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A Geological Assessment of Unconventional Geothermal Targets in Queensland, Australia

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ABSTRACT

In the absence of active volcanism in Australia, geothermal exploration generally targets high heat producing (HHP) intrusives at depth for enhanced geothermal systems. However, in Queensland, very few of these intrusives are within viable range of centres of population and industry, so alternative heat sources must be sought. Queensland possesses abundant coal measures, which can act as excellent insulators within unconventional geothermal systems. By targeting coal-bearing stratigraphy, less established heat sources may also be prospective for geothermal energy development.

The Queensland Government's Coastal Geothermal Energy Initiative (CGEI) targeted a variety of heat sources in a shallow drilling, heat flow, and temperature modelling program across northern and eastern Queensland. In addition to high heat producing intrusives, the program targeted low-medium heat producing granitoids and residual tectonic heat insulated, where possible, by coal-bearing sedimentary basins.

Ten sites were drilled in the CGEI, and moderate to high heat flow was modelled for seven of the sites. Further modelling produced estimated temperatures greater than 187°C at 5 km depth within the Millungera, Surat, Hillsborough, and Maryborough basins.

Excellent results were obtained from the Millungera Basin sites, where there are HHP intrusives at depth insulated by stacked sedimentary basins. However, modelling of the Hodgkinson Province site – the only other site targeting HHP granite – produced high heat flow but very low modelled temperatures at depth, due to the slightly high thermal conductivity of the overlying strata. Thus, the traditional rationale of targeting highly radioactive intrusives may not be the most effective.

Modelling indicates that high temperatures are retained at depth within the less traditional heat sources of the Surat, Hillsborough and Maryborough basins, which targeted low to moderate heat producing intrusives and residual heat from Cainozoic tectonism. This is due to the excellent insulation provided by the coal measures present in the basins. These data show that geothermal energy potential may exist in regions previously thought to be unprospective, and that Queensland's abundant coal may be instrumental for future geothermal energy exploration.

1. INTRODUCTION

As Queensland's population and industry grow, the energy requirements of the state will increase, and geothermal energy has been identified as a potential future low emission energy resource for the State.

