0.0001

quartz precipitation, associated with intense micro-fracturing and veining. The intensity of hydrothermal alteration is less in samples from Habanero 1, whereas no phyllosilicate mineral altyeration is observed in samples from Jolokia. Highly altered granites from former holes are substantially enriched in lithophile elements, particularly in Cs, Rb, Be, Th, U and rare earth elements (REE) relative to the upper continental crust (UCC). U and Th contents with concentrations of up to 30 and 144 ppm, respectively, are 10 and 13 times higher than those of the UCC. We propose that the enrichment of heat-producing elements was promoted by a regional hydrothermal event leading to the precipitation of U and Th- bearing minerals such as illite and thorite. Crystallinity index (illite crystallinity) of the sericite indicates hydrothermal temperatures ranging from 250 °C (in Moomba 1 and Big Lake 1) to 350 °C (in McLeod 1). In the overlying sedimentary rocks, crystallinity of authigenic illites translates to lower crystallisation temperatures (150 - 200 °C). Normalised REE patterns of the mostly altered granite samples show a strong negative Ce anomaly, signifying oxidation of trivalent Ce to less soluble tetravalent Ce. Geochemistry of whole rock and mineral samples suggest that, in contrast to the reducing environment in the current geothermal fluids in Habanero, fossil hydrothermal mineral deposition occurred under oxidising conditions. Oxygen and hydrogen isotope compositions of illites from the granites and sedimentary rocks are very similar, with $\delta^{18}O$ = -1.8‰ to +2.7‰; δD = -99‰ to -121‰ for granites and $\delta^{18}O$ = +2.3‰ to +9.7‰, δD = -78‰ to -119‰ for sedimentary rocks. The calculated oxygen and hydrogen isotope compositions of fluids in equilibrium with the illites are depleted in ^{18}O and deuterium, comparable to those of waters reported for most high-latitude sedimentary basins. Hence, stable isotope data of alteration minerals in the granite and the overlying sedimentary rocks suggest the operation of a hydrothermal system involving high latitude meteoric waters during extensional tectonism in the Cooper Basin region. Rb–Sr dating of hydrothermal illites have identified a hydrothermal event at ~95 Ma (Fig. 2) affected the Big Lake suite granite and the sediments from Warburton and Cooper Basins - this is possibly related to regional heating associated with a rifting events along the southern and eastern Australian margins at this time. Rb–Sr age data are consistent with the reported paleotemperatures that were highest at 90-100 Ma (Gallagher et al., 1994).

CO_2 degassing in seismically active geothermal systems

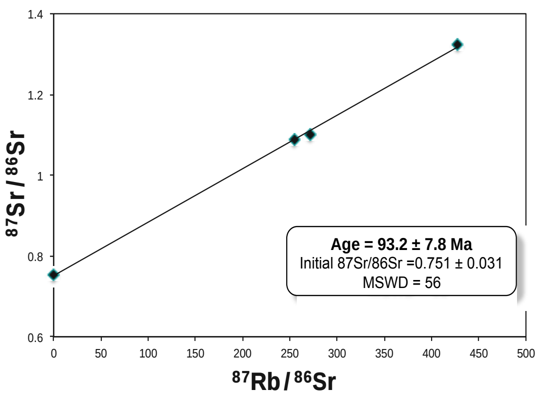

Figure. 2. Rb–Sr isochron diagram for hydrothermal illite from the Big Lake suite granite.

QGECE is pioneering a significant modification to the EGS technology called the supercritical CO2 thermosiphon (Gurgenci et al., 2008, Atrens et al 2009, Atrens et al. 2010). This expands on an earlier proposal of utilising CO_2 as heat transmission fluid (Brown, 2000; Pruess, 2006). In a CO_2 thermosiphon, CO_2 instead of brine is circulated through the hot dry rock reservoir to extract the heat and is directly expanded at the surface to produce electricity. This new approach may significantly enhance productivity, with thermal cycle efficiencies up to 50% higher than those for conventional geothermal binary power plants. An auxiliary benefit is the likely CO2 sequestration through its capture by the reservoir

(Pruess, 2006). The benefits of artificial CO2 injection into a predominantly water-filled HSA reservoir are deduced from past experience with naturally-sourced CO_2 injections into hydrothermal reservoirs. Intensive degassing of CO_2-saturated fluids in the hydrothermal systems has been known to give rise to a high fluid flux and the associated heat release (Chiodini et al., 2007). The presence of large amounts of CO_2 in the fluid makes convection much stronger (Straus and Schubert, 1979). The use of CO_2 injection to augment convection may substantially increase the commercial viability of HSA reservoirs.

