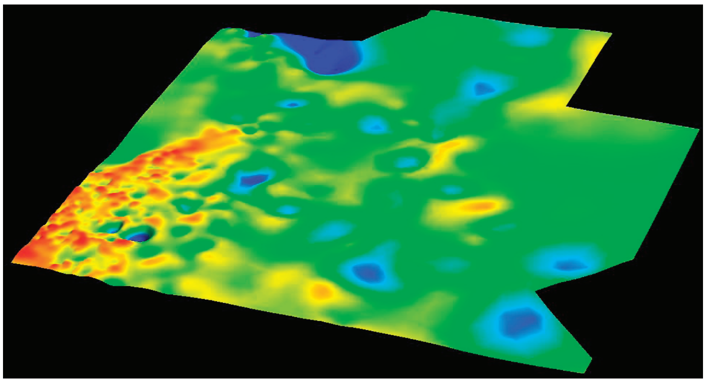
Department of **Natural Resources and Mines**
Geological Survey of Queensland

Queensland Geological Record 2012/14

Digging Deeper 10 seminar
Extended abstracts

Geological Survey of Queensland





Queensland
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Cover: Clockwise from top left; Outcrop of Currawinya Granite, Currawinya National Park, southern Queensland; Precipice Sandstone, Carnarvon Gorge; preliminary depth to basement surface for the southern Thomson Orogen; GSQ Longreach 2 drill core with ammonite shell, Eromanga Basin

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QUEENSLAND GOVERNMENT COLLABORATIVE DRILLING INITIATIVE

Simon Crouch and Malanie Banney

Geological Survey of Queensland

Since 2006 the Queensland Government has committed $9 million ($6 million in 2006 and an additional $3 million in 2010) to directly support exploration through the Collaborative Drilling Initiative grants under the Smart Mining – Future Prosperity program and Greenfields 2020 program.

Under the Smart Mining – Future Prosperity program the Collaborative Drilling Initiative was established in 2006, offering $6 million in grants to directly stimulate exploration in Queensland.

The Collaborative Drilling Initiative provided grants of up to $150,000, or half the drilling cost, to support industry when undertaking new exploration of high risk targets, or when using innovative drilling in frontier areas throughout Queensland. This initiative was continued under the Greenfields 2020 program.

At the end of the Smart Mining – Future Prosperity program, grants of over $3.8 million had been paid to companies who successfully completed 56 projects in the Collaborative Drilling Initiative. Twenty-nine of these projects were technical successes.

Technical success can be defined as the discovery of new mineralisation or a newly acquired understanding of the geological causes of geophysical anomalies. Examples of three projects that discovered new mineralisation include:

- The Champ Prospect: located 300 kilometres (km) south of Mount Isa, where Krucible Metals Ltd has postulated there are four steeply dipping and north-north-west trending lodes all open to the north and south. Core reveals multiple intersections under 100 metres (m) depth; particularly 1.23% copper at 2m; 0.41% copper at 6m; 0.43% copper at 9m; and 0.16% zinc at 12m .
- First pass drilling conducted by Mount Isa Metals Ltd on the Barbara North Lode, 240km north of Mount Isa, returned significant near surface sulphide intersections under 100m depth. Of interest were 3.74% copper at 8m; 3.97% copper and 0.26 grams per tonne (g/t) gold at 7m; 3.25% copper and 0.32g/t gold at 8m; and 4.00% copper and 0.29 g/t gold at 6m.
- The Anglo American Exploration (Australia) Pty Ltd and Falcon Minerals Ltd joint venture found significant gold mineralisation at the Saxby Project, 225km north-east of Mount Isa. Drilling intersected mineralisation of up to 6.75g/t gold from 631 to 648m and 1.98g/t gold from 614 to 621m. Nickel of up to 1268 parts per million was also intersected.

For Round 1 of the Collaborative Drilling Initiative 16 projects were completed and $1.27 million of grants paid. Ten of these projects resulted in technical successes. Round 2 had 12 successfully completed projects with eight technical successes and $1.01 million paid to companies. The relatively low number of completed projects reflected the impact of the 2008/09 financial crisis which resulted in 14 company withdrawals. The completed Round 3 had 12 projects successfully finished with $988,715 in grants paid to companies. Eight projects were technical successes. Round 4 of the Collaborative Drilling Initiative received 33 submissions, with 11 projects from nine companies successful. Five projects were completed with $220,233 in grants paid. Three projects were technical successes with the round finishing in June 2011.

In July 2010 a further $3.0 million was assigned to continue the Collaborative Drilling Initiative under the Greenfields 2020 program. Three rounds were planned.

In response to the summer wet season limiting drilling activity, the project period was extended from 12 months to 15 months. Final reports are still to be required three months after completion of the project. Payments are dependent upon successful assessment of the submitted report.

The $2.2 million Round 5 closed on 19 November 2010. It attracted 56 applications and resulted in 21 projects from 17 companies being allocated $2.35 million in grants. To date six projects from have been completed with the payment of $625,810.

The $1.0 million Round 6 closed on 1 April 2011 and 23 applications were received with nine projects from eight companies being allocated over $1.17 million. This round is anticipated to finish in early 2013.

The 22 applications received for Round 7 were independently assessed in February 2012. Ten successful projects will share a total of $990,250 in grants. This round is anticipated to end in October 2013.

The demand for grants in Rounds 5, 6 and 7 have reflected not only a continued interest in this initiative but greater competition between companies focused on high quality submissions to win support.

Two projects that discovered new mineralisation under Round 5 of the Greenfields 2020 Collaborative Drilling Initiative include:

- Red Metal Limited drilling the Maronan prospect, located 60km south-east of Cloncurry. The results include the highest lead and silver grades intersected on the project to date. Intercepts include 14.5% lead, 371g/t silver over a true width of 2.58m with a nearby parallel zone averaging 11% lead, 245g/t silver over a similar width. The combined true thickness of the separate high-grade silver-lead intervals in both banded iron formation (BIF) horizons total over 8m.
- At the Andy’s Hill prospect, located 53km south-west of Cloncurry, Mount Dockerell Mining Pty Ltd intersected mineralisation and alteration typical of Iron Oxide Copper Gold (IOCG) deposits over a wide zone (+250m true width).

Downhole EM has suggested that the hole was located 50m north of the strongest conductor.

Currently $3.63 million is committed to projects with completion dates up to 2013, as part of Rounds 5, 6 and 7.

These initiatives have encouraged the expansion of frontier exploration in Queensland, resulting in the discovery of new mineral and energy resources. The State Government has received a significant return on its investment with $12.56 million of direct drilling expenditure by industry supported by Collaborative Drilling Initiative funding of $4.11 million.

A NEW MAP AND BOOK PORTRAYING QUEENSLAND GEOLOGY

Ian Withnall

Geological Survey of Queensland

THE MAP

The new *Queensland Geology* map at a scale of 1:2 000 000 was released at the International Geological Congress (IGC) in Brisbane in August 2012.

The map replaces the 1975 edition, which was based on the results of regional surveys from 1951 to 1973. These surveys had resulted in complete state coverage of geological maps at 1:250 000 scale.

The new map brings together the results and new insights gained from the more detailed second-pass (and some third-pass) geological surveys carried out by the Geological Survey of Queensland (GSQ) and Geoscience Australia (GA) of the more complex hard-rock areas since the 1970s. These surveys resulted in the production of maps at a scale of 1:100 000, and in recent years have taken advantage of the many advances in geology and technology, in particular remote sensing techniques, such as satellite imagery, airborne geophysics and better visualisation techniques through image processing.

Compilation was facilitated by GA's 1:1M digital geological map released in 2005, but significant updates were made from new work by GSQ in north-west and central Queensland. The compilation involved the aggregation of almost 2000 geological units on GA's map into 250 units (191 stratigraphic and 59 intrusive units) deemed realistic for portrayal in hard-copy. The linework in GA's data was too complex to use automatic generalisation tools, so boundaries of generalised units were plotted at 1:500K and manually traced and generalised by GSQ geologists and then digitised, polygonised and tagged by cartographers in GSQ's Graphic Services Unit (GSU) and joined into a seamless map. The final map design and production by GSU's Ross Lane used ArcGIS and the map was offset printed at the New South Wales Land and Property Management Authority.

A new map of the structural elements of Queensland, and a time–space relationship diagram of the geological units, accompany the main map. Geochronology methods, which have become much more accessible and reliable since 1975, have allowed dating of many rock units previously of uncertain ages and facilitated significant changes to our understanding of the temporal framework as portrayed in the time–space diagram.

Apart from the printed maps, the data has been released in digital format and is also available on-line on the GSQ's Interactive Resource and Tenure Map system.

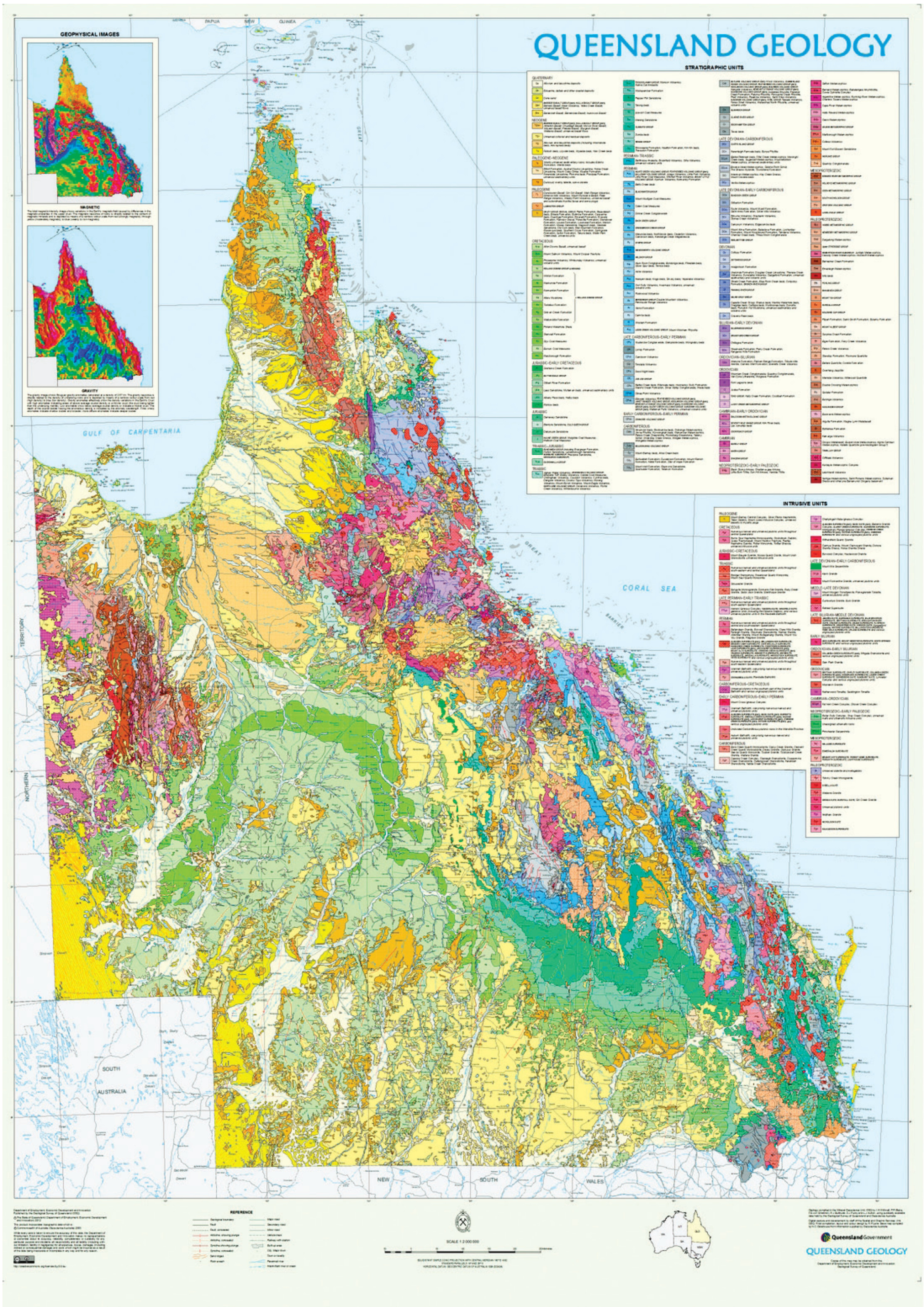


Figure 1. Queensland Geology map

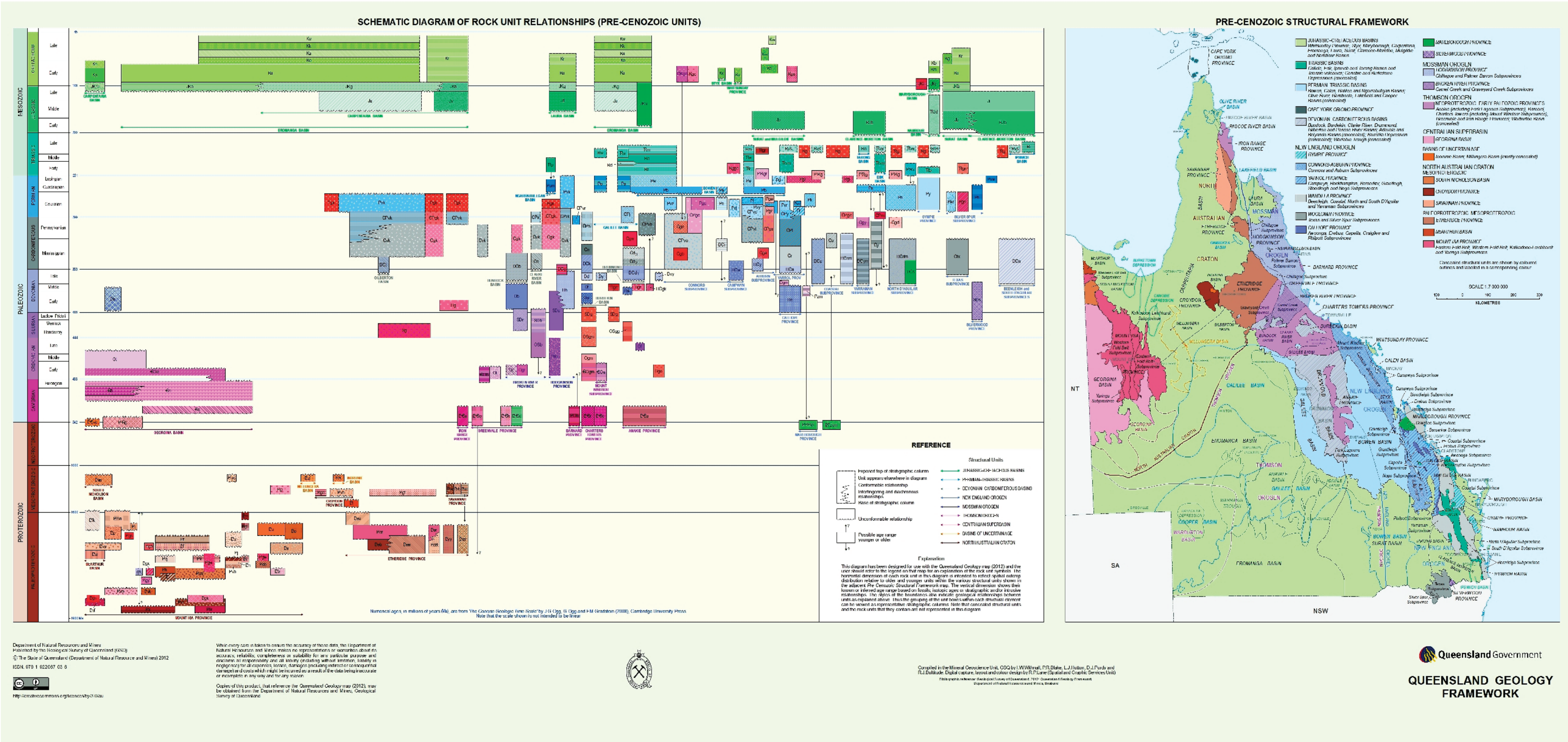
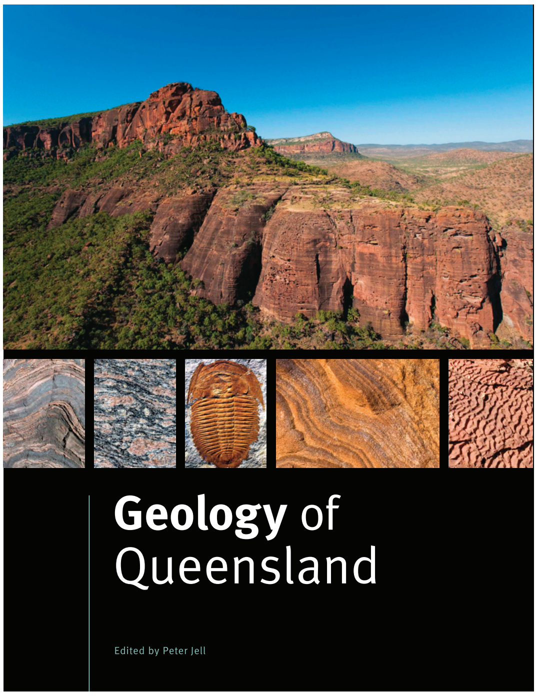


Figure 2. Queensland Geology Framework (pre-Cenozoic Structural Framework and Schematic Diagram of Rock Unit Relationships for pre-Cenozoic units)

THE BOOK

Concurrent with the map production, GSQ has undertaken an ambitious project to produce a modern, comprehensive description and detailed analysis of Queensland's geology. The new *Geology of Queensland* was also intended for release at the IGC in August 2012, but although all of the chapters had been received, final editing and desktop design was delayed, and it is now scheduled to go to the printers in December. However, a mock-up of the book on display at the IGC received much favourable comment. Under the editorial supervision of Dr Peter Jell, the book's 57 contributors include geoscientists from GSQ, GA, various universities and museums and some from industry



The book will be printed in full colour and has 824 pages of text and 114 pages of references as well as an index. It has 723 text figures and photographs. It therefore represents a far more comprehensive treatment of Queensland's geology than either of its predecessors, Volume 7 of the Journal of the Geological Society of Australia, (the 'green bible' of Hill & Denmead, 1960) and GSQ Publication 383 (Day & others, 1983). Both of these were milestone publications, respectively recording the state of knowledge soon after the commencement of systematic 1:250 000-scale mapping and following its completion. Along with the new map, the new volume will also be regarded as a milestone, marking the completion of second pass mapping of most hard-rock areas of the State. It therefore encapsulates the results from the efforts of a generation of GSQ and GA geologists as well as the enormous contribution to geoscientific knowledge by academia and industry over that time.

Organised differently from previous editions, the main chapters cover each of the major geological components or cratonic areas, orogens and basins, as follows:

North Australian Craton
Thomson Orogen
Mossman Orogen
New England Orogen
Kennedy Igneous Association
Post-orogenic Mesozoic basins and magmatism
Paleogene and Neogene
Quaternary

Descriptions of younger rocks such as overlying sedimentary basins and igneous intrusives within the North Australian Craton and Mossman and New England orogens are included within the respective chapters.

These regional geological chapters are followed by a series of thematic chapters addressing mineral and energy resources, seismicity, groundwater, engineering geology, impact structures and meteorites, and geological heritage.

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COASTAL GEOTHERMAL ENERGY INITIATIVE: SHALLOW DRILLING AS A MEANS OF ASSESSING GEOTHERMAL POTENTIAL

Lauren O'Connor

Geological Survey of Queensland

INTRODUCTION

In Queensland, developing alternative energy options in the north and east of the state is particularly favourable due to the close proximity to centres of population, industry including mining or power transmission lines. Regional datasets such as Oztemp, released by Geoscience Australia in 2011, are commonly used to highlight areas with geothermal energy potential using pre-existing data. This dataset has highlighted the south-west portion of the state as having anomalously high temperatures at depth, suggesting substantial geothermal potential. Outside this region, data density and reliability diminish, limiting the accuracy with which the prospectivity of Queensland's coastal regions can be assessed. Thus, the collection of new data is critical for better assessment of the geothermal potential of the state. Shallow drilling programs such as the Coastal Geothermal Energy Initiative (CGEI) provide a means of assessing regional scale geothermal potential for areas with limited data coverage. In lieu of direct measurements of temperature at depth, temperature and thermal conductivity data collected from shallow drilling may be used to determine heat flow — a useful tool through which temperatures can be modelled at greater depths. However, the confidence with which shallow drilling data can be used to represent surface heat flow of a target is a product of the methods of collection and analysis.

The main aims of the CGEI were firstly to increase knowledge of the crustal temperatures along Queensland's north and east coasts where geothermal energy has been less investigated to date; and secondly to facilitate reduction of exploration risks and assist potential explorers to explore for and develop this source of clean energy close to the electricity grid in Queensland.

The CGEI sought to implement the best methods of sampling and hole completion for use in a shallow drilling program. CGEI collected thermal conductivity and temperature data through a regional drilling program. These data were used to determine vertical conductive heat flow, from which temperatures were modelled to 5km depth, and an assessment of the regional geothermal energy potential was made.

Ten fully-cored boreholes were drilled into sedimentary basins and metasedimentary terranes across northern and eastern Queensland (Figure 1), to a total depth from 320 to 500m. The boreholes were cased to total depth with PVC or VAM steel casing, and the annulus was grouted to isolate aquifers and permeable layers to ensure a closed system. The boreholes were left to thermally stabilise for a minimum of six weeks after drilling before precision temperature logs were run. Core samples from representative rock types intersected in each borehole were collected for thermal conductivity analysis. Details of targeting, sampling, and methodologies have been provided by Fitzell & others (2009); Talebi & others (2010); Sargent & others (2011). Talebi & others (2012) describes methods of temperature modelling and detailed results of resource volume and thermal energy content.

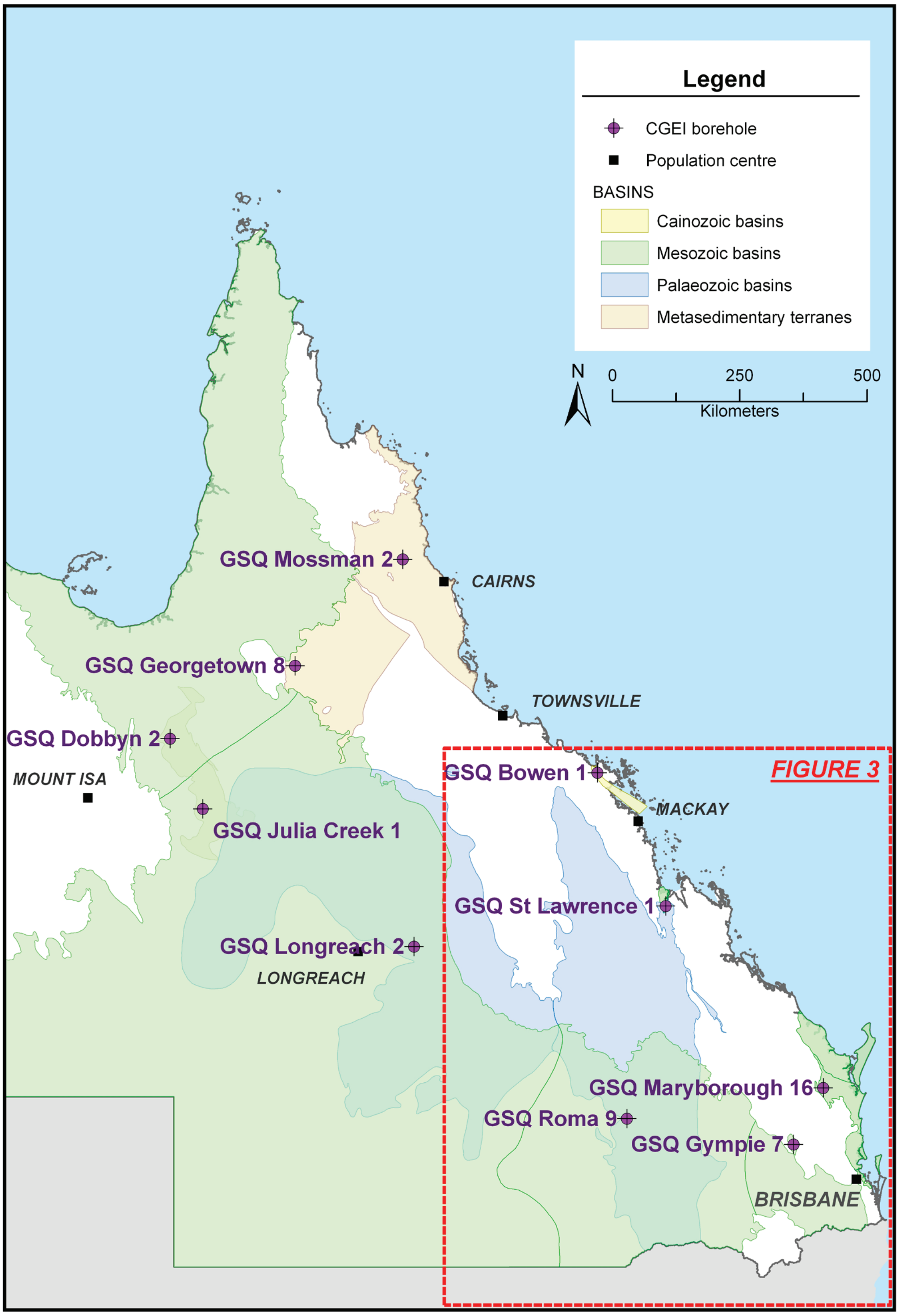

Figure 1. Sedimentary basins and metasedimentary terranes drilled in the CGEI program. Borehole locations are shown with major towns and cities.

RESULTS

Using the collected temperature and thermal conductivity data, vertical conductive heat flow was modelled for each borehole. Five sites were found to have heat flow above the crustal average of 65mW/m^2 (Cull, 1990). The modelled heat flow was then used in conjunction with predicted stratigraphy to 5 km to extrapolate temperature to this depth. Table 1 shows these results, along with the depth to cut-off temperature — 150°C — the minimum temperature for a viable enhanced geothermal system.

Table 1. Heat flow, temperature to 5km, and the depth to cut-off temperature for each site

Tectonic Unit	Borehole Name	Heat Flow (mW/m^2)	Temperature at 5 km (°C)	Depth to cut-off temperature (m)
Hodgkinson Province	GSQ Mossman 2	77.0 ± 0.9	156 ± 10	4810
Georgetown Inlier	GSQ Georgetown 8	48.5 ± 2.3	109 ± 5	7574
Hillsborough Basin	GSQ Bowen 1	71.0 ± 2.3	204 ± 16	3879
Styx Basin	GSQ St Lawrence 1	64.3 ± 1.1	170 ± 16	4734
Maryborough Basin	GSQ Maryborough 16	67.4 ± 2.9	206 ± 14	3342
Tarong Basin	GSQ Gympie 7	37.5 ± 1.5	106 ± 9	8063
Millungera Basin (north)	GSQ Dobbyn 2	107.0 ± 1.7	212 ± 15	3630
Galilee Basin (north-east)	GSQ Longreach 2	60.0 ± 2.5	140 ± 13	5390
Surat Basin (Roma Shelf)	GSQ Roma 9	82.2 ± 2.4	204 ± 14	3615
Millungera Basin (south)	GSQ Julia Creek 1	113.0 ± 2.8	239 ± 18	3178

DISCUSSION

Data collection

Thermal Conductivity

Two methods of thermal conductivity analysis were undertaken, and it was found that using core with preserved *in situ* moisture content better represented the rock under formation conditions. Analysis of these samples gave lower thermal conductivity than those of samples analysed under saturated conditions.

Thermal conductivity of samples from by CGEI boreholes in sedimentary basins were lower than, or in the lower part of, the published range of values (Table 2). The published values are consistent with the spread of values obtained for metasediments intersected in the Georgetown Inlier, Hodgkinson Province and Millungera Basin. Similarity of values may be a reflection of the composition of the rocks — higher silica content, matrix composition or a higher degree of alteration of the rocks. The potential overestimation of the TC values of sedimentary basins such as the Surat, Bowen, and Hillsborough basins an important consideration when modelling heat flow through these regions. The collection of *in situ* samples for thermal conductivity analysis is critical for determining accurate surface heat flow at a specific site.

Table 2. Comparison of CGEI thermal conductivity values to published values from Beardsmore & Cull (2001)

	Thermal conductivity range (W/mK)		
Lithology	**Sedimentary Basins (CGEI)**	**Metasedimentary Terranes (CGEI)**	**Published (Beardsmore & Cull, 2001)**
Sandstone	1.47–3.52	2.50–7.69	2.8–7.1
Siltstone	1.88–2.43	4.12–5.06	2.67–3.2
Mudstone	0.47–2.70	-	1.9–2.9

Temperature

The method of hole completion proved critical to obtaining a reliable temperature profile. Two methods of hole completion were used in this program. The first was to cement aquifers as they were intersected, by drilling 6m below and cementing at least 6m above the permeable zone. However, subsequent temperature logging showed that fluid flow between even minor permeable units distorted the temperature profile. Figure 2 shows the sharp increase in temperature and steep geothermal gradient between two permeable units intersected in GSQ Longreach 2. The recompletion of this hole included cementing of the annulus to isolate any aquifers and permeable zones, which resulted in a steady temperature gradient.

Geology

There were several geological factors which contributed to the modelled heat flow values. The lowest determined heat flow was for the Tarong Basin, where thick coal and sedimentary sequences are interpreted to overlie the moderate heat producing Boondooma Igneous Complex. The entire basin sequence was not penetrated; therefore it is possible that further insulating sequences, potentially including coal, underlie the drilled sequences. This would significantly lower the heat flow within the drilled section, accounting for the anomalously low heat flow value.

Similarly, further coal sequences below the drilled section in the Nambour Basin would account for the average heat flow determined. A fault was intersected towards the bottom of the borehole making it difficult to determine whether drilling intersected the entire coal sequence. These coal measures may have been a factor in previous estimates of low heat flow for this region.

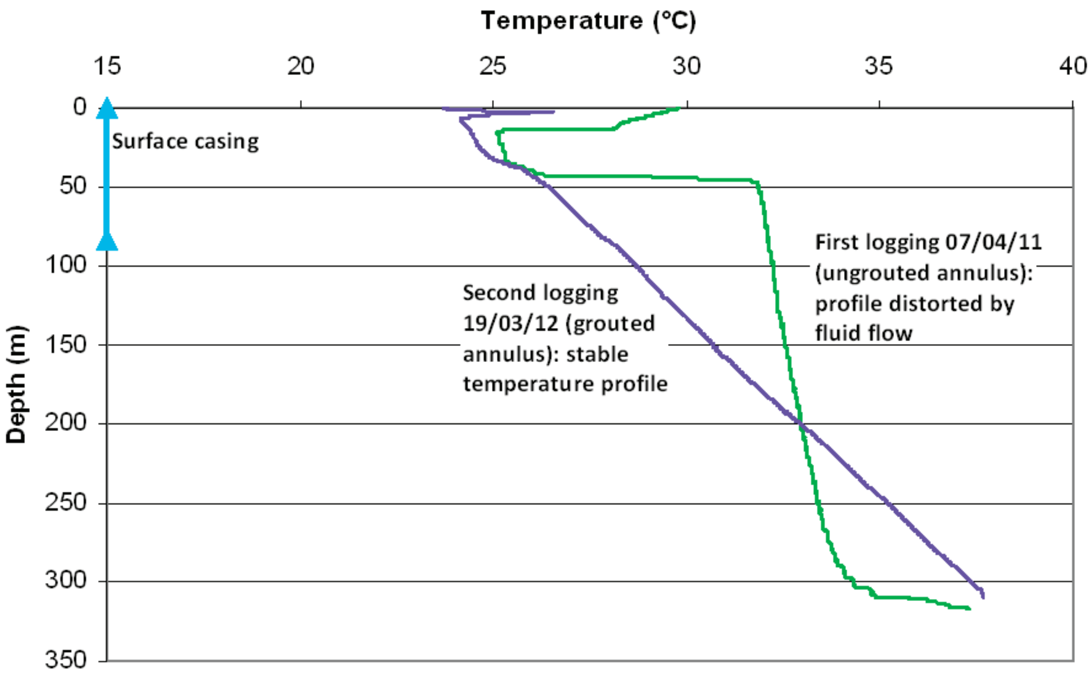

Figure 2. Temperature profile of GSQ Longreach 2. Two minor permeable zones were intersected, and without grouting of the annulus, these caused a sharp increase in temperature and geothermal gradient between the two zones (green line). By grouting the annulus of the borehole, flow between these units was controlled, and thermal equilibrium was achieved (purple line).

High concentrations of heat producing elements within the Proterozoic intrusive of the Mount Isa Inlier are estimated to contribute up to 70mW/m^2 to the regional heat flow (McLaren & others, 2002). However, high heat flow does not necessarily indicate geothermal potential, with high temperatures at depth only generated under insulating cover.

Heat flow modelling results of the sites drilled within the Millungera Basin to the east of the inlier were in excess of 100mW/m^2. Estimated temperatures at 5km depth incorporating the insulating capacity of the Eromanga–Carpentaria basins overlying the Millungera Basin were greater than 220°C, delineating these two targets as highly prospective for geothermal energy.

Further targets with high heat flow included the low to moderate heat producing Roma Granites, and residual heat from Cainozoic tectonism and volcanism under the Hillsborough Basin, which would conventionally be considered less prospective than high heat producing intrusives. Moderate to high heat flow was determined for both these sites, with temperatures in excess of 200°C modelled at 5km depth (Table 1). This is related to the thermal resistance of the overlying sedimentary cover, where the intersected sequences contained coal and had thermal conductivity values below 2.6W/mK.

Shallow drilling

Coal measures are ideal in hot rock geothermal systems as they provide excellent insulation. The high thermal resistance property of coal can result in a localised low heat flow within the coal measures. In cases where the coal seams have not been penetrated by drilling, the low heat flow value may be inferred as reflecting poor geothermal energy potential.

Shallow drilling in coal basins, especially where a borehole does not extend below the coal measures, can be an added risk factor. Deeper drilling penetrating the coal measures should be undertaken in order to obtain the data required to determine the geothermal potential in these geological settings. This requires a good understanding of local geology and structure.

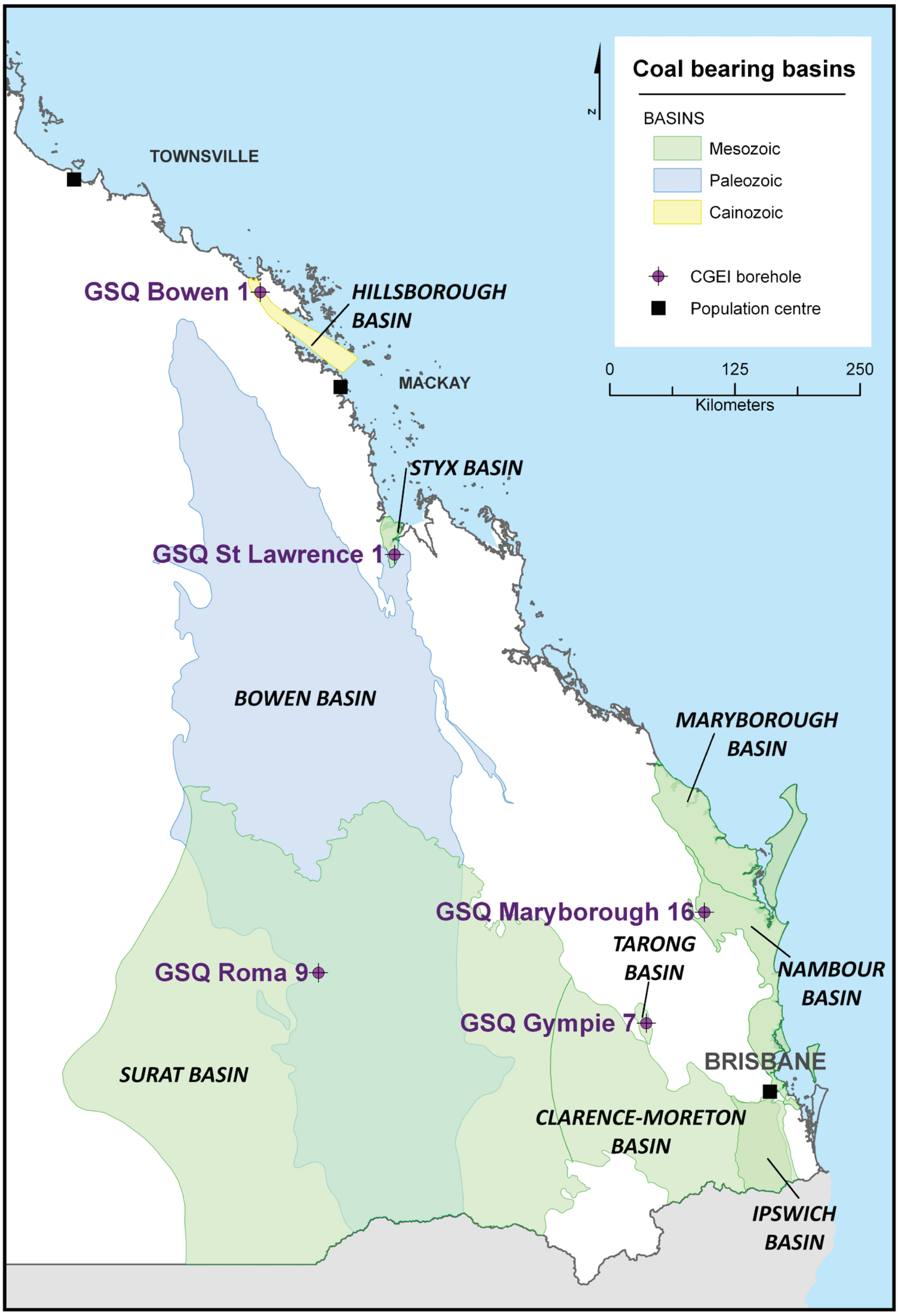

Figure 3. CGEI boreholes in south-east Queensland and coal-bearing sedimentary basins

The stacked sedimentary basins in south-east Queensland commonly contain coal measures (Figure 3), which provide excellent insulation for potential heat sources. Results of the CGEI drilling program also demonstrate that given the high thermal resistance of these sedimentary sequences, temperatures in excess of 200°C can be generated by a range of heat sources.