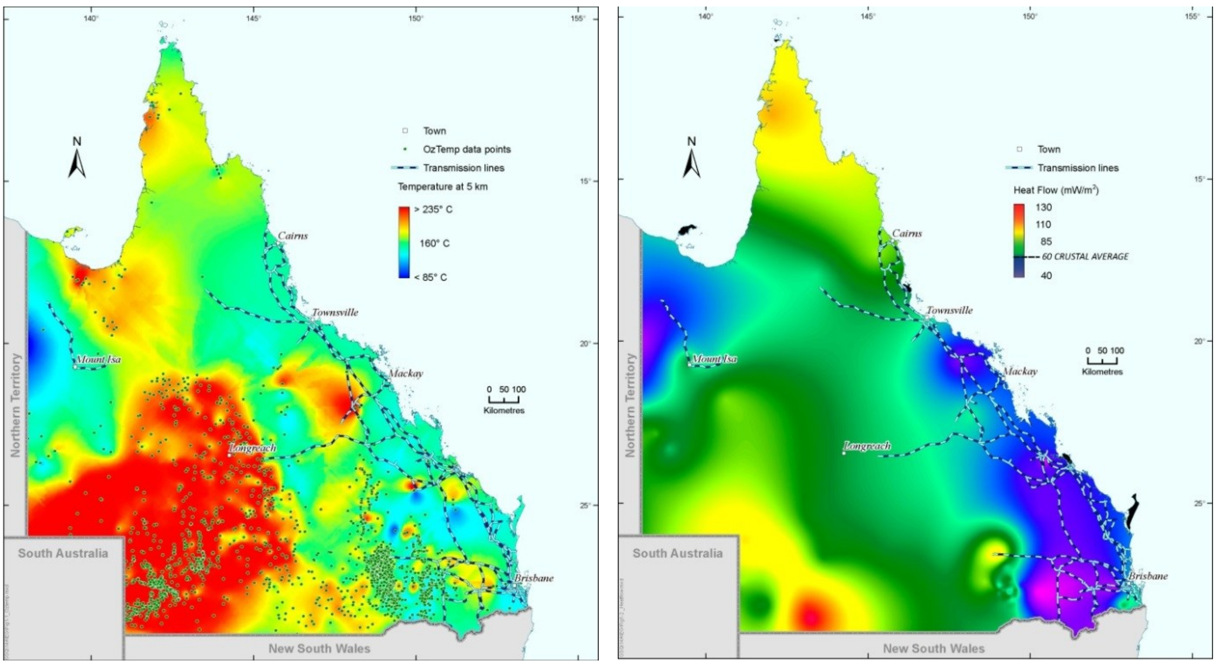

Figure 1: Temperature at 5 km (left) and heat flow (right) maps of Queensland.

1.1 Geothermal Energy in Queensland

As Queensland lacks active volcanism, geothermal exploration must look to unconventional heat sources, primarily enhanced geothermal systems (EGS). Existing temperature (Gerner and Holgate, 2010) and heat flow (Hot Dry Rocks Pty Ltd, personal communication, 2011) data show southwest Queensland to have anomalously high temperature and heat flow at 5 km depth (Figure 1). As such, EGS development is currently focusing on the Cooper Basin, where high heat producing (HHP) intrusives underlie stacked sedimentary basins. However, this potential is located far from existing infrastructure and energy markets, and the high cost of new infrastructure may limit the economic viability of its exploitation. There are few HHP intrusives under sedimentary cover close to Queensland's population centres; however, Queensland contains abundant, world-renowned coal deposits, which can provide excellent insulation in enhanced geothermal systems. This opens potential for alternative heat sources, such as low–medium heat-producing intrusives and residual heat from tectonism, under the insulating cover of coal basins as targets for unconventional geothermal energy.

1.2 The Coastal Geothermal Energy Initiative

The Queensland Government's 'ClimateSmart 2050 – a cleaner energy strategy' allocated $5 million for a project designed to investigate additional sources of hot rocks for geothermal energy close to existing transmission lines. The Coastal Geothermal Energy Initiative (CGEI), implemented by the Geological Survey of Queensland, was the project undertaken to investigate these hot rocks. This project aimed to collect precompetitive data to redefine the State's potential resource areas, expand Queensland's exploration opportunities, and facilitate the reduction of risk for future explorers.

2. METHODS

2.1 Site Selection

Thirty-two potential targets were identified based on the current understanding of the geological and tectonic history of eastern and northern Queensland. These targets were considered to have the potential for hot rocks at depth and elevated heat flow conditions, warranting further evaluation by drilling.

Each geothermal target was assessed using the following criteria:

- heat source at depth – inferred buried intrusives of felsic composition from geophysical surveys (Figures 2 and 3); likely heat production values >5 µW/m^3 from outcropping intrusives (Figure 4); recent volcanism and/or tectonism (Figure 4);
- insulating capacity of overlying sedimentary cover – thermal conductivity values of <3.5 W/mK; thickness of insulting cover >1,500 m;
- other geothermal indicators – e.g. geothermal gradients >40°C/km in nearby boreholes; presence of hot aquifers; higher than global average heat flow >60 mW/m^2; ternary radiometric datasets highlighting high concentrations of radioactive uranium, thorium, and potassium; fluoride anomalies ≥4.0 mg/L; hydrothermal activity.

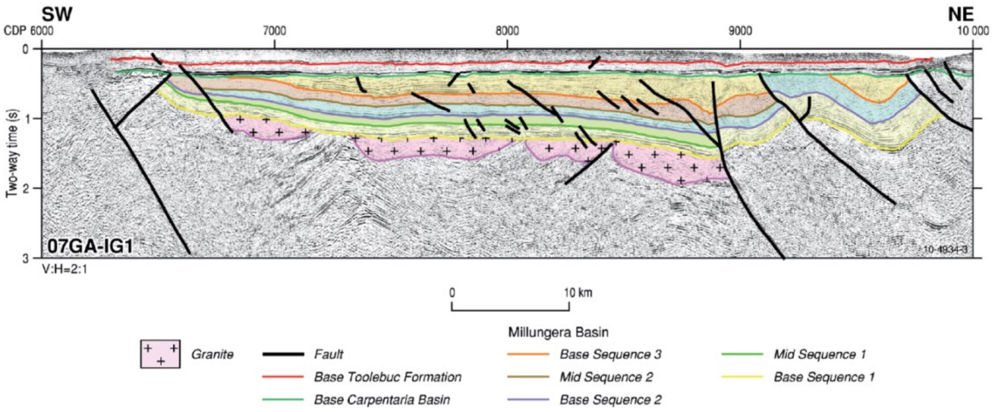

Figure 2: Seismic section across the Millungera Basin showing advantageous geology for EGS: intrusives at depth and stacked sedimentary basins.

