Department of Natural Resources and Mines
Geological Survey of Queensland

Digging Deeper 11 seminar

4 December 2013
Extended abstracts, presentations and posters

1898 – 1904 | 1905 – 1953 | 1954 – 1965 | 1966 – 1986

Geological Survey of Queensland 145 years

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Cover: Geological Survey of Queensland logos from 1898 to 1986.

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Queensland Government exploration incentive funding — new geochemical and geophysical data acquisition programs

Paul Donchak

Geological Survey of Queensland

Over the next 3 years the GSQ will be implementing a number of significant geoscientific projects funded by Queensland Government programs aimed at stimulating exploration interest in Queensland.

Future Resources Program

The largest of these programs is the $30 million Future Resources Program funded over a 3 year period from July 2013 to June 2016. The program includes a number of major data acquisition initiatives including:

- Industry Priorities Initiative
- Mount Isa Geophysics Initiative
- Geochemical Data Extraction Initiative
- Cape York Mineral Resource Assessment Initiative.

The ***Industry Priorities Initiative*** ($2.5 million per year) will run for the duration of the program. A number of proposals were sought by the government (through GSQ) from peak industry bodies including the Queensland Exploration Council (QRC), the Association of Mining and Exploration Companies (AMEC), and the Australian Petroleum Production and Exploration Association (APPEA), to identify priority geoscience projects which will have the greatest contribution to maximising exploration success. The proposals were assessed, ranked and technically evaluated by a panel of GSQ experts, generating four projects judged to be worthy of implementation (including one project amalgamating two of the submitted proposals; see Figure 1).

The first of these will be an evaluation of the prospectivity of the widespread magmatic systems of North Queensland where major new deposits similar to the recently opened Mount Carlton mine are likely to be found. This project will crystallise years of fragmented research, and major current advancements in the understanding of North Queensland's mineral systems, to form a landmark foundation for significant new exploration successes in the region. This project will be funded for the 3 year life of the initiative.

The second major project will shift attention back to the "greenfields" possibilities in the southern Mount Isa Inlier where previous geophysical surveys suggested that base metal-rich black shale basins and other conductive ore bodies may lie concealed beneath thin layers of cover south of Dajarra. These rocks will be explored using a new process that measures the electrical conductivity of the earth called magnetotellurics (MT). This exploration technique is an extremely cost-effective way

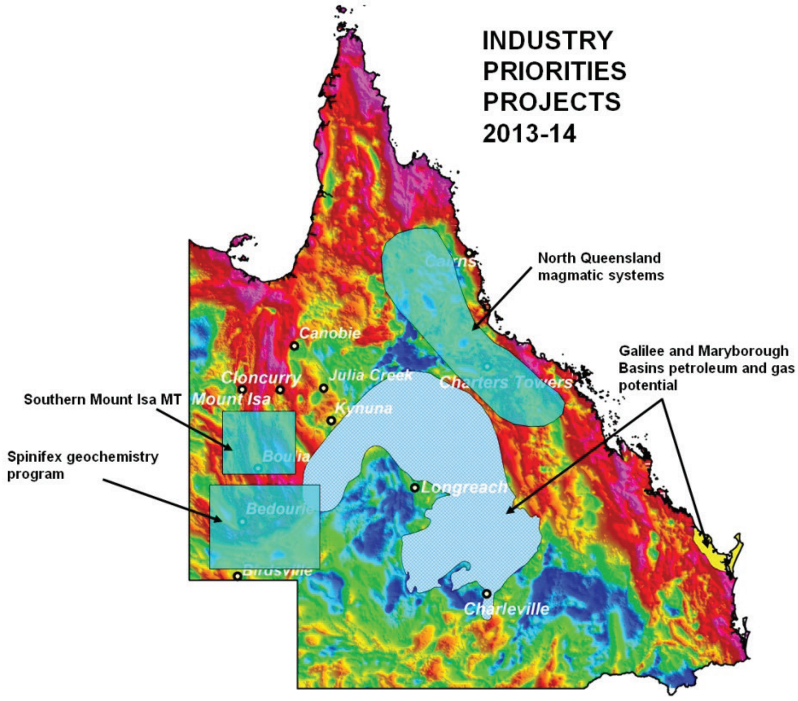


Figure 1: Location of Round 1 Industry Priorities Projects

of viewing large-areas of the subsurface to reveal geologically favourable sites for mineral explorers, and is planned for implementation this financial year.

The third component of the initiative will implement a promising new exploration method based on chemical analysis of the spiny leaves of the spinifex plants which are widespread across many areas of north-west Queensland. The program will focus initially on the soil-covered plains of the Boulia–Bedourie region, where traces of mineralisation from the buried Mount Isa-style basement rock will potentially be brought to the surface by the deep plant root systems. This sampling program is planned for implementation this financial year.

The final component of the initiative is also planned for this financial year and involves chemical analysis and other scientific studies of drill core from the lowermost strata of the Maryborough and Galilee Basins to determine the likelihood of petroleum and shale gas discoveries in these little-explored basins. This project is planned for this financial year with funding of approximately $100,000.

The ***Mount Isa Geophysics Initiative*** ($9 million) will include major seismic and MT surveys in the Cloncurry – Julia Creek and Dajarra–Boulia areas (see Figure 2). These surveys will run from 2014–15 to 2015–16, and are aimed at reducing exploration risk by improving understanding of both regional sub-surface geology and cover thickness and character. The GSQ plans to take advantage of new 3D MT inversion codes, being developed by Geoscience Australia, to build continuous 3D conductivity models of the subsurface constrained by the new seismic profiles and any other available subsurface geological information. This investment in new data and understanding should stimulate further greenfields exploration in one of the most prospective regions of the world.

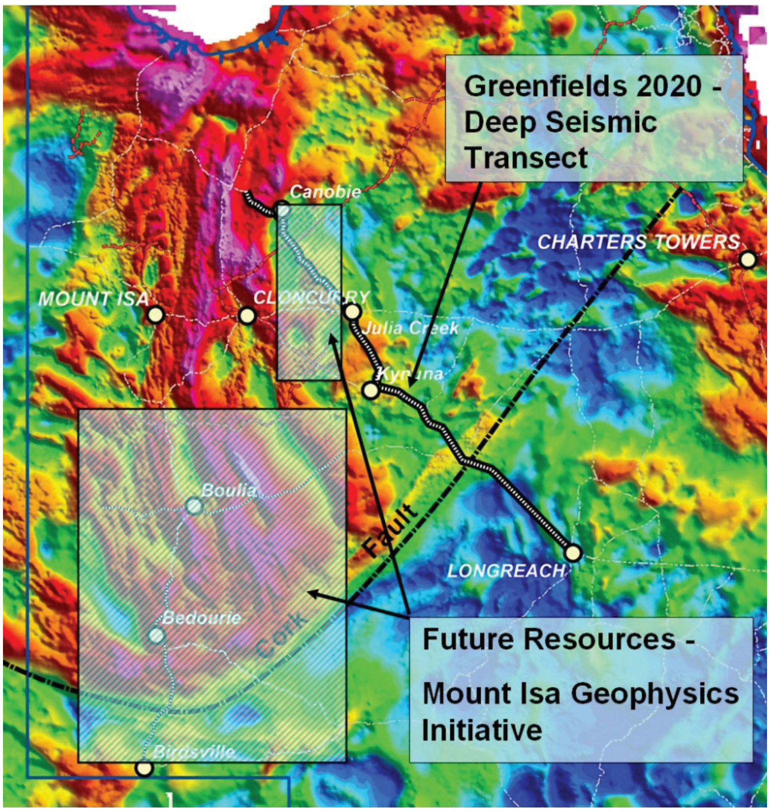


Figure 2: Location of Mount Isa Data Acquisition for Greenfields 2020 and Future Resources Programs

The ***Geochemical Data Extraction initiative*** ($3 million) will run for the duration of the Future Resources Program. It will focus on extracting invaluable geochemical data locked in DNRM's company report archive, and in providing easy searchable access to this data for industry, government and the public. This will promote the attractiveness of exploration potential in Queensland through the provision of comprehensive geochemical coverage of the State's mineralised regions.

The ***Cape York Mineral Resource Assessment Initiative*** ($1 million) will follow-up on anomalous results, particularly for rare earths and uranium, revealed by an earlier national geochemical survey. The new initiative will re-evaluate the Cape's mineral potential in light of the new stream sediment data and renewed support from the indigenous communities toward potential mining. Geological mapping, and sampling to re-evaluate the strategic mineral potential of the region, will be the major focus of this initiative which is scheduled for 2014–15 and 2015–16.

Greenfields 2020 Program

This financial year will see completion of the GSQ's final major data acquisition initiative under the Government's Greenfields 2020 Program, when a major deep seismic and complementary MT transect will be undertaken across the south-eastern segment of the Mount Isa Inlier. This survey will extend for over 650km from Longreach in the south, to Four Ways in the north, (see Figure 2) and is designed to investigate a number of aspects:

- structural controls of the northern Galilee Basin oil, gas, and coal resources and possible gold mineralisation along the southern termination of the Mount Isa Inlier along the Cork Fault
- the nature of the crustal contrast across the Cork Fault (between the Mount Isa Inlier and Thomson Orogen) and its implications for the tectonic evolution and kinematic history of this segment of the Australian continent
- the structural architecture of Soldiers Cap Group mafic domes, potentially highly prospective for Cannington-style base metals
- the stratigraphy and extent of the subsurface Millungera Basin and regionally correlative basins
- the nature of the major magnetic province boundary represented by the northward continuation of the Quamby Fault — this boundary relationship has major implications for linking the history of the Mount Isa and Georgetown Inliers
- the variability of the depth to prospective basement surface, particularly in the northern section of the line.

The wide ranging GSQ data acquisition programs outlined above are aimed at boosting Queensland's exploration profile and providing a solid foundation for future greenfields exploration success over the coming decades.

Queensland Government Collaborative Drilling Initiative

Simon Crouch and Sarah Sargent

Geological Survey of Queensland

Since 2006 the Queensland Government has committed $12 million to directly support exploration through the Collaborative Drilling Initiative grants under the Smart Mining – Future Prosperity Program ($6 million), the Greenfields 2020 Program ($3 million), and the Future Resources Program ($3 million).

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 and now the Future Resources Program.

To date grants of over $5.56 million had been paid to companies who successfully completed 67 projects in the Collaborative Drilling Initiative. Twenty-nine of these projects were technical successes. Currently $325,000 is committed to projects with completion dates up to June 2014.

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 6m at 4.00% copper and 0.29g/t gold.
- 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 were still to be required three months after completion of the project. Payments were 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. Eleven projects were completed with the payments totalling over $1.14 million.

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 has seen four projects completed with one technical success and companies being paid $382,976.

The 22 applications received for Round 7 were independently assessed in February 2012. Ten successful projects shared a total of $990 250 in grants. Seven of the ten projects were completed with the payments totalling $550,910. This round is anticipated to end in June 2014.

The demand for grants in Rounds 5, 6 and 7 has 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 were:

- 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.