Modelling and resource potential

Temperature Projection

Determination of subsurface temperature at target depth is a key parameter when assessing geothermal energy potential of a target area. In lieu of deep drilling and direct measurements, downward extrapolation of steady-state temperature to a depth *z* can be performed using the thermal conductivity (λ), the thickness of the regarded interval (d), and the temperature at the top and bottom of the interval (T_0 and T_z respectively).

$$T_z = T_0 + q_0 \cdot \int_0^z \frac{d_z}{\lambda_z}$$

The heat flow at the top of the interval, q_0, is assumed purely conductive and therefore constant to depth. Although this linear relationship is a simplification of a complex dynamic system, it is a reasonable first order approximation in the absence of direct measurements at depth.

In the case of CGEI boreholes, the established conductive heat flow values have been used to predict temperatures at greater depths. First, the geological succession to 5km was inferred from geological and geophysical data to estimate the stratigraphic thicknesses and bulk thermal conductivities to that depth using the weighted harmonic means of values measured in this initiative or assigned from published data in the literature. It is considered that 5km is deemed an economically drillable depth for electricity generation from a geothermal energy resource. Temperatures at 5km depths were then modelled in one dimension assuming that the established conductive heat flow values remain relatively constant and predictable with depth, with negligible advection.

The modelled temperatures at 5km depth range from 204 to 239°C across the Millungera, Surat, Hillsborough and Maryborough basins implying possible geothermal energy potential within these basins. Using the same modelling approach, depth to a cut-off temperature of 150°C — the minimum temperature of the resource which could allow commercial deliverability from a production well — has also been estimated for each basin. This depth is used to determine thickness of the inferred resource when assessing geothermal energy potential. Results of temperature projection at 5km and depth estimation to the cut-off temperature are summarised in Table 1. Uncertainty in the projected temperatures is calculated solely by propagating the relative uncertainty in the average thermal conductivity of the rock units predicted to 5km.

Heat does not always flow vertically in areas where significant lateral contrasts in thermal conductivity exist. Similarly, lateral variations in heat producing elements will also cause local variations in heat flow. Therefore, 1D-modelling of heat flow and temperature should only be considered as a first pass assessment of potential energy. For the CGEI targets, lateral contrasts in thermal conductivity as well as heat producing elements must be investigated in more than one dimension in future work.

Thermal energy assessment

An important factor in the assessment of the geothermal energy potential of a target area is the evaluation of the volume of the geothermal system in question. For the CGEI targets, a volumetric approach has been used as the preferred method for geothermal assessment. In the application of the volumetric method it is assumed that the volume is a box. In the CGEI program the surface area has been estimated, generally on the basis of geophysical data or the area over which sediment is within an ideal thickness range. Thickness of the inferred resource is determined from the 150°C cut-off temperature depth to 5km. For simplicity, it can be assumed that the heat capacity and temperature are homogeneous laterally, and are only dependent on depth. The thermal energy content of the system (Q) can then be calculated using the following equation:

$$Q \approx \rho_r C_r V (T_R - T_r)$$

where:

ρ_r	rock density
C_r	specific heat capacity of the CGEI inferred resource rocks at the cut-off temperature of 150°C
V	rock (resource) volume (m^3)
T_R	resource mean temperature — taken as the average between the cut-off temperature (150°C) and the temperature at the base of the resource (5km depth), listed in Table 1
T_r	reference temperature — the temperature relative to which the thermal energy will be estimated (70°).

The total thermal energy content of the highlighted areas has been estimated and reported in petajoules (PJ) in this paper.

The estimated thermal energy is reported in Table 3; for comparative purposes and to present a more tangible figure, estimated thermal energy content of CGEI inferred resources is reported in terms of equivalent electric power generation potential. Figure 4 shows the inferred resources areas for the highlighted areas, and their proximity to transmission lines and major cities.

Table 3. Modelling parameters and estimated resource thermal energy content

Tectonic Unit	Resource mean temp. (°C)	Inferred resource thickness (m)	Resource surface area (km^2)	Thermal energy estimate (PJ)
Millungera Basin (south)	195	1822	848	553,995
Millungera Basin (north)	181	1370	596	261,025
Surat Basin (Roma Shelf)	177	1385	430	155,410
Hillsborough Basin	177	1121	464	143,758
Maryborough Basin	185	1542	342	145,644

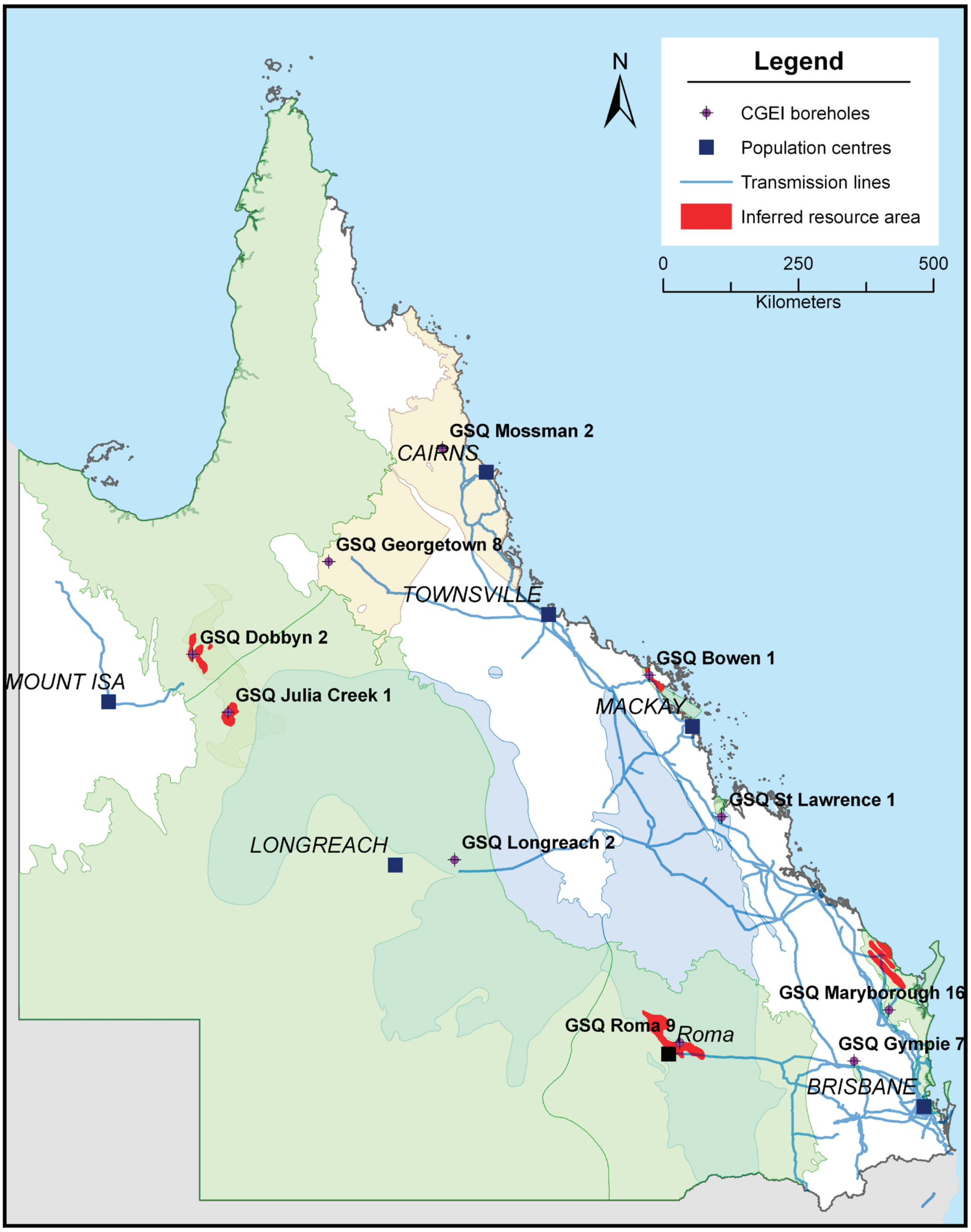

Figure 4. Inferred resources areas for the highlighted regions and their proximity to transmission lines and major cities

Electric power generation potential

There are a few parameters that govern the conversion process of thermal energy to electricity. Only a small fraction of the total stored thermal energy in a geothermal system is recoverable and can be converted to electricity. While conceptually simple, recovery factor is very difficult to predict and is hard to define. Even in convective geothermal reservoirs with long production histories, there is no definitive guideline in the literature as to how the recovery factor should be defined or determined (e.g. Grant, 2000). Generally, recovery factors vary between 5–50% depending on the geological conditions, mainly porosity, with an average value of 25% for hydrothermal resources (Muffler, 1979) and 40–50% for Enhanced Geothermal Systems (EGS) (Sanyal & Butler, 2005). At this stage there is no sound basis for predicting the net recovery factors for the thermal energy estimates of the highlighted areas.

From the recoverable thermal energy of the geothermal system, only a small portion can be converted to electricity, and this is determined by the thermal conversion efficiency of the power plant in use. The conversion efficiency of geothermal power plants is mainly dependent upon the temperature of the geothermal fluid. Compared with conventional fossil-fuel or nuclear powered plants, which operate with superheated steam over temperature ranges of about 550°C, geothermal power plants operate over relatively lower temperature ranges, generally between 150 and 250°C. At these relatively low temperatures, thermal conversion efficiencies are inherently lower than conventional power plants.

The percentage of time a power plant operates is the plant's capacity factor. Base load geothermal power plants typically produce electricity about 90% of the time, but can be operated up to 98% of the time in some cases.

The economic life of a geothermal plant/project is the period it takes the whole investment to be recovered within its target internal rate of return. This is usually between 25–30 years.

The assumptions used to convert the estimated thermal energy to equivalent electric power generation potential in the CGEI highlighted areas, assuming conservative estimates, are:

- thermal energy recovery factor: 5%
- plant thermal conversion efficiency: 7%
- plant capacity factor: 90%
- plant/project economic life: 25 years.

Based on the above parameters and assumptions, the gross electric power generation potential is estimated to be between 700 and 2700MWe for the highlighted areas (Table 4).

Obviously the estimates are based on a purely hypothetical case, and therefore should not be taken as an implication that the authors endorse the parameters and assumptions for use in any decision making effort or practical application. These parameters, assumptions and estimates should be revised once detailed exploratory work is undertaken in the future, and when more direct measurements at subsurface conditions are available for the highlighted regions.

Based on the modelled temperatures at greater depths, total thermal energy content is estimated between 144,000 and 554,000PJ at the selected targets using the volumetric approach under stated assumptions. The distribution of the heat per unit volume ranges between 260 and 360PJ/km^3 which is relatively similar to the energy density reported for other geothermal prospects in Australia. The highlighted areas may be prospective for both EGS and Hot Sedimentary Aquifer (HSA) development depending on the rock type intersected at the target temperature and also mitigating other risks such as poor permeability.

Table 4. Estimates of recoverable thermal energy and equivalent electric power potential of the highlighted areas

Tectonic Unit	Inferred resource - recoverable heat estimate (PJ)	Equivalent gross electric power generation potential (MWe)
Millungera Basin — south	27700	2730
Millungera Basin — north	13051	1290
Surat Basin	7770	760
Hillsborough Basin	7188	710
Maryborough Basin	7282	720

CONCLUSIONS AND RECOMMENDATIONS

Shallow drilling is an applicable method of collecting data for determining heat flow — a useful tool for assessing the geothermal prospectivity of a region. However, the use of high quality data is critical for precision and accuracy in the modelling of heat flow and temperature.

Complications may arise from shallow drilling in coal basins, where thick coal measures mask the heat flow regime and, as such, have the potential to distort heat flow and give a potentially misleading evaluation of geothermal potential. The risk factors associated with this may influence future shallow drilling in these regions, despite the benefit of these coal measures to the overall geothermal system. Deeper drilling to penetrate all coal measures is required.

The collection of multiple precision temperature logs not only provides excellent quality data, but also allows for assessing whether the system has returned to a state of thermal equilibrium. The isolation of all aquifers intersected by a borehole is critical to ensuring thermal stabilisation. Cementing the annulus provides the most effective way of isolating these aquifers.

The CGEI program highlighted the differences between published thermal conductivity values and samples with preserved *in situ* moisture content. Sedimentary strata (from the Carpentaria, Eromanga, Surat, Bowen, Styx, Hillsborough, Nambour and Tarong basins) had much lower thermal conductivity than published thermal conductivity values. This highlights the limitations associated with using published thermal conductivity values for determining the geothermal potential of an area.

Moderate heat sources present under high thermally resistant sedimentary sequences of south-east Queensland may generate sufficiently high temperatures at depth to be considered viable geothermal targets. The geothermal potential presented by these less traditional heat sources lends credence to the notion that despite the lack of high heat producing intrusives, the prospectivity of south-east Queensland may be much better than previously estimated.

The newly established heat flow data ranges from 71 to 113 mW/m^2 across Millungera, Surat, Hillsborough and Maryborough basins implying possible geothermal energy potential within these basins. These results have greatly improved the geothermal potential of these regions, with some of the regions previously estimated to have limited potential. Using the new heat flow dataset, temperatures of 204–239°C have been predicted at 5km depth in one-dimension in the selected regions.

The depth to cut-off temperature at the remaining sites was too great to constitute a viable geothermal resource.

Based on the modelled temperatures at greater depths, total thermal energy content is estimated between 144,000 and 554,000PJ. The highlighted areas may be prospective for both EGS and Hot Sedimentary Aquifer (HSA) development depending on the rock type intersected at the target temperature and also mitigating other risks such as poor permeability.

Equivalent gross electric power generation potential of the highlighted areas has been estimated to be 700–2700MWe in the highlighted regions. Analysis has indicated that the electric power generation potential of 585–2150 MWe can be expected from the highlighted basins with 90% probability. Obviously, the estimates are based on a purely hypothetical case under certain assumptions due to the lack of sufficient quantitative data, and therefore should be revised once detailed exploration programs are undertaken in the future and direct measurements at greater depths are available.

Overall, this method for estimating thermal energy has limitations. It provides no information about the practicalities of development, particularly whether there may be resource-specific constraints such as poor permeability, scaling or corrosion problems. However, it can still give an understandable, rational basis for comparing the size of different geothermal resources, taking into account both volume and temperature.

The following recommendations are made in order to more accurately define geothermal energy potential in the highlighted basins:

- Spatial distribution of heat flow data needs to be increased in each area by incorporating all wells or boreholes previously drilled or currently being drilled as well as drilling new holes if necessary. This would require precision temperature logging to be undertaken in the holes and more extensive measurements of rock thermal conductivity to be made.
- A three-dimensional geological model of each area needs to be developed for facilitating 3D heat flow modelling to better constrain the 3D distribution of the temperature field. This would require triaxial thermal conductivity analysis of rock samples to investigate effects of anisotropy.
- Extensive stress field study is required across the highlighted basins at both regional and prospect scales for initiating numerical hydro-mechanical modelling to constrain expected geothermal reservoir growth direction.
- Exploratory drilling is required to validate the prospectivity of the identified areas. This would initially require drilling of low-cost slim-holes to 2–3km depth to verify predicted temperatures at depth, confirm geological succession, perform downhole logging and revise geothermal resource assessment.
- An engineering feasibility study needs to be undertaken by collating and integrating all the available geoscientific data, engineering and economic parameters to individually evaluate commercial viability of geothermal energy development programs in the highlighted basins.

DELIVERABLES

Individual well completion reports of CGEI boreholes are being released progressively as they are completed. A final report to outline the assessment of geothermal energy potential across the State's north and east coasts is due for publication by mid-2013.

ACKNOWLEDGMENTS

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Coastal Geothermal Energy Initiative

Behnam Talebi, Sarah Sargent, Mark Maxwell, Lauren O'Connor.

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NATIONAL VIRTUAL CORE LIBRARY (NVCL) — SPECTRAL MINERALOGY OF QUEENSLAND CORES

Suraj Gopalakrishnan, Daniel Killen, Phil Burrows and Phil Thompson

Geological Survey of Queensland

The National Virtual Core Library (NVCL) is a collaborative research infrastructure funded by the Commonwealth Government's National Collaborative Research Infrastructure Strategy (NCRIS) within the Department of Innovation, Industry Science and Research (DIISR). This project is one component of the many earth science programs managed by AuScope Ltd and implemented by CSIRO and all State and Territory geological surveys. The Queensland node of NVCL is operational at the Geological Survey of Queensland (GSQ) at their Exploration Data Centre (EDC) facility at Zillmere on Brisbane's northside. The HyLogger will be moved to our regional libraries at Mount Isa and Central Queensland at a later date in tune with our data collection priorities.

The NVCL project has the goal of progressively building up a high-resolution hyperspectral, digital database of the upper 2km of the Australian continent, thus facilitating world-class geoscience research. The back-bone behind this project is the CSIRO developed and built HyLogger™ machine that is capable of non-destructively scanning core in its original core trays, without involving sample preparation. This instrument rapidly measures reflection/emission spectra within visible-near infrared-shortwave infrared and thermal infrared regimes of the electromagnetic waves along with continuous high resolution (~0.1mm) digital colour images of the core surface. The spectral data obtained by HyLogger can be interpreted using The Spectral Geologist™ (TSG™) software suite which interprets mineralogy from spectral information, and displays them based on standard colour codes for individual minerals along the depth of the hole. The interpretations of mineralogy are indicative and the software provides the user with options for making alternative conclusions. Specialised scalars can be derived for mapping complex mineral information using HyLogger derived information as well as other relevant external inputs. Other methods of validation should be used in conjunction with HyLogger data to better understand mineral systems.

Based on other available datasets (like geophysics) and in alignment with other AuScope programs, certain buffer zones were proposed by AuScope called Geotransects (Figure 1). GSQ has identified all mineral and stratigraphic bore holes that fall within this proposed Geotransect to be scanned initially, and continuing with HyLogging these bore holes as priority. Most of these datasets are presently available on request by contacting the EDC and in future will be available as free web delivery. Recently, there has been a steady growth in external interest in this technology, both from mining industries and university research.

DATABASE MANAGEMENT

Millions of dollars spent annually on drilling in Australia remains under-utilised due to the inefficiencies in core preservation. The legacy cores in the GSQ Core Libraries at Zillmere, Mount Isa and Mount. Morgan alone account for more than 900km of cores and a significant portion can be value added.

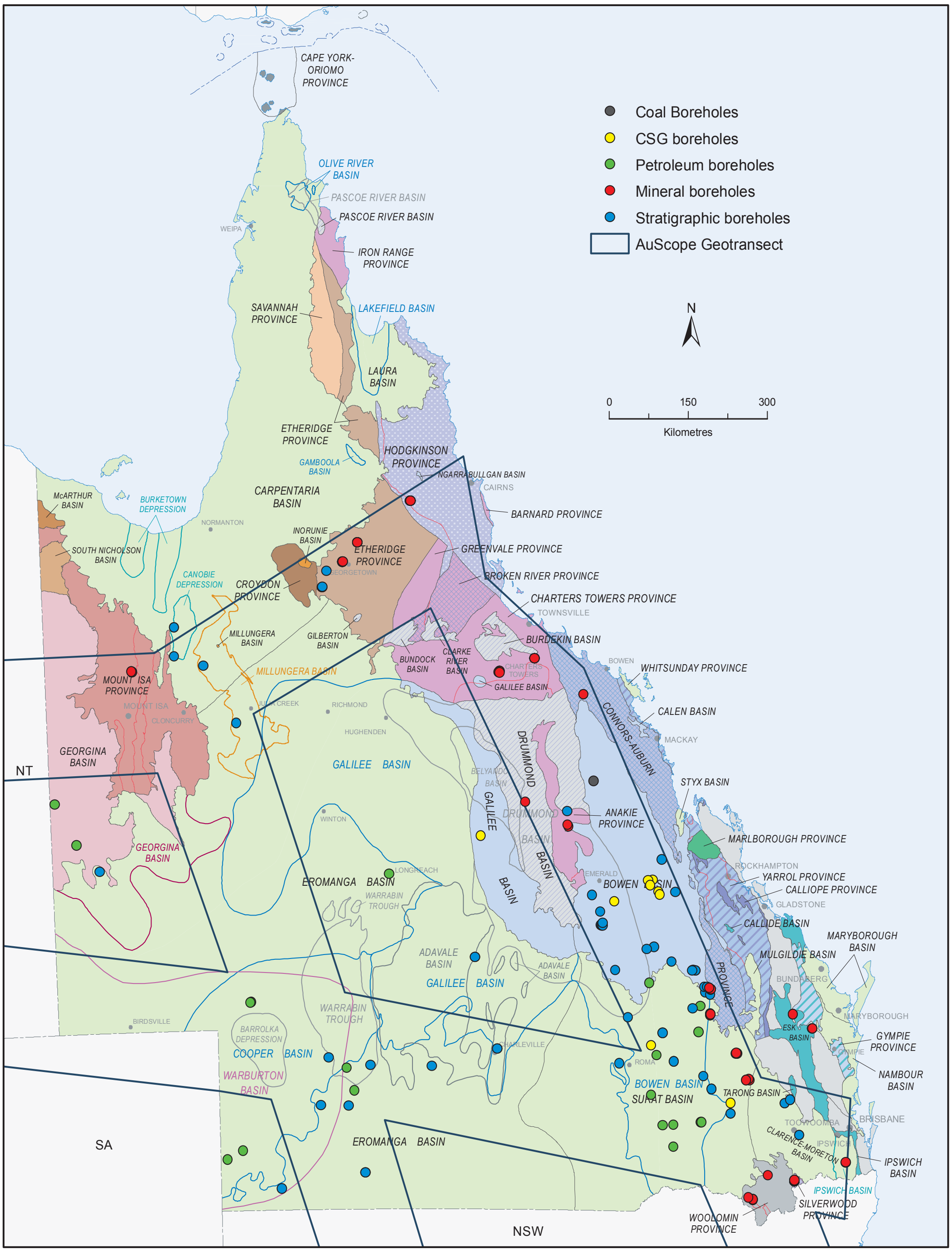

Figure 1. Map showing the AuScope Geotransects and the location of mineral bore holes that have been HyLogged since September 2009

Generally, HyLogger produces 3Mb of data for every metre of core and the sheer mass of information to be scanned and published is remarkable. HyLogger systems are built to handle enormous data volumes, however moving this amount of data over the internet would not be easy. AuScope Grid will access those databases hosted by individual surveys at their servers, extract data and publish simplified versions to the internet for examination. Full resolution versions of these datasets are available on request as standard media deliveries.

QUALITY CONTROL / COLLECTION OF MINERAL SPECTRA USING HYLOGGER

With the development of automated drill core scanning spectrometers, visible-near-shortwave infrared (400–2500nm) and thermal infrared (8000–14000nm) reflectance and emission spectra can be collected, respectively, from the surface of the drill core, and these spectra contain information about mineral chemistry, mineral abundance, and the physical state of the drill core (e.g. porosity, gain size, etc.) (Hunt, 1977; Clark, 1999; Tappert & others, 2011). Even though this technique produces large datasets (1000s of spectra) within a short span of time, interpretation of the resulting data, which is the key to gaining the correct mineralogical information, requires an in-depth knowledge of the spectral properties of the minerals and rocks involved. In general, interpreting the spectral dataset can be difficult when the rocks are composed of many minerals and when the physical properties of the rocks (e.g. grain size) interfere with the amplitude and position of absorption features (Clark, 1999). As a result, computationally intensive algorithms are often used to interpret the spectra, which become quite demanding for large volumes of cores. Moreover, these algorithms are not designed to handle complex mineral mixtures or metallic minerals, meaning that the logs produced using these algorithms are often rough approximations. Hence it is our responsibility to validate those minerals identified using HyLogger in order to maintain data integrity, and a general validation routine ensures the authenticity of the data collected.

APPLICATION TO UNKNOWN SAMPLE IDENTIFICATION

HyLogging of GSQ cores has identified many minerals that are consistent with visual logging, but interesting new information has also been revealed, most of which required validation using other analytical methods for confirmation. Some of those interesting examples are discussed below.

GSQ Tambo 4

This drill-hole is located 43km west-north-west of Tambo in the eastern Eromanga Basin over the Pleasant Creek Arch (Figure 2). Tambo 4 penetrated the sedimentary rocks of the Eromanga Basin overlying the sedimentary rocks of the Galilee Basin to a depth of 1263m finishing in the Black Alley Shale.

The HyLogger data on Tambo 4 generally displayed montmorillonite dominated Wallumbilla Formation followed by Kaolinite dominated layers downhole. But there

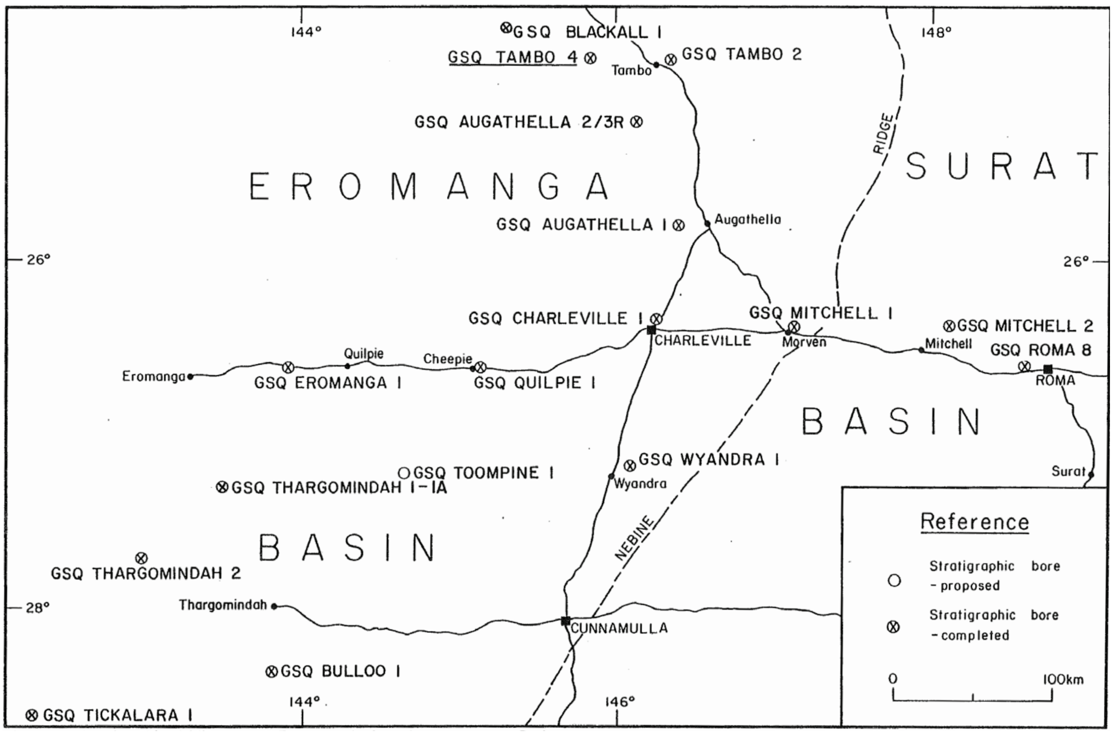

Figure 2. Location map of GSQ Tambo 4

were specific zonations of Dickite distribution aligned against the sandstone beds. Kaolinite and Dickite are the two most widespread polymorphs of the kaolin group, kaolinite being far more common than dickite. Even though dickites are first reported in hydrothermal system, both authigenic kaolinite and dickite are common polytypes within the sandstone reservoirs and other sedimentary rocks (Beaufort & others, 1998; Fialips & others, 2003). Within rocks with similar sedimentary facies and petrographic properties at the first stage of burial, the kaolinite crystals progressively coarsen, increase in their degree of stacking order, and appear to be replaced progressively by blocky dickite within increasing burial depth (Shutov & others, 1970, Beaufort & others, 1998). But kaolinite is highly regarded as the stable mineral in the group while halloysite, nacrite and dickite would then be metastable minerals whose geological occurrences must be interpreted in terms of kinetics and as a result of specific formation paths. Hence the formation of dickite within the sandstone beds on Tambo 4 was suspicious and warranted a validation study.

The X-ray diffraction studies on randomly oriented powdered samples using CuKα radiation source revealed the mineral dickite in the sample, overshadowed by quartz, mica and kaolinite. The textural characterisation of these samples was made using a Scanning Electron Microscope (SEM), where the micrographs displayed blocky dickite strewn alongside the kaolinite flakes (Figure 4). Fig 4b shows the transformation of kaolinite booklets to blocky dickite, suggesting a temperature related "dickitisation" at shallow depth conditions (Beaufort & others, 1998). In fact, dickite is reported to have its origins in deep seated conditions with an average depth of 2500–5000m from the surface with kinetically controlled evolution as described by Zotov & others, (1998). The presence of dickite in the surface as seen in GSQ Tambo 4 was quite intriguing. The influence of water/rock ratio on the kaolinite-to-

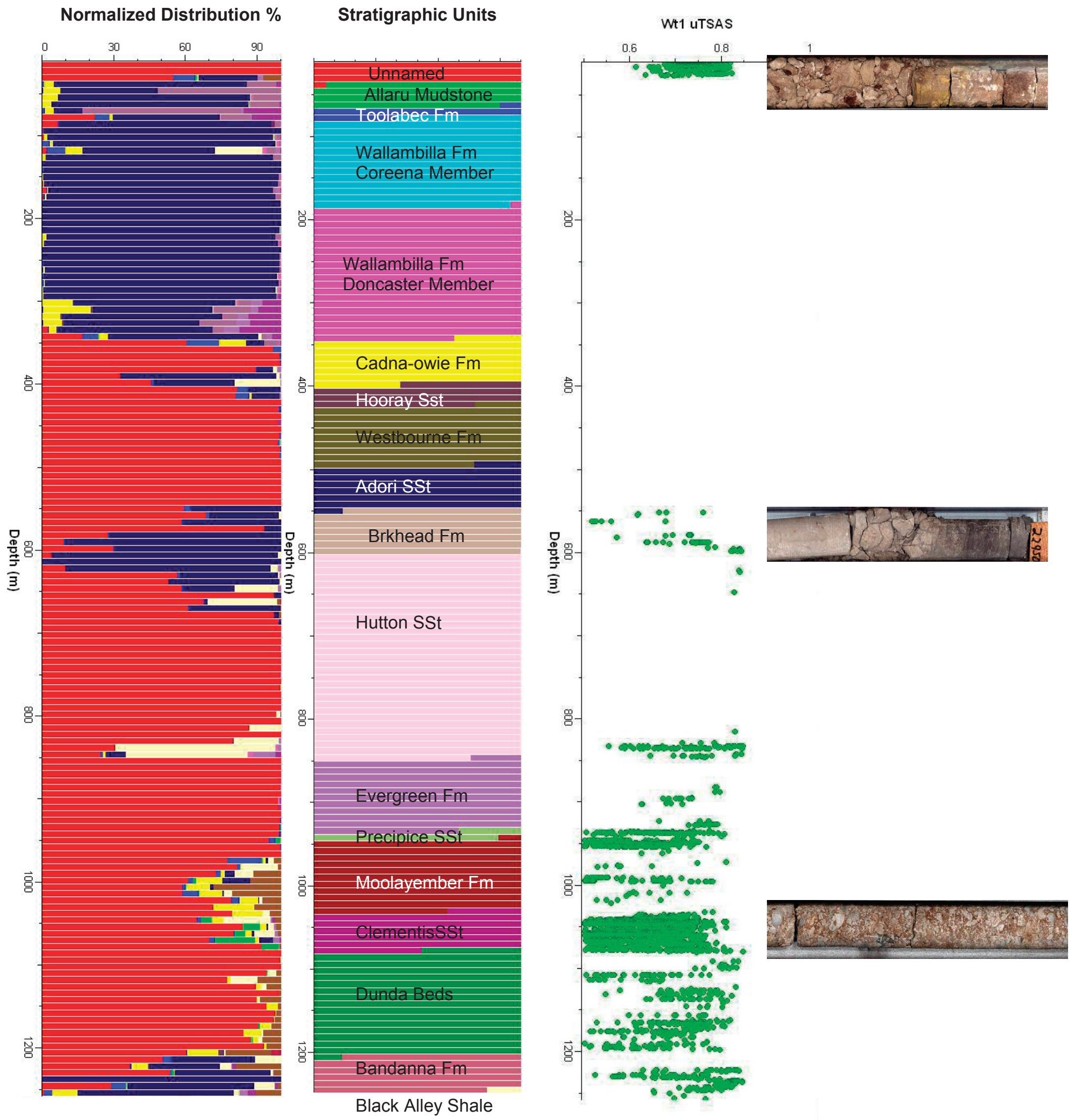

Figure 3. Normalised mineralogical distribution on GSQ Tambo 4 drill hole along the depth of the hole. The distribution of Dickite is given separately and the inset shows the core images showing dickite samples specific to that zone.

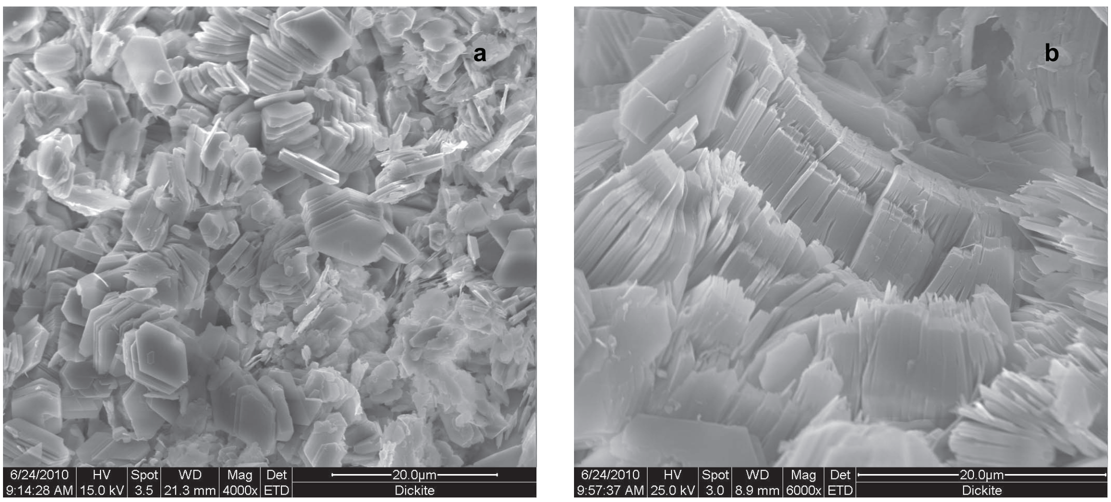

Figure 4. Dickite is seen along with Kaolinite in these SEM pictures of GSQ Tambo 4 at a depth of 1077m. Vermicular structure is suggestive of authigenic formation.

dickite formation could be a viable explanation as discussed by Lanson & others, (2002). In rock types varying from shales to medium-grained sandstones, kaolin exhibits an extreme textural and crystal chemical variability where the kaolinite-to-dickite reaction rate depends not only on temperature (burial depth) but also on other parameters like porosity, petrology, hydrocarbon invasion, etc.