Once suitable target areas were identified, the site for each borehole was selected using the following criteria:

- location away from any major topographic feature and relief;
- within 100 km of a population centre and/or transmission line;
- good access to site requiring minimal clearing and track preparation.

2.2 Drilling and Data Collection

The drilling commenced in November 2010, with 10 boreholes successfully completed by July 2012 (Figure 5). Boreholes were chipped to consolidated material, and upon reaching this level, continuous coring was undertaken to total depth, and each borehole was cased to total depth and the annulus grouted with cement.

After completion, the boreholes were left to thermally stabilise for a minimum of six weeks before precision temperature logs were run.

Core samples of the dominant rock types were taken from the core approximately every 20 m for thermal conductivity analysis; these were analysed under *in-situ* moisture conditions.

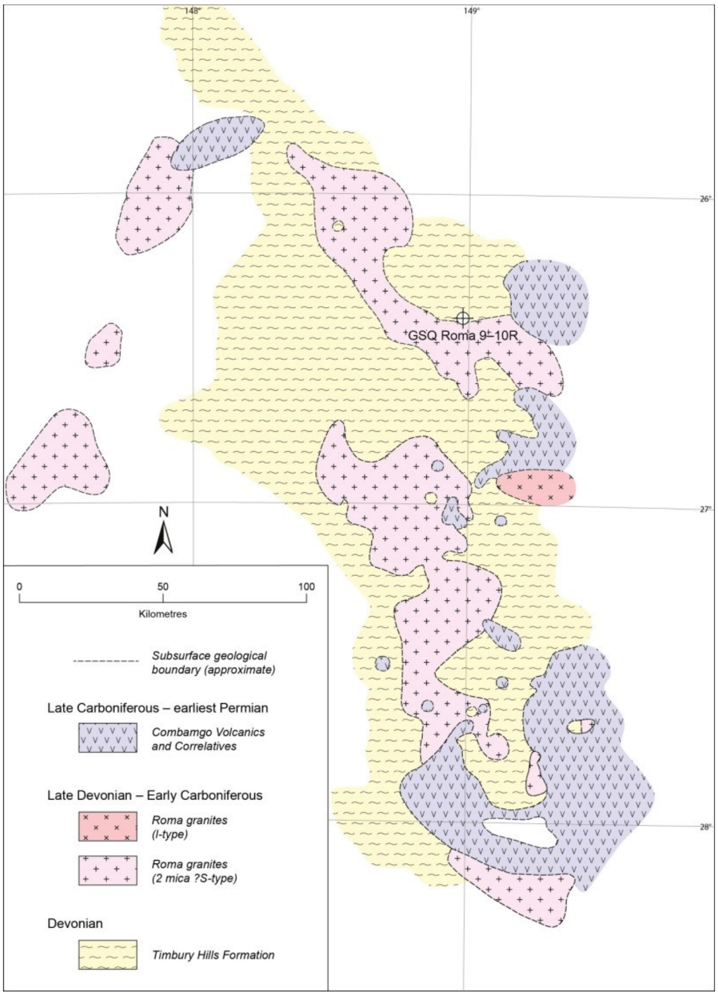

Figure 3: Basement geology of the Roma Shelf region (adapted from Murray, 1994) showing the extent of the Roma granites below the stacked Bowen and Surat basins.