Drilling under Round 7 of the Collaborative Drilling Initiative has commenced. To date, two projects have resulted in information about mineralisation being reported by the following companies:

- Roar Resources Limited's three holes with a total of 1200m were drilled and all intersected gold mineralised zones. One intersection at Bringham Young defined 6m at 3.85g/t Au, 10.0g/t Ag, and 0.1% Zn from 188m (including 1m at 21.5g/t Au, 44.6g/t Ag and 0.2% Pb).
- The drilling by ActivEx Limited at the Sterling prospect found all seven holes showed encouraging results. Initial results suggesting focussing on an area consisting of coincident SAM anomaly and magnetic low immediately north-east of the high copper and REE intersection of AST003. Similar geological characteristics to the large Gawler Craton deposits. Potential exists for a major IOCG discovery in the Wimberu Granite.

Under the $30 million Future Resources Program the Collaborative Drilling Initiative grants of $3 million extends the popular and successful Collaborative Drilling Initiative of the Greenfields 2020 Program. Two rounds of drilling grants will be offered in 2014–15. Details of the two areas are as follows:

- Round 8
    - Closing date for applications: 11 April 2014
    - Planned commencement of drilling: July 2014
- Round 9
    - Closing date for applications: 21 November 2014
    - Planned commencement of drilling: March 2015.

More details and documentation including the guidelines and funding deeds can be found at http://mines.industry.qld.gov.au/mining/collaborative-drilling.htm

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 $17.23 million of direct drilling expenditure by industry supported by Collaborative Drilling Initiative funding of just over $5.56 million.

New ideas regarding mineralisation at Sherwood Deposit Agate Creek

Scott Hall

Laneway Resources

Recent deep drilling as part of the Queensland Government's CDI collaborative drilling program (round 6) at Sherwood Deposit has revealed that the upper part of the Agate Creek Fault may not have been the main fluid conduit for mineralisation. Historically, the Agate Creek Fault has been considered to be the main fluid conduit and as such, the focus of much drilling including bonanza zone targeting. CDI drilling, targeting the potential bonanza zone at Sherwood, was completed in June 2013 and encountered a large zone of significant mineralisation which has highlighted the role of brittle rhyolites in the mineralising process. Best results from drilling were in CCDD482 with 31m@5.96g/t Au from 124m but this is too shallow to be the potential bonanza zone which was the primary target of the drill program.

Drilling intercepted the Agate Creek Fault in two places between 250–350m down hole, and determined the dip of the Agate Creek Fault to be between 60–70 degrees which is significantly shallower than expected. The fault clearly shows evidence of multiple phases of reactivation, predominantly as milled clay infilled breccias, with gold grades mostly below detection. The fault also shows zones of unmineralised chalcedonic breccia and it may be this unit that is responsible for the upper portion of the fault being cut off to mineralising fluids. No rhyolites or banded veining were seen within the Agate Creek Fault (with the exception of rare small fragments within breccias) and in both Sherwood West and Zig Zag these rhyolites focus the highest grade mineralisation. Mineralisation is concentrated within the rhyolites at Sherwood West and Zig Zag, where rhyolites have been emplaced along both structures, and these have consequently provided dilational sites for gold deposition. At Sherwood, mineralisation is within granites and rhyolites on the hanging wall to the west of the Agate Creek Fault. Rhyolites have been emplaced along lithological boundaries and weaknesses within individual lithologies rather than along the Agate Creek Fault. As the rhyolites are of similar age to the mineralisation it seems that those structures and weaknesses that were available to the rhyolite were still available to the mineralising fluids. At Sherwood, the Agate Creek Fault appears to have been sealed off at some point prior to the main period of rhyolite emplacement and mineralisation, with the upper portion of the fault acting as a boundary rather than a fluid conduit.

The possibility remains that the Agate Creek Fault may have been open at much greater depth during mineralisation which makes the down dip extension of the newly defined mineralised zone at Sherwood a priority target along with the intersection of the Agate Creek, Sherwood West and Zig Zag Faults. Further work will be concentrated on these structural locations.

One Stop Shop and Open Data — changes to GSQ information delivery

Mark Thornton

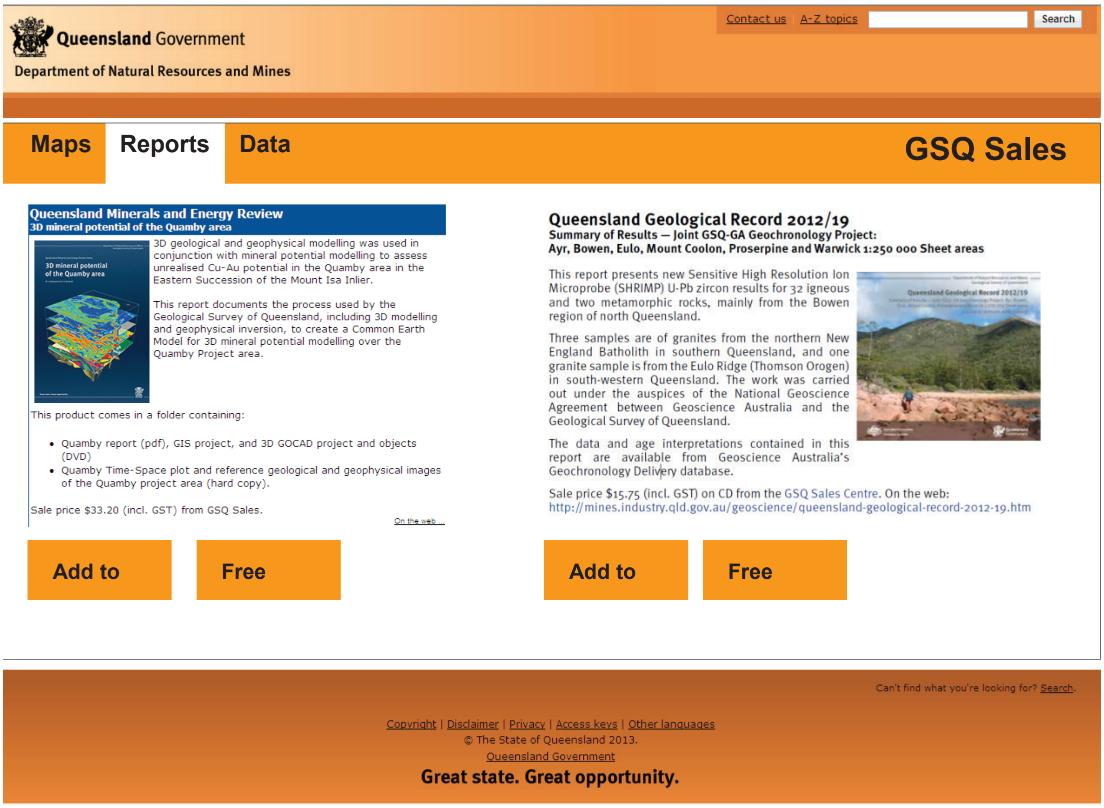
Geological Survey of Queensland

As part of the Queensland Government's One Stop Shop and Open Data Initiatives, the Geological Survey of Queensland (GSQ) is transforming the way it delivers information products and services. Information and data will be made more freely available, online where possible, and production of physical publications significantly reduced.

This transformation of services at GSQ will include new telephone and fax numbers for GSQ Sales which will be advised when they are available. Existing numbers will be redirected to ensure continuity of service.

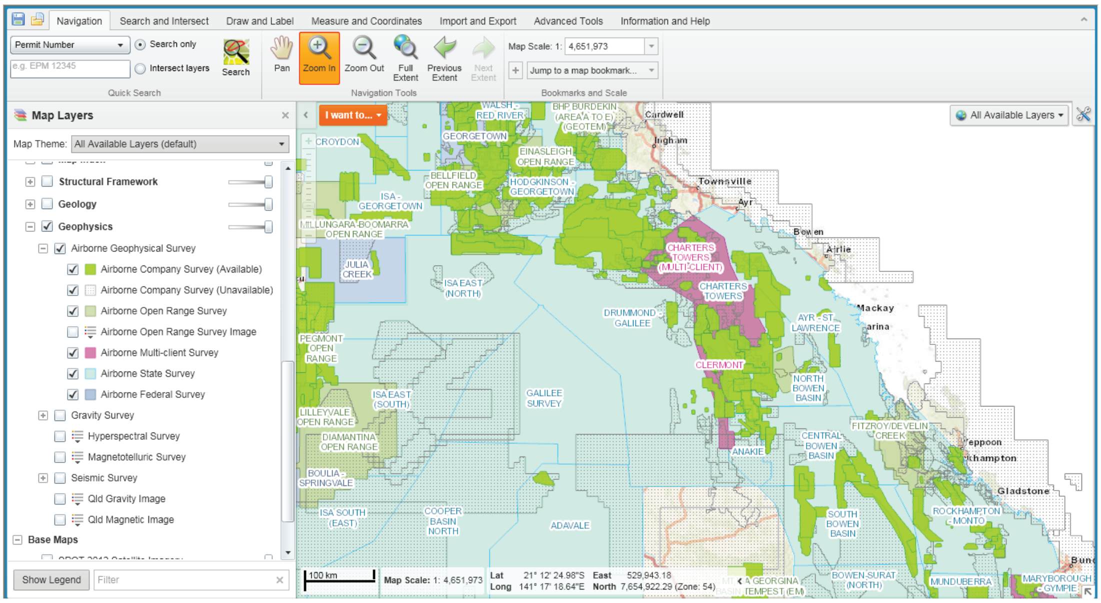
Email: geological_info@dnrm.qld.gov.au Telephone: +61 7 3006 4666

The GSQ Sales Centre at 119 Charlotte St Brisbane closed for counter transactions on Friday 27 September 2013. All GSQ maps, geoscience publications and digital data are still available for purchase by telephone or email from the renamed GSQ Sales. A new online shopping facility is planned to enable ordering and payments. Many GSQ products will become available for free online as part of this initiative.