GSQ Duaringa 3A

This dominantly carbonaceous and clay drill hole (Lat. 23º09’12”S, Long. 149º18’18”E) displayed unusual, but consistent doublets at around 1730 and 2300nm (Figure 5). The brown colour of the core is suggestive of organic material, which is usually hard to detect by the HyLogger due to its dark nature. Kerogen is a mixture of complex organic chemical compounds found in sedimentary rocks with high molecular weight (>1000 atomic mass units) and is insoluble in normal organic solvents. When present in high concentrations in rocks, such as shale, and those not subjected to warmer temperatures, they form good source rocks for hydrocarbons (e.g. shale gas). The presence of absorption doublets at 1730–1760nm and 2300–2350nm in the short-wave infrared region with a broad absorption at ~1900nm is characteristic of Kerogen (Rowan & others, 1991;1995).

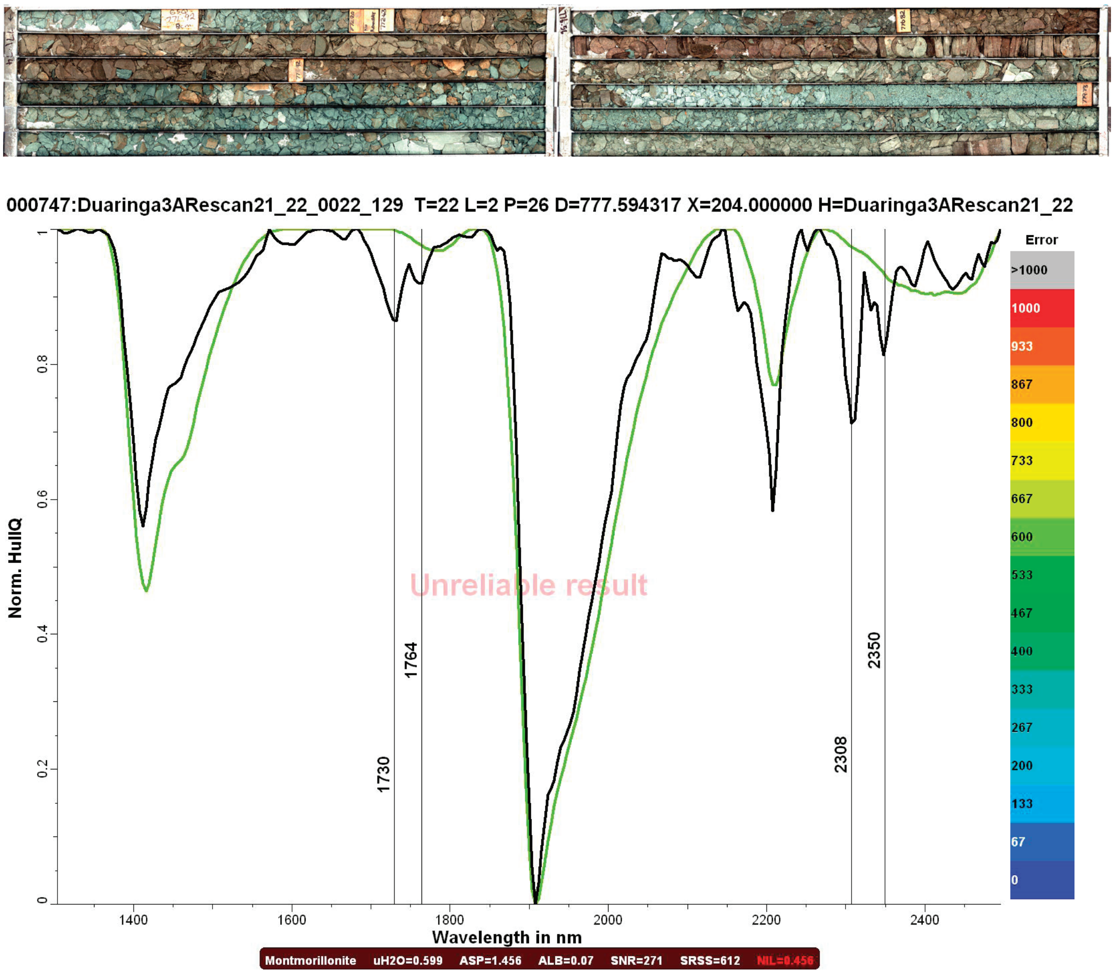

Figure 5. Tray images of GSQ Duaringa 3A drill hole (top) showing brownish tinge of Kerogen in a smectite rich sample. The SWIR spectra shows the doublets at 1730 and 2300nm, indicative of Kerogen.

CONCLUSION

The NVCL project with an aim to progressively build up a high-resolution hyperspectral, digital database of the upper 2km of the Australian continent, uses HyLogger™ to non-destructively scan drill cores in their original core trays. This robotic scanner measures reflection and emission spectra within visible-near-shortwave infrared and thermal infrared regimes of the electromagnetic waves along with continuous high resolution (~0.1mm) digital colour images of the core surface, and interprets mineralogical information using the TSG™ software suite.

HyLogging of GSQ cores identified many minerals that are consistent with visual logging, but much interesting new information was also revealed, which requires alternative supportive data to better understand the complex mineral systems. Some of our initiatives to understand such new systems are discussed. The high concentration of dickite within a kaolinite dominated clay horizon was validated to confirm its presence, especially those observed towards the core surface. A complex organic mixture, Kerogen, which is considered to be a viable alternative hydrocarbon source, could also be easily identified by monitoring its characteristic absorption positions in the spectra.

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SEQUENCE STRATIGRAPHY OF THE LOWER JURASSIC SUCCESSION IN THE SURAT BASIN, QUEENSLAND

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To better assess the carbon-dioxide storage potential of the Lower Jurassic sandstones in the Surat Basin, the Carbon Geostorage Initiative of the Geological Survey of Queensland (GSQ) undertook a sequence-stratigraphic study of the Precipice Sandstone and overlying Evergreen Formation.

These formations are considered to have potential as a storage reservoir-seal pair. The Evergreen Formation, however, is not an effective seal over the whole basin, as hydrocarbon shows in the succeeding Hutton Sandstone suggest some hydrocarbon leakage has occurred in eastern and western areas (Hodgkinson & others, 2012). Hydrodynamic studies, where multiple formation tests in the Jurassic aquifers of the Surat Basin have been assessed, suggest that the Precipice Sandstone is not in hydraulic communication with younger aquifers in the south-eastern area of the basin (Hodgkinson & others, 2010).

Geological modelling relies on standardised formation tops but, over the years, different picking methodologies have been used, causing inconsistencies in basin-wide interpretation. A sequence-stratigraphic approach is employed here to focus on a detailed facies and sequence analysis of the section from the sequence boundary at the base of the Precipice Sandstone [which generally forms the basal unit of the Surat Basin, except where the Eddystone and Chong beds are present (Cook & others, in press)] to the sequence boundary at the Evergreen Formation – Hutton Sandstone boundary, in drill holes GSQ Chinchilla 4 and GSQ Roma 8 (located respectively, in the north-eastern area of the basin on the up-thrown side of the Leichhardt Fault and in the north-western area on the cratonic basement high referred to as the Roma Shelf; Figure 1).

Three sequences have been identified in these two stratigraphic drill holes and a selection of petroleum wells across the Surat Basin, with their sequence boundaries (SB1, SB2, SB3, SB4) being extrapolated on seismic data, in order to determine if they can be correlated on a basin-wide scale. In comparing the section studied in GSQ Roma 8 with that examined in GSQ Chinchilla 4, the former is assessed as being a condensed-section and can be correlated with equivalent sequences in the latter section.

The lowermost sequence delineated, from the sequence boundary at the base of the Precipice Sandstone (SB1) to the base of the ‘Boxvale Sandstone Member’ (BSM), delineated as SB2, consists of high-energy, braided-stream deposits (Precipice Sandstone), which fine upwards into swamp and peat-mire sediments (lower

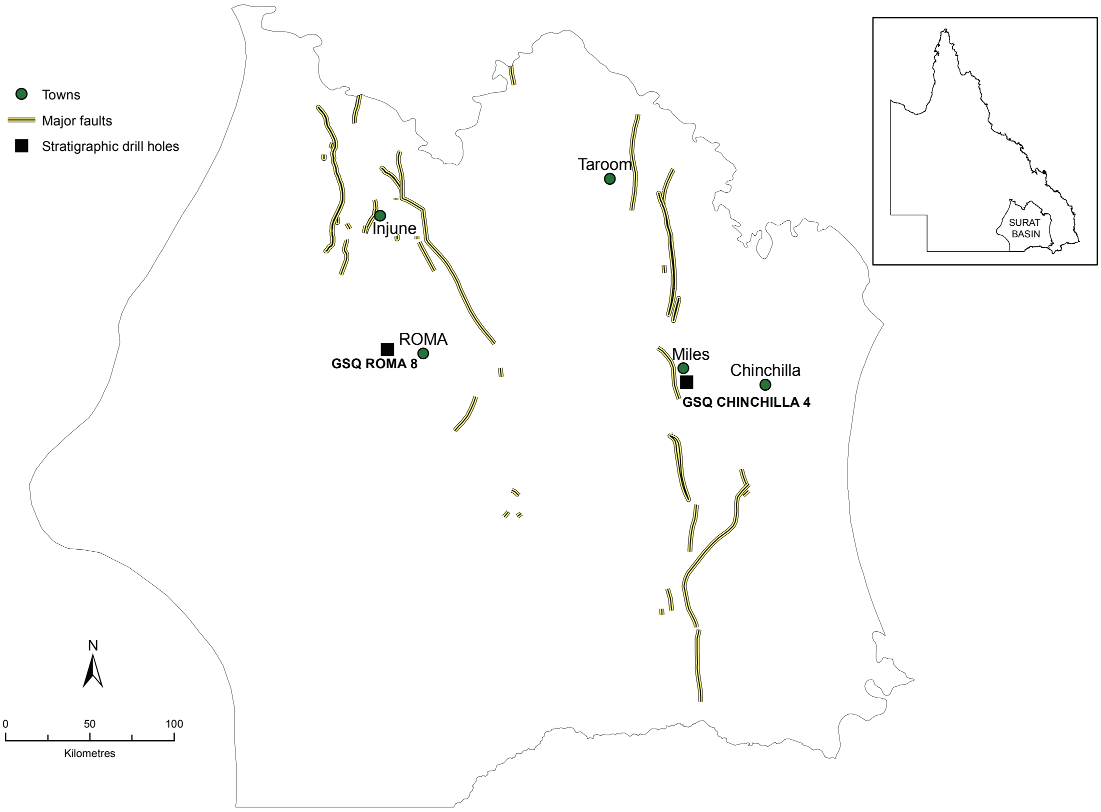

Figure 1. Location of the stratigraphic wells investigated in this study, in relation to the major fault systems in the Surat Basin

Evergreen Formation). The facies at the top of this sequence, although differing in character between GSQ Chinchilla 4 and GSQ Roma 8, are nonetheless present in both sections and indicate basin infilling during a highstand.

The sequence-stratigraphic analysis has shown that the Westgrove Ironstone Member (WIM) is present in both GSQ Roma 8 and GSQ Chinchilla 4. Fundamentally, in both cases, the WIM overlies sandy facies (Figure 2). In GSQ Roma 8, SB2 is placed at the base of the WIM, whereas, in GSQ Chinchilla 4, this sequence boundary is located at the base of the underlying BSM, which is absent from the Roma section.

Thus, the sandstones in GSQ Roma 8, below SB2, are not the sequence-stratigraphic-facies equivalent of those in GSQ Chinchilla 4 (although both lie immediately below the WIM). The GSQ Roma 8 sandstones are interbedded with thin to medium beds of siltstone and minor coal. Very low-energy conditions of deposition are indicated, and some sub-aerial exposure is implied by the presence of rootlets in both the siltstones and the sandstones; there is also evidence of low-energy channel and shoreface deposition. These facies are associated with basin infilling during a highstand, where sediment supply is at, or near, equilibrium with slow subsidence (Catuneanu & others, 2011).

The sandstones in GSQ Chinchilla 4 (associated with the BSM and the base of the second sequence) locally comprise energetic, sand-dominated, river-mouth-bar to river-mouth and distributary-channel deposits and are very well-sorted. These facies are indicative of a drop in base level and a basinward shift in facies, with fluvio-

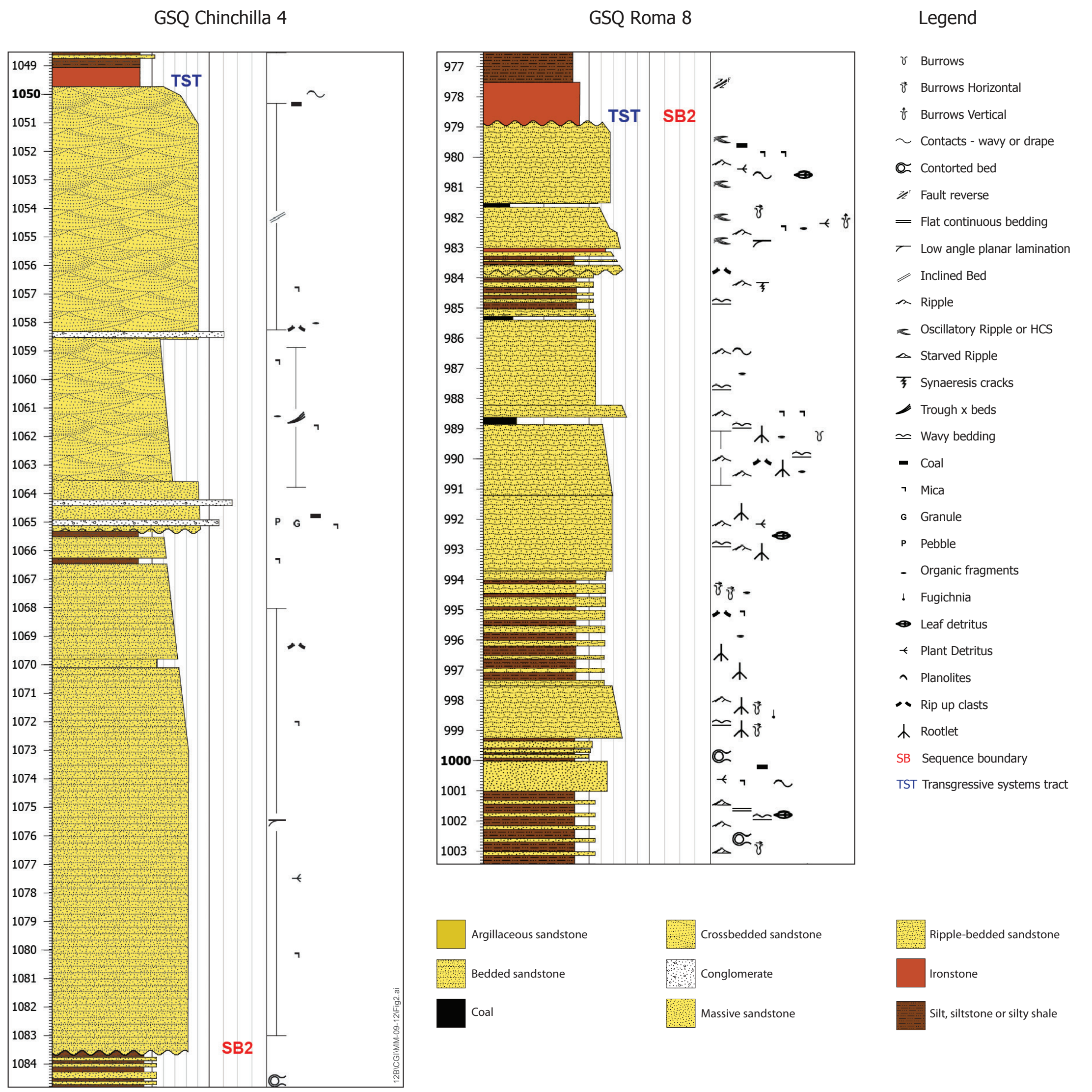

Figure 2. Different facies associations between sands below the WIM in GSQ Chinchilla 4 and GSQ Roma 8. The BSM underlying the WIM in Chinchilla 4 is coarser and represents the base of the second sequence, whereas the sands below the WIM in GSQ Roma 8 are finer and lie at the top of the first sequence.

deltaic deposits overlying low-energy, flood-plain deposits of the previous sequence (Figure 2). Fielding (1989) suggested that the coarse sediments of the BSM near Injune were supplied episodically and that the increased sand content represented progradation with decreasing water depths.

The base of the WIM (at 1049.8m in GSQ Chinchilla 4) marks the onset of a major flooding event and forms the base of a trangressive-systems tract (TS — Figure 2). This TS is of regional extent across the Surat Basin and related basins further to the east in south-eastern Queensland (Turner & others, 2009, McKellar, in press). The WIM consists of mudstone and chamositic mudstone with a pelletal or oolitic structure and sideritic cement and minor labile sandstone (Green, 1997). Wells & O’Brien (1994) have suggested that, during the deposition of this unit, there was a degree of access to the open sea in the Surat Basin, but there is no evidence to indicate marine conditions. This surface has been correlated with the eustatic Toarcian transgressive event (Hallam, 1992, Hallam & Wignall, 1999, McKellar, in press).

To assess the regional extent of the WIM, thirty-one petroleum wells, spread across the Surat Basin, were studied. Well completion reports and wireline logs were examined for evidence that this unit is present. In fourteen wells across the basin, direct evidence of oolites or ironstone was identified in the upper Evergreen Formation. However, in fifteen wells, the presence of the WIM was inferred only from wireline-log correlation; in some cases, evidence for the presence of the unit was subjective and, in two wells, there was no evidence of ironstone deposition (Figure 3).

The third sequence boundary (SB3), which was picked in GSQ Chinchilla 4, in the upper Evergreen Formation, can be correlated generally across the basin. However, its position in the core from GSQ Roma 8 is ambiguous (Figure 4). SB3 represents a minor basinward shift in facies, which some workers have mistakenly picked as the base of the Hutton Sandstone, due to increased sand content. This highlights the subjectivity of lithostratigraphic-picking methodologies for correlation, because identification of lithostratigraphic boundaries is based on a purely descriptive approach.

Sequence boundary four (SB4), at the base of the Hutton Sandstone *sensu stricto*, shows a marked change from the low-energy, fluvial-channel and lacustrine deposits of the upper Evergreen Formation in the third sequence, to braided, fluvial channels, with an erosional base (representing the base of a fourth, undefined sequence). SB4 is a major sequence boundary that formed in response to a sudden drop in base level (Hoffmann & others, 2009). Cores from both GSQ Chinchilla 4 and GSQ Roma

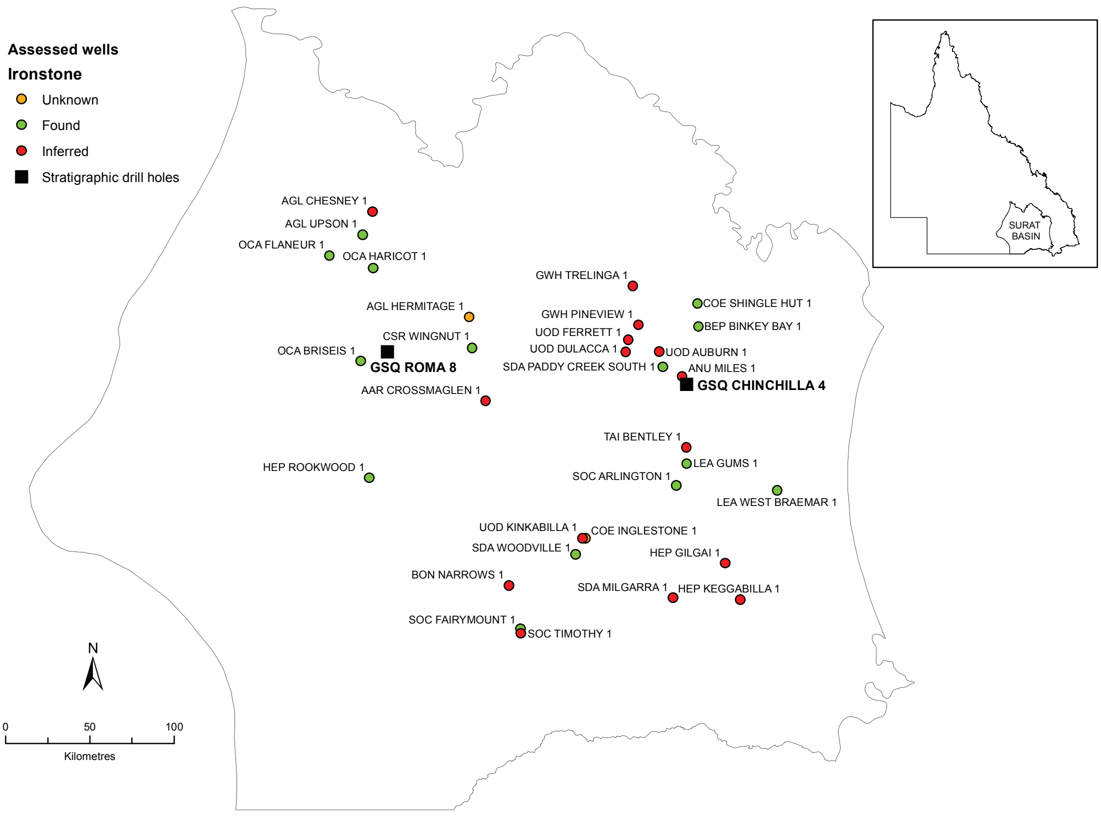

Figure 3. Petroleum wells assessed for evidence of deposition of the Westgrove Ironstone Member in the Evergreen Formation (stratigraphic drill holes GSQ Chinchilla 4 and GSQ Roma 8 inserted for reference).

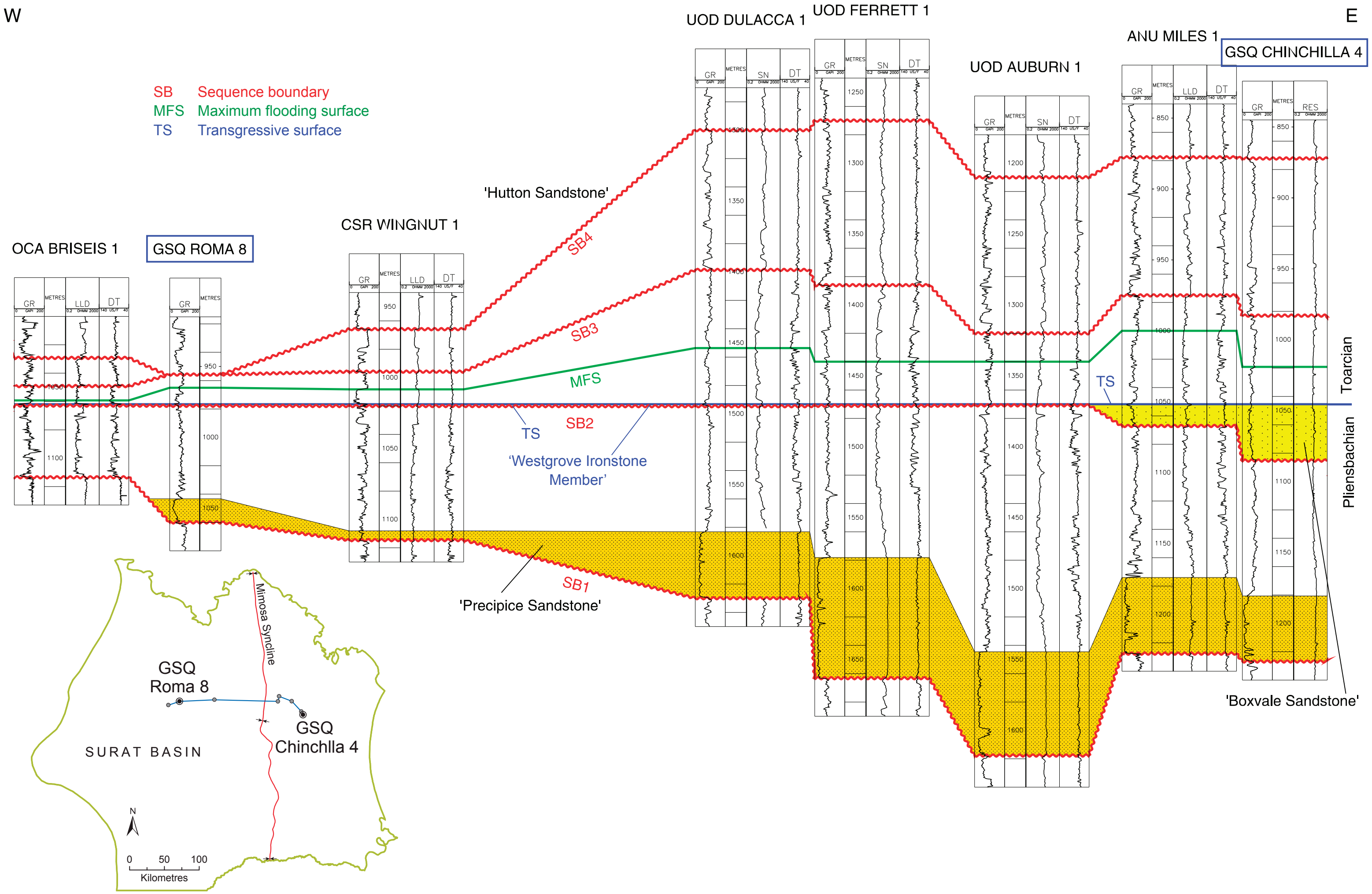

Figure 4. Sequence stratigraphic section of the Lower Jurassic in the Surat Basin. Note the 'TS' is placed at the base of the Westgrove Ironstone Member, which is a major transgressive systems tract in the second sequence.

8 contain very coarse sandstone at the base of this sequence, contrasting with the underlying, finer-grained rocks of the upper Evergreen Formation (third sequence).

Overall, seven cross sections using correlated wireline logs were plotted. Of these, Figure 4 shows the section that includes both GSQ Roma 8 and GSQ Chinchilla 4, on which this study is primarily based. The use of a sequence-stratigraphic approach provides a less subjective basis for regional correlations, as opposed to lithological changes, which are based on descriptive-log character and not interpretation of sedimentary-facies associations. This sequence-stratigraphic approach has permitted a more accurate method of correlating time-equivalent events on a regional scale.

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QUEENSLAND GEOCHEMISTRY: THE PAST, THE PRESENT AND THE FUTURE

Joseph Tang

Geological Survey of Queensland

INTRODUCTION

Geochemistry is a cornerstone of modern geological science, and its roles have evolved over the past 60 years from the classic applications in rock classification and chemical-profiling, to highly specialised investigative roles that establish geological processes, tectonic settings and source regions (e.g. Krauskopf & Bird, 1995; Rollinson, 1993). The scope of geochemistry has expanded from the analysis of major and trace element whole rock geochemistry to highly refractory rare-earth, radiogenic and stable isotopic elements using a variety of analytical media (whole rock, minerals, fluid inclusions and gases) by means of ultra-sophisticated instruments. Modern analytical methodologies have improved the sensitivity and precision of assays to parts-per-trillion, which has enabled the measurements of minute concentrations close to or below the natural background levels. As the result of these improvements, geochemistry is applied in different aspects of geological investigations that include petrogenetic studies, experimental petrology, tracing magma and fluid paths, identifying source regions, geochronology, medical geology, isotopic fingerprinting and mineral exploration.

In mineral exploration, geochemical surveys are fundamental in defining prospectivity and mineral potential. They are used at all stages of a mineral exploration program from reconnaissance study to targeting and anomaly definition. In Queensland, systematic geochemical sampling has been used in exploration since the 1950s to target base and/or precious metals in areas of well-exposed geology and more rarely in areas overlain by post-Mesozoic rocks. A data scoping exercise undertaken by the Geological Survey of Queensland (GSQ) in 2006 estimated that the amount of money spent on geochemical data acquisition for approximately 5 million data points by the mineral industry was $200 million dollars in today’s financial terms. Most of these data were reported in hard copy company reports and theses, which are inaccessible to most users and costly to extract.

Whole rock geochemical sampling has been routinely undertaken by the GSQ as part of its mapping program since the 1970s. Up until 2005, these analyses were provided by the Government Chemical Laboratory, although some analyses were also done through the Bureau of Mineral Resources (now Geoscience Australia) in joint projects. Up until 1983, the Government Chemical Laboratory offered free assay and mineral examination services to the public, particularly small-scale prospectors.

However, the GSQ’s involvement with geochemical data greatly expanded in July 2003 with the purchase of 1,415,053 data points from Terra Search Pty Ltd that formed the basis of the Queensland Exploration Geochemistry and Drill hole database. A data point is defined as one surface or drill hole geochemical sample or a drill hole description. Since 2006, funding from the Queensland Government Smart Exploration initiative has enabled the database to expand through data extraction by external contractors and the recruitment of additional staff to build up a geochemistry team. Subsequent collaboration with Queensland universities, Geoscience Australia, CSIRO, other scientific agencies and the mining industry, has resulted in more diverse geochemical datasets that included exploration, whole rock, isotopic and baseline-geochemistry, geochronology and diamond indicator mineral databases.

DATA BACKLOG

The main geochemical data acquirers in Queensland are from the mineral industry with an estimated 120,000 new geochemistry and related data added to the state each year (Figure 1). In accordance with the Mineral Resource Act 1989, companies undertaking exploration in Queensland have to submit annual exploration reports (including all new geoscientific data) to the GSQ. However, the legislation excludes mining operations and therefore countless geochemistry and drill hole data acquired by such operators are not reported.

The geometric increase in the number of exploration reports submitted since 2000 reflects a significant increase in exploration activities in the state. A significant number of post-2000 reports had "confidential" status when contracts were prepared for the 2006–2010 data extraction and therefore were not included in the data extraction list. This is reflected in the large drop in the data captured into the GSQ database after 2000. The implication of accelerated exploration activities and lag in data capture since 2000 represents a backlog in data extraction (estimated at 2 million data points) that would require a significant amount of time, personnel and funds to capture.

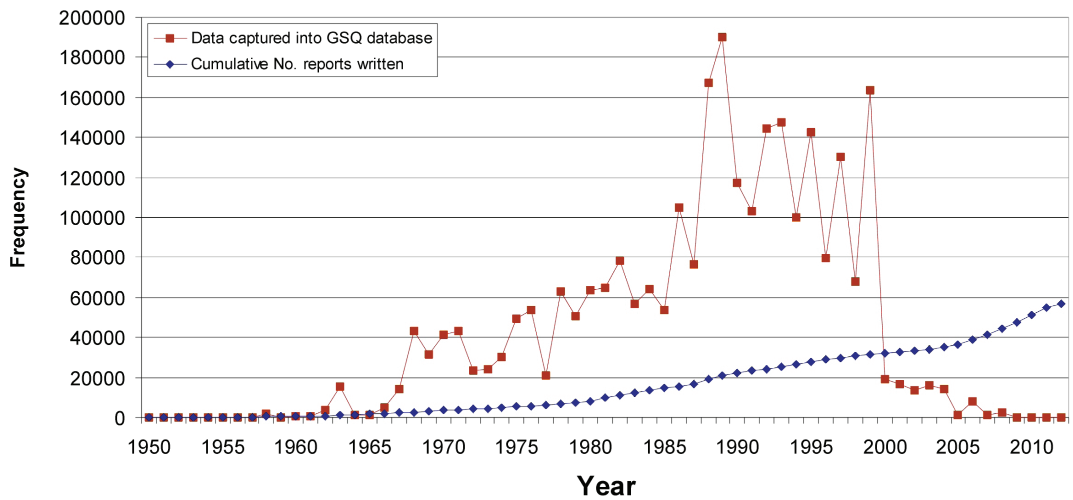

Figure 1. The number of exploration company reports written and received by the Geological Survey of Queensland between 1950 and 2012, compared to the number of exploration data compiled into GSQ database over corresponding period (data sourced from QDEX and Queensland Exploration Geochemistry database).

GSQ GEOCHEMISTRY PROGRAMS

The GSQ has aligned its geochemistry and related programs with the modern needs of the geological community to support research and exploration in the state. Geochemical data is in high demand by both the mineral industry and researchers for geological modeling and ore targeting.

The following sections summarise GSQ geochemical programs since 2003, and highlight future plans for its expansion to cater for the needs of geosciences in Queensland.

Major past geoscientific programs

1. The Queensland Exploration Geochemistry and Drill Hole database (2003–2010)

2,909,063 publicly available exploration geochemical data points (current to June 2010) have been compiled from open-file reports submitted by companies undertaking mineral exploration within Queensland. The data were compiled by Terra Search Pty Ltd and by a GSQ team under the Smart Exploration funding initiatives, which expired in 2010. The data were meticulously compiled and carefully validated, and each is a stand-alone data point with references to sampling, analytical, laboratory methodologies and source reference. The amount of data captured to date covers three hundred 1:100 000 map sheets or approximately 40% of Queensland, but represented approximately 60% of all data held in company reports (Figure 2).

2. Diamond Indicator Minerals Database (2007–2008)

A geological review of exploration for diamonds in Queensland was completed by GSQ in 2008. A diamond indicator mineral database and related surface geochemistry (Cranfield & Diprose, 2008) was compiled for this review using the diamond indicator mineral template devised by the Northern Territory Geological Survey.

3. The National Geochemical Survey of Australia (NGSA) project (2006–2011)

The National Geochemical Survey of Australia (NGSA) project was a collaborative program between the GSQ and Geoscience Australia (GA) to sample all major river catchments in Queensland as part of the nation-wide project. The project aimed to establish the baseline geochemistry of Australia using a consistent geochemical dataset (up to 60 elements). In Queensland, a total of 311 major catchments were sampled (Figure 3). The NGSA program concluded in June 2011 with the release of the final report and accompanying data (Tang & Brown, 2011).

4. Whole rock geochemistry data (ongoing acquisition and compilation)

Whole rock geochemistry was routinely collected during geological mapping programs and the chemistry was used as a tool to understand tectonic setting, rock

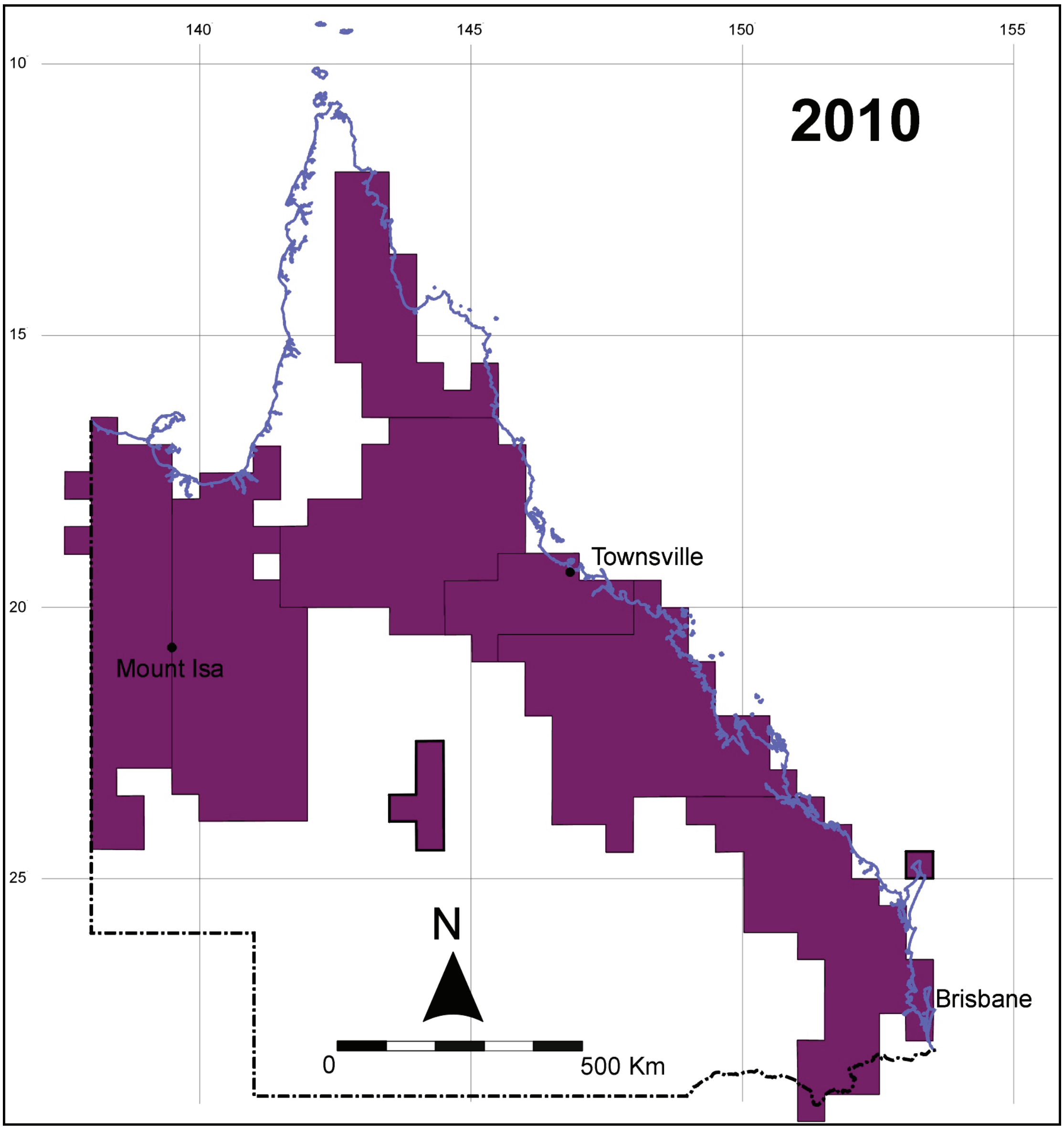

Figure 2. Spatial coverage of Queensland exploration data current to 2010

classification, source, paragenesis and conditions of emplacement. The GSQ has compiled whole rock geochemistry for 12,608 samples (containing major elements and up to 45 trace elements of varying precision) representing 1,464 geological units. Updates of this database are released annually with the Mineral Occurrence and Geology Observations database (GSQ, 2011a)**.** It also incorporates analyses of Queensland rocks by GA and its predecessors and some analyses from university theses. In many cases, attributes of the GA and university samples have been updated to conform to more recent mapping.