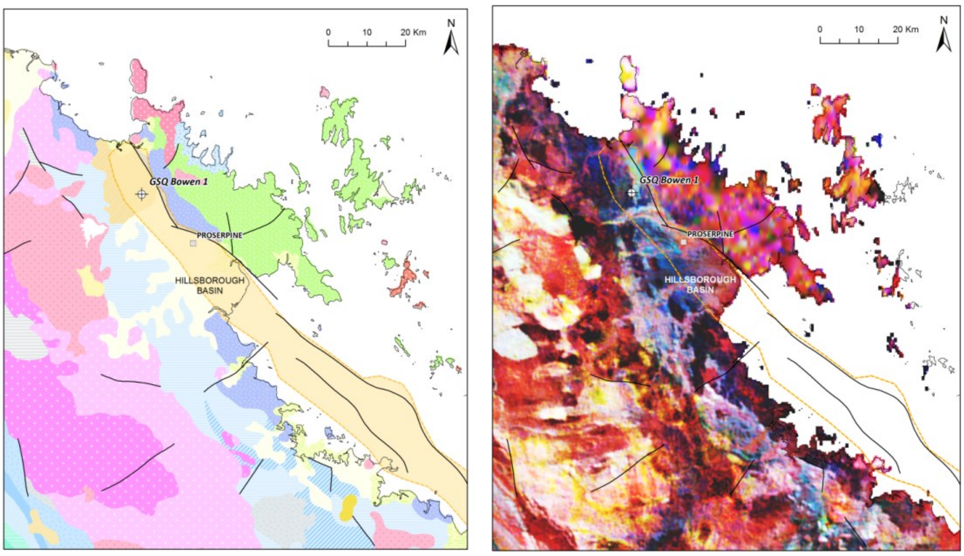

Figure 4: Geology (left) and radiometrics (right) of the Hillsborough Basin region. The geological map shows extensive faulting in the area; the Hillsborough Basin (orange) lies over and adjacent to a range of volcanics (blue and green) and intrusives (pink). The radiometric image shows a high response from several of the intrusives and volcanics, indicating enrichment in radioactive elements.