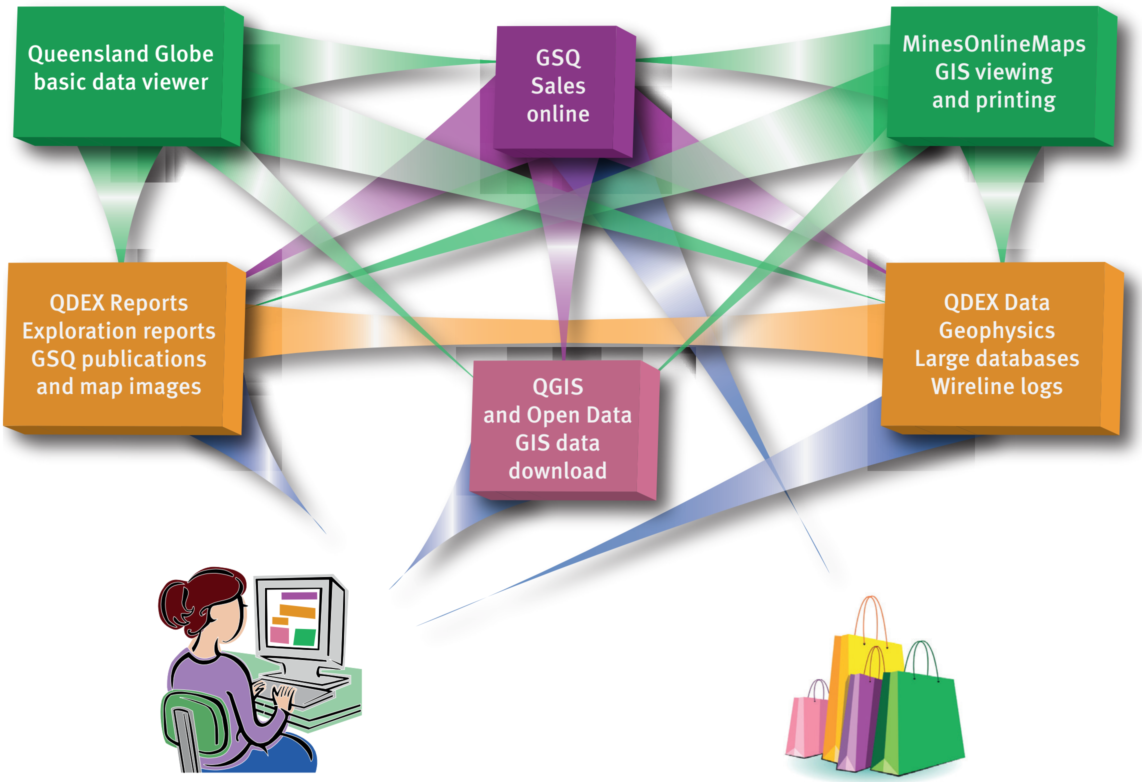


(Example image only)

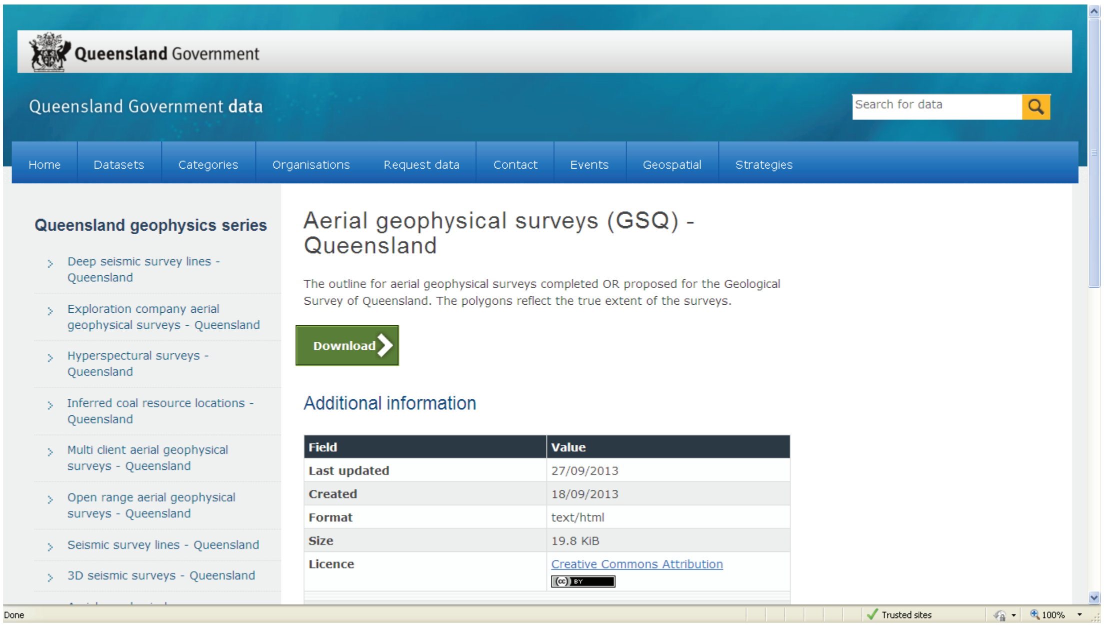
For customers conducting in-person lodgement and payments for tenure business, a new counter is operating at Queensland Minerals and Energy Centre, Level 16, 61 Mary Street, Brisbane.



A new online mapping system, MinesOnline Maps, is replacing the Interactive Resource and Tenure Maps (IRTM) system after 12 years of sterling service.



It is planned that future releases of this system will include links to the new online shopping facility, and a new QDEX Data download facility, in a similar manner to the way that IRTM currently links to the QDEX Reports system. This will enable spatial searching for relevant data, publications, maps and products, and links to enable viewing and free download or ordering and online payment for products.

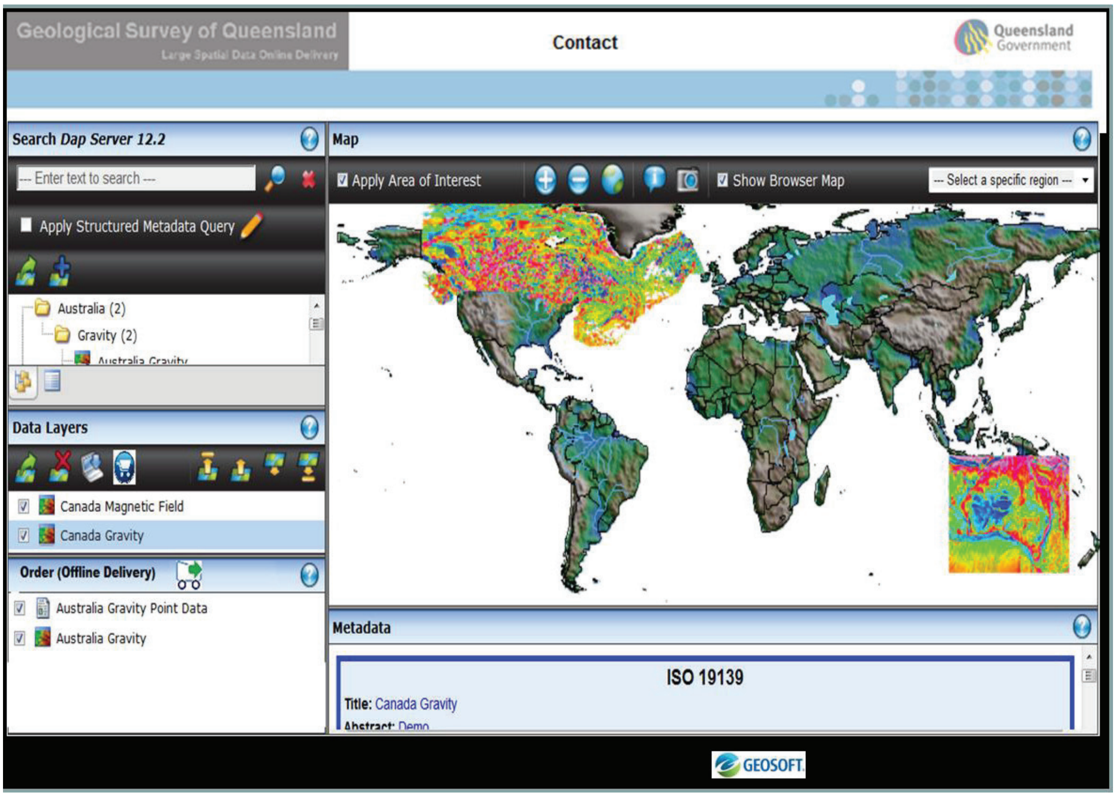


https://data.qld.gov.au/

The IRTM download service and Web Map Service are being relocated to the Queensland Government Information Service (QGIS) as part of the Government's Open Data Initiative and the replacement of IRTM. All GSQ spatial mapping data sets are already available there for download.

https://qdexguest.deedi.qld.gov.au/portal/site/qdex

The existing QDEX Reports system will be populated with all digital GSQ publications and images of maps for free viewing and download. The system will be modified to link to the new QDEX Data system where data is available for a report or publication. Use of QDEX Reports is still increasing 10 years after launch of version one in April 2003.



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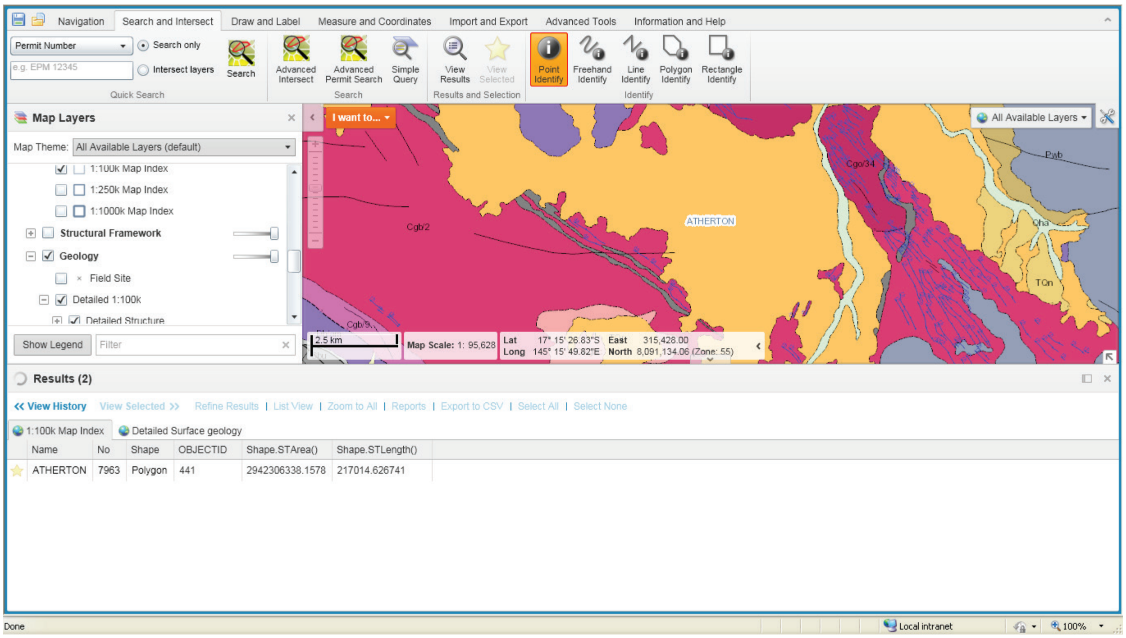
Large data sets in proprietary formats such as gravity, magnetic and radiometric survey data, seismic data and geophysical well logs, large databases for geochemistry, and other larger file items will be available for streaming download from the new QDEX Data system currently under customisation by Geosoft Australia for installation this financial year.