5. North-West Queensland Mineral and Energy Province data (2010–2011)

Exploration geochemistry and drill hole data for north-west Queensland were extracted from open-file exploration company reports and included in the North-West Queensland Mineral and Energy Province report (GSQ, 2011b). The geochemical data were statistically analysed and ranked to display the regional mineral potential.

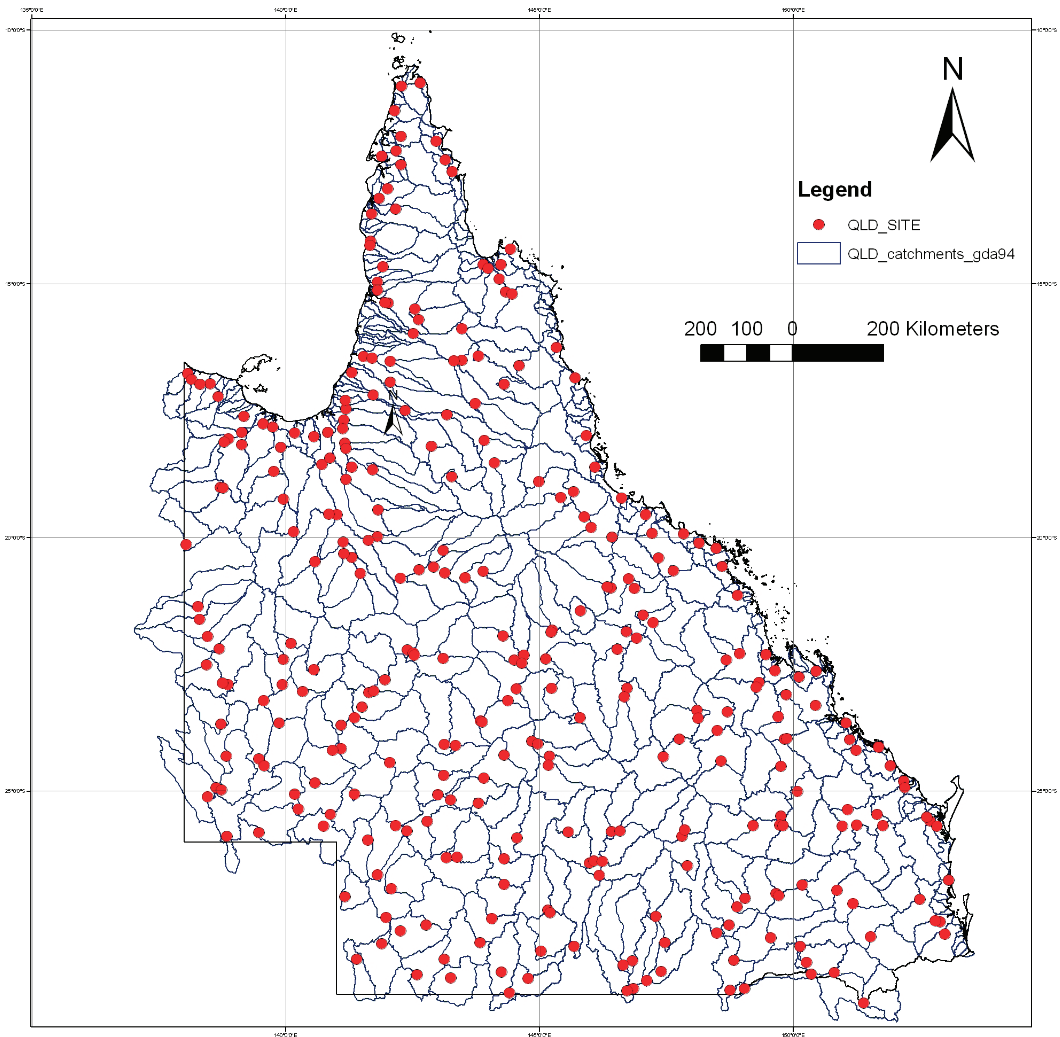

Figure 3. National Geochemical Survey of Australia: catchment samples in Queensland

In addition to the geochemical data extraction, depth-to-basement information from drill holes in the province were compiled and used for Proterozoic basement depth modelling.

6. Kalman deposit characterisation project (2010–2012)

GSQ has a HyLogger facility that is capable of identifying mineralogic composition of rocks using spectral signatures of minerals. The application of this technology in mineral deposit study is relatively new, and GSQ collaborated with CSIRO and Kings Minerals NL to undertake a case-study of the technology using the Kalman deposit drill cores. The Kalman Prospect lies within the Mary Kathleen zone of the Eastern Succession of the Mount Isa Inlier, north-west Queensland. Geochemistry of the cores were analysed by a GSQ team using Niton XL3t handheld XRF analyser at every metre intervals, and 3,500 analyses were taken for the trial. The geochemical data were used in conjunction with spectral interpretations to characterise the mineralised zone and to complement paragenetic studies of the copper-molybdenum mineralisation (Jones & others, 2012).

Present geochemistry programs

1. Whole rock and isotopic geochemistry and geochronology data (2009–present)

A data scoping exercise undertaken by the GSQ in 2008 estimated that the ~2000 geoscientific theses held at the University of Queensland (UQ), the Queensland University of Technology (QUT) and the James Cook University (JCU) contain approximately 22,000 whole rock analyses and 35,000 mineral chemistry, fluid inclusion, geochronology, regolith chemistry and isotopic analyses. These high quality data could provide crucial geochemical information for detailed geological and mineral systems research to identify sources of mineralisation, tectonic settings and magmatic processes. GSQ has collaborated with staff from the universities in compiling the hard copy data into a digital database. The aim is to make all geochemical data held at universities accessible to the geoscientific community.

Data from UQ theses have been collated over a four year collaborative program. A total of 5823 whole rock, 4782 mineral chemistry, 1605 stable isotopes and 10,285 radiogenic isotope analyses have been compiled to July 2012. An interim database for the UQ data is available to the public at https://espace.library.uq.edu.au/view/UQ:185174. A report and the final database are being prepared by GSQ and will be released at the completion of the validation process.

Data from QUT and JCU have yet to be compiled. The data from both universities will require at least one full time worker over a 4-year period to compile. With limited funds, no geologist has been assigned to the task but ~1000 whole rock geochemistry analyses from QUT were compiled by GSQ staff between other tasks.

2. National reporting standard and MRT template (Version 4)

GSQ has been involved the preparation of the Australian Requirements for the Submission of Digital Exploration Data (Version 4), as part of the Government Geoscience Information Committee (Government Geoscience Information Committee, 2010). The national standard set out the reporting standards and data templates, which will enable future online data delivery and automated data uploading into standard database. Though GSQ has not yet implemented the MRT template for data submission and uploading, the groundwork for this process has been completed.

3. Thomson project (2011–2014)

The geochemistry group has been involved in the compilation of depth-to-basement information from exploration boreholes within the Thomson Orogen. To date, 1445 reports were reviewed and data from 18,000 boreholes were collated and interpreted. The borehole information will be used for basin-basement modelling in this mineral prospectivity study. The second phase of the project will involve the extraction and compilation of surface and drill hole assay data from open-file company reports. These pre-competitive data will be included into the final report, which will be released in 2014.

Future geochemistry wish list

GSQ has identified numerous high priority geochemistry tasks that will potentially enhance future geoscientific research and mineral prospectivity studies in Queensland.

1. Online geochemical data delivery (2013?)

GSQ has compiled over 3 million geochemical data points, and at present, these data are disseminated as different DVD products at the cost of provision through the Sales Centre. Although geochemistry is one of the most requested sales products, the mode of delivery has limited outreach.

GSQ is pursuing the concept of free online geochemical data delivery through the department's Mines Online website and the Large Spatial Data Online Delivery (LSDOD) initiatives. These systems are currently under development, and the LSDOD solution will be trialed in the near future. The Queensland Exploration and Drill Hole database will be one of the first databases delivered online but has to be repackaged into convenient database block/size according to the network capabilities. The final online products have yet to be decided and will depend on the network cache size.

2. Create a consolidated Queensland whole rock database (2012–?)

Queensland has approximately 41,000 whole rock geochemistry analyses in five different databases (GSQ whole rock, GA OZCHEM, Queensland Exploration Geochemistry database and in theses from UQ, QUT and JCU databases). About 17,000 data from theses, mainly QUT and JCU, have yet to be compiled. There is significant duplication of data between the GSQ and GA databases, and between the GSQ and the various university databases. The various databases have to be combined into one simplified database and filtered to eliminate duplications. The geochemistry team has started on this program and is in the process of combining the GSQ and GA OZCHEM data.

3. Upgrading the Exploration Geochemistry database (?)

The Queensland Geochemistry and Drill Hole database is one of the GSQ products most sought after by explorers. The last database version is July 2010, capturing mainly data prior to 2000. An estimated 2 million data in the company reports have not been compiled and with accelerated exploration activities by industry, GSQ is falling behind the target by approximately 120,000 to 140,000 data per year. The estimated cost of capturing the 2 million outstanding data is $3.4 million and will cost approximately $250,000 per year to keep pace with incoming data. Unless such funding is forthcoming, GSQ does not anticipate any update of the database in the near future.

4. Implementation of the MRT software for automated data uploading (?)

GGIC has finalised the latest version of the MRT software (Version 2.0, July 2011) to enable automated online data submission and upload using national templates into standard spreadsheets. The implementation process (including information session, training and trial period) will take at least one year based on interstate experience before data are correctly submitted and uploaded. No time frame has been set to implement such a system.

5. Undercover geochemical and hydrochemical prospectivity modelling (2012–2014)

Approximately 75% of Queensland is overlain by post-Mesozoic rock and minimal exploration activities have been carried out over this ground. The Thomson Orogen is mostly concealed, predominantly by the Eromanga Basin. Pioneering work to establish the mineral prospectivity of the Thomson Orogen is ongoing. Depth-to-basement data from drill holes were extracted for the structural modelling, and geochemical data will be extracted for prospectivity modelling. To better predict undercover mineral potential, GSQ has been in consultation with scientists from the CSIRO (Minerals Down Under Team) and from the Queensland Water Planning Sciences (Department of Science, Information Technology, Innovation and the Arts). Collaboration between these agencies should produce a hydrochemical database and new techniques that can be applied to predict conceal mineral potentials below cover rocks.

6. Medical geology (2012–?)

GSQ and Queensland Health commenced collaborative research to establish the baseline (background) terrestrial gamma radiation levels for Queensland using drainage sediment geochemistry. Radiation potential values are calculated from the NGSA U-Th-K data to produce a theoretical gamma radiation baseline map. Field validation has been completed for the Lynd River, but additional river systems need to be investigated before the two data sets are mathematically computed for comparison. However, because of the current state austerity measures, this project has been deferred pending new funding arrangement.

7. Isotopic database (2013–?)

GSQ has the support from the various Queensland universities and CSIRO to develop a geochronology and isotopic database. The radiogenic isotopes can be used for dating rock formation (formation age, model ages, cooling ages, metamorphic ages, crustal residence age, crystallisation ages etc) and fingerprinting ore systems. Dr Graham Carr from CSIRO will audit his Pb isotopic inventory for Queensland, and will assist in developing a Pb isotopic database that can be used to identify Mount Isa style mineralisation from other mineralisation styles.

A stable isotope database will be developed in the future to expand the existing data collated by the GSQ–UQ project. The stable isotopic data has the potential to be used for fluid source and pathway identification.

8. Follow-up work program for the NGSA and salt lake sampling (?)

The Queensland NGSA results have been analysed and many catchments were identified as highly prospective for precious, base metals and trace and rare-earth elements (Figure 4). Approximately 26% of Queensland catchments are anomalous for one or more elements and warrant follow-up work. A detailed follow up program has been designed to sample the anomalous catchments with an increased sample density of one sample per 500 to 1000 sq km. The follow-up program targets the second- and third-order catchment cells within the earlier identified anomalous catchments.

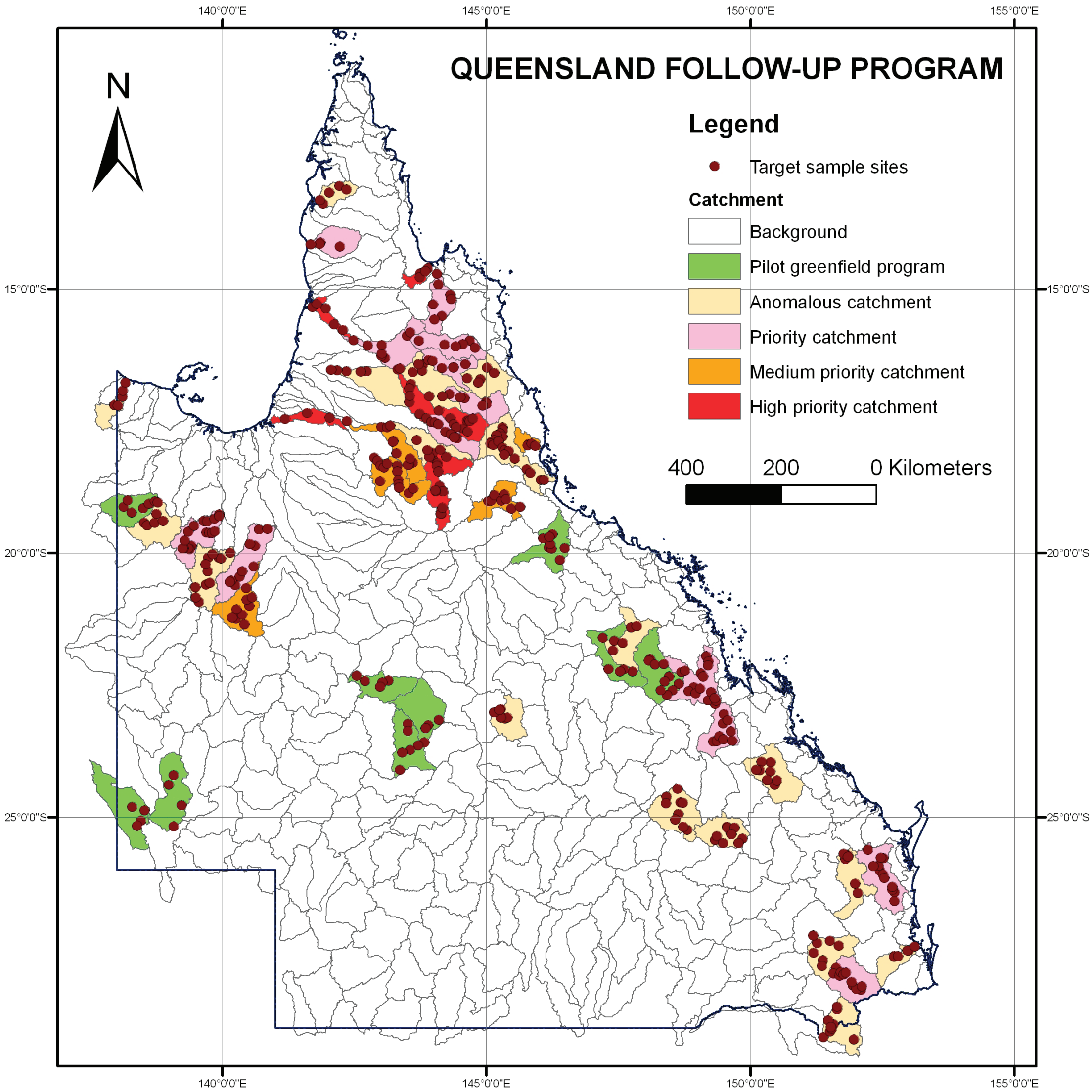

Figure 4. Proposed follow-up program for anomalous Queensland catchments identified by the earlier NGSA project.

A salt lake sampling has recently been proposed by GA to assess the lithium potential in Queensland. This is a follow-on program from the NGSA style sampling and will cover saline basins and lakes. GSQ has agreed in principle to participate in this program.

Special funding will be needed if these projects are to go ahead and the follow-up work has not been implemented.

SUMMARY

GSQ has a small but very proactive geochemistry team with well established achievements and goals. The geochemical programs are tailored within the limited GSQ funding to maximise outputs suited to both mineral industry and geoscientific research. Proposed current and future directions are to develop supporting information packages that can be used by the next generation of researchers and explorers targeting brownfield as well as concealed, greenfield mineral systems. These proposed geochemical programs are strongly dependent on fund allocation and government priorities.

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GSQ AND GEOSCIENCE AUSTRALIA COLLABORATIONS AND THE UNCONVENTIONAL PETROLEUM PROGRAMME

Andrew Stacey

Geoscience Australia

The Geological Survey of Queensland and Geoscience Australia collaborate on a vast array of projects. The advantage to Geoscience Australia of such collaborations is access to GSQ's data, experience and local geological expertise. This allows Geoscience Australia to research issues of national importance and to provide advice from a national perspective.

An example of such collaboration is Geoscience Australia's Unconventional Hydrocarbon Resource Assessment programme. The goal of this programme is to provide nationally consistent and internationally benchmarked assessments of Australia's undiscovered unconventional hydrocarbon resources. To achieve this Geoscience Australia is working with our colleagues in the state and territory geological surveys to compile the assessment geology of basins in their entirety regardless of state boundaries (border faults). The resource assessment component of the programme is completed by the United States Geological Survey (USGS) who have many years experience in producing probabilistic resource assessments.

Geoscience Australia has been working with GSQ on two assessments; the Georgina Basin and the Toolebuc Formation in the Eromanga Basin. Geoscience Australia has taken the lead on the Georgina Basin assessment, while GSQ is completing the Toolebuc assessment with the support from Geoscience Australia's laboratories and geochemists. Both basins are scheduled for assessment by the USGS in February 2013.

UNCONVENTIONAL PETROLEUM RESOURCE ASSESSMENT IN QUEENSLAND

Alison Troup

Geological Survey of Queensland

INTRODUCTION

Recent developments in shale gas and shale oil in North America have led to a review of formations across Queensland for unconventional petroleum potential. A desktop study has identified the Toolebuc Formation as having a series of characteristics that may represent a new unconventional petroleum exploration target.

Exploration for shale gas plays in North America over the past decade has revealed key parameters that are required for a successful unconventional petroleum play. The United States Geological Survey (USGS) assessment methodology screens formations for assessment based on the following criteria:

- Total Organic Carbon (TOC) >2 weight percent
- Kerogen type I, II or IIS
- Vitrinite Reflectance (Ro) > 1.1 percent
- net thickness >15m
- thermogenic gas
- evidence of gas in matrix/organic storage.

This study has focussed on mapping these parameters regionally across the Toolebuc Formation to define an area that might represent a ‘sweet spot’ or play fairway. This preliminary regional assessment has consisted of:

- defining a lithological framework from fifteen GSQ stratigraphic bores
- examining HyLogger™ mineralogy across these stratigraphic bores
- mapping depth to top of formation based on stratigraphic picks from wireline logs
- mapping gross thickness of formation based on wireline log picks
- mapping TOC based on pyrolysis data (where available) and calculated TOC using the Δ log R ‘Passey equation’
- mapping regional thermal maturity based on R_{Vmax} determined from well profiles in the Eromanga Basin
- mapping of gas composition, based on chromatography results presented in mudlogs.

METHODS

Lithological Framework

The Early Cretaceous Toolebuc Formation is a relatively shallow, thin, and regionally extensive unit within the Eromanga and Carpentaria basins in western Queensland, and extends across the Queensland border into South Australia and the Northern Territory. It comprises laminated calcareous and kerogenous mudstone, with minor coquinitic limestone and labile sandstone.

Lithological logging of the lowermost Allaru Mudstone, Toolebuc Formation and uppermost Wallumbilla Formation was completed on fifteen GSQ stratigraphic wells across the extent of the Toolebuc Formation (Figure 1). Based on this logging, the Toolebuc Formation can be subdivided into three lithofacies:

1. An upper calcareous mudstone interval with or without calcite laminae.

2. A middle calcareous kerogenous mudstone interval with high abundance of calcite laminae. These laminae are shells of *Inoceramus* and *Aucellina* (Ozimic, 1986).

3. A basal highly kerogenous, slightly calcareous mudstone interval with no calcite laminae. Fish scales, phosphatic fish debris and pyrite nodules are also common.

Not all facies are present in all locations. For example, in GSQ Manuka 1, GSQ Blackall 1 and GSQ Maneroo 1, the Toolebuc Formation comprises predominantly calcareous kerogenous mudstone with 15–40% calcite laminae, decreasing in abundance towards the base.

Across most of its extent, the Toolebuc Formation exhibits a distinct gamma-ray anomaly, typically with a serrated appearance. Multiple peaks may be present. The peak of this anomaly typically coincides with the top of the basal kerogenous mudstone facies.

HyLogger Mineralogy

The stratigraphic wells were scanned by the HyLogger™ to investigate the clay, mineral and carbonate distribution over the study interval. The Toolebuc Formation can be divided into three distinct intervals based on the distribution of clay and carbonate mineral assemblages (Figure 2). These mineral assemblages correlate with the three lithological facies intervals. The distribution of clay and minerals also delineates the formation boundaries with the overlying Allaru Mudstone and underlying Wallumbilla Formation.

The lowermost facies of the Toolebuc Formation returns a largely aspectral signature from the HyLogger™, meaning the spectra returned did not match any of those in the

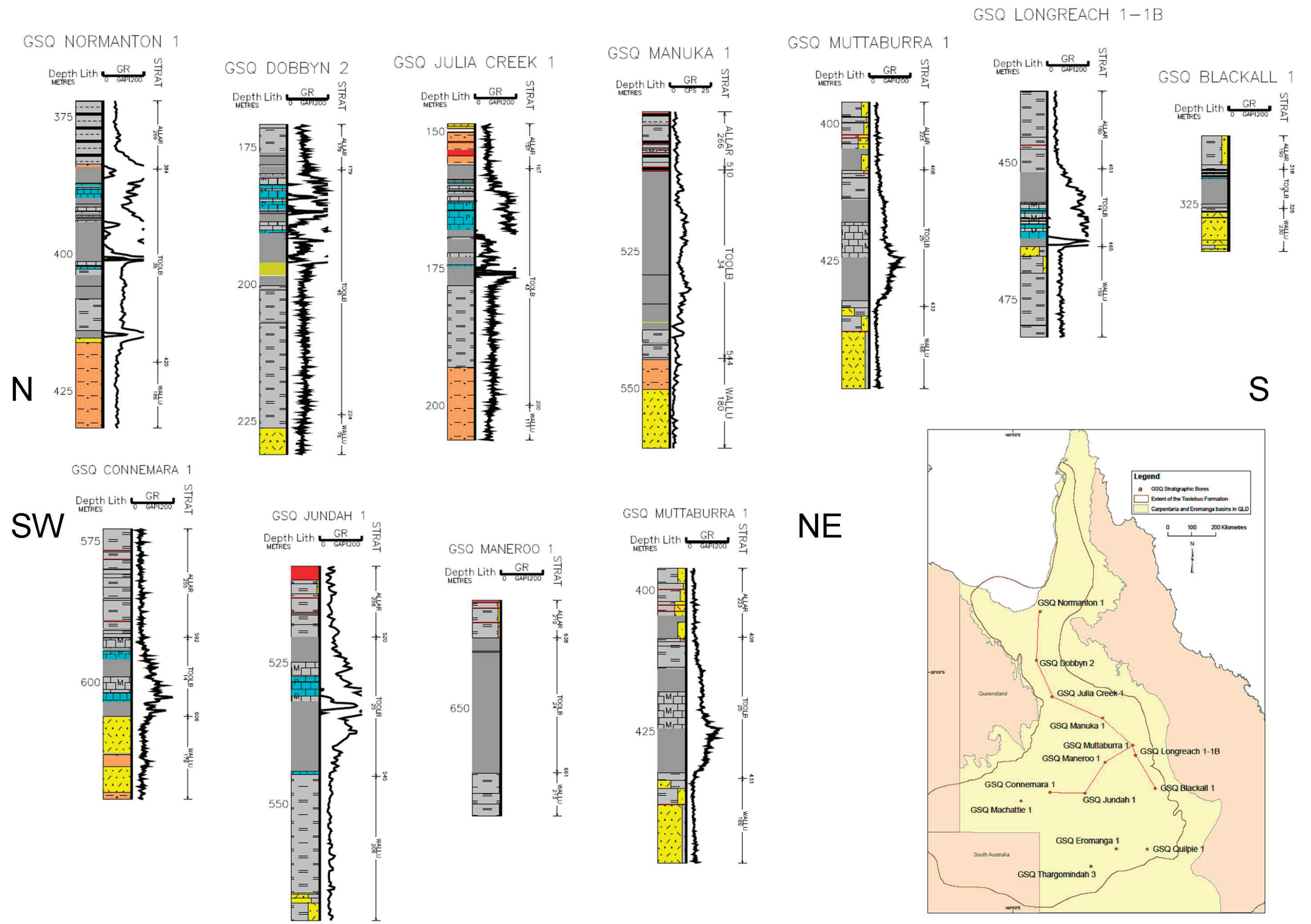

Figure 1. Lithological logs of ten stratigraphic core holes across the Toolebuc Formation plotted next to recorded gamma ray responses. All gamma ray plots are in API units except GSQ Manuka 1, which is plotted in counts per second.

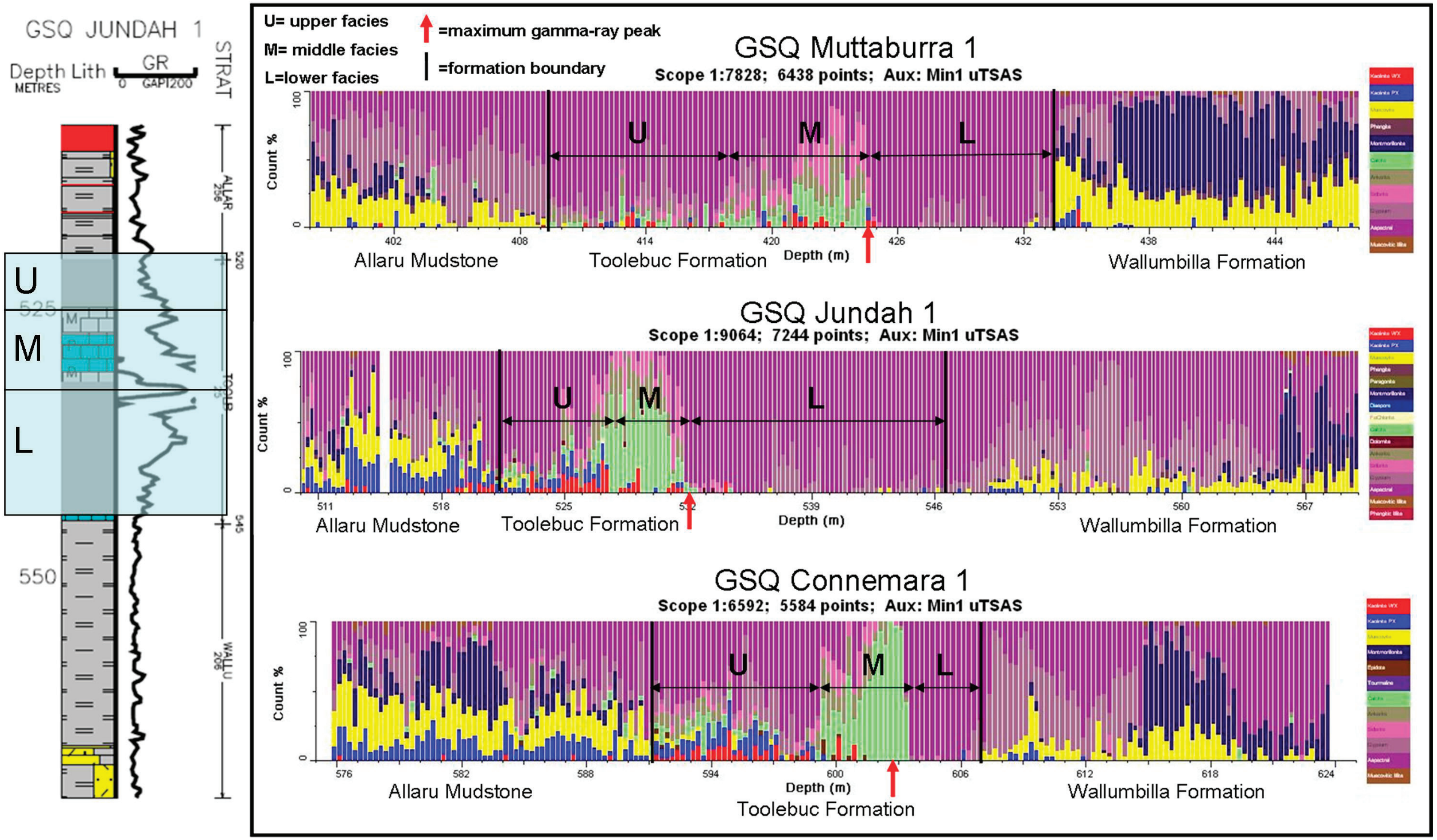

Figure 2. Hylogger™ mineralogy for GSQ Muttaburra 1, GSQ Jundah 1 and GSQ Connemara 1. Lithological log for GSQ Jundah 1 is plotted comparing the lithological facies to the mineralogical zones detected in the Hylogger™ data.

HyLogger's spectra database. This may be due to the dark, fine-grained nature of this lithofacies.

Depth

The Toolebuc Formation is relatively shallow (outcrop to approximately 1500m) across its entire extent (Figure 3). This makes it an easy target for exploration. The formation crops out close to the edges of the Carpentaria and Eromanga basins and deepens to the south-west where the Eromanga Basin overlies the Cooper Basin. In the north, it shallows over the Euroka Ridge (a structural feature separating the Eromanga Basin from the Carpentaria Basin) before deepening again into the Carpentaria Basin.

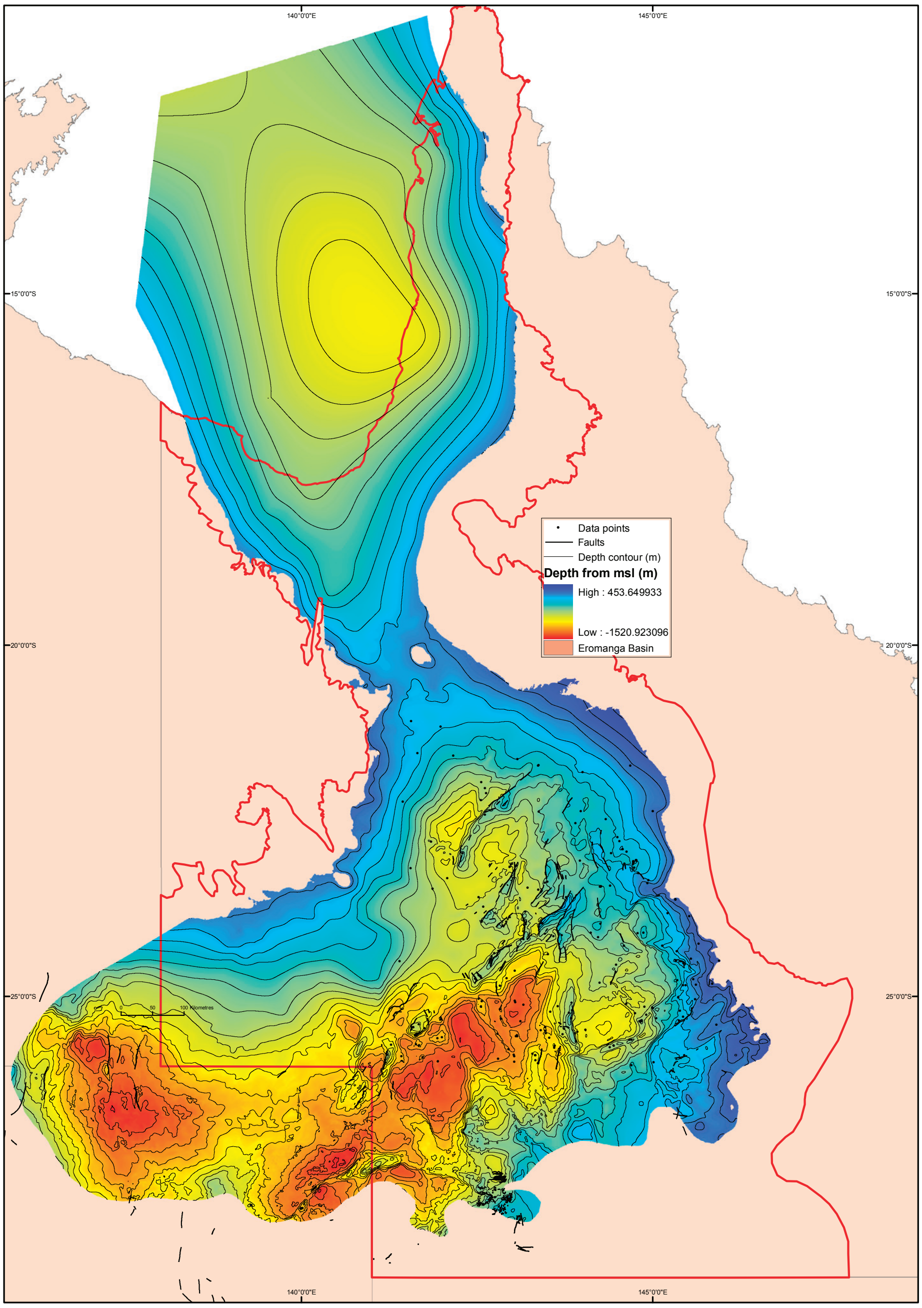

Figure 3. Depth to top Toolebuc Formation (m from mean sea level)

Thickness

The Toolebuc Formation averages approximately 23m in thickness, with a range of <10m to approximately 40m. It is thickest in a belt trending SW–NE through the centre of the Eromanga Basin (Figure 4).