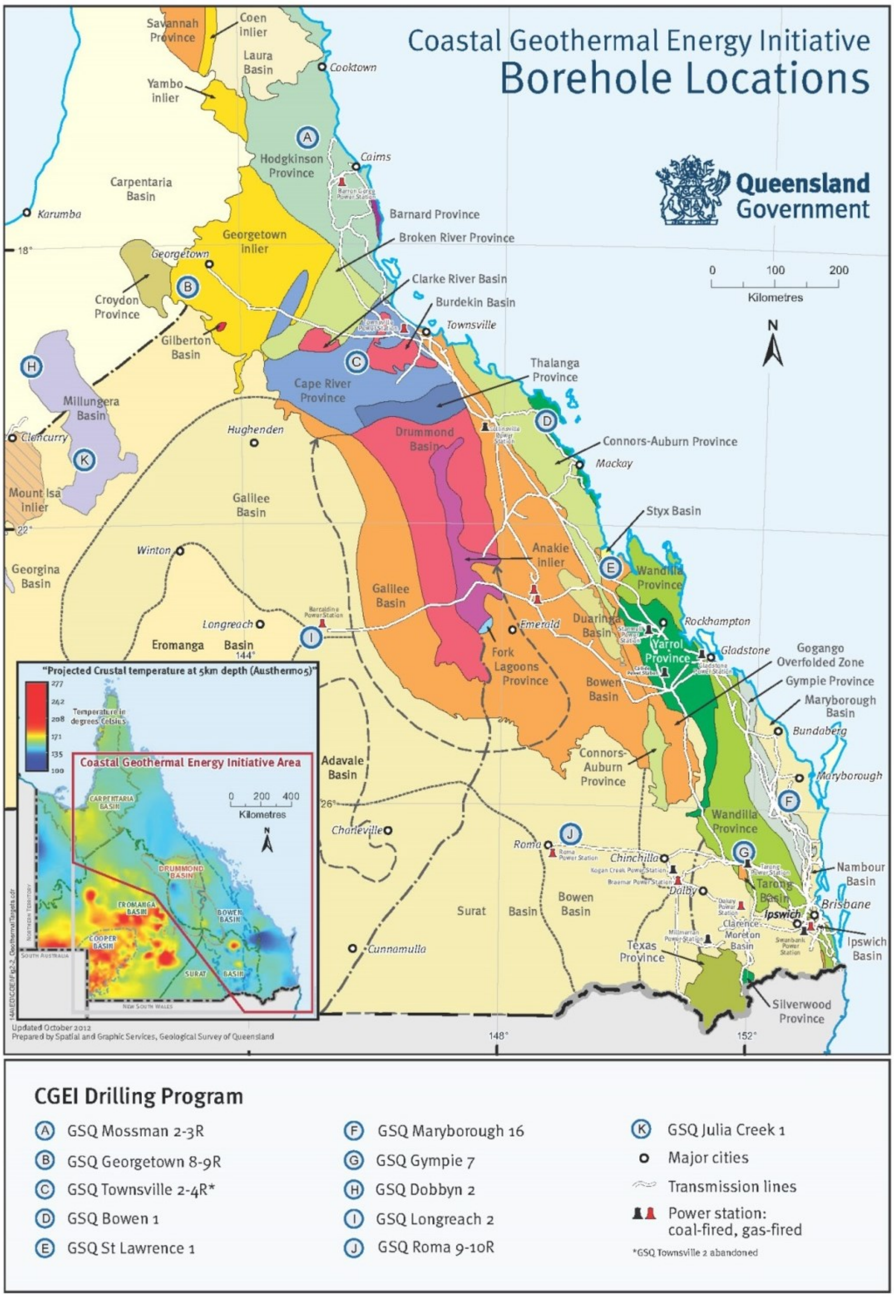

Figure 5: Boreholes drilled in the CGEI drilling program.

2.3 Modelling and Resource Assessment

The temperature and thermal conductivity data were then used to model heat flow for each site. For each target drilled, the geological succession to 5 km was inferred from geological and geophysical data to estimate the thicknesses of the stratigraphic units and their representative rock types to that depth. Thermal conductivity values were assigned to formations with uniform rock types using either the measured values or those reported in the literature. Where a mixture of rock types is present in a formation, a representative thermal conductivity was calculated from the weighted harmonic mean of the component rock types (Beardsmore & Cull, 2001). These established thermal conductivity profiles were then used to estimate temperatures to 5 km. The details of each process of modelling and energy calculation can be found in Talebi et al. (2015).

3. RESULTS

A summary of the heat flow modelling results is shown in Table 1. The uncertainty in the heat flow is calculated by propagating the relative uncertainty in the average thermal conductivity of the rock units intersected. Further calculations indicate temperatures ranging from 106 to 240°C at 5 km depth for the CGEI sites. These data and the calculated depth to 150°C isotherms below the CGEI boreholes are also shown in Table 1.

Based on the modelled temperatures at 5 km and the dimension of the inferred resource areas, total thermal energy content of the resource areas is estimated between 88,000 and 402,000 PJ (Talebi et al., 2014). For comparison purposes and to present a more tangible figure, the estimated thermal energy of CGEI inferred resources is reported in terms of equivalent electric power generation potential and annual electricity generation (Talebi et al., 2015).

Table 1: Modelled heat flow values and temperatures at 5 km depth for the CGEI boreholes.

Borehole Name	Latitude	Longitude	Total Depth (mGL)	Heat Flow (mW/m^2)	Temperature at 5 km
GSQ Maryborough 16[1]	-25.84517	152.44472	387.40	67.0 ± 2.9	207 ± 15
GSQ Gympie 7[2]	-26.69179	151.86641	338.60	37.5 ± 1.4	106 ± 9
GSQ Longreach 2[3]	-23.35250	145.23220	330.00	60.0 ± 2.5	140 ± 13
GSQ Roma 9-10R[4]	-26.38600	148.97110	335.90	82.5 ± 2.4	187 ± 14
GSQ St Lawrence 1[5]	-22.64077	149.66777	340.00	64.5 ± 1.1	171 ± 16
GSQ Julia Creek 1[6]	-20.90445	141.47260	500.02	113.0 ± 2.9	238 ± 18
GSQ Dobbyn 2[7]	-19.54532	140.88399	500.04	107.5 ± 1.7	240 ± 15
GSQ Georgetown 8-9R[8]	-18.40550	143.14143	320.15	48.5 ± 2.3	109 ± 5
GSQ Mossman 2-3R[9]	-16.51797	145.03100	339.70	77.0 ± 0.9	138 ± 1
GSQ Bowen 1[10]	-20.28725	148.46589	321.00	71.0 ± 2.3	204 ± 16

*Datum: GDA94 1 Sargent et al., 2012a; 2 Sargent et al., 2012b; 3 Brown et al., 2012a; 4 Faulkner et al., 2012b; 5 Troup et al., 2012; 6 Faulkner et al., 2012a; 7 Fitzell et al., 2012; 8 Maxwell et al., 2012; 9 Brown et al., 2012b; 10 O'Connor et al., 2012.