These works are designed to provide a seamless and integrated range of tools linking all relevant information into a spatial information catalogue, ordering and payment system. Using MinesOnlineMaps you will be able to select a published geological map area, then be offered a link to GSQ Sales where you can order and pay for a paper map to be shipped to your delivery address, a link to QDEX Reports where you can view and download an image of the map, and a link to QGIS where you can download a GIS version of the map.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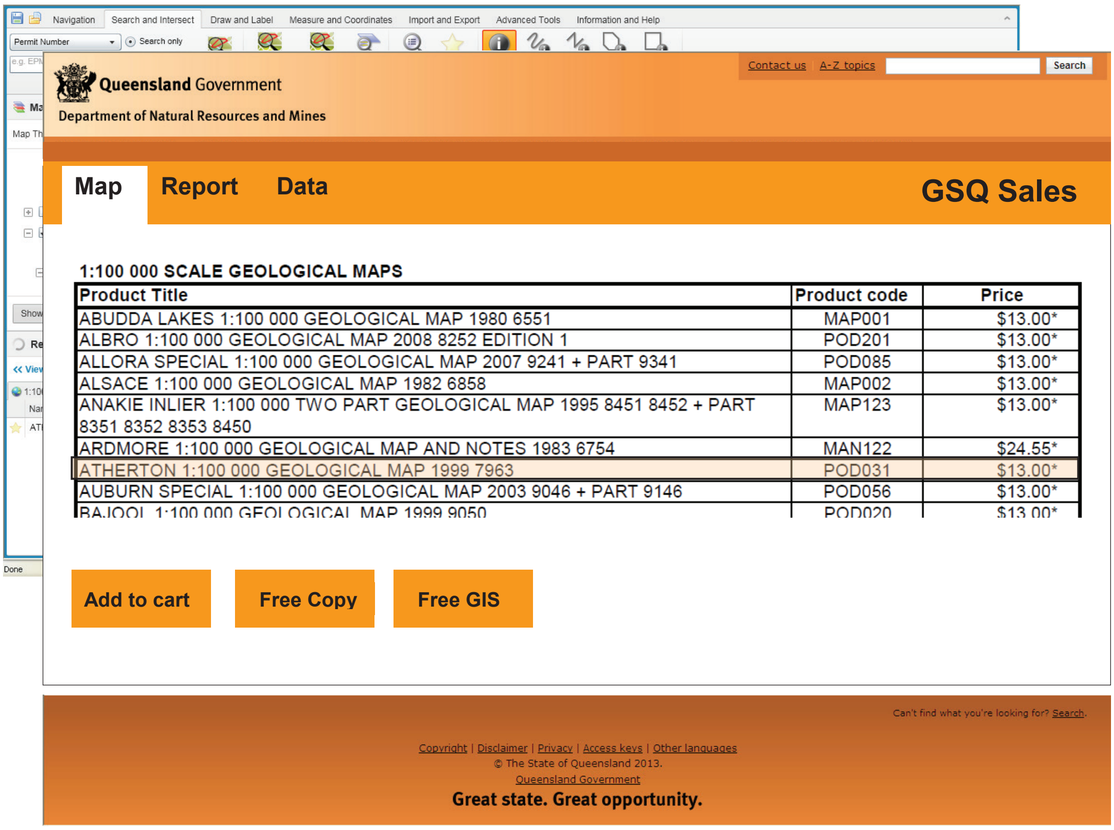
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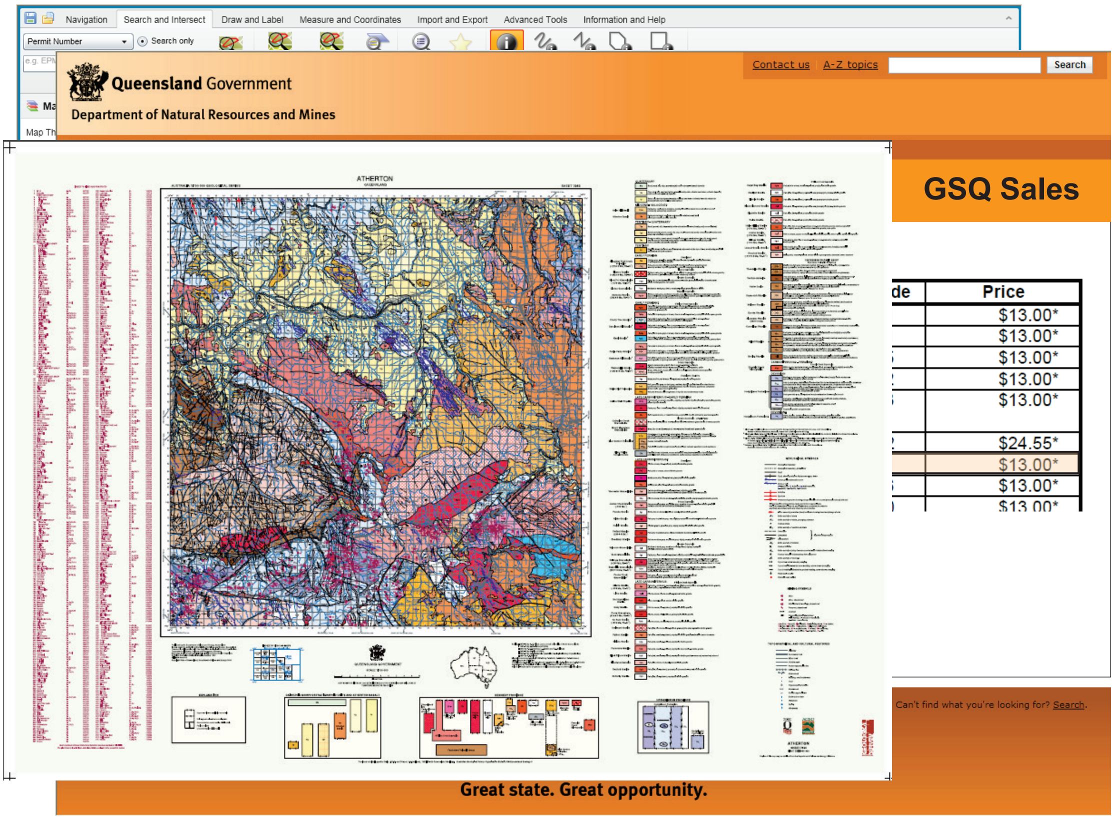
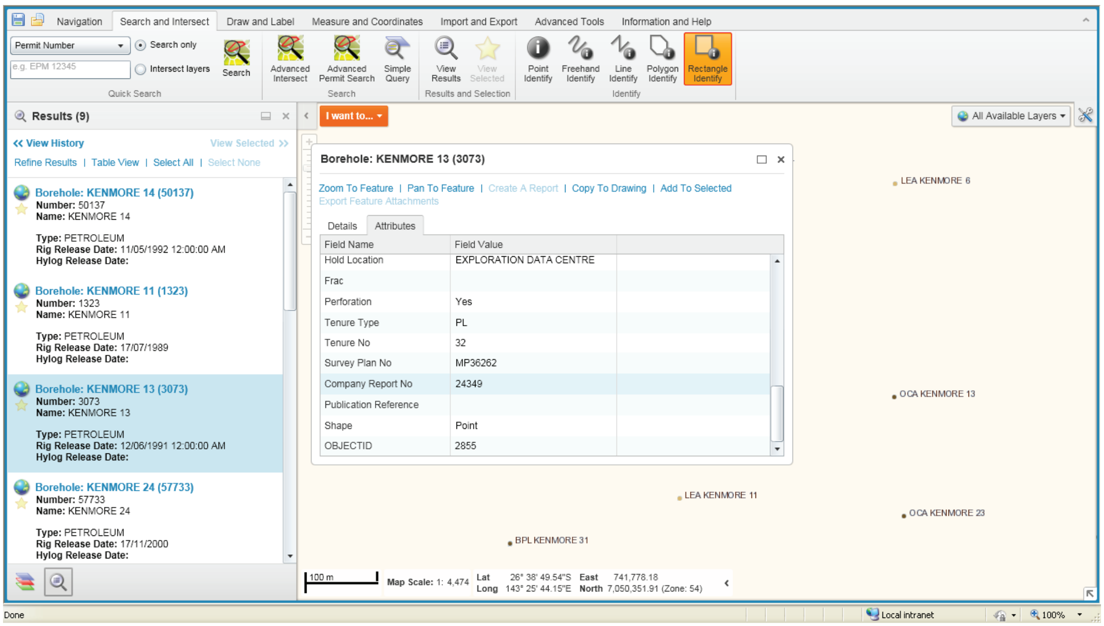
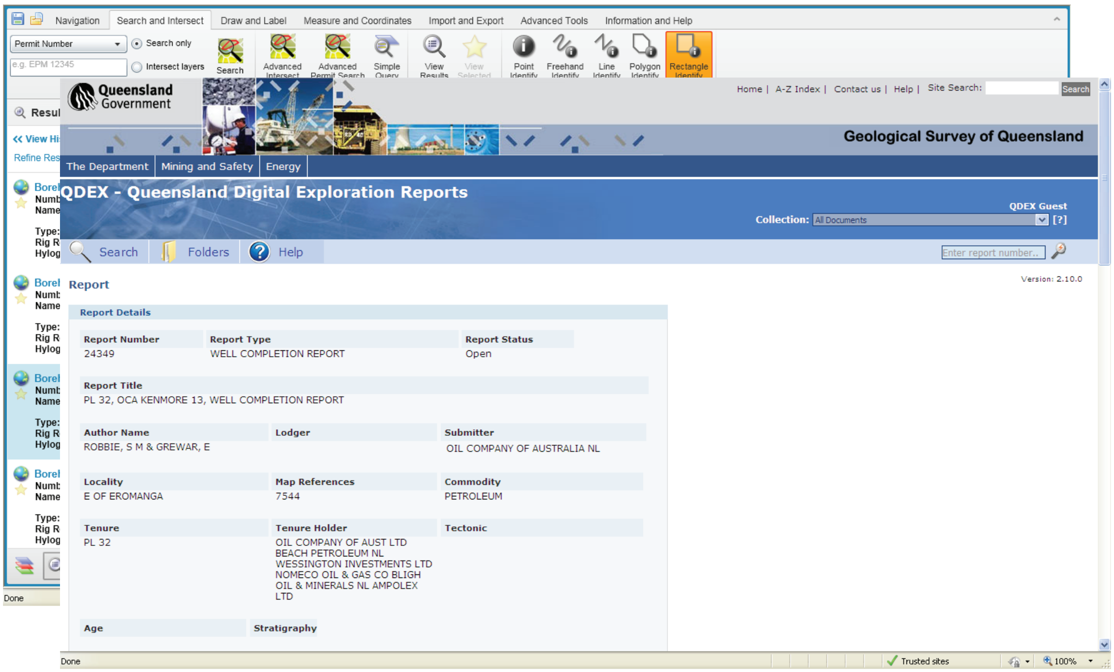


Using MinesOnlineMaps you will be able to select a borehole, then be offered a link to QDEX Reports where you can view and download the well completion report or a survey plan of the borehole location, link to QDEX Data where you can download the wireline log data for the borehole, and a link to QGIS where you can download a GIS of the borehole layer spatial data for the whole state.