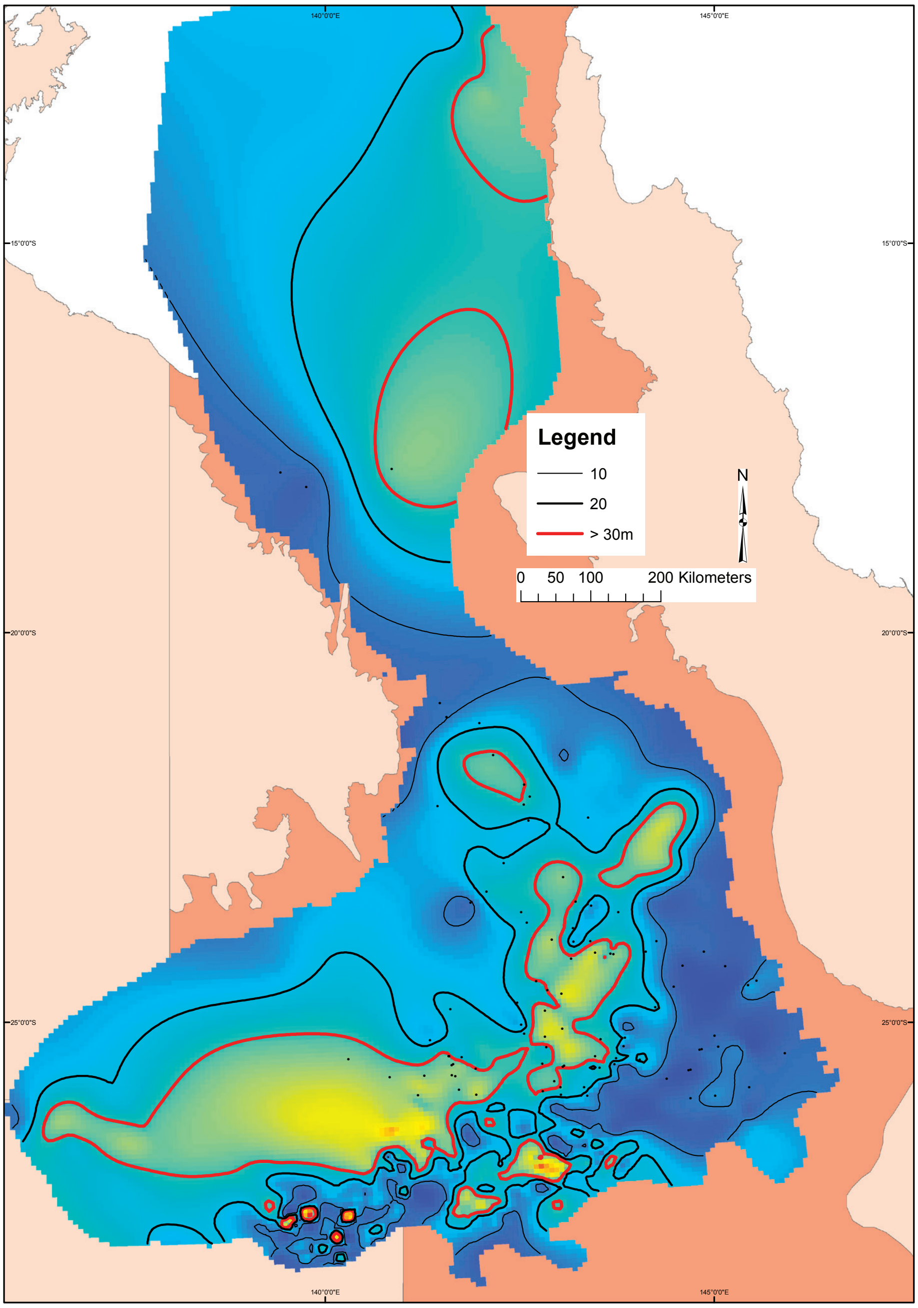

Figure 4. Thickness of the Toolebuc Formation. The solid red line outlines areas where the Toolebuc Formation exceeds 30m in gross thickness.

TOC

The Toolebuc Formation is rich in organic matter, with TOC contents ranging from 0.2 to 26.1 weight percent (Figure 5). The Toolebuc Formation is well known as a high quality source rock through the presence of oil shale resources near Julia Creek in north-western Queensland. Pyrolysis data are rare over the Toolebuc Formation. The majority of the data points are concentrated in the central Eromanga Basin.

Average TOC for the Toolebuc Formation has been mapped using TOC values obtained from pyrolysis results and supplementing the pyrolysis dataset by using the Δ log R technique (Passey & others, 1990). The mean value was applied for all wells with multiple readings.

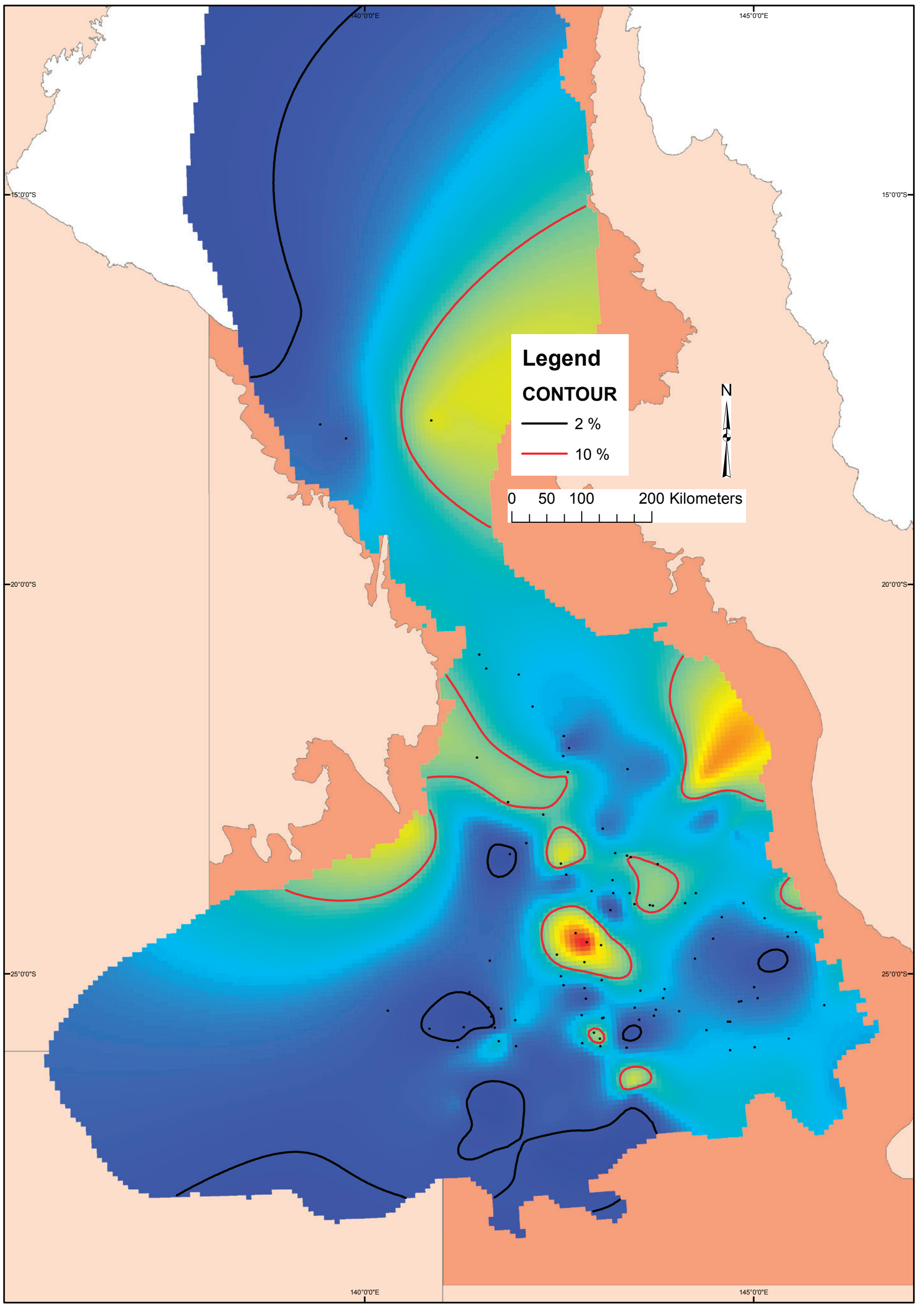

Figure 5. Average TOC (wt%) of the Toolebuc Formation. The solid red line outlines areas where TOC exceeds 10wt %.

Thermal Maturity

Due to the limited pyrolysis data, the thermal maturity of the Toolebuc Formation has been mapped in the central Eromanga Basin based on reflectance profiles established from petroleum wells across the Eromanga Basin (Figure 6). Based on the reflectance profile data, a belt of marginally mature to mature Toolebuc Formation trends SW–NE across the areas where the formation is deepest.

Mapped Tmax data from the limited pyrolysis data suggest a much smaller area where the formation is mature for oil generation (Figure 7).

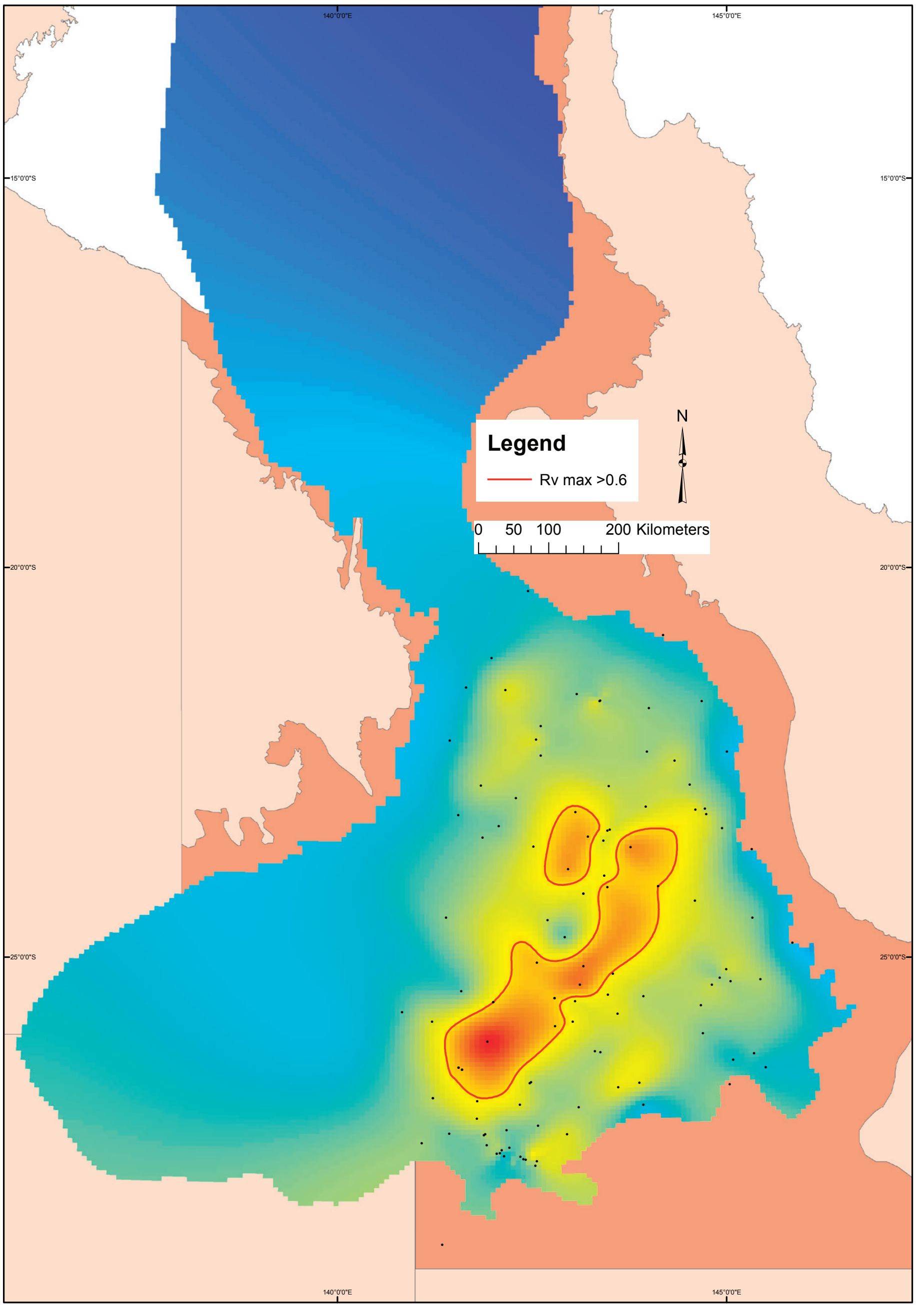

Figure 6. Vitrinite reflectance map of the Toolebuc Formation. The solid red line outlines the area where R_{Vmax} >0.6%.

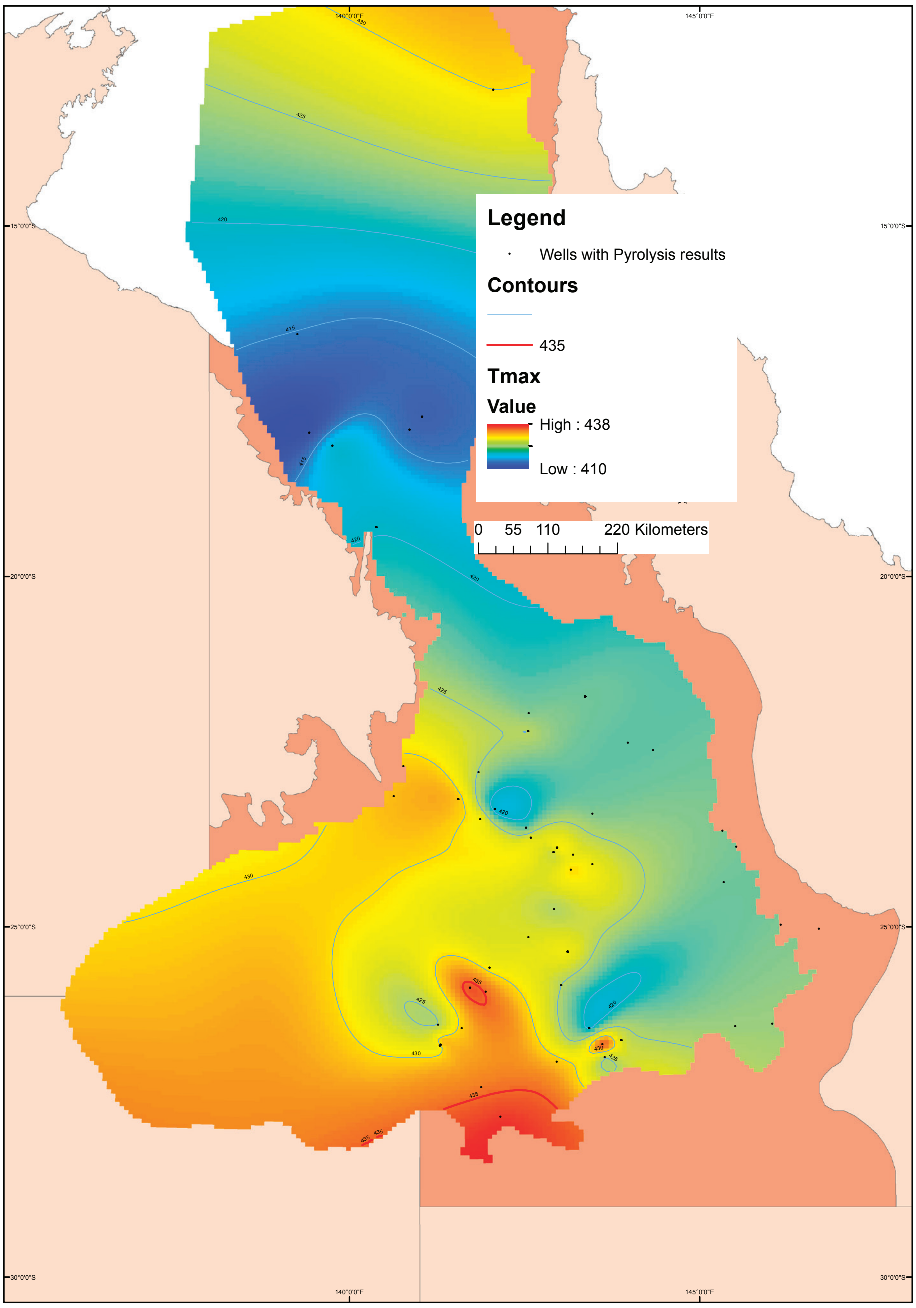

Figure 7. Map of Tmax across Toolebuc Formation. The solid red line outlines the area where Tmax >435 degrees C

Gas Composition

Gas composition has been mapped from mudlogs from conventional drilling across the Carpentaria and Eromanga basins. Where gas chromatography was available, methane, butane and pentane gas distribution has also been mapped.

Methane is present across most of the extent of the Toolebuc Formation where depths are greater than 300m. Butane and pentane may also be present, generally where depths are greater than 600m. However, the windows of butane and pentane recordings extend to the north where the formation is shallower and has been mapped as thermally immature (Figure 8).

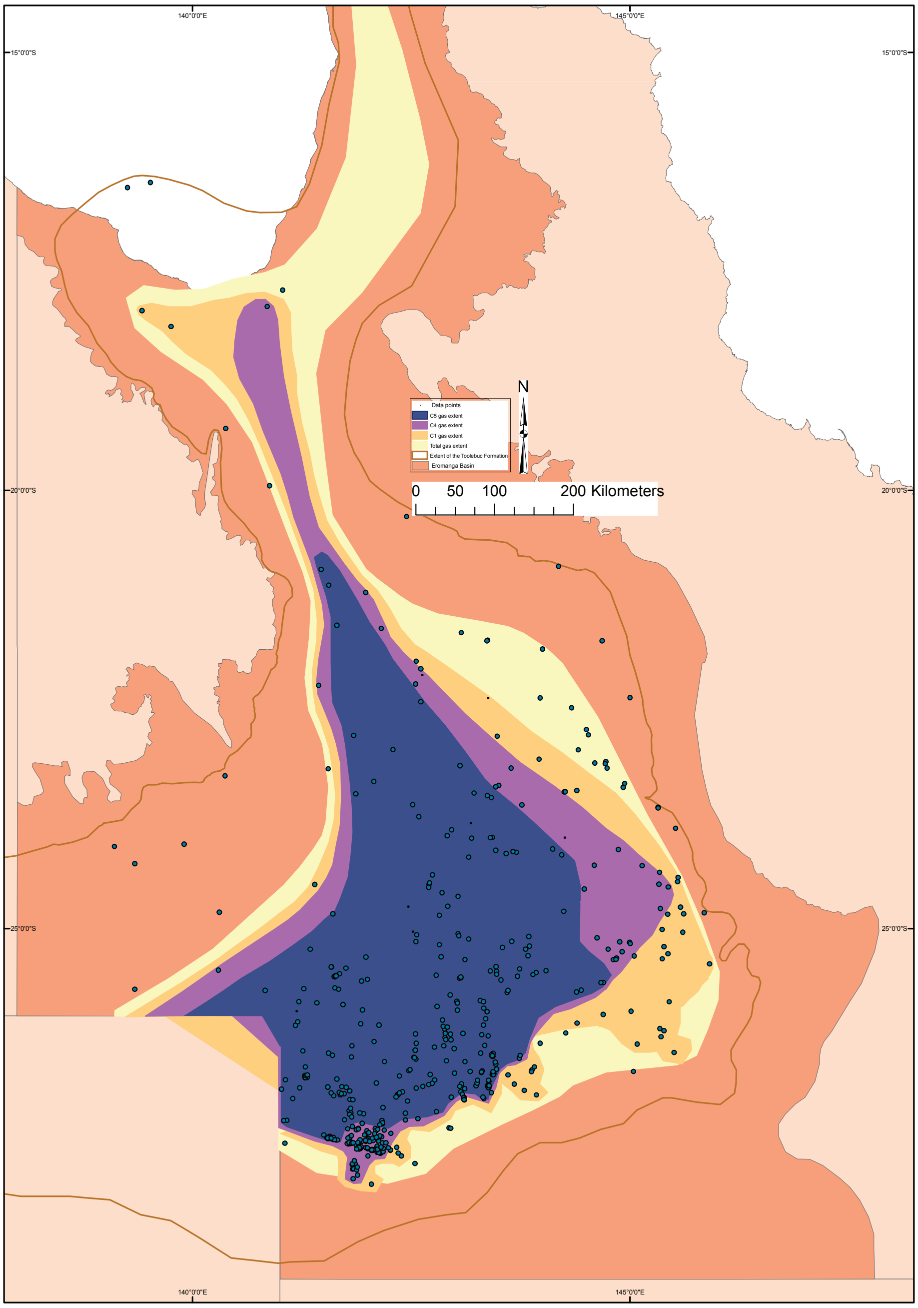

Figure 8. Gas composition outlines showing total gas (yellow), C1 (orange), C4 (light purple) and C5 (dark purple). The red dot shows the approximate location of GSQ Julia Creek 1.

Desorption samples were collected from GSQ Julia Creek 1 and GSQ Dobbyn 2, two recently drilled stratigraphic bores in the northern Eromanga Basin and southern Carpentaria Basin, respectively. The Toolebuc Formation is approximately 180m deep in both of these wells, and despite this shallow depth, these samples produced small volumes of gas upon crushing. Isotopic analysis of the sample from GSQ Julia Creek 1 suggests an immature thermogenic origin of this gas (Fitzell & others, 2012).

'Sweet spot'

A variation of the key criteria identified by the USGS assessment methodology was used to identify an area of higher potential for shale oil and/or shale gas within the

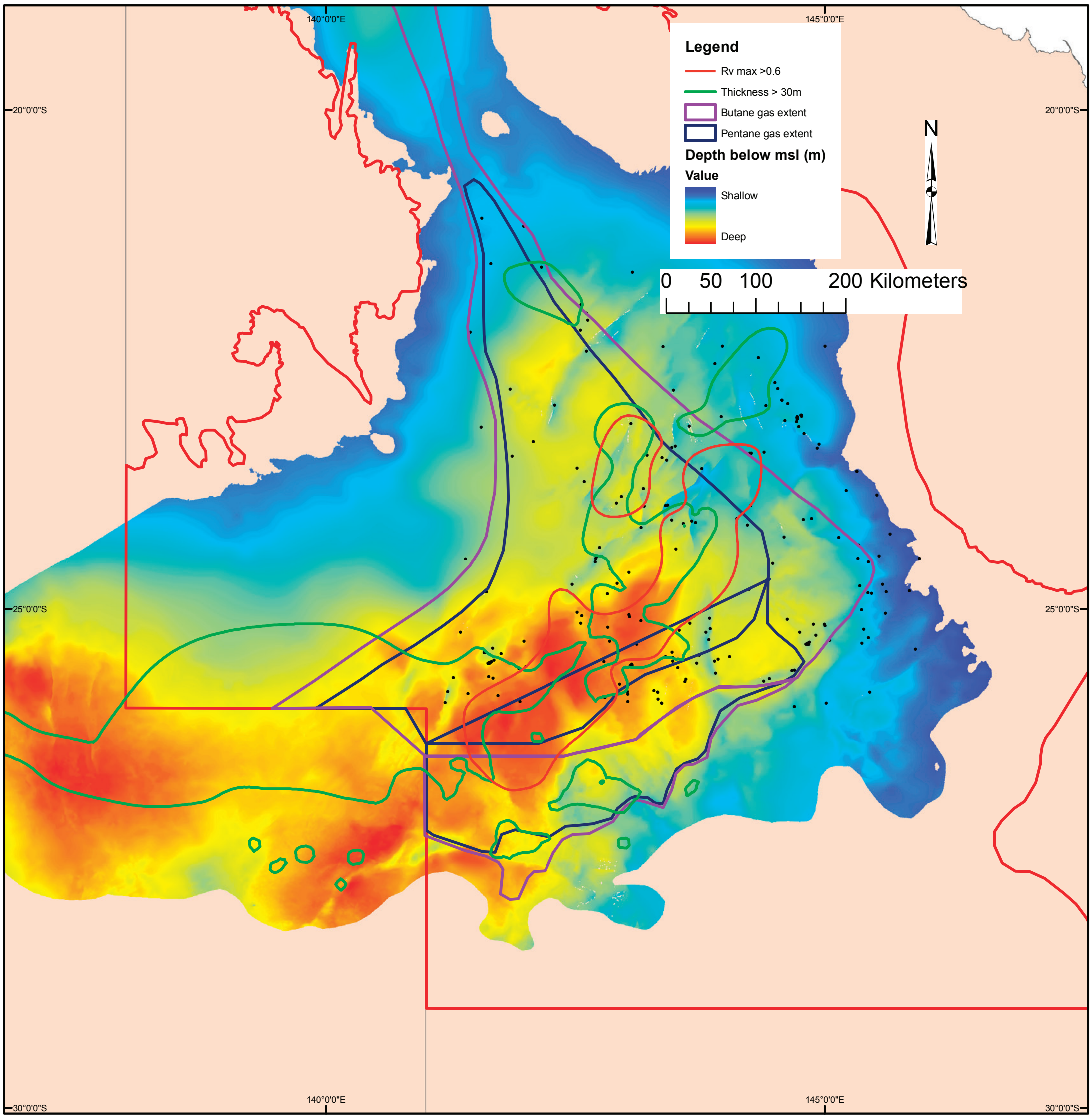

Figure 9. Fairway map for the Toolebuc Formation

Toolebuc Formation. The following criteria were used to map areas with greater potential for shale oil and shale gas:

1. thickness is greater than 30m

2. total organic carbon > 2.0wt%

3. Vitrinite Reflectance >0.6 Rv_{max}

4. butane and pentane gas composition.

Mapping of these parameters has highlighted an area in the south-west of the Toolebuc Formation where these parameters overlap. This area generally correlates with the deepest portions of the formation (Figure 9).

SUMMARY AND CONCLUSIONS

The extent, thickness, lithology, organic content and maturity of the Toolebuc Formation bear some similarities with commercially successful shale formations in North America. Vitrinite reflectance data suggest that parts of the Toolebuc Formation are within the oil generation window, yet gas composition analysis indicates immature thermogenic gas has been generated, even where the formation is at depths less than 200m.

An initial assessment of the Toolebuc Formation has highlighted a potential 'sweet spot' within the central Eromanga Basin that may have greater unconventional hydrocarbon prospectively. Further assessment of shale gas characteristics will be undertaken to fully evaluate the potential of the Toolebuc Formation as a shale gas and shale oil play.

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GEOLOGY AND GEOCHRONOLOGY OF THE THOMSON OROGEN IN QUEENSLAND

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INTRODUCTION

The Thomson Orogen is an expansive, largely subsurface tectonic domain of the Tasmanides which record the break up of Rodinia in the Neoproterozoic (Li & others, 2008) and construction of the eastern Australian continent until the Triassic (see Glen, 2005 for summary). Study of the Thomson Orogen has been almost entirely on outcropping units. However a new GSQ project aims to increase the understanding of the undercover rocks to both aid in the development of a coherent model for the Tasmanides, and provide a greater understanding of where mineralisation and other economic resources could occur.

In Queensland, outcrop of the Thomson Orogen is comparatively rare, covering nearly 22 000 km^2 predominantly along the eastern margin of the domain. Outcrop is distributed across four separate tectonic provinces (Barnard Province, Greenvale Province, Charters Towers Province and Anakie Inlier) (Figure 1) with possible northerly extensions into the Iron Range Province, and as thin thrust slices between the Paleoproterozoic Etheridge Province, and Siluro-Devonian Hodgkinson Formation. Small outcrops of granite occur in southern Queensland at Eulo, Currawinya, Granite Springs and Hungerford. Similarly in north-western NSW, granite crops out within the Tibooburra Inlier, however here host metasedimentary rocks of the Warratta Group are also exposed. These metasediments also occur much more prominently within the nearby Warratta Inlier.

The undercover Thomson Orogen is far more extensive (Figure 1 inset), covering approximately 800 000 km^2, yet far less understood with only a handful of authors (Murray, 1994; Draper, 2006; Purdy & Brown, 2011; Brown & others, 2012) contributing to an understanding the geology and tectonics of the region. Following the pioneering work of Murray (1994), continued work at the GSQ is focussed on these undercover rocks in order to constrain the geology, tectonics and economic potential of the Thomson Orogen. Basement rocks concealed by the Bowen Basin in the Roma Shelf area are also included within this study because of their uncertain relationship with the Thomson Orogen. Although a Devonian age for the Timbury Hills Formation in the Roma Shelf area is suggested (Murray, 1994), most rocks display lithological and structural characteristics more similar to the Thomson Orogen than temporally comparable basins (e.g. the Adavale Basin). Murray (1994) also postulated that the Timbury Hills Formation could include packages of various ages.

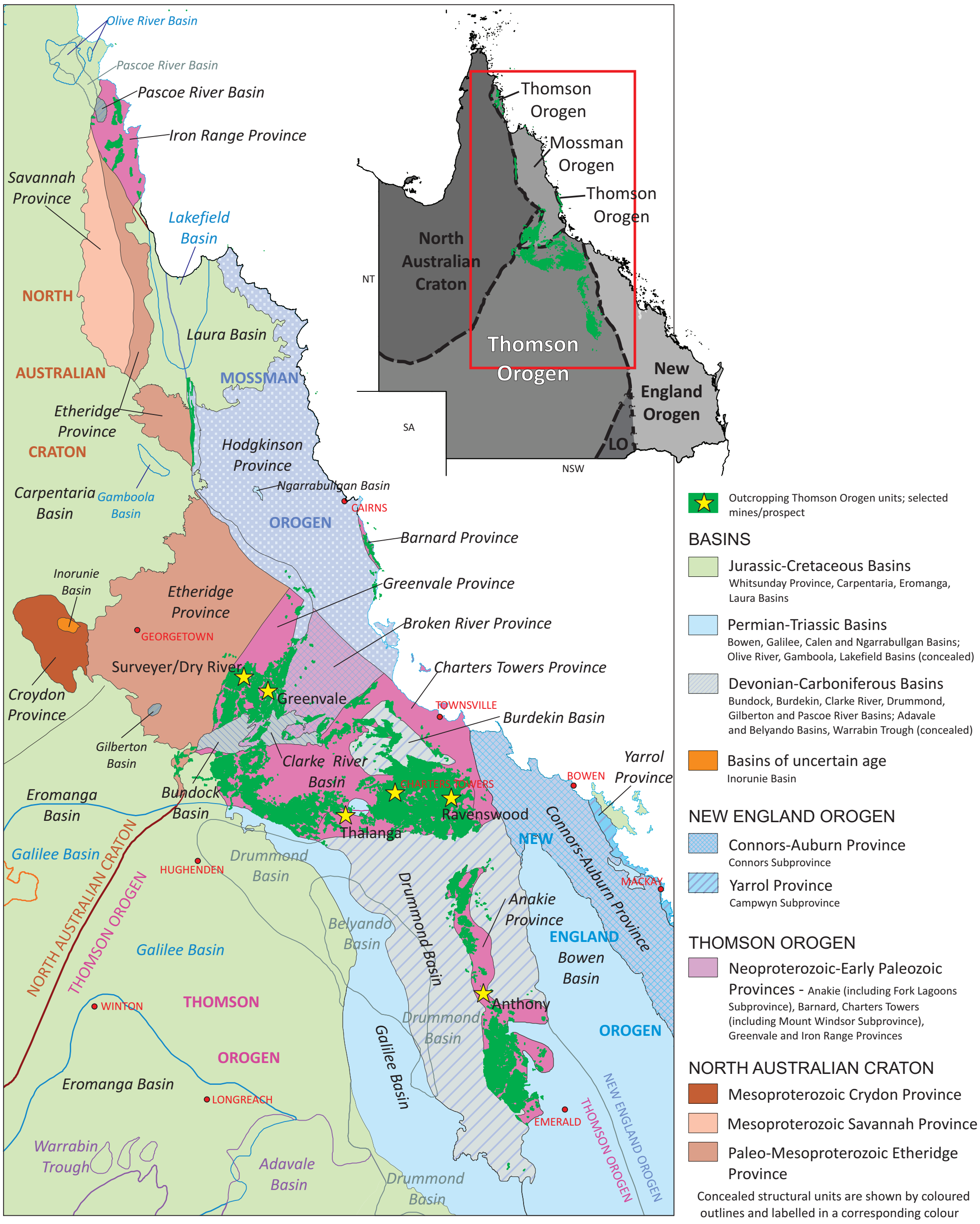

Figure 1. Tectonic provinces and overlying basins within Queensland (Geological Survey of Queensland, 2012). Inset shows the mega-elements that make up Queensland.

In addition to holding keys to the tectonic development of eastern Australia, the undercover Thomson Orogen may also host significant mineralisation. Outcropping units in Queensland are well endowed and many different deposit styles are represented including VHMS (e.g. Thalanga), orogenic gold (e.g. Charters Towers Gold Field), porphyry Mo (e.g. Anthony), other porphyry related systems (e.g. Ravenswood) and lateritic nickel and scandium (e.g. Greenvale) (Figure 1). Mineralisation also occurs at Granite Springs in southern Queensland and at Tibooburra in north-west New South Wales. The occurrence of gold in these areas of restricted outcrop raises the prospectivity of adjacent areas of shallow cover.

The undercover Thomson Orogen is also partially co-incident with a major temperature anomaly interpreted at 5km depth (OzTemp, GA). The origin of this anomaly, which represents a significant target for geothermal energy exploration and development where it extends into South Australia remains poorly constrained. The contribution of Thomson Orogen granitoids to the anomaly is currently under investigation (e.g. Siegel & others, 2012).

GEOLOGY OF THE UNDERCOVER THOMSON OROGEN IN QUEENSLAND

Information sources for the undercover Thomson Orogen are restricted to petroleum and stratigraphic drill holes, mineral drill holes, water bores and geophysical datasets of varying quality. Petroleum and stratigraphic drill holes provide the best direct information on the basement (Thomson Orogen) geology. A recent GSQ compilation (Brown & others, 2012) shows that 1398 petroleum and stratigraphic and drilholes intersect the Thomson Orogen surface. These are unevenly distributed over the region and only 221 have core available within the GSQ's core library. Information from all of these holes has recently been used along with data from mineral exploration drill holes and water bores to construct a depth to basement surface (Figure 2) and lithology map (Figure 3). Compilation of data from waterbores and drillholes is ongoing.

Depth to the top of the basement differs significantly across the area (Figure 2) from ~600m at the margins of the Eulo Ridge (e.g. GSQ Bulloo 1) and Roma Shelf (e.g. AOP Donnybrook 1) to ~4000m under parts of the Adavale Basin (e.g. PPC Lissoy 1), and ~3500m below the Cooper Basin in the far south-west (e.g. DIO Innamincka 2). Steep gradients are observed in both the Thomson Orogen and Roma Shelf regions. Additionally, broad north-east trends are apparent in the Thomson Orogen area, defined by basement lows below the Cooper Basin and Adavale basins and a high forming the Eulo ridge and extending north-west to the Nebine Ridge and outcrop of the Anakie Inlier (Figure 2).

The overwhelming majority of basement drill hole intersections in the Thomson Orogen area are metasediments (Figure 3), typically interbedded sandstones and phyllitic siltstones (e.g. Figure 3a) metamorphosed to a low grade and exhibiting a single cleavage parallel to, or at a low angle to bedding. The only constraints on deposition and deformation of these metasediments comes from an undeformed 472.9 ± 2.7Ma rhyolite sitting atop the deformed sediments (GSQ Maneroo 1; Draper, 2006) and maximum depositional ages of ~495Ma from U-Pb SHRIMP dating of detrital zircons (Kositcin, GA unpublished report).