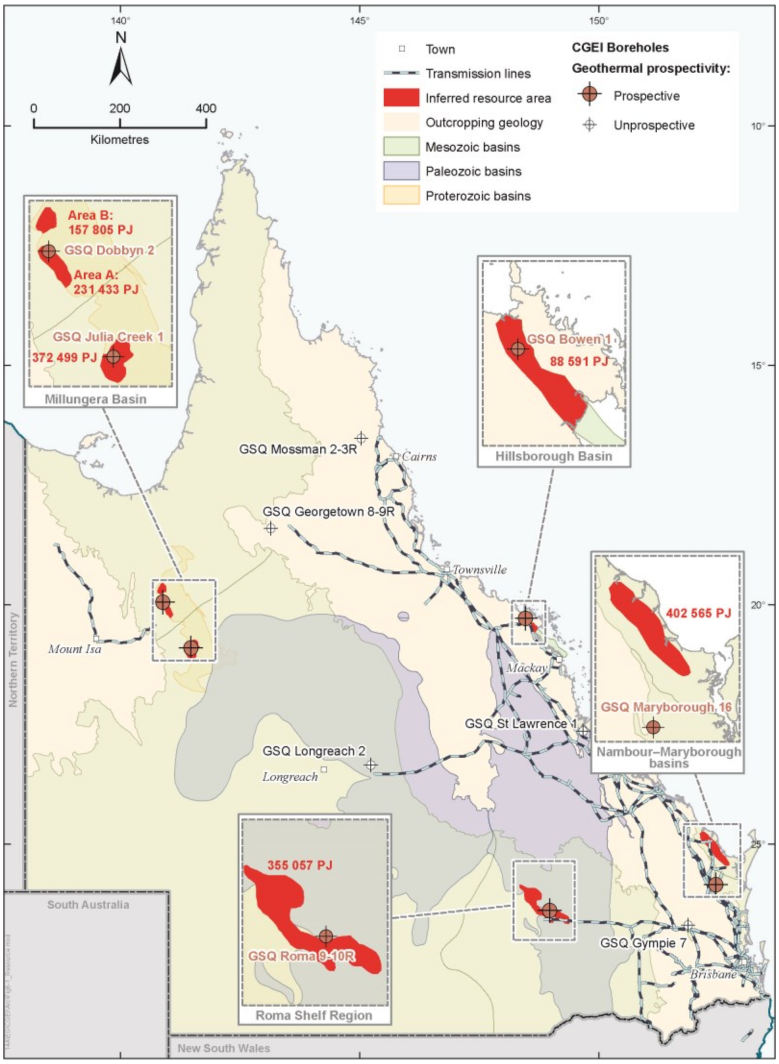

Figure 6: Areas of inferred geothermal energy potential highlighted by the CGEI program (Talebi et al., 2015).

4. DISCUSSION

4.1 Site Geology

The CGEI program highlighted good geothermal energy potential within the Millungera, Surat, Hillsborough, and Maryborough basins (Figure 6), which represent contrasting geological setting, and not necessarily fitting the traditional settings targeted for enhanced geothermal systems. A summary of these geological settings, specifically an assessment of the critical aspects of each target for EGS prospectivity, is shown in Table 2.

The best results were obtained from the two Millungera Basin sites, which had heat flow values of 107.5–113.0 mW/m^2 and an estimated 229–238°C at 5 km. These sites targeted the high heat-producing Williams Supersuite (6.72–7.50 µW/m^3), insulated by stacked sedimentary basins with highly varied thermal conductivity. The majority of the sedimentary sequence comprised highly conductive quartzite (6.64 W/mK), but the thin layer of relatively insulating sandstone and mudstone (<2.00 W/mK) had allowed high temperatures to be retained at depth.