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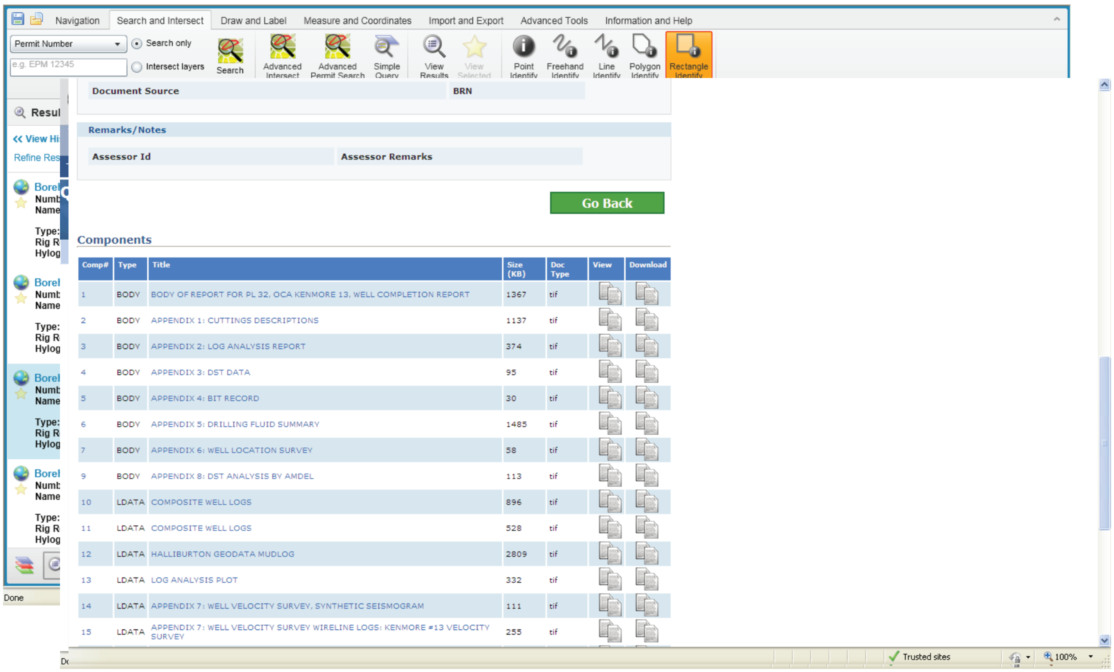
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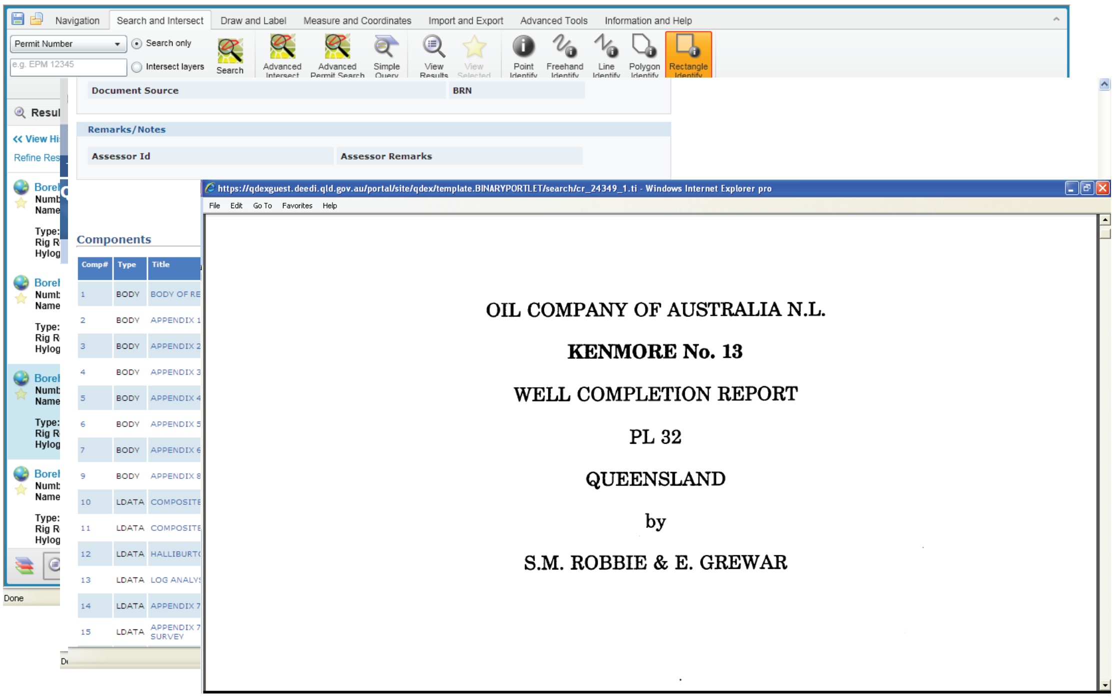
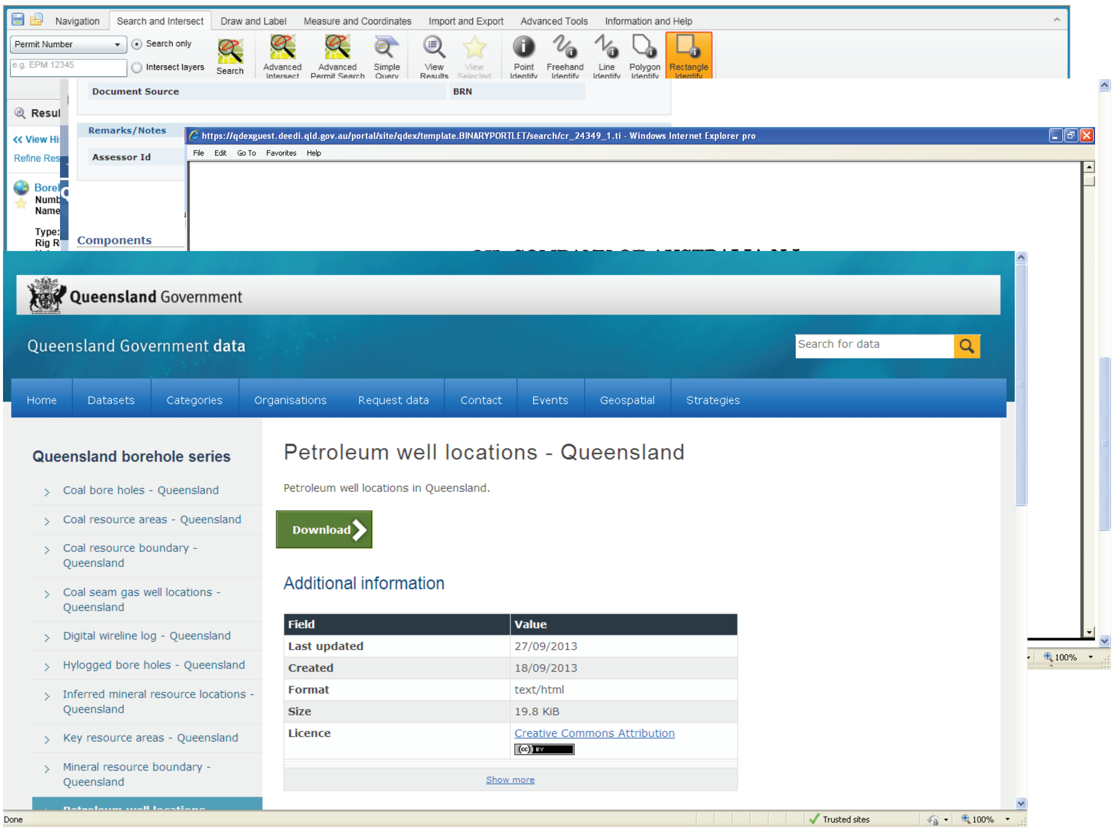
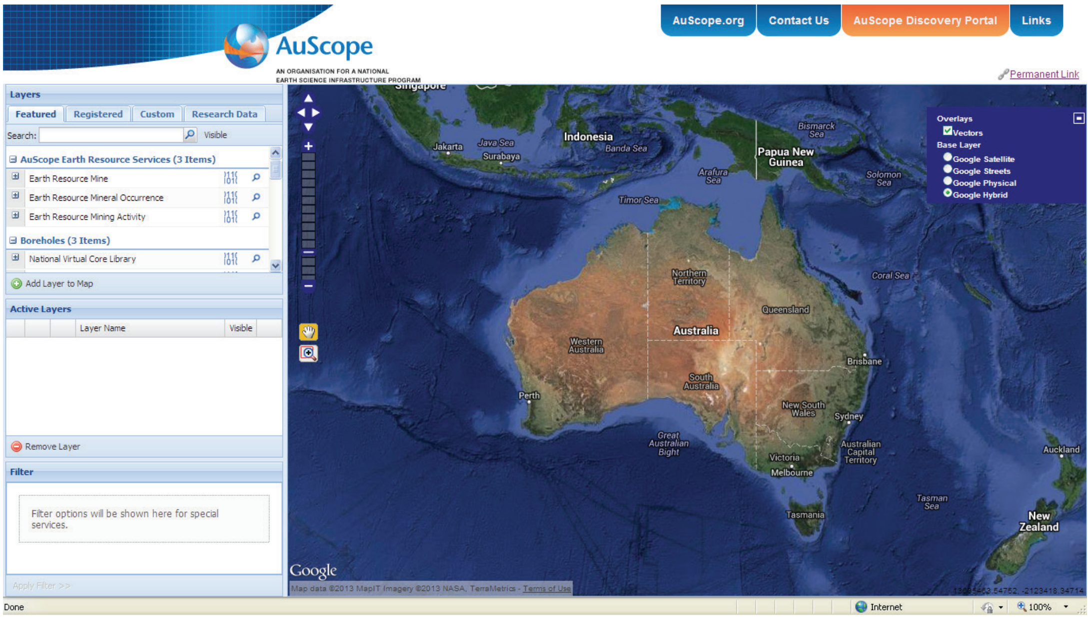


Reports in QDEX Reports will be linked to relevant data in QDEX Data and the GSQ Sales web site will link to QGIS, QDEX Reports and QDEX Data as necessary.