In south-west Queensland, some basement intersections are attributed to the Warburton Basin, with possible correlations suggested (e.g. with the Dullingari Group or Innamincka Red beds). Fossils are abundant within the Warburton Basin of South Australia suggesting sedimentation occurred between the Early Cambrian to the Early Ordovician (Gatehouse, 1986; Sun, 1996). This is confirmed with U-Pb zircon dating of the Mooracoochie Volcanics (517 ± 9Ma, PIRSA, 2007). In Queensland,

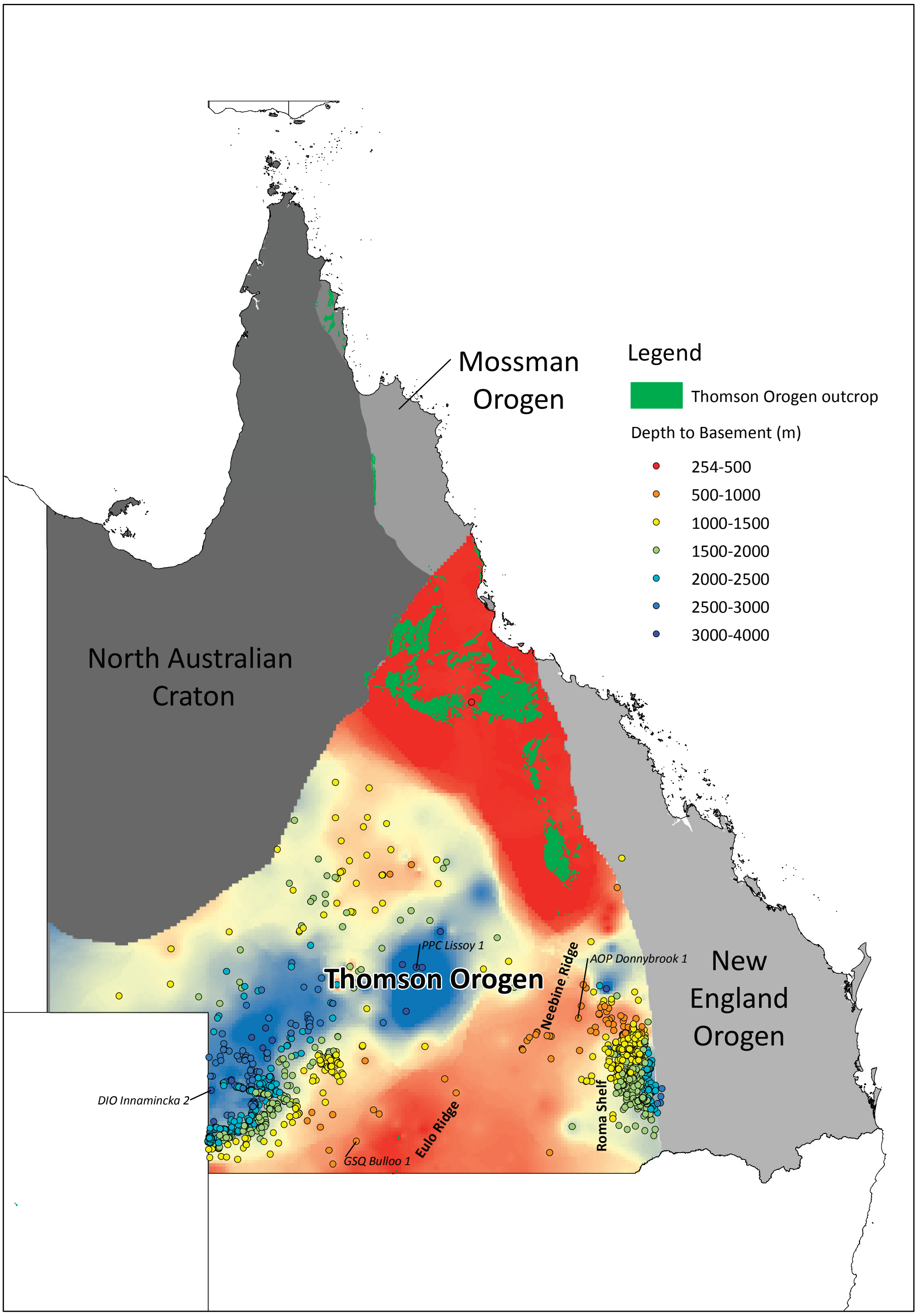

Figure 2. Depth to the top of the Thomson Orogen within Queensland. Data used to create this map includes drill hole (marked) and water bore (not shown) intersections.

metasediments attributed to the Warburton Basin are commonly calcareous, and also include red bed siltstone, sandstone and a rare conglomerate (Figure 3b). However, in many instances it is unclear whether red bed and carbonate units belong with the Warburton Basin/basement or the overlying Devonian basins systems (e.g. Adavale Basin; Figure 4). Identification of flat-lying red sandstones and siltstones in our work (e.g. AAP Tanbar 1, and AOD Gilpepee 1 – Figure 3c), along with interpretation of

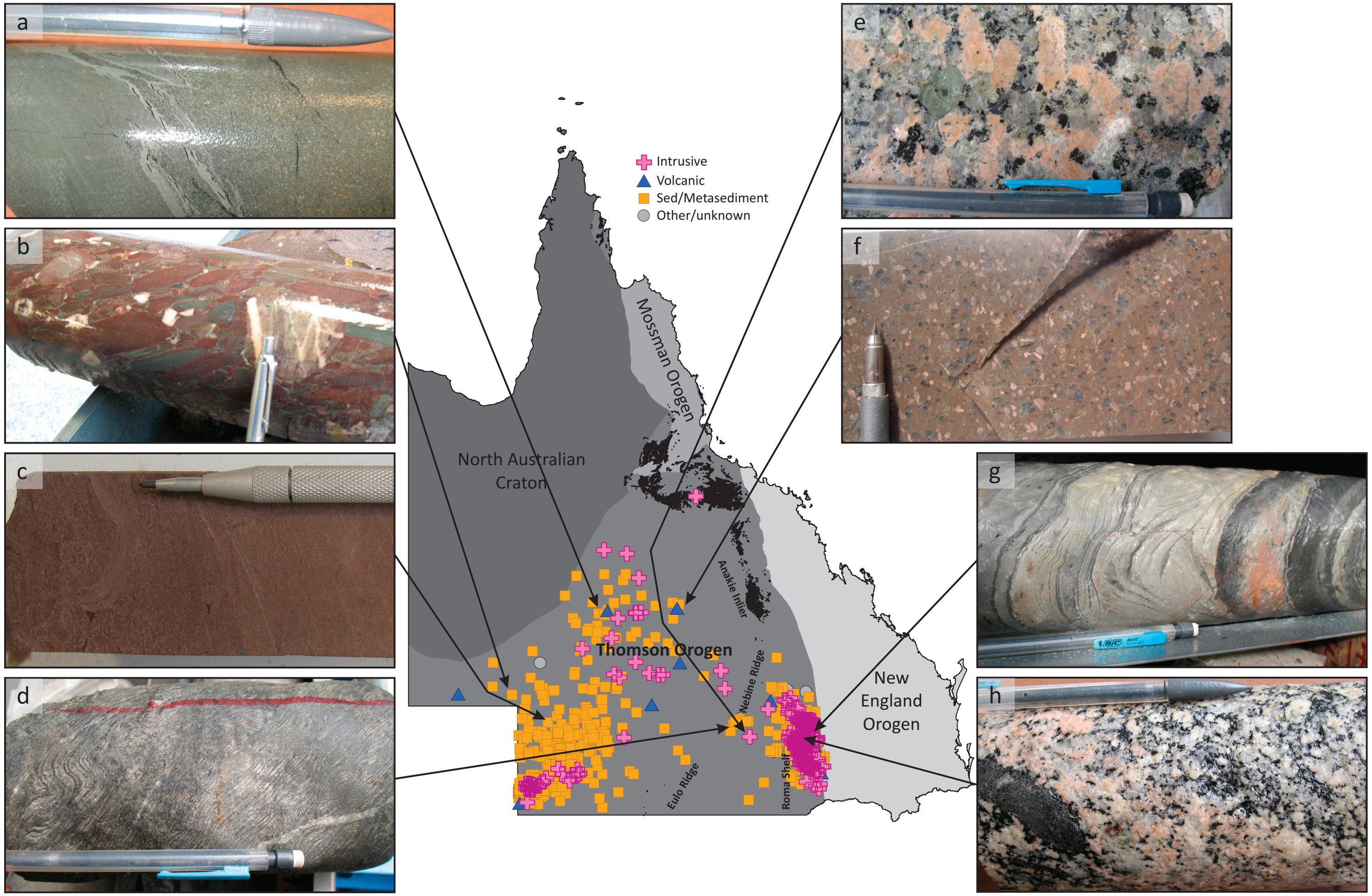

Figure 3. Lithologies of the undercover Thomson Orogen. Map shows the distribution of the different lithologies intersected by drill holes. a) metasandstone/siltstone (GSQ Maneroo 1), b) red, polymict conglomerate (DIO Betoota 1), c) red volcaniclastic sandstone (AOD Gilpeppee 1 – Barrolka Trough), d) multiply deformed metasediments (AOP Alba 1 – Nebine Ridge) 1, e) rhyolitic volcanic (BEA Coreena 1), f) biotite-muscovite monzogranite (AOP Scalby 1), g) metasandstone/siltstone (AAO Timbury Hills 2 – Roma Shelf), h) weakly foliated biotite granite (AAO Brucedale 1 – Roma Shelf).

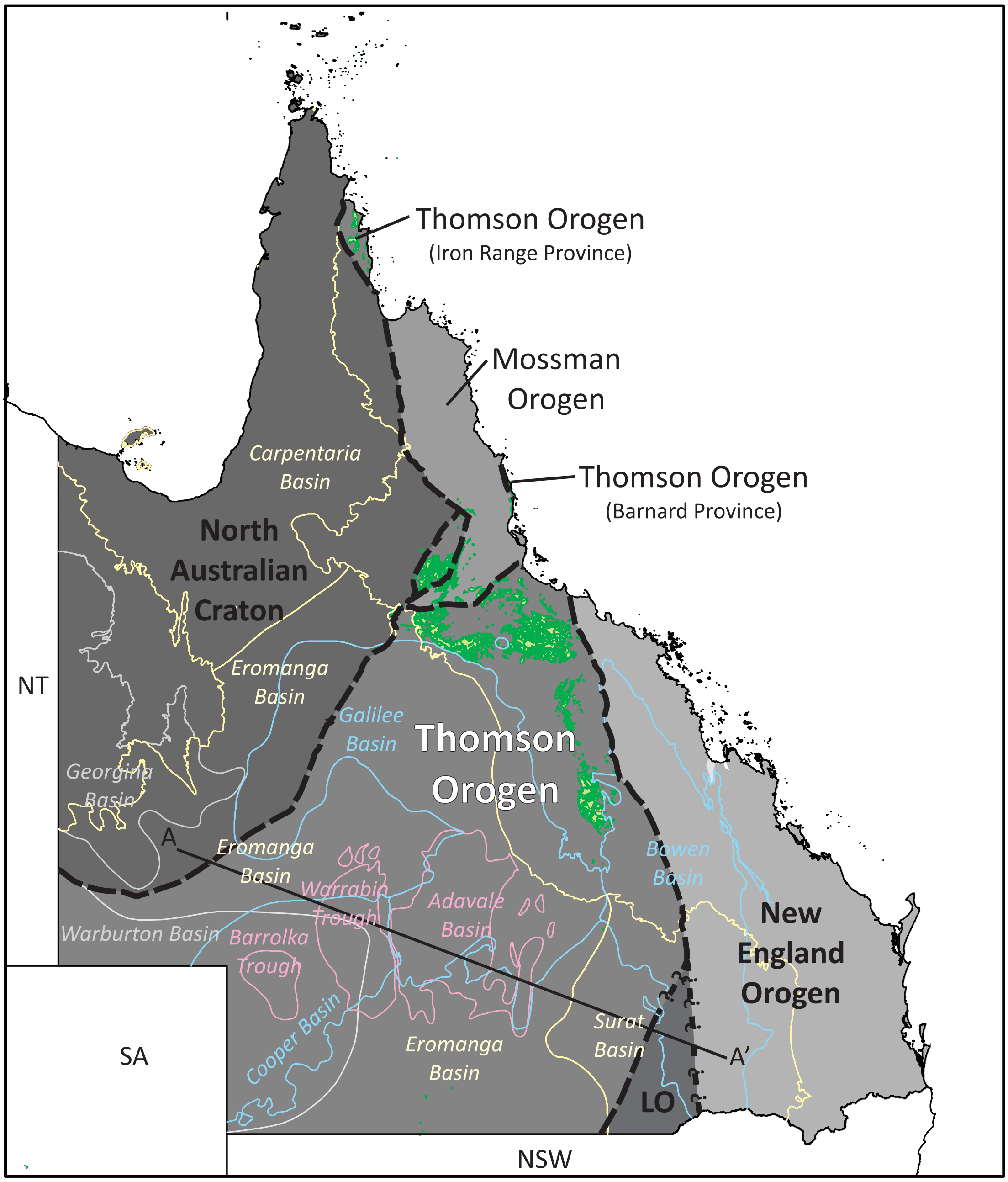

Figure 4. Basins overlying main structural elements of Queensland. Basins outlined in grey are Neoproterozoic to Ordovician, in red are Devonian, in blue are Carboniferous to Permian, and in yellow are Mesozoic. LO = Lachlan Orogen.

existing seismic data has seen re-instatement of the formerly defunct (McKillop & others, 2007) Barrolka Trough to the Devonian basin system (Figure 4).

In the eastern part of the undercover Thomson Orogen, along the Nebine Ridge, metasediments are multiply deformed and generally higher grade (e.g. Figure 3d). However, the relationship between these rocks and the remainder of the Thomson Orogen or Roma Shelf area is unknown.

Intersections of intrusive rocks are less abundant. In the far south-west, where drilling density is high, clusters of intrusive intersections are apparent (Figure 3). Elsewhere, intrusive intersections appear more scattered but this may simply relate to drilling density. Intrusive rocks are intersected below the Adavale Basin (e.g. PPC Lissoy 1, PPC Etonvale 1, HEP Grey Range 1), in the vicinity of Longreach (e.g. LOL (Cleeve) 1, LOW Longreach 1, and LOL Longreach 2 to 4), and further north (e.g. BRP Cairnhope 1, MPC Corfield 1). The intrusive rocks are mostly biotite-muscovite granites but range from leucocratic fine-grained, biotite-muscovite syenogranite to coarse-grained biotite-muscovite monzogranite (e.g. Figure 3e). Only two modern U–Pb SHRIMP zircon dates are published (DIO Ella 1 – 428.3 ± 5.2Ma; AMX Toobrac 1 – 469.4 ± 7.7 Ma — Draper, 2006) and these are older than previously reported K–Ar dates.

Nine drill holes have intersected volcanics in the basement interval, although in cuttings these may be difficult to distinguish from siliceous sediments. Essentially undeformed, Early Ordovician felsic volcanics are intersected in GSQ Maneroo 1, BEA Coreena 1 (Figure 3f) and PPC Carlow 1 (~473–484 Ma; Draper 2006), and a deformed and metamorphosed Middle Cambrian, rhyolitic ignimbrite is intersected in DIO Adria Downs 1 (510 ± 2.8 Ma; Draper 2006). Mafic volcanics and volcaniclastic sediments are intersected in PPC Gumbardo 1 and dated (by K–Ar on pyroxenes) at 489 Ma with a large (50 my) error (unpublished well completion report CR1049). These deposits are flat-lying and essentially unmetamorphosed and we question whether they may be part of the basal Adavale Basin sequence (Gumbardo Formation) rather than basement.

The Roma Shelf region has a much higher density of drill holes that intersect basement. Metasediments intersected in the Roma Shelf region are grouped into the Timbury Hills Formation. Plant fossils identified in one drill core (AAO Pickanjinne 1) indicate a Devonian age but differing degrees of deformation are apparent and it is possible that this region comprises several units of different ages (Murray, 1994). The metasediments generally comprise interbedded quartzose sandstones and siltstones which are lithologically and structurally similar to those in the Thomson Orogen area to the west (e.g. Figure 3g). They are intruded by abundant granitoids referred to as the ‘Roma Granites’. The Roma Granites are mostly biotite-muscovite granites and have early Carboniferous ages based on K–Ar dates (compiled in Murray, 1994). S and I-types are both present and many exhibit weak foliation (e.g. Figure 3h). Volcanic rocks intersected in the Roma Shelf area are part of a younger sequence associated with the Bowen Basin (Murray, 1994).

The uneven distribution of drill holes throughout the undercover Thomson Orogen has led to the ironic circumstance that the area of shallowest cover and therefore the most prospective for mineralisation is the area we know least about. To combat this, the GSQ have recently conducted a higher resolution airborne magnetic and radiometric survey and upgraded gravity data coverage (Figure 5). Initial interpretation of the magnetic data in particular highlights significant structural and lithological complexity. Two dominant trends (NE-SW and NW-SE) are apparent among large faults and other major lineaments. Large belts comprising probable metasediments and metavolcanics with various orientations are observed truncated by major faults. Additionally, single zoned plutons and possible larger batholiths are apparent (Figure 5). Interestingly, and perhaps disappointingly, most areas of known granitoid outcrop in this area (e.g. Eulo, Granite Springs, Hungerford, Currawinya),

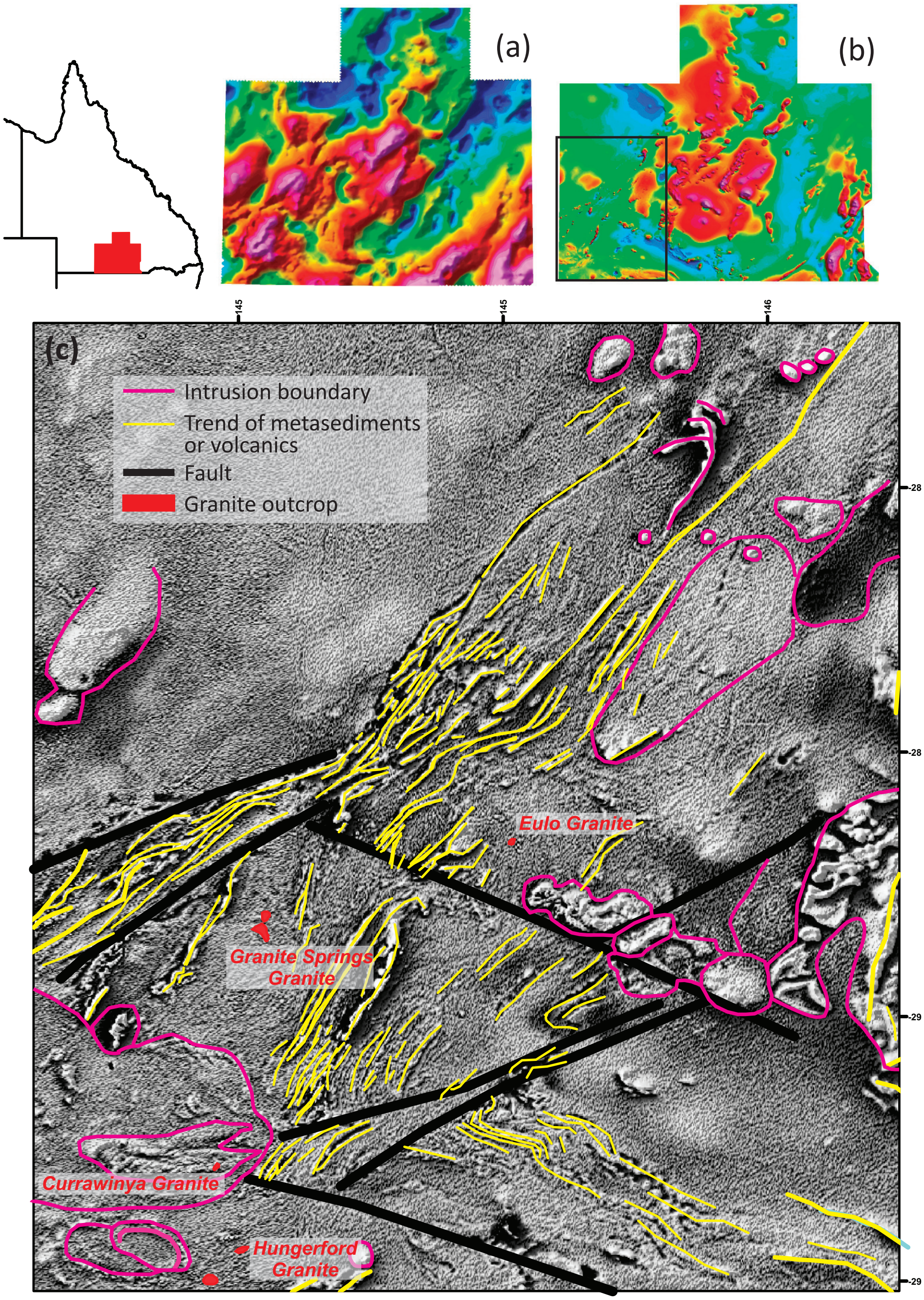

Figure 5. New geophysics obtained by the Geological Survey of Queensland. a) Gravity data, b) Magnetic data (TMI), c) Initial interpretation of new magnetic data (1vd) showing extensive belts of possible metasediments and metavolcanics truncated by major faults as well as large intrusions. Outcropping intrusions in this area also shown.

do not appear to correlate with intrusive features identified in an initial interpretation of magnetic data (Figure 5). However the granites do occur within a broad NE-SW trending gravity high which is often attributed to a disjointed basement ridge known as the Eulo Ridge in the SW and the Nebine Ridge in the NE (Finlayson, 1990).

REGIONAL CORRELATIONS

Fundamental to our understanding of the Thomson Orogen and the broader development of the Tasminides is correlation (if any) between the undercover area and other, better known regions such as the outcropping parts of the Orogen, the NSW portion, and other potentially contemporaneous terrains such as the Warburton Basin and Koonenberry Belt.

Initial interpretations of new geophysical data suggest some continuation of domains identified in the NSW portion of the Thomson Orogen into the far southern part of QLD. However, significantly greater structural complexity is apparent to the north. On a wider scale, geophysical data do not support a direct continuation of Neoproterozoic to Cambrian passive margin and arc rocks in southern Australia to north Queensland as suggested in some reconstructions (e.g. Fergusson & others, 2007). The major post-emplacement tectonism required by such a model is not apparent in regional geophysical images. Continuation of the Anakie Inlier undercover to the Nebine Ridge area (as suggested by Murray, 1994) is supported by similar lithologies and degree of deformation but is yet to be confirmed by detrital zircon age spectra and other themochronological data.

Granites of the undercover and southern Thomson Orogen have been targeted in geochronology studies (Draper, 2006) and via collaboration with QUT (e.g. Siegel & others, 2012) The range of ages (Early Ordovician to Devonian), geochemistry (I- and S-types), and spatial distribution (i.e. mostly occurring in large batholiths) of these correlate well with the outcropping Thomson Orogen (e.g. Ravenswood, Lolworth, Reedy Springs, Retreat Batholiths). More geochemical work is required to understand any tectonic correlations.

Another tool that the GSQ is using, in conjunction with GA to constrain the extent of the undercover Thomson Orogen, is U-Pb SHRIMP dating of detrital zircons. Modern dating techniques have scarcely been used within the Thomson Orogen, with the majority occurring within the outcropping units (Figure 6). This tool is particularly useful in providing a maximum depositional age, and also a provenance signature that may be used to delineate separate depositional basins and/or potential correlations with other terranes. Preliminary results from 3 widely dispersed drill holes (DIO Betoota 1, AAO Beryl and DIO Naryilco 1) have been used to identify an undercover Thomson Orogen signature which includes a maximum depositional age of ~495Ma, and major inheritance peaks between 500–520Ma, 565–580Ma and 1050–1200Ma. These signatures correlate well with those in outcropping areas of Queensland (upper Argentine Metamorphics; Fergusson & others, 2007) but correlations with limited data from New South Wales are less clear (e.g. Greenfield & others, 2010; Glen & others, 2010). A sample adjacent to the North Australian Craton (HPP Goleburra 1) has a maximum depositional age of 1074Ma and a major inheritance peak at

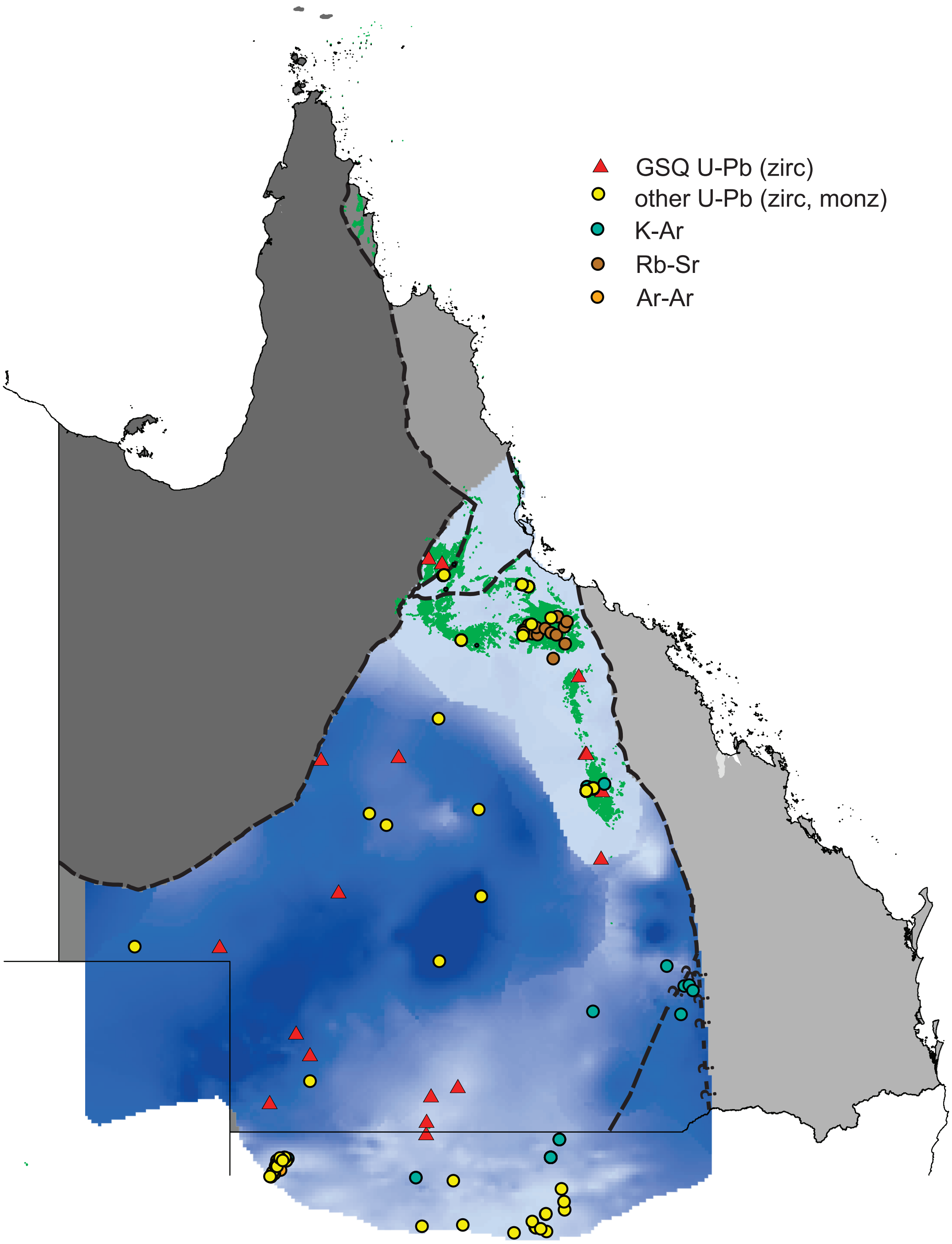

Figure 6. Geochronological methods used on the outcropping and undercover rocks of the Thomson Orogen. A depth to basement map is shown with darker colours representing deeper areas. GSQ samples are those collected during the current project, whilst all others are from the published literature. Note the relatively poorly sampled undercover Thomson Orogen prior to this study.

~1560Ma and no other peaks (Cross, unpublished). This signature is comparable with units within the Cape River Metamorphics, and the lower Argentine Metamorphics (Fergusson & others, 2007). These geochronological studies are continuing and a result of this project will be a thorough database of detrital ages for the undercover Thomson Orogen.

The relationship between the Warburton Basin and the Thomson Orogen has yet to be satisfactorily defined. The Warburton Basin overlaps in time with the Thomson Orogen, being a Cambrian to Middle Ordovician basin of calcareous and carbonaceous sediments thought to have formed within a shallow marine environment (Gatehouse, 1986). However they are generally flat lying and relatively undeformed (Sun, 1997) whilst rocks of the Thomson Orogen are consistently steeply dipping and display a minor bedding parallel foliation. More broadly, the influence of central Australian basins and deformation events versus those on the eastern Gondwana margin are yet to be fully explored for the Thomson Orogen. Of particular interest will be provenance and thermal history comparisons between the Thomson Orogen, the Warburton Basin, and other elements of the Centralian Superbasin (e.g. Georgina Basin).

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DEPTH TO BASEMENT CALCULATION IN THE SOUTHERN THOMSON

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INTRODUCTION

Depth to crystalline basement is a major consideration when conducting minerals exploration. Areas of unknown depth to crystalline basement can potentially cause difficulties for planning and conducting effective exploration. In areas of intensive exploration and drilling, a reasonably accurate depth to basement surface can be created using drill hole intercepts. The highlighted area in central southern Queensland has limited drilling data and the calculated depth to basement surface contains large areas which are unconstrained due to the absence of drill holes (Figure 1). Using magnetic data from the new Thomson and Thomson Extension airborne surveys the Geological Survey of Queensland is creating another depth to basement surface using modelling software . This depth to basement study aims to compare and better constrain areas of the original depth to basement surface where little or no drilling information was available.

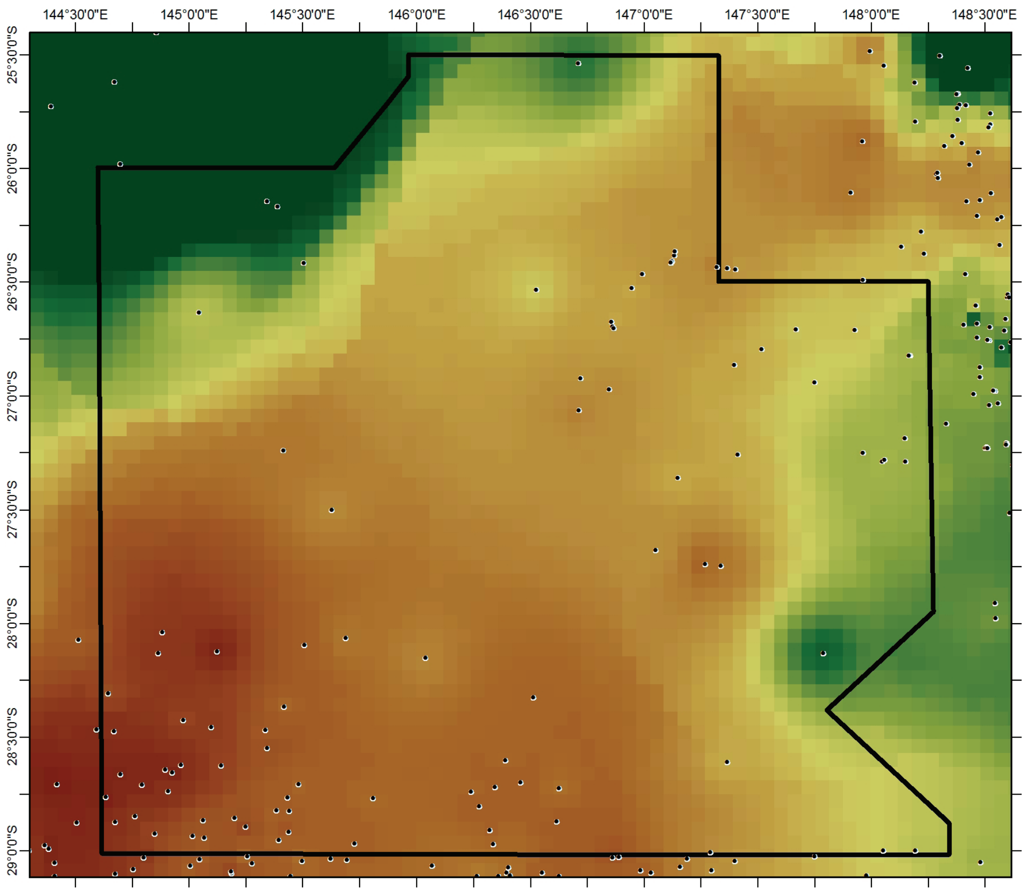

Figure 1. Study area showing the drill holes in the study area and the depth to basement grid calculated from them (Brown & others, 2012)

DATA

The total magnetic intensity (TMI) data from the Thomson and Thomson Extension airborne surveys was collected during 2011–2012 by the Geological Survey of Queensland (Figure 2). The survey was flown along east–west flight lines spaced at 400m with a nominal flying height of 80m.

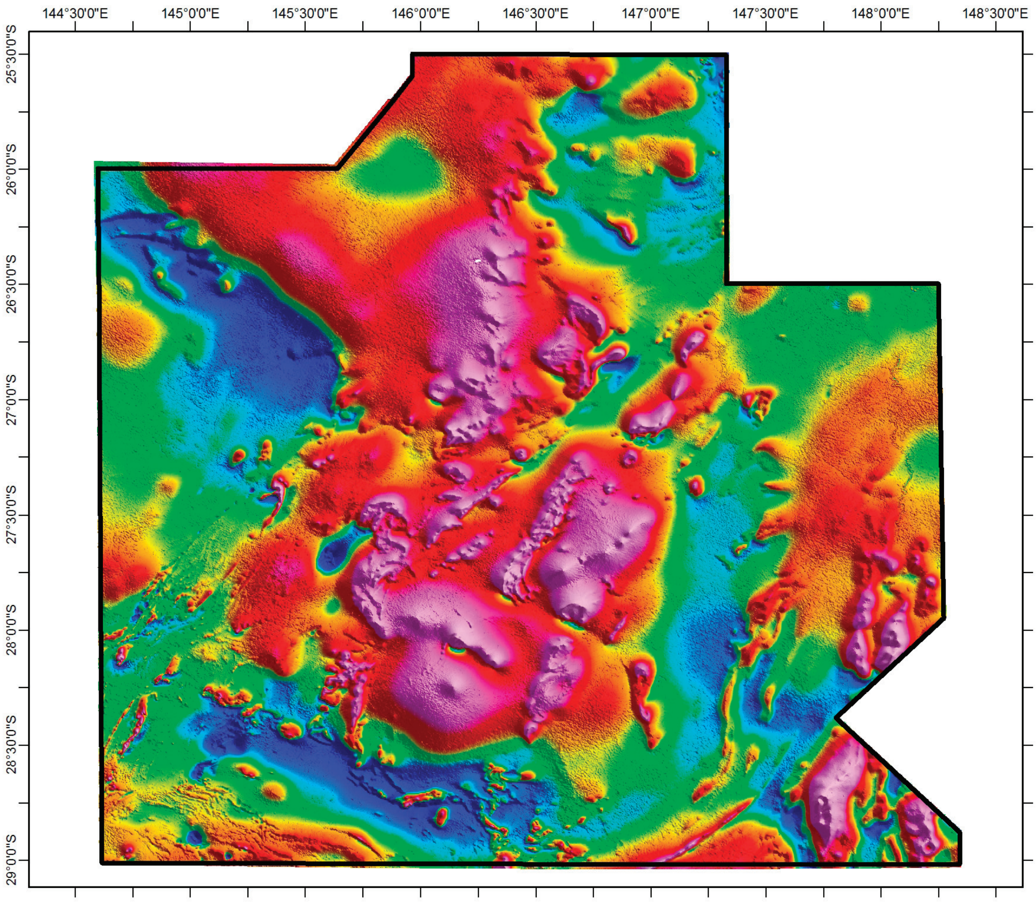

Figure 2. TMI data for the Thomson and Thomson Extension airborne surveys

BACKGROUND

There are many depth estimation methods which use magnetic data. These methods include: Naudy, Werner deconvolution, analytic signal, Euler deconvolution, Euler deconvolution of the analytic signal, source parameter imaging, and continuous wavelet transform (Li, 2003). Each method has individual strengths and weaknesses which must be assessed in relation to the data quality and purpose of the depth estimation. For example, some depth estimation techniques use higher order (at least 2nd order) vertical derivatives which accentuate noise and shallow sources in the data, and should not be used on noisy data. It is good practice to use more than one method to obtain more accurate depth estimates (Li, 2003; FitzGerald, 2004). Due to the noise in the surveys, Euler and Naudy depth estimation techniques were used as they do not require the use of higher order derivatives.

ASSUMPTIONS

All of the aforementioned estimation techniques use depth to magnetic sources as a proxy for depth to basement and assume that there are no significant magnetic sources in the cover sequences. Based on magnetic susceptibility data collected from drill core in the study area this appears to be a valid assumption. However, visual inspection of the data shows a very short wavelength response covering the entire survey area (Figure 3). This signal has the same characteristics in areas where the drill holes indicate that the basement is over 1km deep as it does in areas where the basement is only 100m deep, indicating that it is completely unrelated to the basement depth. The very short wavelengths suggest that the sources of the anomalies are shallow and in some areas the signal appears to be fluvial; however, the extensive nature of it indicates that it is not solely related to fluvial environments.