Although the use of CO_2 in either context offers substantial promise, there are a number of geological, geochemical, and environmental uncertainties. It has to be demonstrated that: 1) the CO_2 injected will largely remain in the reservoir of the selected site without being degassed to the surface; 2) CO_2-bearing fluids will act as an optimal heat transmitter rather than a substance that damages the reservoir and the expander. In order to provide some understanding of the long-term fate of sub-surface CO_2 we are investigating existing conventional geothermal sites that have naturally elevated CO_2 concentrations. This project examines the periodic degassing of CO_2 from geothermal waters in Turkey leading to calcite vein and breccia deposition. Natural CO_2 discharges are abundant in Turkey as evident from ongoing deposition of recent terrace-mound travertines and emplacement of widespread carbonate vein and breccia deposits in fractured damage zones of active fault systems. Our field observations indicate that the calcite veins and breccias were initiated as hydro-fractures in basement rocks by CO_2-rich fluid overpressure and propagated to the surface (Uysal et al., 2009, 2011). As we demonstrated successfully in our recent studies, such unique fracture-filling carbonate deposits can be dated precisely by U-series dating technique (Uysal et al., 2007, 2009, 2011). Tectonism, climate and hydrology are considered to control the distribution and accumulation of CO_2 in spring or thermal waters in geothermal systems (Rihs et al., 2000; D'Alessandro et al., 2007). Previous studies have argued that travertine deposition in geothermal systems occurs preferentially during warm and humid periods in the late Quaternary probably due to increased availability of geothermal water of meteoric origin (Sturchio et al., 1993; Rihs et al., 2000). By contrast, a large number of carbonate veins we dated by the high-precision U-series technique coincides with times of cold/dry climate events (Uysal et al., 2009, 2011). We proposed that a significant reduction in surface discharge of CO_2 by spring or geothermal waters during dry climate periods may have promoted oversaturation of CO_2 in deep reservoirs. Host rock fracturing in response to seismic shaking and fluid overpressure results in rapid exsolution and expansion of the dissolved gas and consequently hydrothermal eruptions leading to massive and transient travertine vein deposition in the hydrothermal system (Uysal et al., 2009). In the non-hydrothermal but seismically active systems, CO_2 degassing occurs as a result of episodic seismic cycles, with the vein formation through repeated fracturing and sealing by new calcite precipitation (crack-seal mechanism) (Uysal et al., 2011).

Trace element geochemistry of near-surface quartz deposits in the Drummond Basin as an exploration tool for geothermal systems

Silica is the most abundant chemical compound in the Earth's upper crust; yet the trace element geochemistry of SiO_2 has not been utilised routinely in addressing not only exploration of mineral resources but also different geological problems. This is mainly due to the crystal structure of silica and the small size of the Si^{4+} ion, allowing only small amounts of trace elements to be incorporated into the crystal lattice. If some trace elements are present in quartz, they mostly occur either in micrometer-scale mineral inclusions, or more commonly in fluid inclusions (Götze et al., 2004). A number of studies used various minerals other than silica phases (e.g., carbonates and clays) for the geochemical tracing of hydrothermal fluid flow events in various tectonic settings (Bau and Dulski, 1995; Uysal and Golding, 2003; Uysal et al., 2009). However, only a few studies have reported trace element contents in quartz specifically to evaluate the petrogenetic and geochemical evolution of selected metamorphic, hydrothermal, and pegmatitic environments (Götze et al., 2004). Extensive Paleozoic sinter deposits occur at the surface associated with sub-surface quartz veining and epithermal Au mineralisation in the Drummond Basin, Australia. We investigated the trace element composition of the sinter deposits and quartz veins in an attempt to develop a new geochemical exploration guide for geological resources. We demonstrated in our recent study that rare earth elements and some other trace elements in siliceous materials may provide important information on the source of hydrothermal fluids, fluid chemistry, and physico-chemical environments of hydrothermal fluids (see Uysal et al., 2009, 2011 for more detail).

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