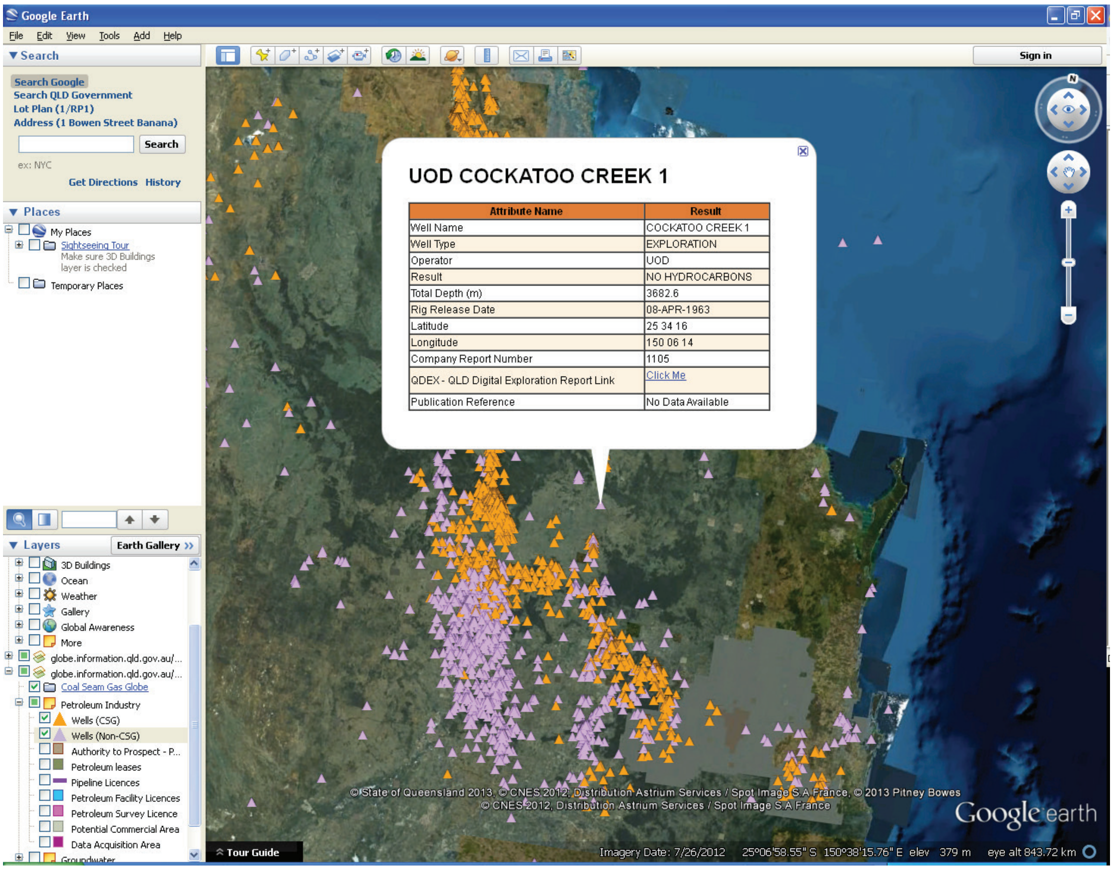


In addition to the above projects GSQ is implementing the AuScope Spatial Information Services Stack to deliver HyLogger and mineral occurrence data via the AuScope Portal initially and with further data delivery in the future. The portal itself is likely to be replaced by the new national geoscience portal currently under redevelopment by Geoscience Australia and CSIRO with guidance from the Government Geoscience Information Committee.



http://portal.auscope.org/portal/gmap.html
http://www.geoscience.gov.au/

GSQ will also be contributing content to the Queensland Globe to provide a simpler portal experience with reduced functionality. This globe or globes will provide another portal to access geoscience data.



http://www.dnrm.qld.gov.au/mapping-data/maps

Mineral systems of north-east Queensland

Vladimir Lisitsin and Courteney Dhnaram

Geological Survey of Queensland

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 styles of mineral deposits, including:

- gold-quartz veins and refractory gold
- stibnite-quartz veins
- hydrothermal breccia pipe hosted gold
- epithermal 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), as well as the rare earth elements, 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.

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 under the Greenfields 2020 program (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.

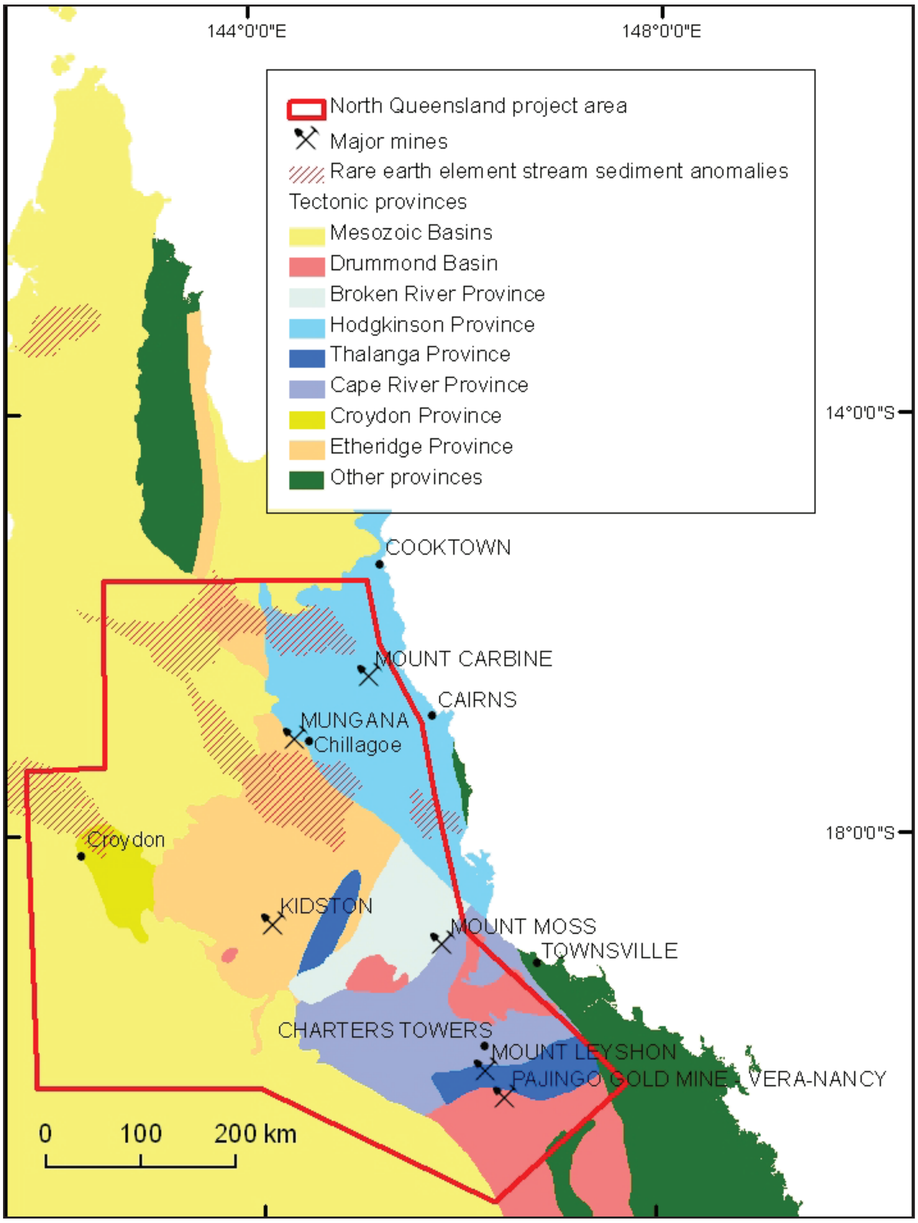


Figure 1: Location of North Queensland Gold and Strategic Metals Project and regional tectonic elements

Performed mineral prospectivity assessments focus on mineral systems, rather than deposits of particular commodities and mineralisation styles. Deposits of various styles characterised by different main commodities often represent parts of the same distinct mineral system which operated at a scale of many tens to hundreds of kilometres, affecting a significant part of a geological province. It is beneficial to characterise properties of such large-scale mineral systems and define their major spatial manifestations when performing a regional mineral prospectivity assessment. This paper reviews major gold mineral systems of north-east Queensland.

Major gold mineral systems in north Queensland

At least three major gold mineral systems operated in north Queensland:

- the Early Devonian orogenic gold system in the Charters Towers Province

- the Carboniferous orogenic gold system in the Mossman Orogen (the Hodgkinson and Broken River provinces)
- the Carboniferous to Permian intrusion-related (in a broad sense) system(s) of the Kennedy Igneous Association.

The orogenic gold mineral system in the Charters Towers Province produced the major Charters Towers Goldfield, containing >180t (6Moz) of gold, but it was also manifested in other parts of the province, particularly to the west and east of the town of Charters Towers. This mineral system is discussed in more detail by Dhnaram & Lisitsin (2013 — this volume).

The Carboniferous orogenic gold mineral system in the Mossman Orogen produced the bulk of gold and gold-antimony deposits in the Hodgkinson and Broken River provinces. Three distinct styles of orogenic gold deposits are present in the region. Their properties are reviewed by Denaro (2013). Most of the historically mined deposits are characterised by free gold (0.01mm to >1mm) in quartz veins, with minor pyrite and arsenopyrite (Peters & others, 1990; Garrad & Bultitude, 1999). Deposits of this style jointly account for more than 11t of gold bullion production.

The second major deposit style 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. Total identified endowment includes 5t of gold production from oxidised ores and 19t of gold contained in remaining primary sulphidic ores. Typical gold grades of the refractory gold deposits range between 1.5g/t and 10g/t, mostly averaging less than 5g/t.

The third deposit style is represented by quartz-stibnite±gold veins. They were of a limited historic significance as a source of gold, producing mostly stibnite concentrate.

The bulk of significant orogenic gold deposits in the Hodgkinson Province occur in a narrow belt (<20km wide), discordant to most of the surface geological structures (Figure 2). This metallogenic zone lies along the inferred edge of the Proterozoic Etheridge Province underlying the south-western Hodgkinson Province in the middle crust. The position of this deep crustal feature is indicated by a recent deep seismic survey (Korsch & others, 2012) and marked by a change from I- and A-type Permo-Carboniferous magmatism (Champion & Bultitude, 2013a) and the sub-greenschist facies regional metamorphic grade in the south-western Hodgkinson Province to the S-type Permian magmatism and the greenschist facies in the rest of the province. It is also supported by Sm-Nd and Hf isotopic data (Champion & Bultitude, 2013b; Murgulov & orthers, 2013).

Properties and prospectivity of orogenic gold mineral systems in the Hodgkinson and Broken River provinces are discussed in detail by Lisitsin & others (2013a,b).

The Carboniferous to Permian intrusion-related mineral system(s) of the Kennedy Igneous Association are represented by very diverse styles of gold, silver and base

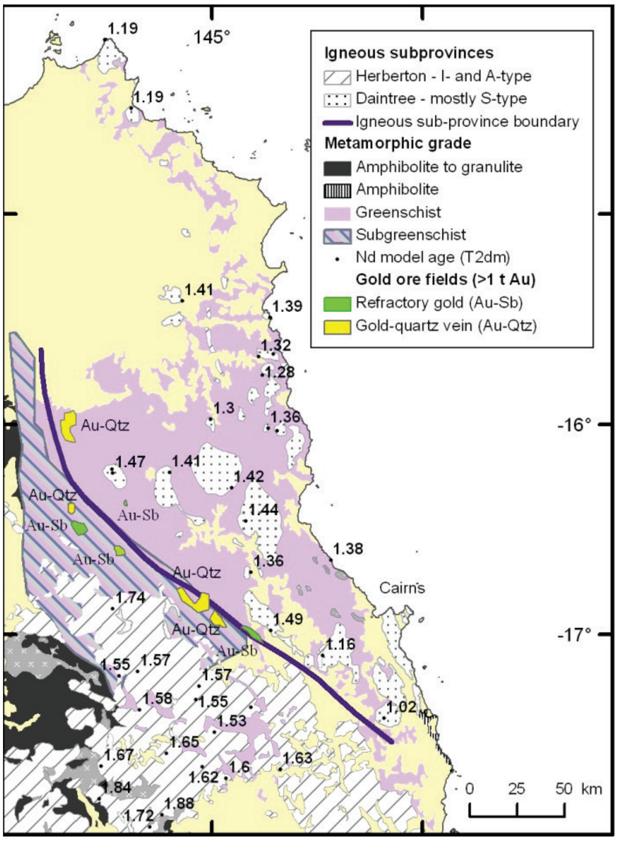


Figure 2: Regional metamorphic grades, igneous geochemistry and significant orogenic gold ore fields in the Hodgkinson Province

metal (Cu, Zn, Pb, Sn, W, Fe) deposits. Characterising these major mineral systems is a focus of ongoing research by GSQ.