Initial modelling conducted as part of this project suggested that the depth of source for this short wavelength anomaly is up to 250m deep. These modelled depths were deeper than expected so an inspection of the top 300m of drill core from GSQ Mitchell 1 and GSQ Quilpie 1 was conducted. GSQ Mitchell 1 did not have any elevated magnetic susceptibility values. GSQ Quilpie 1 had an area of anomalous magnetic susceptibility values at depths between 96.5 and 120.5 metres. The core

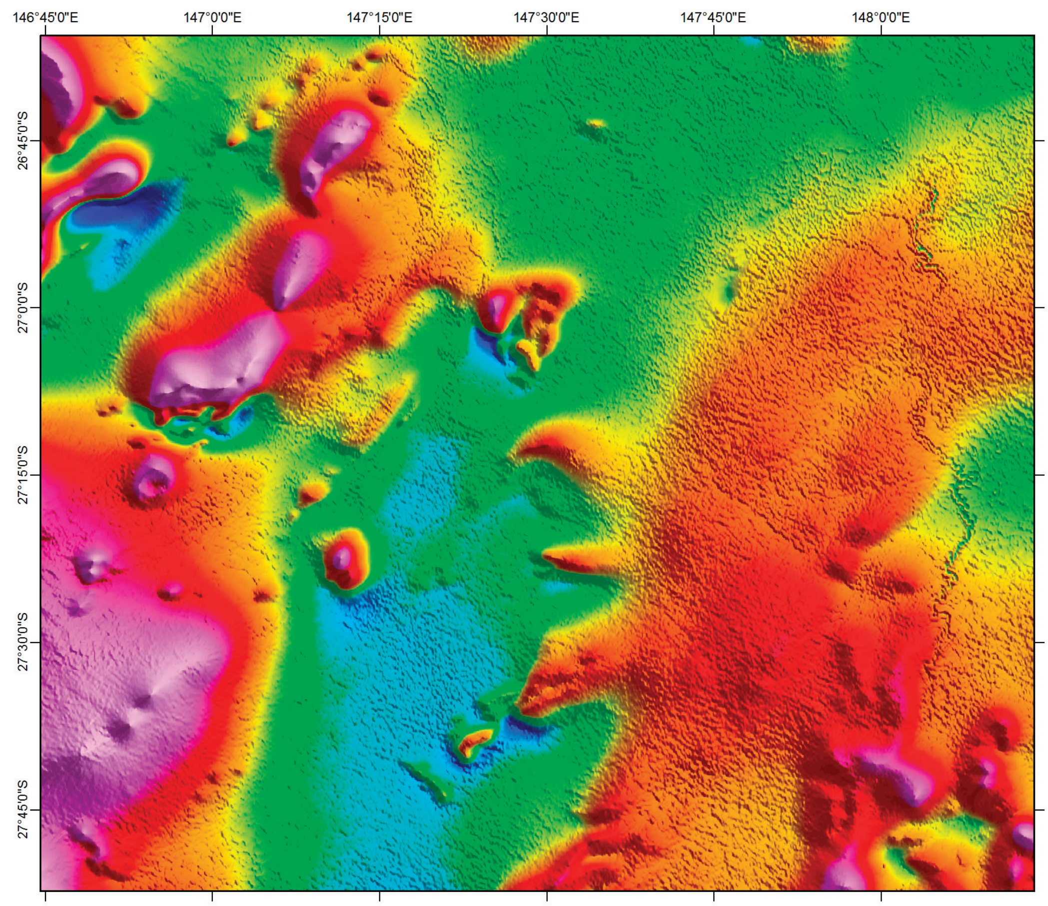

Figure 3. Part of the Thomson airborne survey displaying the very short wavelength, regionally extensive magnetic signal. The east of the image shows an area where the magnetic signature appears be of fluvial nature.

in this section is a silty sandstone with minor carbonates and has been interpreted as part of the Mackunda formation (John, 1987). There was little or no visible magnetite present in this core, however, when a magnet was run through the crumbled core some very small magnetite grains were found. The magnetic susceptibility values measured with KT-9 metre for the anomalous section were generally between 0.3 x 10^{-3} and 0.5 x 10^{-3} SI. The susceptibility was not evenly distributed with localised values of up to 6.4 x 10^{-3} SI measured. The average values are at least an order of magnitude higher than would be expected for sandstone. It is very likely that this section of core is the cause of the high frequency signal displayed in the magnetic data. Having no relationship to the basement, this shallow signal can therefore be filtered out if it is found to cause interference with the depth to basement solutions.

TRIAL

A trial Euler deconvolution was conducted on the smaller Thomson Extension area to assess the impact of the short wavelength signal on the depth to basement estimation. The results showed that the short wavelength signal had a very large impact on the solutions causing the depth solutions to be very shallow across the entire area. Drilling in the area intersects basement at 700m in the south-east and approximately 1700m in the north; however, the Euler solutions typically modelled basement at 100 to 400 metres. The distribution of the solutions also showed the same patterns as the short wavelength signal. The solutions had a large amount of scatter, causing difficulty in interpreting the results and making it necessary to try to filter out the short wavelength signal.

METHODS

Low pass filtering and upward continuation were both trialled to determine which would filter out most of the shallow signal without losing too much signal from the rest of the data. Maintaining as much signal as possible was particularly important in areas where the drill hole information indicated that the basement was shallow. In these areas the wavelengths of the basement signal is much closer to the wavelength of the shallow response. Both filters could eliminate much of the shallow signal but the low pass filter was better at preserving the remaining signal. The filtering was applied to the line data, which was then gridded for use in the depth estimation. This method is preferred over filtering the gridded data as spurious artefacts can appear when filtering gridded data.

Both chosen depth estimation techniques involve the use of a moving window to calculate depth solutions. Choosing an appropriate window size is critical for depth estimation as the window must be large enough to properly analyse the anomalies present in the data. If the window is too large, interference from nearby anomalies will occur causing scattering of solutions. The window size used during Euler deconvolution also dictates the maximum depth of reliable solutions (Intrepid Geophysics, 2009). The drill hole depths were utilised to aid selection of appropriate window sizes for the depth estimation but were not used as constraints during the depth estimation. This was done so that they could act as independent quality control measures for the solutions.

Many iterations of the Euler/Werner deconvolution were run. The structural index (SI) and the window size were varied in an effort to produce more reliable solutions. The SI is a value which ranges from 0 to 3, and represents different anomaly source geometries. For the total field magnetic data the following values are used to represent geological features: SI = 0 is a contact; SI = 1 is a sill or dike; SI = 2 is a vertical or horizontal cylinder and SI = 3 is a dipole (spherical body like an intrusion) (Saleh & others, 2012). Intermediate values of SI (e.g. 0.5) can be used to approximate the response from intermediate structures, such as a fault with a small amount of throw (Reid & others, 1990). Euler deconvolution of the analytic signal enable calculation of both depth and SI, however it involves the calculation of higher order derivatives. Instead of using this method, Euler deconvolutions were run at SI=0, SI=1 and SI=3. An SI of 2 was not used as there are few or no cylindrical source bodies in the area, but rather a combination of intrusions, dykes and the basement contact.

A located Euler deconvolution was also run and analysed. This is a slight variation on Euler deconvolution which uses the analytic signal grid to determine the location of anomalies (Whitehead, 2010). Window size is automatically selected by software analysis of the anomaly size. Solutions are then calculated at locations where an anomaly has been identified. This method limits the solutions which are produced enabling easier interpretation.

RESULTS TO DATE

A preliminary depth to basement surface has been produced (Figure 4). This surface was produced using selected Euler solutions for SI = 1 and SI = 3 (multiple window sizes). Solutions from the located Euler deconvolution were also used in conjunction with the available drill holes. A surface was fitted to the selected points using GoCAD and interpolated until an acceptable fit to the data was obtained.

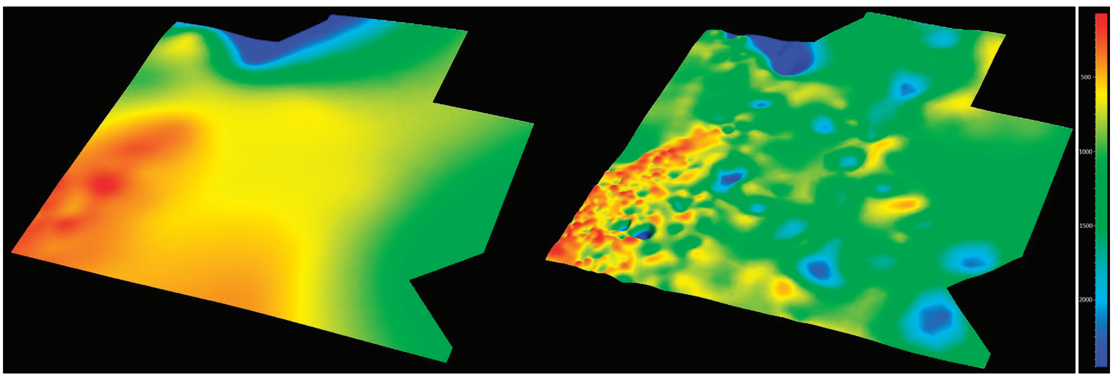

Figure 4. The image on the left shows the surface produced from drill hole intercepts. The image on the right shows the preliminary depth to basement surface.

FURTHER WORK

Work on producing a coherent depth to basement surface is ongoing. Future work includes more work on Naudy modelling, incorporating the available seismic data into the surface as another constraint, and further refining of the selected Euler depth solutions.

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MINERAL PROSPECTIVITY AND UNDISCOVERED RESOURCES OF NORTH QUEENSLAND

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Geological Survey of Queensland

OVERVIEW OF THE NORTH QUEENSLAND GOLD AND STRATEGIC METALS PROJECT

North Queensland is known for its significant historic production of a wide range of commodities, including gold, copper, zinc, nickel, tin and tungsten. Based on the properties of known mineralisation, as well as high-level metallogenic characteristics of the region, North Queensland can be considered geologically prospective for various types of mineral deposits, including:

- orogenic and intrusion-related gold
- epithemal gold–silver
- porphyry molybdenum–copper
- skarn copper–zinc–gold–iron
- polymetallic veins
- volcanic-hosted massive sulphide zinc–copper–lead–silver–gold
- vein, greisen and skarn tin and tungsten
- lateritic nickel–cobalt–scandium
- magmatic-hydrothermal and sedimentary basin-related uranium.

Additionally, there is a potential for deposits of new strategic minerals (such as beryllium, bismuth, gallium, germanium, niobium and tantalum) which have received little attention from exploration companies in the past and are not currently known in the region.

Despite such a diverse mineral prospectivity, recent mining and exploration activities in the region have been relatively subdued and mostly restricted to the areas in the close vicinity of known mineral deposits. While the near-mine exploration will undoubtedly lead to the discovery of additional mineral resources and extend the operation at existing mines, the medium to long term future of the mining industry in the region largely depends on the discoveries of major new mineral deposits. Such future discoveries are likely to be in areas where little exploration has happened in recent years, especially where no significant mining took place in the past.

Exploration in the poorly explored areas is associated with significantly increased technical and economic risks and uncertainties, which largely accounts for a low level of greenfield exploration in North Queensland. In particular, there is little information on the likely abundance, spatial distribution and scale of different types of undiscovered mineral deposits in North Queensland. Additional factors impeding effective greenfield exploration in many parts of the region include barren cover, a lack of essential geological data and limited understanding of the mineral systems that may have operated in the region.

To address some of the critical information gaps and to evaluate and reduce exploration risks, the Geological Survey of Queensland (GSQ) is undertaking the North Queensland Gold and Strategic Metals Project (Figure 1). The project's main aims are to quantify the resource potential of the region and to delineate areas of enhanced mineral prospectivity. This information can be used to support informed decision making by the government and to facilitate better exploration targeting by explorers. The overall approach uses an integrated application of quantitative methods of mineral resource assessment, GIS-based prospectivity analysis and geophysically constrained 3-D modelling. Major results of the first phase of the project, which focuses on the orogenic gold prospectivity of the Hodgkinson and Broken River Provinces, were reported at the 34th International Geological Congress in Brisbane in August 2012 and are discussed in this paper. Other project activities, including a regional geodynamic and metallogenic synthesis and the Red River subproject (Figure 2), are currently under way.

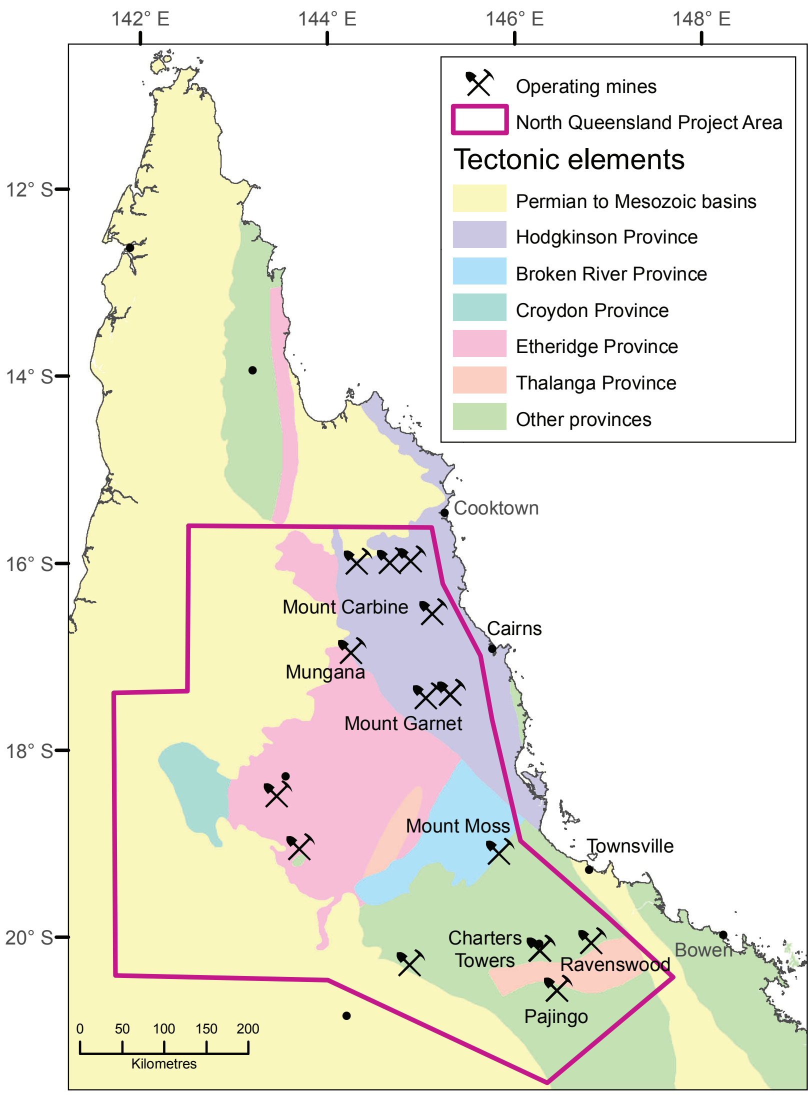

Figure 1. Location of North Queensland Gold and Strategic Metals Project and regional tectonic elements.

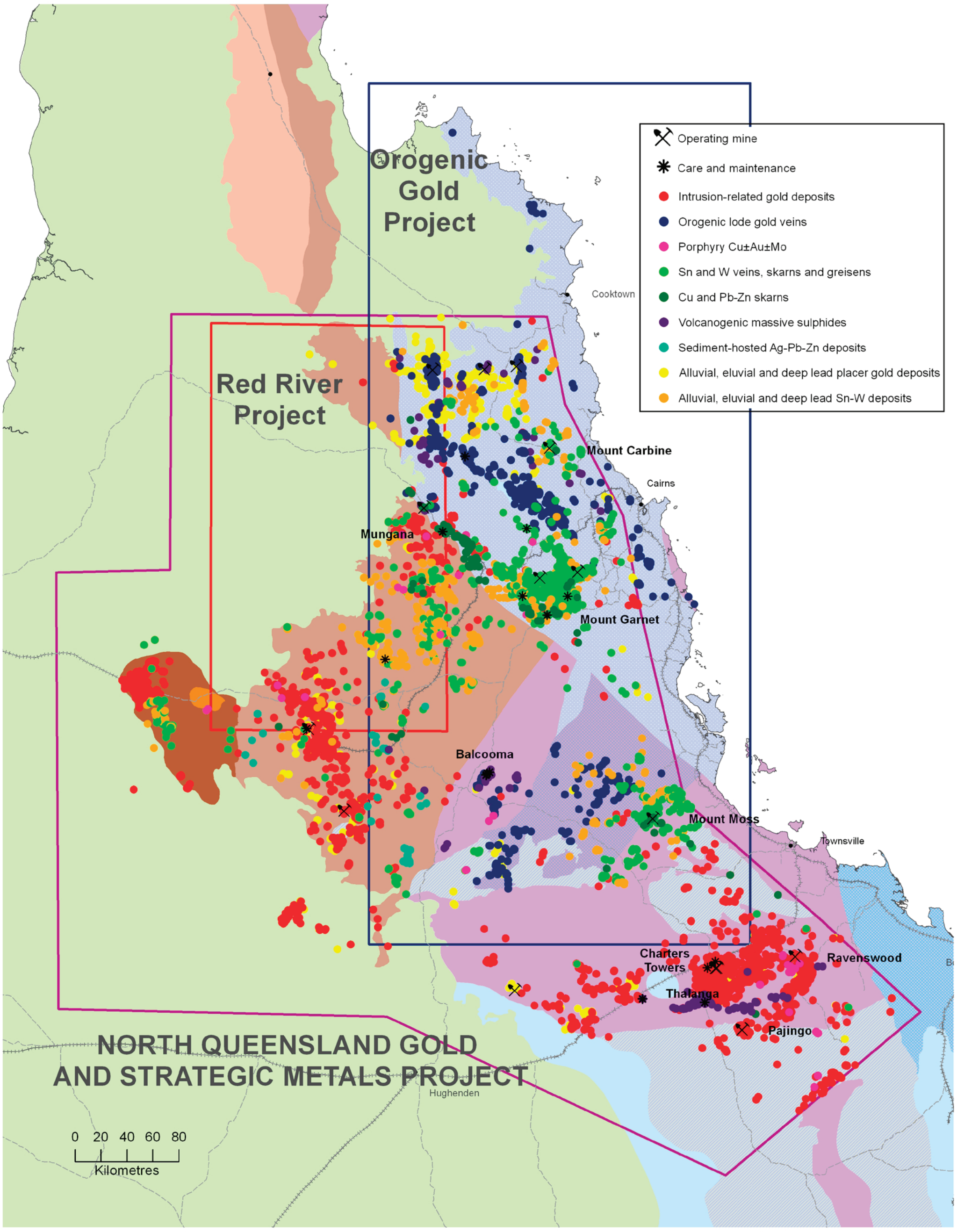

Figure 2. Location of the Orogenic Gold and Red River project areas and recorded mineral occurrences

GEODYNAMIC RECONSTRUCTION OF THE GEOLOGICAL HISTORY OF NORTH QUEENSLAND

A detailed synthesis of the current understanding of the tectonic evolution of the region is currently under way. This involves an extensive literature review and ongoing expert discussions on the tectonic history of the North Queensland region from the Proterozoic to Quaternary, in the context of the broader continent-scale evolution of eastern Australia. A time-space chart correlating major stratigraphic units, episodes of magmatic activity and deformation events across the region will be used as a framework to reconstruct the regional tectonic evolution. Results of this component of the project, including a discussion of the province-scale metallogeny of the region, will be released in early 2013.

RED RIVER PROJECT

The Red River Project area (Figure 2) is approximately 300km long and 170km wide, extending west from the town of Chillagoe and north from the town of Georgetown. Proterozoic and Palaeozoic rocks, which host various types of mineralisation, outcrop in the eastern and southern parts of the project area but are entirely concealed by younger volcano-sedimentary cover sequences in the west and north. Cover thickness is poorly constrained, estimated to exceed 500m in the west. The prospective basement in the covered area has been poorly explored.

The project aims to create a regional 3D model of the area and to develop a better understanding of the mineral systems that operated in the region, which will facilitate a subsequent mineral resource assessment and prospectivity analysis. Mineral systems associated with Permo-Carboniferous magmatism are of a particular interest. Numerous intrusions of the Townsville – Mornington Island magmatic belt are interpreted to be present under cover. Evaluation of the depth to basement across the area is currently under way, with the results due to be released in 2013.

OROGENIC GOLD POTENTIAL OF THE HODGKINSON AND BROKEN RIVER PROVINCES

Overview of gold mineralisation in the Hodgkinson and Broken River provinces

Primary orogenic and associated alluvial gold mineralisation is relatively common throughout the Hodgkinson and Broken River provinces (Figure 3). Many areas of known mineralisation were extensively mined in 1870s – early 1900s, with only relatively minor intermittent production in recent times. General characteristics of primary gold deposits and the mining history in the region have been extensively discussed by Garrad & Bultitude (1999) and Denaro (2012).

The bulk of primary gold production before 1990 (totalling approximately 11t gold bullion) was from deposits characterised by free gold in quartz veins, with minor sulphides and ferroan carbonates. Deposits of this group compose the bulk of the historic primary goldfields in the region: e.g., Maytown, Groganville (Anglo-Saxon), Hodgkinson, Munburra (Starkie No. 2), West Normanby and Mount Peter. Such deposits were often described in other regions as 'gold only quartz vein', 'turbidite-hosted quartz-gold', 'slate-belt', 'mesothermal gold', etc. Typical average gold grades recovered at the time of historic mining ranged between 30g/t and 60g/t.

Another major style of gold deposits in the region is characterised by the prevalence of refractory, or ultra-fine (usually <10μm), gold in sulphide grains (arsenopyrite and pyrite) which occur in thin veins and stockworks or disseminated in host turbidites. This deposit style had been largely unknown in the region until 1980s. Extensive exploration in parts of the region has identified significant deposits of this style at

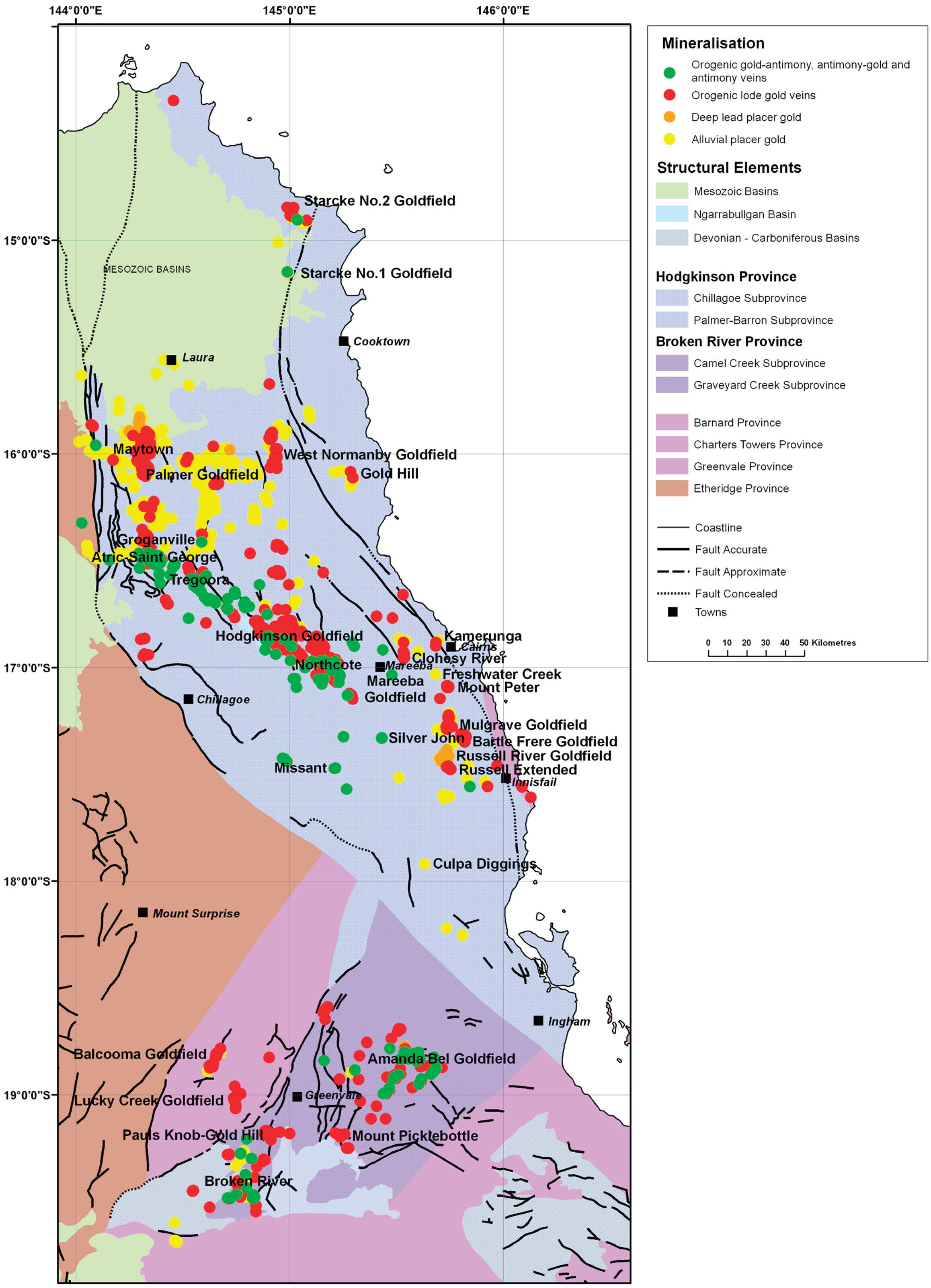

Figure 3. Distribution of primary and alluvial gold occurrences in the Hodgkinson and Broken River provinces

Northcote, Tregoora, Atric and Reedy in the Hodgkinson Province and Camel Creek, Golden Cup and Big Rush in the Broken River Province. Oxidised ores from several ore fields have been mined by shallow open cuts in 1990s, producing almost 7t of gold. However, most of the identified mineralisation occurs in primary sulphidic ores, with the remaining identified resources exceeding 19t. Typical gold grades of the refractory gold deposits range between 1.5g/t and 10g/t, mostly averaging less than 5g/t.

Assessment of undiscovered gold endowment

The quantitative assessment of undiscovered gold endowment in the region was based on the 3-part form of assessment developed by the United States Geological Survey and discussed in detail by Singer (1993) and Singer & Menzie (2010). It involved the following stages:

- definition of the areas (permissive tracts) that may contain orogenic gold deposits — Ordovician to Devonian volcano-sedimentary rocks
- estimation of likely grade and tonnage characteristics of undiscovered deposits by an appropriate grade and tonnage model based on known deposits
- estimation of the number of undiscovered deposits consistent with the grade and tonnage model — performed by an expert panel composed of three GSQ staff and four external experts.

The total amount of undiscovered metal endowment was estimated through a Monte Carlo computer simulation that combined the grade and tonnage distributions with a probabilistic estimate of the number of undiscovered deposits.

The assessment results are summarised in Table 1 and Figures 4–5. The Hodgkinson Province is estimated to host between 1 and 10 undiscovered refractory orogenic gold ore fields, with a 50% probability of three or more ore fields, each containing more than 1t of gold. The mean undiscovered gold endowment in the province is estimated to be approximately 30t of gold, with a 90% probability of at least 1t and a 50% probability of at least 12t.

Table 1. Estimated number of undiscovered ore fields. The estimates are for refractory gold ore fields with at least 1t of contained gold.

Probability	Number of undiscovered ore fields	
	Hodgkinson Province	Broken River Province
90%	1	0
50%	3	3
10%	10	5

The Broken River Province is estimated to host up to five undiscovered refractory orogenic gold ore fields, with a 50% probability of three or more ore fields, each containing more than 1t of gold. The mean undiscovered gold endowment in the province is estimated to be approximately 20t, with an 80% probability of at least 1t and a 50% probability of at least 20t.

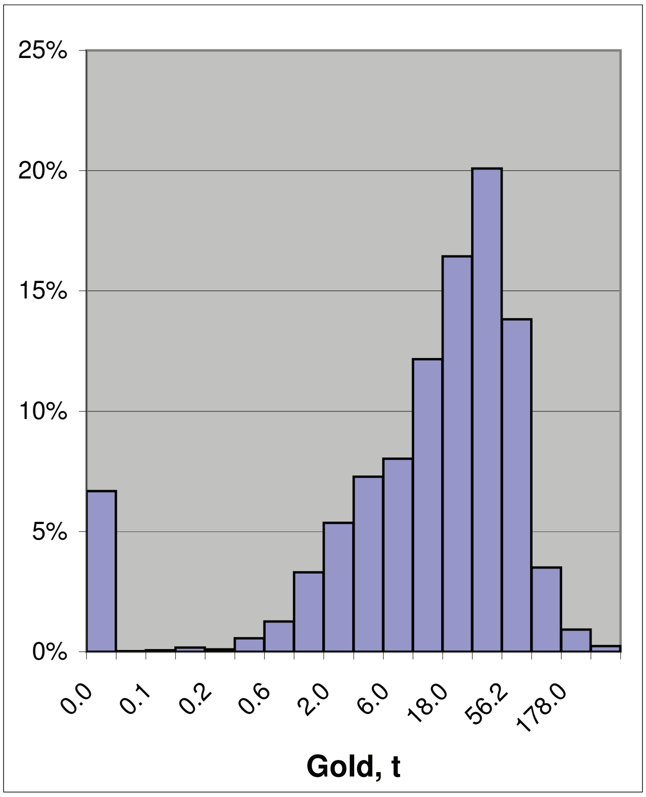

Figure 4. Estimated primary orogenic gold endowment in undiscovered refractory gold ore fields in the Hodgkinson Province. Heights of the bars represent percentages of Monte Carlo computer simulations. The median estimate is 21t Au.

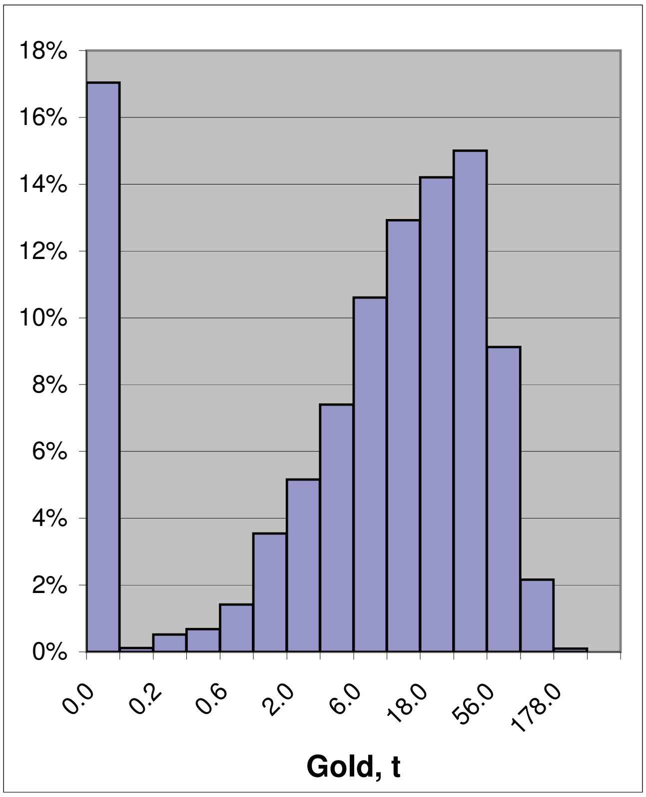

Figure 5. Estimated undiscovered primary orogenic gold endowment in undiscovered refractory gold ore fields in the Broken River Province. The median estimate is 12t Au.

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3D MINERAL POTENTIAL OF THE QUAMBY PROJECT

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Geological Survey of Queensland

The Quamby project covers an area 95km long by 80km wide extending east from the Mount Rosebee Fault and north from Cloncurry in north-west Queensland (Figure 1). The Quamby project area is located within the 2011 North-West Queensland Mineral and Energy Province Study (Geological Survey of Queensland, 2011) region, lying immediately north of the Mount Dore project area. Proterozoic outcrop in the area varies from good to poor in the west to completely concealed in the east. Mesozoic sediments cover >50% of the area (with most cover depths interpreted to be less than 200m). Consequently, much of the area has been under-explored.

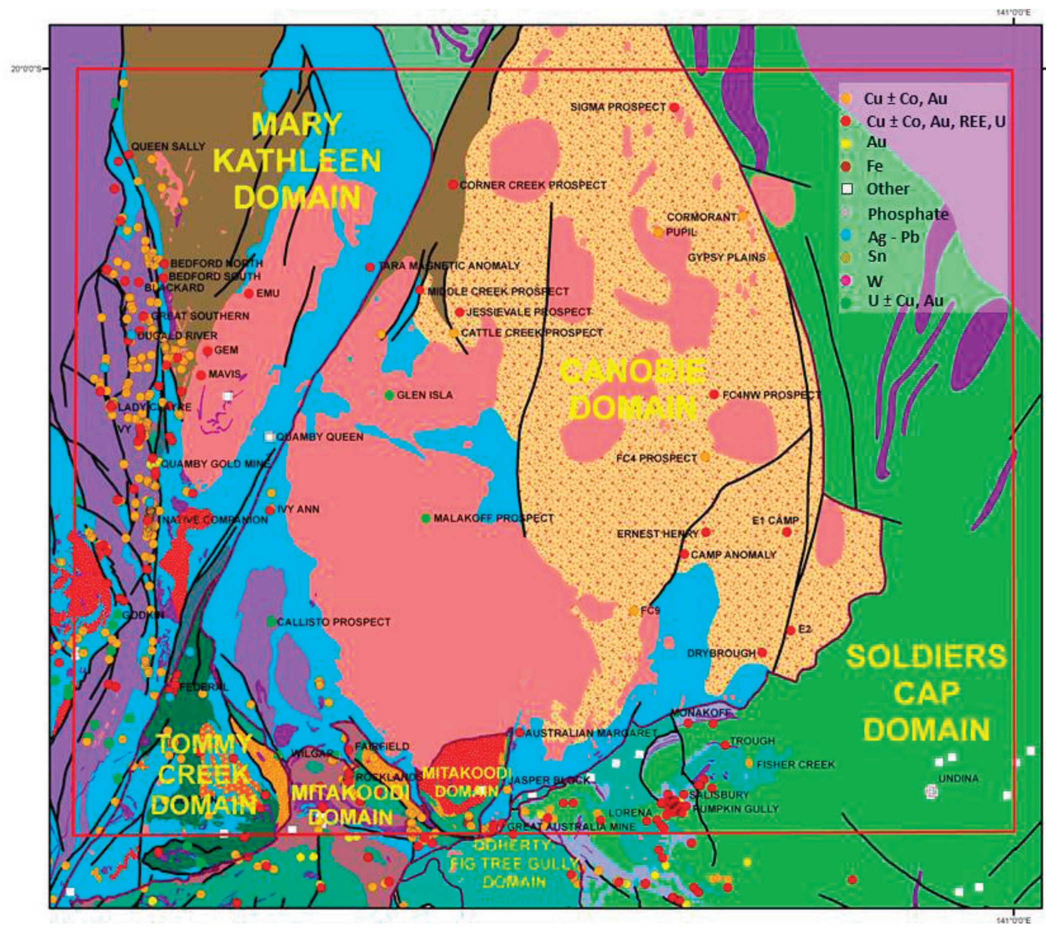

Figure 1. Location of Quamby Project area with NWQMEP study geological domains and known sites and styles of mineralisation

The Quamby project area includes the major operating Ernest Henry Cu-Au mine as well as significant Cu-Au projects such as E1/ Mount Margaret, Rocklands and Roseby, and the Dugald River Ag-Pb-Zn deposit. The Quamby study is centred on the Canobie Domain but the project area contains regions of the Mary Kathleen, Tommy Creek, Mitakoodi and Soldiers Cap Domains (Figure 1). The Quamby area is prospective for numerous styles of mineralisation including Cu±Au±iron oxide deposits, stratabound sediment-hosted Cu deposits, sediment hosted Ag-Pb-Zn deposits, Au and Cu veins, Cu skarns, roll-front uranium in Mesozoic sediments, and magnetite-hematite in Cu±Au±iron oxide deposits, ironstone lenses and banded ironstones.

The purpose of the study was to investigate the geological, structural, geophysical and geochemical characteristics of the mineralisation and use this data as an input into a regional Common Earth Model to create 3D mineral potential models of the Quamby area targeting specific mineralisation styles. The 3D mineral potential model represents the relative probability of each individual cell within the model hosting the chosen style of mineralisation and can be used to aid targeting for further mineralisation, particularly under cover, within the Quamby area. This report is the culmination of the project initially presented by Greenwood (2011).

MODELLING

The initial component of the Quamby project involved creating a 3D model of the region using GOCAD and SKUA. Key datasets used for the modelling included deep crustal seismic and company seismic datasets, magnetotellurics, potential field datasets, solid geology and drill holes where available. Depth to basement modelling was undertaken across the project area to define the depths to prospective Proterozoic units. A 3D fault model was created and refined in SKUA before the major stratigraphic units were modelled. Finally three separate suites of granitic intrusive bodies were incorporated into the model to ultimately build a complete 3D surface model of the Quamby project area (Figure 2).