In contrast, modelling of the Hodgkinson Province site, the only other site targeting HHP granite, produced high heat flow (77.0 ± 0.9 mW/m^2) but very low temperatures at depth (138 ± 1°C at 5 km). This is due to the thermal conductivity of the overlying strata (2.50–4.74 W/mK; Brown 2012b) – higher than that of the sedimentary strata of coal basins (generally <2.00 W/mK). However, if a coal basin like those covering large portions of Australia were present, it is highly likely that high temperatures would remain at depth.

GSQ Roma 9-10R targeted the low–medium heat-producing Roma granites under the Surat and Bowen basins. Despite having an average heat production value (~2.7 µW/m^3) less than half that of the Williams Supersuite, the site had high heat flow (82.5 ± 2.4 mW/m^2) and an estimated high temperature at 5 km (204°C). This is largely due to the excellent insulation provided by the overlying basins, especially the coal measures present.

Similarly, the high temperatures estimated for the Maryborough and Hillsborough basins are attributed to the excellent insulation provided by the coal measures of the basins. Both sites had modelled heat flow values only slightly above the global crustal average (67 and 71 mW/m^2 respectively), but modelling produced temperatures in excess of 187°C at 5 km.

Table 2: Summary of prospectivity for geothermal applications.

Site	Heat flow	Insulation	Temp @5km	Stress regime	Prospectivity for EGS
Millungera Basin – North	Good	Good	Good	Average	Good
Millungera Basin – South	Good	Good	Good	Average	Good
Surat Basin – Roma Shelf	Good	Good	Good	Average	Good
Hillsborough Basin	Good	Good	Good	Average	Good
Nambour and Maryborough basins	Good	Good	Good	Average	Good
Styx Basin	Average	Good	Average	Good	Average
Eromanga and Galilee basins	Average	Good	Average	Poor	Poor
Hodgkinson province	Good	Poor	Poor	Poor	Poor
Etheridge Province	Poor	Poor	Poor	Poor	Poor
Tarong Basin	Poor	Average	Poor	Poor	Poor

4.2 Influence of Coal Measures

Geothermal potential was identified in several locations previously thought to have low prospectivity to have low heat flow and low temperatures at depth (as can be seen in Figure 1). Both the good potential and low heat flow may be attributed to the presence of coal measures.

Rawling et al. (2014) showed that isotherms are at greater depths in areas overlying coal measures due to the high thermal resistance of the coal, with the coal measures may be masking the underlying elevated heat flow. This could be the cause for the lower heat flow values indicated in previous datasets. In addition to lowering the isotherms above, coal measures raise the isotherms below them. Further, higher temperatures may be retained at depth due to the thermal resistance of the coal measures.

An example of the influence of coal is the Nambour-Maryborough basins, where a moderate heat flow value of 67.0 mW/m^2 was obtained. Temperature modelling to 5 km immediately under the borehole drilled in the CGEI program produced a temperature of 178°C. However, factoring in an additional 2000 m of coal-bearing strata, as exist to the north of GSQ Maryborough 16, resulted in an estimated temperature of 207°C, indicating a region with high geothermal energy potential (Talebi et al., 2015).

Figure 7 shows the interpreted stratigraphic section under the Maryborough Basin, showing over 4000 m of coal-bearing sedimentary strata. The presence of such an excellent thermal blanket, insulating recent intrusions and tectonism, is the reason this site was selected. However, this thermal resistance can be problematic for shallow drilling, thus the drill site was moved to the south, where the coal measures and sedimentary strata are thinner.