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Mineral systems of the Charters Towers Province

Courteney Dhnaram and Vladimir Lisitsin

Geological Survey of Queensland

Orogenic gold deposits in the Charters Towers Province in north Queensland have been a significant historical source of gold production, particularly from within the historical Charters Towers Goldfield.The Charters Towers Goldfield has produced >6 million ounces of gold between 1872 and 1918 (Levingston, 1972), with historical and recent production from the Charters Towers town area and the outlying areas (Hadleigh Castle, Warrior – Black Jack and the Brookville areas).

Current work by the Greenfields Prospectivity Unit within the Geological Survey of Queensland (GSQ) has focused on updating existing GSQ reports over the Charters Towers Province with the recent mineral occurrence mapping completed in 2009–10 over the Charters Towers, Ravenswood and Homestead 1:100 000 map sheets, along with the updated mineral resources and known mineralisation in the area. This work supports a regional assessment of mineral potential of north Queensland for orogenic gold deposits, conducted by GSQ as part of the Greenfields 2020 program.

The Charters Towers Province, previously called the Cape River and Thalanga Provinces by Bain & Draper (1997), lies within the Northern Thomson Orogen in north Queensland and extends from the coast near Townsville to 150km west of Charters Towers (Figure 1). The province is bounded to the east by the New England Orogen and the coast, and to the north by the Clarke River Fault (which separates the

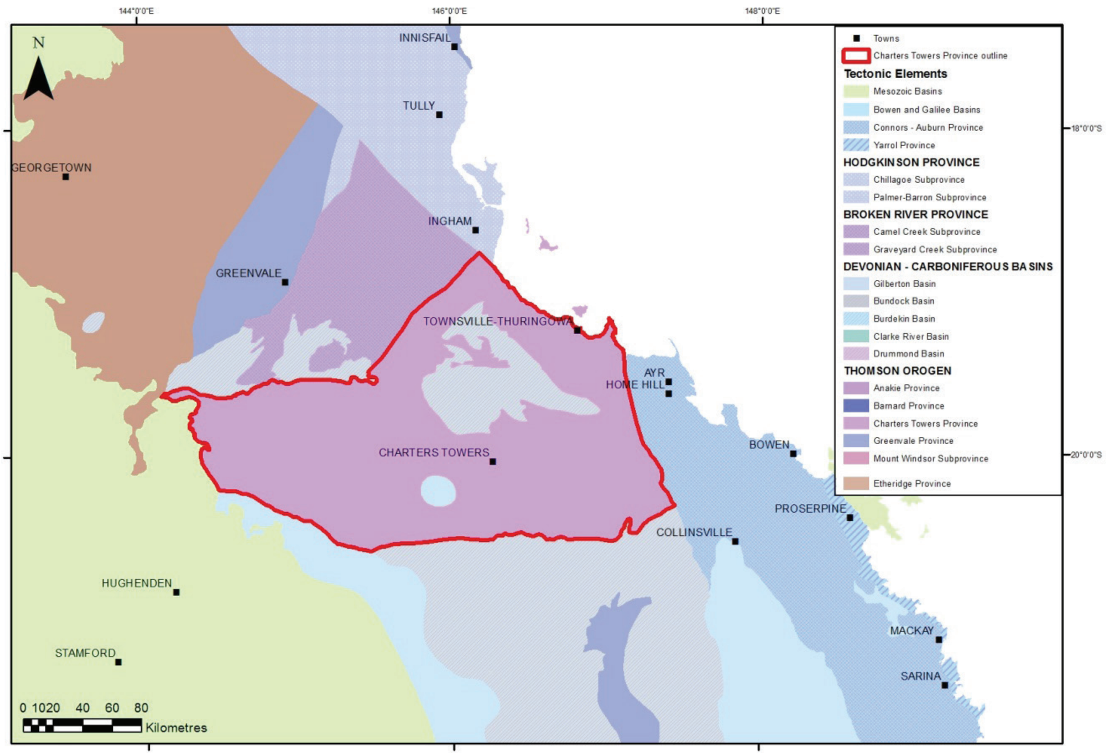

Figure 1: Map of the Charters Towers Province boundary and the surrounding geological provinces

Charters Towers Province from the Broken River Province), with both the western and southern boundaries masked by the sedimentary cover of the Galilee and Drummond basins. The Charters Towers Province covers an area of 38 840km^2 and includes the Ingham, Townsville, Clarke River, Bowen, Charters Towers, Ayr and Hughenden 1:250 000 map sheets. A detailed compilation of the geology and mineralisation of the Charters Towers Province as part of a larger study on the Thomson Orogen was recently released by GSQ (Purdy & others, 2013).

The area hosts a number of different styles of gold mineralisation, which have been classified as orogenic gold (Charters Towers town), epithermal gold and a broad category of intrusion related gold deposits (Ravenswood town, Lolworth, Mingela, Mount Wright, Mount Leyshon).

Previous mineral occurrence mapping, by Hartley & Dash (1993), Sennitt & Hartley (1994) and Hartley (1996) over the Charters Towers, Homestead and Ravenswood 1:100 000 map sheets, defined a classification system which combined all the above styles of gold mineralisation as mesothermal, magmatic related deposits, dividing them into:

- Mesothermal granite hosted — Charters Towers type
- Mesothermal granite hosted/multiphase — Ravenswood type
- Mesothermal sediment-hosted — Puddler Creek type
- Mesothermal breccia hosted — Mount Leyshon type
- Mesothermal greisen pipe — Big Hit type.

Both the Charters Towers and Puddler Creek type deposits are believed to be similar in nature and age, but occur within different host rocks (granite hosted versus sediment hosted), and therefore display different alteration associated with gold mineralisation. A fundamental problem with this classification scheme was that all gold deposits in the region, despite genetic and timing differences, were grouped within GSQ databases into a single class of mesothermal, magmatic related deposits. On the other hand, the subdivision of that class into individual deposit “types” was largely based on their morphological, textural and host rock characteristics, which resulted in separating genetically related deposits into different “types”. These limitations of the above classification scheme impeded a meaningful regional metallogenic analysis of gold mineralisation in the province and required reclassification of the mineral occurrences within the province into consistently defined genetic classes.

Classification of gold deposits at Charters Towers

Previous work in the Charters Towers Province (mostly within the Ravenswood Batholith, including the town of Charters Towers) suggested that gold mineralisation was either related to magmatic fluids from widespread intrusive emplacement at depth or to fluids of a metamorphic origin. For example, Peters & Golding (1989) suggested that the source of the mineralisation was from either metamorphic or deep-seated magmatic fluids. Morrison & Beams (1998, updated from previous studies) in their study on ore deposits in north Queensland classified the gold mineralisation in the Charters Towers Goldfield as plutonic (lode and vein style) based on the close spatial association and similar timing of granite emplacement and ore deposition. Sillitoe & Thompson (1998) classified the deposits as Au-As-Zn-Pb-Cu-Ag intrusion vein deposits based on the spatial and timing relationships with the host intrusives. Hutton & Crouch (1993) proposed that the outcropping granites within the western Ravenwood Batholith were restite-controlled and therefore showed minor fractionation, which reduced their potential to produce a volatile-rich phase needed to produce magmatic fluids needed for gold deposition. Field relationships also showed that mineralisation cuts through the host granites and therefore is younger than the outcropping granites in the batholith.

Recent work by Kreuzer (2004; 2005; 2006) and Kreuzer & others (2007) related the mineralisation at Hadleigh Castle (located on the western edge of the Ravenswood 1:100 000 map sheet) to that at Charters Towers by age dating, fluid inclusions and stable isotope studies. Results suggested that the mineralisation is similar to granitoid-hosted vein deposits (which are commonly classed as orogenic) and is related to a single episode of gold mineralisation and reef formation during the D4 deformation event, a NE–SW to NNE–SSW shortening, under low stress and supralithostatic fluid pressure (Kreuzer & others, 2007). Consistent with results of this work and other geological observations, gold-quartz veins in the historic Charters Towers, Hadleigh Castle, Rishton, Rochford and Donnybrook goldfields are classified here as orogenic. Notwithstanding the remaining uncertainties on a genetic mechanism of their formation, those deposits are considered to represent a distinct Devonian hydrothermal mineral system, significantly different from the younger mineral system(s) displaying much closer genetic relationships with igneous rocks of the Kennedy Igneous Association.

Smaller gold mining centres, including Kirk, New Homestead Diggings, Upper Cape River, Dreghorn and the group of mines between the Bismark mine and the Bosworth workings (south of Disraeli), have gold mineralisation similar to better studied deposits at Charters Towers and Hadleigh Castle classified in this study as orogenic. There is no specific geochemical evidence (such as fluid inclusions and age dating) to either confirm or contradict this general similarity. These smaller mining centres have no direct confirmed links to the Kennedy Igneous Association rocks or any documented geochemical or textural evidence to indicate their intrusion-related nature (e.g. porphyry Cu-Au or epithermal). These mineral occurrences have been included as part of the larger Devonian orogenic gold mineral system.

Extent of the orogenic gold mineral system

Significant gold mineralisation within the province mostly occurs in several clusters, spatially defined as ore fields with >1t of original contained gold (based on total past mining and remaining resources). These ore fields (Figure 2) predominantly lie within the historical Charters Towers and Ravenswood goldfields where the bulk of the historical mining occurred. In the case of the Hadleigh Castle ore field, the smaller adjacent Rishton and Rochford historic goldfields (both with >1t of contained gold) were combined based on their close spatial proximity. The same logic was used to define the boundaries of the Donnybrook and Charters Towers Town ore fields.