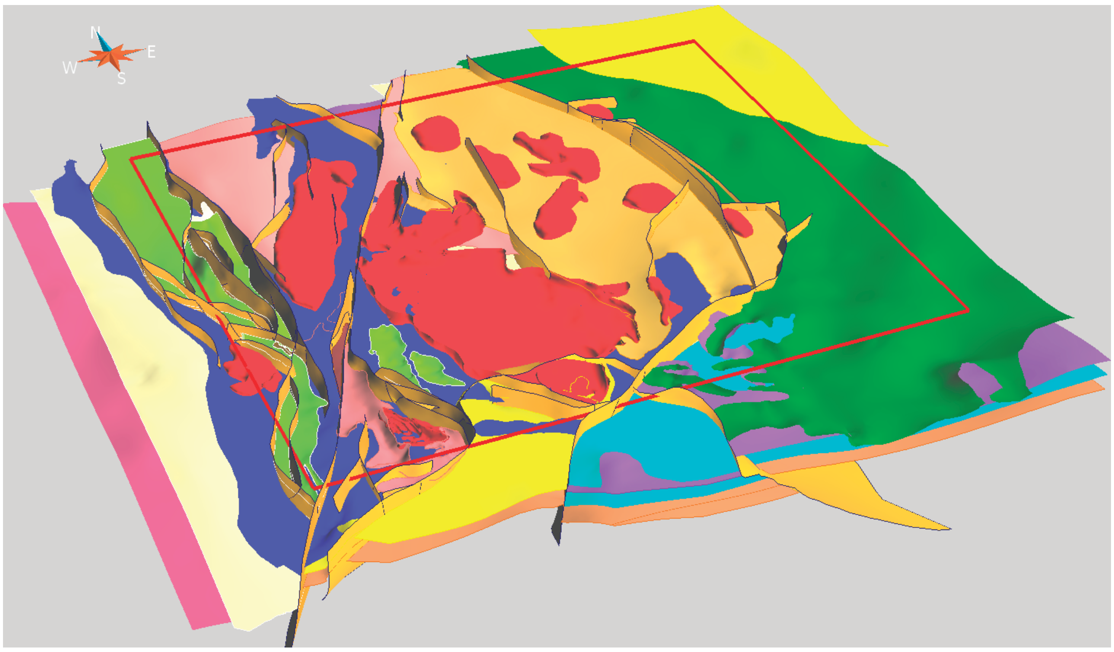

Figure 2. 3D surface model of the Quamby project area viewed from south-west

INVERSION

A regional voxet, or raster, model (500 metre lateral resolution and 100 metre vertical resolution) was constructed from the GOCAD horizon model (vector) with each geological domain populated with corresponding physical properties (density and magnetic susceptibility) based on an assessment of collected rock property information. The aim of potential field inversions is to create 3D density or magnetic susceptibility models that adequately reproduce anomalies consistent with the observed gravity or magnetic data. Potential field inversions of the gravity and magnetic data were undertaken to create a robust geologically and geophysically valid model.

A series of constrained potential field inversions of the magnetic and gravity data of the Quamby region were conducted with VPmg (Fullagar & others, 2000), initially involving homogenous property inversions to optimise the properties assigned to each geological domain and achieve a better fit to the observed data. Following this a second inversion stage was implemented using the optimised densities and susceptibilities as inputs for heterogeneous unit inversions. Heterogeneous unit inversions of the gravity and magnetic data allow the density or magnetic susceptibility of each cell to vary within the range of the constraints set by the initial modelled lithology to best fit the observed response. This stage of inversion highlights anomalous regions within the geological domains of the 3D density model (Figure 3) and 3D magnetic susceptibility model (Figure 4) which may represent broad alteration, metamorphism or unrealised intrusive bodies.

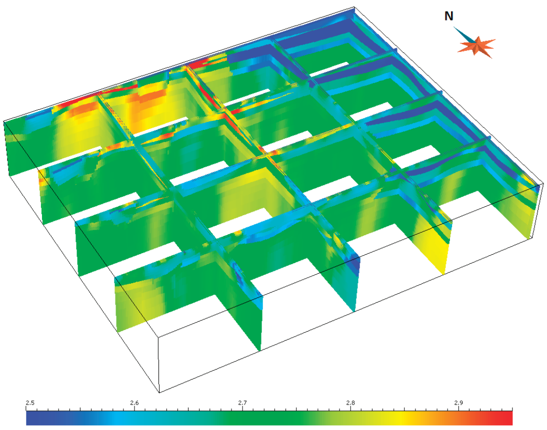

Figure 3. Fence diagram of results of geologically constrained regional 3D density inversion of the Quamby project viewed from south-west.

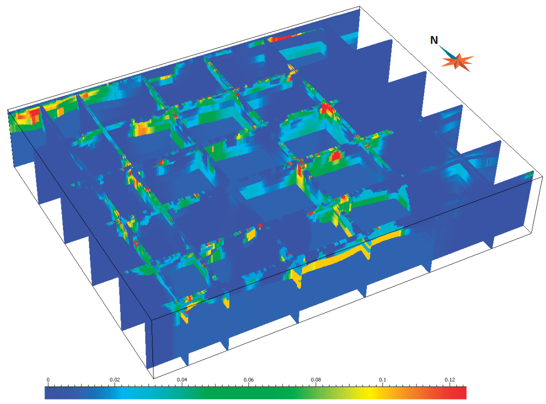

Figure 4. Fence diagram of results of geologically constrained regional 3D magnetic susceptibility inversion of the Quamby project viewed from south-west.

MINERAL EXPLORATION TARGETING

The results of the magnetic and gravity inversion were incorporated into a Common Earth Model (CEM; McGaughey, 2006) along with the lithological model. The key output created from the CEM was a full 3D Weights-of-Evidence (WoE; Bonham-Carter, 1994) model to assess the potential for further economic mineralisation using the existing location of known mineralisation as training data. The WoE approach is a quantitative, data driven method for assessing evidence in support of a hypothesis. Exploration or targeting criteria can be statistically analysed with sites of known mineralisation to assess their effectiveness. The exploration criteria (e.g. geophysical or geochemical anomalies, distance to faults, geological complexity etc) are based on the mineral systems conceptual model and are created in the CEM. The spatial relationship between these exploration criteria and sites of known mineralisation is assessed to understand the statistical significance of each exploration criterion with regards to mineralisation targeting.

Separate WoE models were created for the Canobie Domain and the Mary Kathleen Domain as the mineral systems conceptual model and targeted style of mineralisation differs between the domains. In each model key targeting criteria were tested to in an attempt to ascertain controls on mineralisation. The final 3D mineral potential models (Figures 5 and 6) were constructed by combining weighted statistically significant exploration criteria. The mineral potential models highlight regions of high discovery potential — areas which contain multiple overlapping favourable exploration criteria. While this technique can define and highlight new prospective regions in a model (hot colours in Figures 5 and 6), it can also determine areas of low prospectivity (cool colours) where no, or only few, favourable exploration criteria exist.

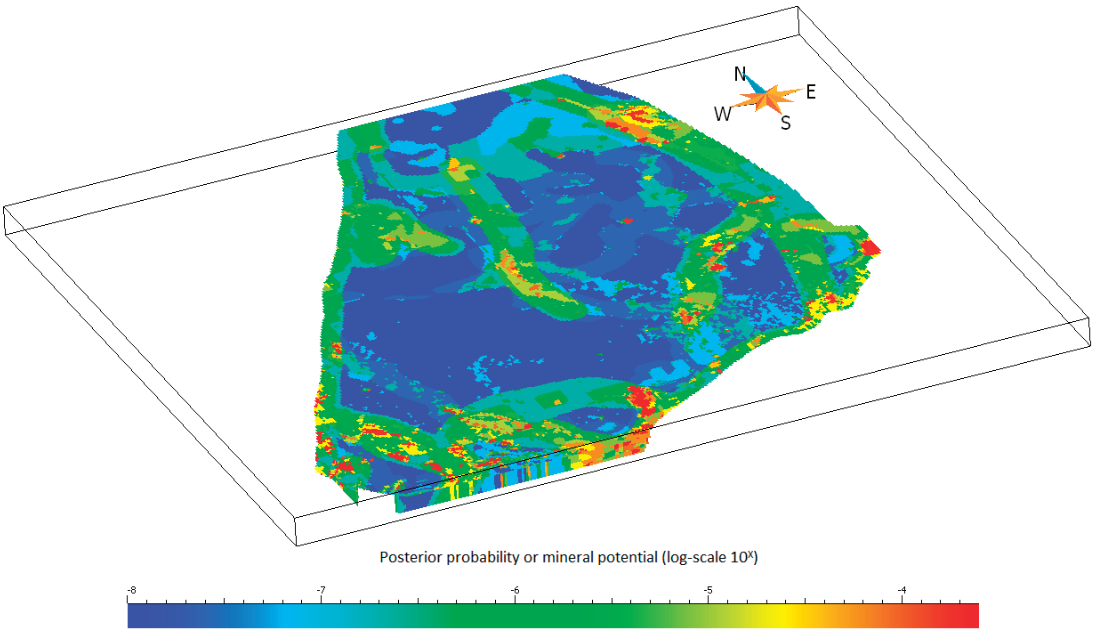

Figure 5. 3D view of a horizontal slice (200 metres below Australia Height Datum) of mineral potential model of Canobie Domain viewed from south-west. Hot colours represent multiple overlapping favourable weighted exploration criteria, while cool colours represent areas where no, or only few, favourable exploration criteria exist.

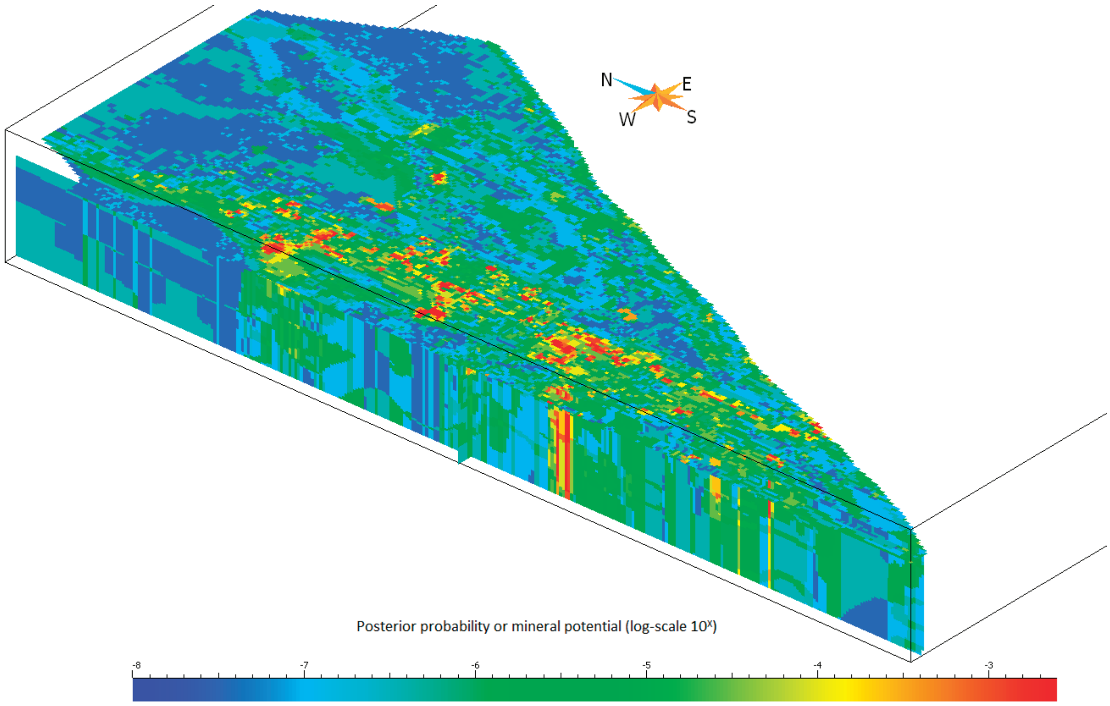

Figure 6. 3D view of horizontal slice (200 metres below Australia Height Datum) and north–south section of mineral potential model of Mary Kathleen Domain viewed from south-west. Hot colours represent multiple overlapping favourable weighted exploration criteria, while cool colours represent areas where no, or only few, favourable exploration criteria exist.

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EVALUATING THE ROLE OF DEEP GRANITIC ROCKS IN GENERATING ANOMALOUS TEMPERATURES IN SOUTH-WEST QUEENSLAND

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INTRODUCTION

Across central Australia and south-west Queensland, a large (~800,000km^2) subsurface temperature anomaly occurs (Figure 1). Temperatures are interpreted to be greater than 235°C at 5km depth, *ca.* 85°C higher than the average geothermal gradient for the upper continental crust (Chopra & Holgate, 2005; Holgate & Gerner, 2011). This anomaly has driven the development of Engineered Geothermal Systems (EGS) at Innamincka, where high temperatures have been related to the radiogenic heat production of High Heat Producing Granites (HHPG) at depth, below thermally insulative sedimentary cover (Chopra & Holgate, 2005; Draper & D'Arcy, 2006; Meixner & Holgate, 2009). To evaluate the role of granitic rocks at depth in generating the broader temperature anomaly in SW-Queensland, we sampled 25 granitic rocks from basement intervals of petroleum drill cores below thermal insulative cover along two transects (WNW–ESE and NNE–SSW — Figure 1) and performed a multidisciplinary study involving petrography, whole-rock chemistry, zircon dating and thermal conductivity measurements.

RESULTS

The petrography, composition and degree of alteration vary widely for the sampled granitic rocks. They range from fine-grained to porphyritic, extensively altered to fresh, and tonalite to syenogranite in composition (Figure 2). Additionally, S-type granites (indicated by abundant primary muscovite and a large degree of zircon inheritance), and I-type biotite granites (indicated by accessory titanite) are both present. In many instances, factors such as the Aluminium Saturation Index (Chappell & White, 2001) are not applicable due to the alteration-induced peraluminous nature of the granites. Ti temperatures calculated for concordant zircons (calculated with a TiO_2 activity of 1; Watson & others, 2006) are generally low and with minimal variation (from 670 to 720°C). None of the samples consistently plot in the A-type or within-plate fields of discrimination diagrams based on whole-rock chemistry (Pearce & others, 1984; Whalen & others, 1987; Bonin, 2007), and A-type mineralogies are not observed. A-type granites, therefore, are absent from the sample suite.

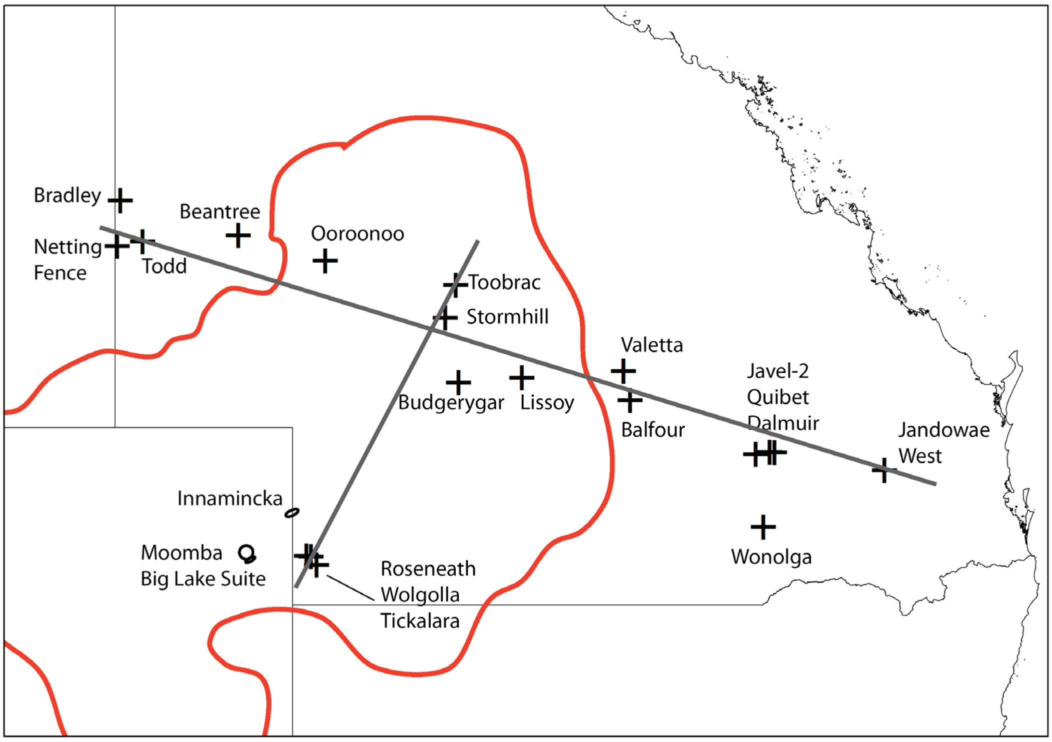

Figure 1. Map indicating the location of granitoid samples selected for this study, as well as the two transects (WNW–ESW and SSW–NNE). The red contour represents the boundary of the subsurface temperature anomaly from Chopra & Holgate (2005).

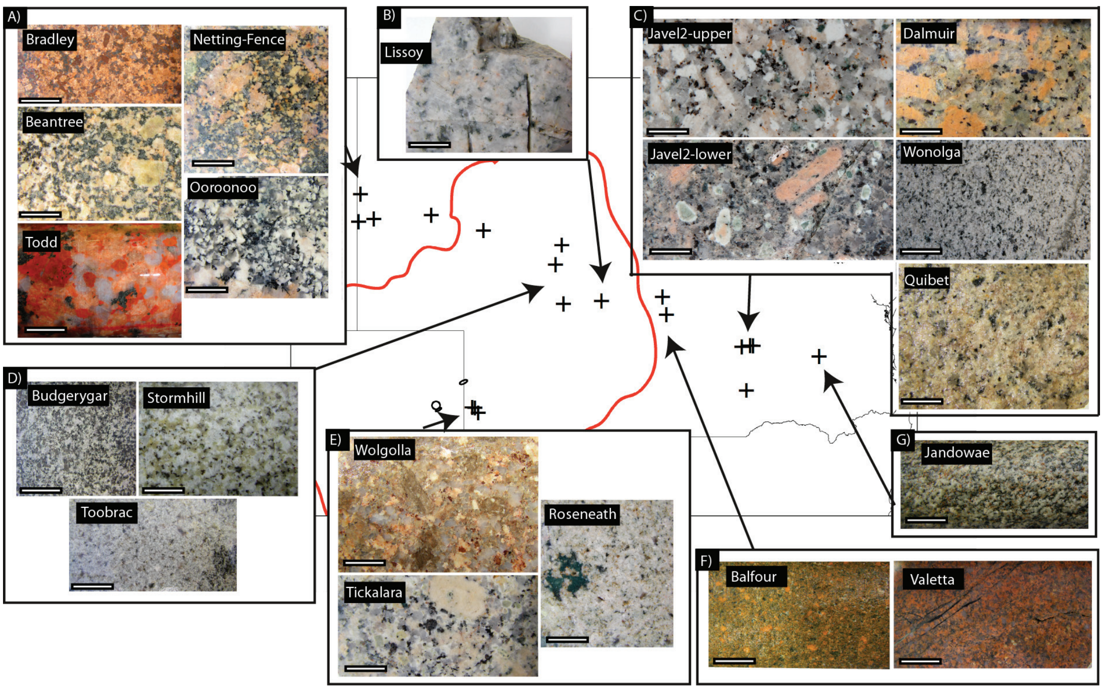

Figure 2. Photographs of granitic rocks from this study, organised by age grouping. A) Proterozoic. B) Age is unknown, but Rb/Sr geochronology (whole-rock and feldspar concentrate) of a closed granitic rock (PPC Etonvale 1)(Lewis & Kyranis, 1962) suggests a Late Silurian age. C) Permo-Carboniferous. D) Mid-Ordovician. E) Late Silurian. F) Mid-Devonian. G) Permo-Triassic. Scale bar is 2cm.

New U-Pb (zircon) LA-ICP-MS geochronology indicates a regional trend of increasing emplacement age from E to W from Permo-Triassic (TEP Jandowae West 1), Permo-Carboniferous (Roma-Shelf), mid-Devonian (AOP Balfour 1), mid-Ordovician (AMX Toobrac 1, LOL Stormhill 1 and AOD Budgerygar 1), to Proterozoic ages (PGA Todd 1). Late Silurian granitic rocks (TEA Roseneath 1 and DIO Wolgolla 1) occur in southern areas relatively close to the Permo-Carboniferous granites of the Big Lake Suite (~100km) (Gatehouse & others, 1995). Abundant zircon inheritance has been detected in AMX Toobrac 1, which is recorded by xenocrystic cores. Inherited core populations in this sample are generally Proterozoic with distinct populations at 894±32Ma, 1158±19Ma and 1544±34Ma. Granites from the Roma Shelf with an interpreted emplacement age of 340Ma exhibit more subtle inheritance with population ages of ~360 and ~380Ma and minor Proterozoic inheritance. In contrast, zircon populations from some samples (e.g., TEP Jandowae West 1 and AOP Balfour 1) are exclusively magmatic, with no inheritance.

The majority of the intrusives are silicic with silica contents ranging from 74 to 78wt%. Calculated heat production values are generally low and range from 0.8 to 5.1$\mu W/m^3$, with a general enrichment of the Heat Producing Elements with increasing silica content (from 0.8$\mu W/m^3$ at 58wt% SiO_2 to 4$\mu W/m^3$ at 76wt% SiO_2). However, granitic rocks with the highest heat production (~ 5$\mu W/m^3$; >35ppm Th) do not have the greatest silica content (~73wt% SiO_2). These correspond to the Proterozoic intrusions (PGA Bradley 1 and PGA Todd 1) located at the border between Queensland and Northern Territory. Interestingly, the Proterozoic to Permo-Triassic age range and generally low heat production values of our sample suite, both within and outside the temperature anomaly, contrast strongly to the HHPG and the mainly Permo-Carboniferous Big Lake Suite which exhibit much higher heat production values (7 to 9.7$\mu W/m^3$) (Middleton, 1979; Gatehouse & others, 1995).

Thermal conductivities determined for a suite of 8 samples range from 2.5 to 3.7W/mK and are within the range of published values for similar lithologies (Zoth & Haenel, 1988). Granitic rocks generally exhibit low porosities (< 5%); therefore, the variation of thermal conductivity mainly depends on mineralogy. For instance, the low bulk thermal conductivity (2.5W/mK) of the more mafic intrusion (TEP Jandowae West 1) is explained by the large abundance (~70vol%) of low thermally conductive plagioclase minerals (~2.1W/mK (Clauser & Huenges, 1995)).

DISCUSSION

To investigate the contribution of granitic rocks to the high crustal temperatures identified by OzTemp in Queensland (Chopra & Holgate, 2005), we firstly refined the distribution of anomalous temperatures by restricting data to deep temperature measurements (i.e. >1000m). This removes climatic and shallow-aquifer advection effects and reveals several areas of anomalously high temperatures (Figure 3):

- A distinctive NE- trend of high temperatures is apparent in SW Queensland and correlates with a series of granitic rocks at 1000 to 2500m depth; extrapolation of this trend along strike to the north-east suggests it may correlate to the Stanage

Fault Zone recognised along the central Queensland Coast (e.g., Holcombe & others, 1997) (Figure 3).

- High temperatures are also identified in the NE part of the subsurface temperature anomaly, where basement granites are relatively shallow (<1500 m)
- and in the northern part and to the west of the Roma Shelf
- high temperature is also recognised for TEP Jandowae West 1. At this point, the extrapolated temperature at 5km depth is 248°C, *ca.* 100°C higher than the average geothermal gradient of continental crust. The low heat production (0.8μW/m^3) of the intersected granite and the relatively shallow temperature measurement (64°C at 470m) suggest an advective contribution to the anomalously high temperature. However, thermal modelling remains to be undertaken to understand the contribution of the low thermal-conductivity granitoid to this high temperature.

The origin of these anomalously high temperature areas and the relative roles of granitic heat production and insulative cover are unclear. Some key points are:

- Areas of anomalously high temperature do not correlate with particular cover basins.
- Some high temperature areas (e.g., just west of the Roma Shelf) do not correlate with granite intersections raising the possibility that HHPG's occur at greater depth. As observed in Figure 4, most drill cores in SW Queensland have not drilled deeper than 3km depth, and at Innamincka, HHPG occur between 3 and 5km depth. It is therefore possible that HHPG occur at greater depth but have not been intersected.
- The broadly linear arrangement of some high temperature zones (i.e. along the NE-SW trending extension of the Stanage Fault Zone) may suggest a contribution of high mantle heat flow (as suggested by Italiano & others, 2012) along major crustal lineaments.
- Some areas (e.g. towards the SW of the Stanage Fault Zone trend) coincide with abundant granite intersections (Figure 3). However, these granites are not considered HHPGs and have low to moderate heat production values (2.6, 2.7, 3.2μW/m^3). In contrast, some other areas of abundant granite with comparable or higher heat production values (e.g. southern part of the Roma Shelf area and the Queensland/Northern Territory border area, respectively) do not correlate with high temperature zones.

Since there is no compelling correlation between occurrences of granites with high radiogenic heat production and positive temperature anomalies, an alternative explanation is required. We suggest that layers of insulating sedimentary cover rocks combined with the presence of moderately heat producing granites at depth explain the observed high subsurface temperatures. This hypothesis is tested with multi-layer, one-dimensional steady-state thermal modelling, which is currently in progress. Preliminary results from the most well constrained area (far SW Queensland), using the measured heat production and thermal conductivity values in these granites and overlying sedimentary cover, yield a relatively high modelled surface heat flow of *ca.* 85mW/m^2. This value is 14mW/m^2 higher than the average continental surface heat

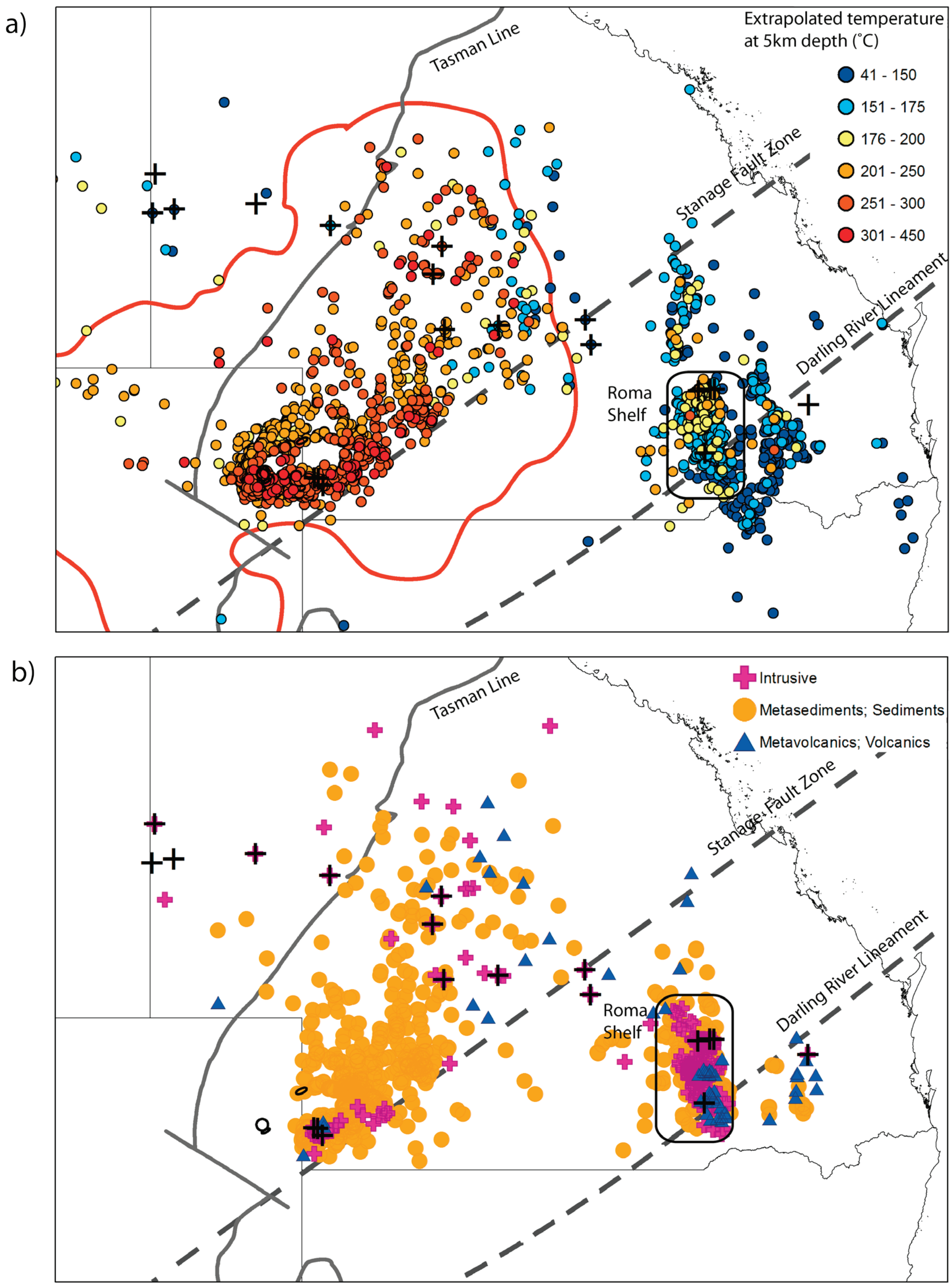

Figure 3. a) Map indicating high temperature anomaly areas. Data points are extrapolated temperatures at 5km depth and originate from a selection (temperature flagged and >1000m) of the Oztemp database (Holgate & Gerner, 2011). Major crustal lineaments are also indicated by a dashed line for the interpreted Stanage Fault Zone and Darling River lineament (Katz, 1976) and a bold grey line for the Tasman line. Other features as in Figure 1. b) Map indicating the lithology of basement intersected. Note the WSW–ENE trend of granitic rocks in the SW-corner of Queensland.

flow (Davies & Davies, 2010) but still lower than modelled surface heat flow values at Innamincka (90–110mW/m^2 — Middleton, 1979; Beardsmore, 2004). Using the measured heat production value of the granites and assuming it is constant with depth, *ca*. 6.5km of granite thickness is required to explain the higher surface heat flow at this location. This thickness is plausible and much lower than that predicted by gravity modelling at Innamincka, where the HHPG plutons have been estimated to be up to 12km thickness (Meixner & Holgate, 2009).

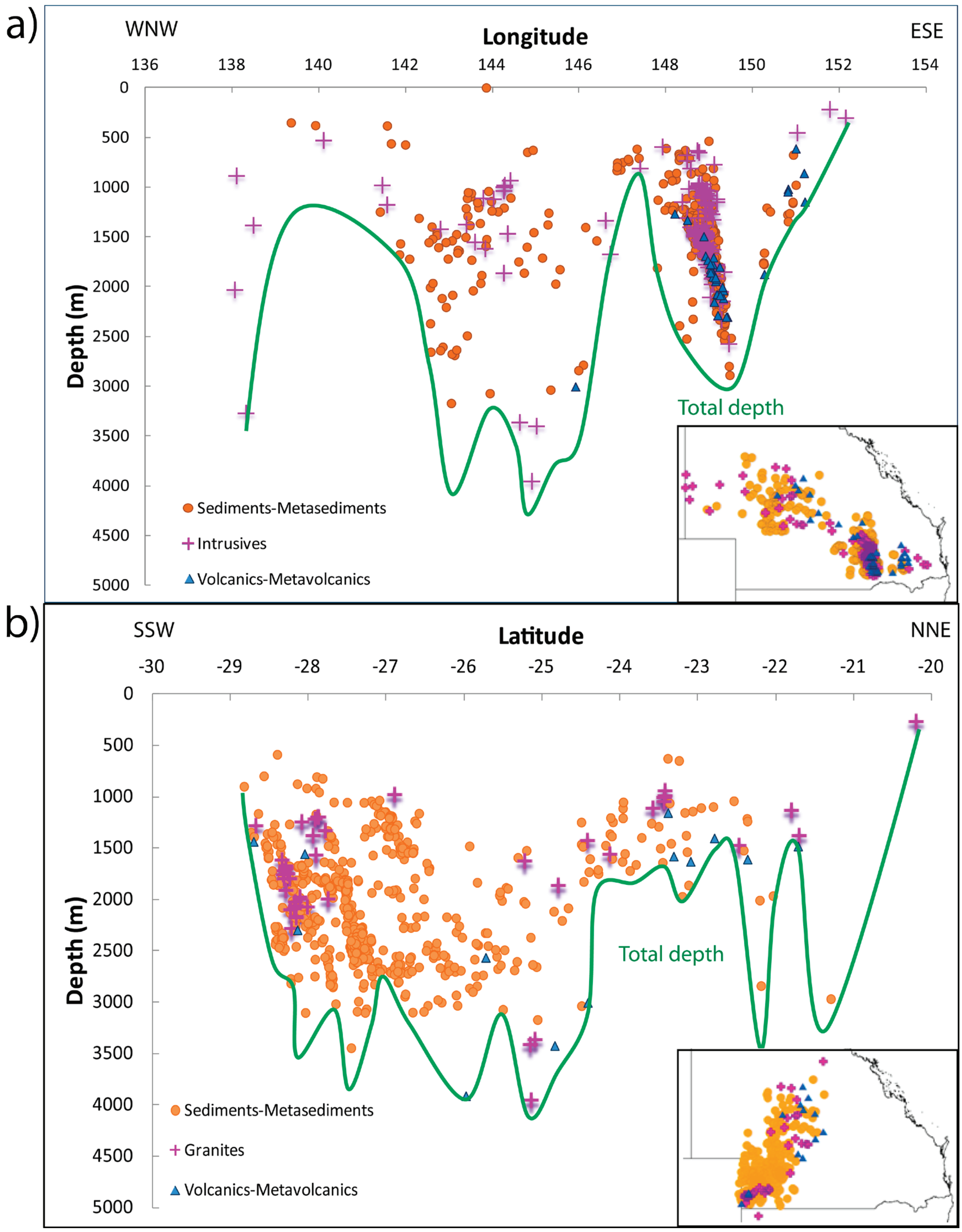

Figure 4. Depth profiles of intersected basement rocks along two transects. The green lines join the total depth of all drill cores. The inset maps indicate the drill cores taken into account in the depth profile. a) WNW–ESE transect. b) SSW–ENE transect.

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CONTROLS ON SPATIAL VARIABILITY OF METHANOGENESIS IN THE WALLOON SUBGROUP, EASTERN SURAT BASIN, QUEENSLAND, AUSTRALIA

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RESEARCH OBJECTIVE

Biogenic methane is an important contributor to fossil coal seam gas (CSG) resources, and extant methanogens have the potential to generate future resources if subsurface ground conditions optimum to their cultivation can be determined (microbially enhanced coalbed methane; MECoM; Scott, 1999). The primary objective of this research is to develop ancient analogue models for biogenic (microbial) methane generation through the integration of geological, hydrological, and geochemical (gas, water and host coal) data for the Walloon Subgroup in the eastern Surat Basin, Queensland. This basin has known biogenic methane resources (Draper & Boreham, 2006) and preliminary trials suggest that it has significant *in situ* bioreactor potential (Golding & others, 2009; Papendick & others, 2011). The research focuses on the factors affecting biogenic methane distribution, on a regional and local scale. The primary research objective is achieved through the step-wise integration of four separate study components, each having implications for Walloon coals as *in situ* methane bioreactors.

TARGETING OPTIMUM LOCATIONS FOR BIOGENESIS: A FOUR-FOLD SEQUENTIAL APPROACH

A sedimentary framework model forms the foundation to the project, based on the interpretation of open-file geophysical, core log and surface coal mining data. A desktop study using derived model layers, structure, coal, and topographic data has been employed to formulate refined hypotheses relating to gas distribution and origins (Hamilton & others, 2012). A finer-scale field study integrating geochemical (gas, water and host coal) and geological data is currently underway to test these hypotheses. Lastly, conceptual exploration targets for MECoM will be identified by integrating the results of all three previous studies with relevant findings from parallel studies on the bioreactor potential of the Surat Basin.

RESULTS TO DATE

Ongoing deterministic and stochastic geological modelling indicates that the Middle Jurassic Walloon Subgroup is strongly heterogeneous, comprising an upper (Juandah) and lower (Taroom) coal measures separated by a relatively coal-barren unit (Tangalooma Sandstone). Within these units lateral variation in coal character is high, precluding a regionally agreed coal group or seam correlation. Nonetheless, the units themselves are laterally extensive, facilitating an assessment of down-hole gas trends in a regional stratigraphic context. Whereas the measured gas contents (dry-ash-free basis, d.a.f.) show a general increase with increasing depth as a function of hydrostatic pressure, there is wide scatter in the distribution. To dissect this distribution, gas content (d.a.f.)-depth relationships were examined by well to derive three basic profiles. Gas content either (1) increases; (2) increases, then decreases; or (3) decreases with depth. This iterative process revealed that the majority of Walloon CSG wells display a parabolic (Trend 2) profile, which inflects around the Tangalooma Sandstone, regardless of depth. As such, a number of hypotheses for gas distribution and origins have been proposed and discussed. Detailed stable isotopic analysis of desorbed gas profiles suggests that the Walloon CSG play is a compartmentalised system, with discrete gas zones of biogenic versus thermogenic origin that follow the stratigraphy.

SIGNIFICANCE

Continued successful exploration and production, and possible future microbial regeneration of the Walloon CSG resource, require an improved understanding of its stratigraphy, and the controls on gas content distribution across the core region of production in the eastern Surat Basin. The present study is the first regional synthesis aimed towards understanding the *in situ* bioreactor potential of the Walloon Subgroup, and will add to the limited body of research on its internal architecture and CSG characteristics. The study outputs will provide a holistic foundation framework to identify conceptual exploration targets for MECoM.

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