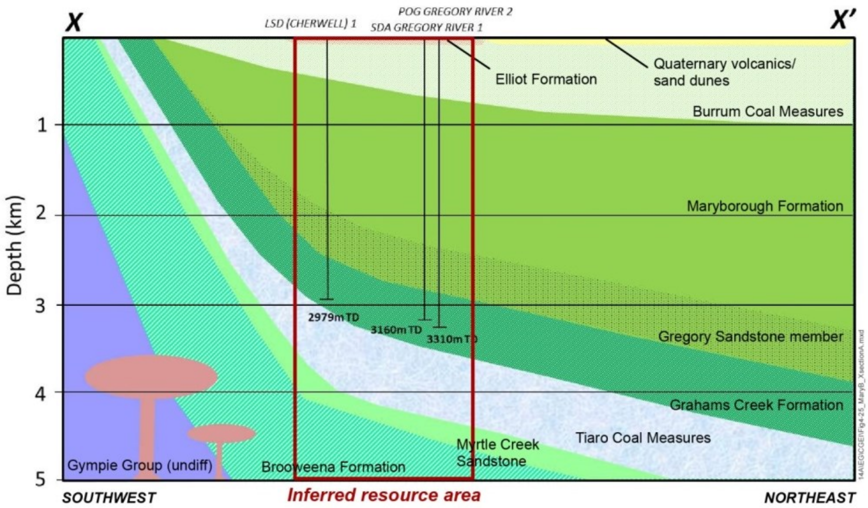

Figure 7: The interpreted stratigraphic section under the Maryborough Basin.

GSQ Mossman 2-3R, drilled in the Hodgkinson Province in North Queensland, had high modelled heat flow – 77.0 mW/m^2. However, the high thermal conductivity of the sedimentary strata (3.79–4.54 W/mK) left a low temperature at 5 km depth (138°C). Further modelling was done to estimate temperatures under the insulation of the Laura Basin. The scenario included 300 m of sedimentary strata at the top of the model, with a thermal conductivity value of 1.26 W/mK – similar to that of the coal-bearing Carpentaria and Eromanga basins, which are contemporaneous with the Laura Basin. This resulted in an increase of nearly 30°C at 5 km depth, raising the temperature to 167°C. While this may not be viable for EGS development, it does show the importance of coal basins in geothermal systems, and the potential that may exist under the numerous basins in Queensland.

The lowering of isotherms above coal measures may present an additional risk to geothermal exploration utilising shallow drilling. In cases where boreholes do not fully penetrate the coal measures, a lower heat flow value may be calculated, indicating poor geothermal potential. Consequently, deeper drilling that penetrates the coal measures should be undertaken in order to obtain the data required to determine the true geothermal potential of such geological settings.

4.3 Further Geothermal Potential

Coal basins have improved potential for EGS due to the thermal resistance of the coal measures. As demonstrated by the geothermal potential identified within the Surat, Hillsborough and Maryborough basins moderate heat sources present under high thermally resistant coal basins may retain sufficiently high temperatures at depth to be considered viable geothermal targets.

The results from the modelling of the Nambour-Maryborough Basins and the Hodgkinson Province demonstrate the significant difference even a couple of hundred metres of coal basin strata can make in a geothermal system. This may be critical in targeting prospective sites, and also in site selection.

As Talebi et al. (2015) have demonstrated, significant energy resources are inferred from less traditional geothermal targets, which suggests further potential may exist in Queensland.

Queensland's coal basins are generally located close to population and electricity infrastructure, owing to their proximity to the coast or mining towns that grow around them. There exist many low–moderate heat-producing intrusives along the east coast of Australia, overlain by coal basins. Further, residual heat may remain at depth, generated by extensive rifting and subduction along the east coast of Queensland during the Cainozoic, such as that in the vicinity of the Hillsborough Basin.

The results of the CGEI program show that geothermal energy potential may exist in regions previously thought to be unprospective, and that Queensland's abundant coal may be instrumental for unconventional geothermal energy exploration.

5. CONCLUSIONS

1. The Coastal Geothermal Energy Initiative has identified five areas as highly prospective for geothermal energy, within the Millungera, Surat, Hillsborough, and Nambour-Maryborough basins.

2. It was found that the presence of coal measures greatly increases the prospectivity of a geothermal system. Modelling shows that the presence of even just 200 m of coal-bearing strata (assigned a thermal conductivity value of 1.3 W/mK) can increase the temperature at 5 km by 30°C.

3. Even moderate heat sources under sufficient insulation may form viable geothermal targets. The abundant coal measures in Queensland may provide said insulation to moderate heat sources, opening up new geothermal potential in Queensland.

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