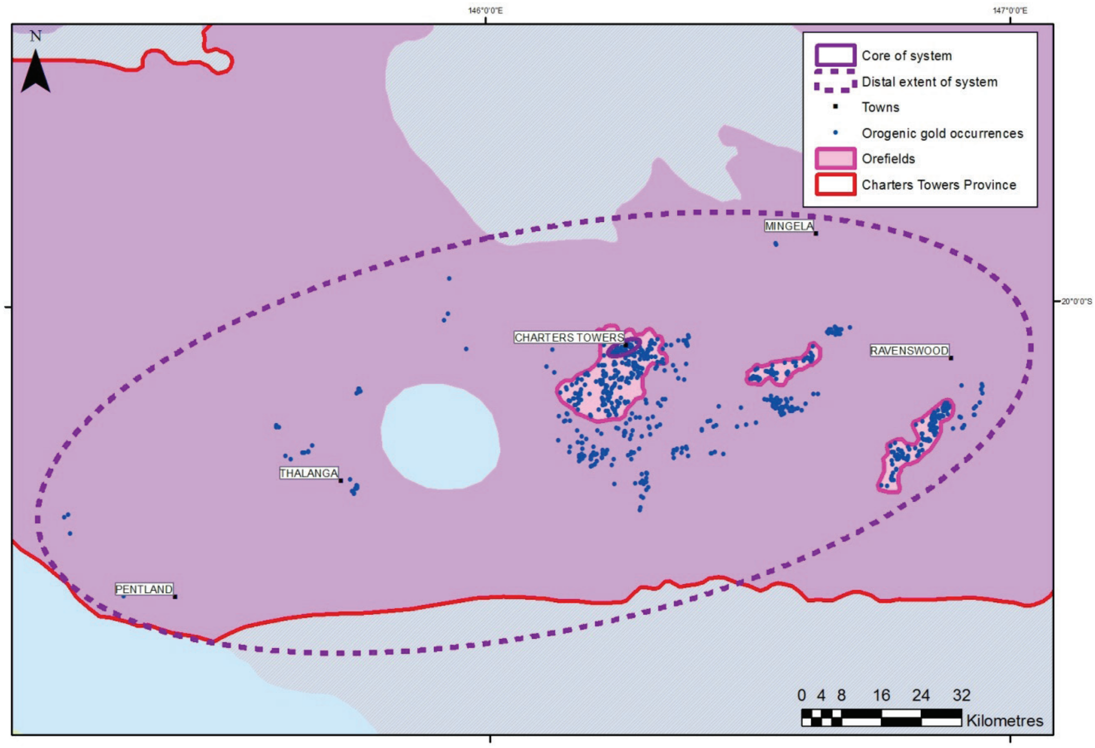

Figure 2: Orogenic gold mineral occurrences within the Charters Towers Province, showing the main three orefields and generalised geology. The purple circles show the core and distal extent of the mineral system.

The vast majority known orogenic gold endowment in the Charters Towers Province has been contained in the Charters Towers ore field. However, geologically similar gold mineralisation (hosted by both magmatic and meta-sedimentary rocks) has been documented in a much wider area both to the west and east of Charters Towers (Figure 2). Given the documented Early Devonian age of orogenic gold deposits and non-specificity of their host rocks, any Early Devonian and older rocks within the broadly defined outline of the orogenic gold mineral system (including the areas under younger volcano-sedimentary cover) may contain orogenic gold mineralisation.

While the main mineralised area surrounding the town of Charters Towers within the Ravenswood Batholith has been relatively well explored (particularly at shallow depths) for orogenic gold-quartz vein deposits, the Neoproterozoic to Ordovician metamorphosed volcano-sedimentary units are likely to be under explored for this type of gold mineralisation. It has been traditionally assumed that gold-quartz vein deposits of the "Charters Towers type" are closely associated with the host intrusives. However, the current study suggests a much wider spatial extent of the mineral system which formed the major gold deposits at Charters Towers — not restricted to the magmatic rocks of the Macrossan and Pama igneous associations.

Outsider the Charters Towers ore field, there is a particularly high potential for undiscovered orogenic gold mineralisation in the areas under the sedimentary cover sequences younger than Early Devonian. Only a few gold occurrences have been identified in the Charters Towers Province in the covered areas. In particular, the areas to the north-west and west of the town of Charters Towers have been subjected to very little past exploration and drilling under cover.

Future work will focus on further constraining the extent of the orogenic gold mineralisation through geochronology and geochemistry, specifically to the west of the Charters Towers town area. Another study into intrusion related gold systems (IRGS) focuses on defining distinguishing characteristics and spatial extents of the two major gold mineral systems in the province and their resource potential.

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Illite crystallinity as an exploration tool in hydrothermal systems

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Alteration mineralogy can be useful to determine the spatial distribution of the mineralised hydrothermal zones (Duba & Williamsjones, 1983; Kelley & others, 2006). Clay mineralogy and particularly illite crystallinity (IC) studies assist in highlighting hydrothermal fluid flow activity, especially in conjunction with trace element geochemistry as we demonstrated in our pilot study (Uysal & others, 2011). Although IC has been showed to be controlled mainly by temperature in diagenetic and geothermal systems (e.g., Yang & Hesse, 1991; Underwood & others, 1993; Ji & Browne, 2000), it can be used only as a semi-quantitative measure. In addition to temperature, varied inputs of detrital illite and changes in water/rock ratios can also affect the IC. In this paper, application of IC studies is presented to discuss hydrothermal systems controlling gold and copper mineralisation in the Drummond Basin and Mt Isa Basin, respectively.

In the Twin Hills area, strongly silicified and mineralised samples typically contain illite — kaolinite mineral association with lower illite crystallinity values (<0.45° 2θ), whereas the unmineralised carbonate cemented rocks have no kaolinite, but instead contain chlorite with illite having higher illite crystallinity values. IC values for the mineralised 309 samples range from 0.21° to 0.52° (Δ2θ) clustering mainly around 0.25° and 0.45° (Δ2θ). In analogy with published studies (Ji & Browne, 2000; Merrriman & Frey, 1999), clusters of IC values around 0.25° and 0.45° (Δ2θ) indicate two crystallisation events at temperatures of about 300°C and 200°C, respectively. Alternatively, samples with higher IC values of around 0.45° (2θ) precipitated during transient fluid flow events at very high fluid/rock ratios. IC values between around 0.25° and 0.45° (Δ2θ) indicate either mixing of two illite populations or the effect of less dominant sporadic fluid pulses at temperatures between 300°C and 200°C (Ji & Browne, 2000). Unsilicified samples from deep unmineralised zones have IC values higher than 0.55° (Δ2θ). Similarly, barren Lone Sister samples are characterised by significantly higher IC values, whereas illites from highly mineralised rocks are better crystalline with lower IC values (larger crystallite or domain size, less swelling layers and crystal defect, Eberl & Velde, 1989) indicating higher crystallisation temperatures. In summary, increasing illite crystallinity with lower IC values (<0.5 Δ2θ) indicate zones of high grade systems, which can be used as a reliable indicator tool to locate high grade deposits or areas of intense geothermal activities.

IC values for the northern Lawn Hill Platform boreholes (Desert Creek, Egilabria and Amoco 83/4) show a wide range. By analogy with results of earlier studies (e.g., Yang & Hesse, 1991; Underwood & others, 1993), these IC values indicate roughly diagenetic to very low-grade metamorphic temperatures (200–250°C) for the formation of the clays. Samples from boreholes in the south-central part of the region (Amoco 83/1, 83/5, GSQ LH 3, RVD 047 and RVD 051) show more consistent and lower IC values that indicate these clays formed at higher temperatures. Thus illites from Amoco 83/1 and 83/5 are characterised by high diagenetic-anchizone IC values (~250°C), whereas RVD samples indicate anchizone conditions (~300°C, cf. Arkai, 1991). The majority of samples from boreholes in the Century area (PCM 056, LH 102, LH 265, LH375, LH376 and LH532) exhibit a narrow range of IC values around 0.6 $\Delta 2\theta$, which may indicate temperatures of ~200°C. In contrast to the illites from the northern boreholes show more consistent crystallinity values. Based on the results of earlier studies (e.g., Yang & Hesse, 1991), these values broadly indicate temperatures of 200–250°C, which are consistent with those deduced from IC data.

IC values for samples from the northern (Desert Creek, Egilabria and Amoco 83/4) and central (Amoco 83/1, 83/5, GSQ LH 3, RVD047 and RVD051) areas are plotted as a function of depth down hole. A linear correlation of depth-IC values is indicated for Desert Creek in the north, and for RVD051 and Amoco 83/5 in the centre of the basin. However, even in these boreholes, the scatter of samples is substantial indicating that the effect of other factors than temperature was also important in illite formation. Significant detrital illite contamination of samples can be ruled out on the basis of TEM photomicrographs that show euhedral illite crystals, the result of neoformation from fluids. Hence changes in the fluid flow regime and consequently water/rock ratios are considered to be the most likely factor causing the data scatter. The anomalies in IC values commonly coincide with high total organic carbon (TOC) concentrations and often occur immediately above or below Supersequence boundaries. It is probable that these clays precipitated from fluids that migrated through more reactive lithologies or along sequence boundaries. The significant increase in IC values may be due to the effect of transient fluid flow in relatively permeable zones causing direct precipitation of illite or dissolution/precipitation processes of earlier formed illites. K-Ar data indicate that organic matter alteration and the subsequent illite precipitation within the organic matter occurred during the regional hydrothermal event at 1172±50 (2σ) Ma. Hot circulating fluids are considered to be responsible for organic matter alteration, migration and removal of volatile hydrocarbon, and consequently porosity-permeability creation. Those rocks lacking sufficient porosity-permeability, such as sandstones, siltstones and organic matter poor shales, may not have been affected by fluid movement.

3D geological and mineral potential modelling in Queensland

Matthew Greenwood

Geological Survey of Queensland

The Geological Survey of Queensland has been involved the construction of geological 3D models to aid explorers with an understanding of geological concepts, stratigraphic and structural framework, and mineral and energy prospectivity. To date these models have been focused primarily in north-west Queensland; however modelling is currently being undertaken in the Red River Project area of north Queensland.

The North-West Queensland 3D model

North-west Queensland is a richly endowed region containing over 75% of Queensland's mineral wealth and housing numerous world class deposits such as the Mount Isa Pb-Zn-Ag and Cu deposits, Century Pb-Zn-Ag and Ernest Henry Iron Oxide Cu-Au. Over 80% of the region is undercover and as a consequence a vast area remains under-explored. There remains huge potential for further significant discoveries in the region. To better aid explorers to uncover the resource potential of this under-explored region the North-West Queensland Mineral and Energy Province (NWQMEP) Study was released in 2011.

The North-West Queensland 3D model (Figure 1) covers an area of 500 000km^2 to 20km depth and is a critical aspect of the NWQMEP Study. It incorporates current geological concepts and a range of data sets to form a coherent physical representation of the current state of geological understanding of the north-west Queensland region. The model was constructed as a visualisation tool for displaying the spatial associations of geological features at depth and beneath cover, as well as providing a conceptual framework for more specific basin evolution, deformation, fluid flow and mineral systems studies.

District-scale modelling

Following the regional-scale modelling in north-west Queensland, smaller district scale models were prepared for studies targeting specific styles of mineralisation (Figure 2). The purpose of these studies was to attract exploration investment into covered greenfields terranes by providing robust models to improve targeting outcomes. The district-scale studies investigate the geological, structural, geophysical and geochemical characteristics of mineralisation in an area and use this data to create a 3D mineral potential model. The areas selected for this style of mineral potential modelling were chosen for their anticipated high discovery potential and a mix of exposed and covered terranes with the goal of extrapolating knowledge of mineralisation processes into adjacent covered areas.

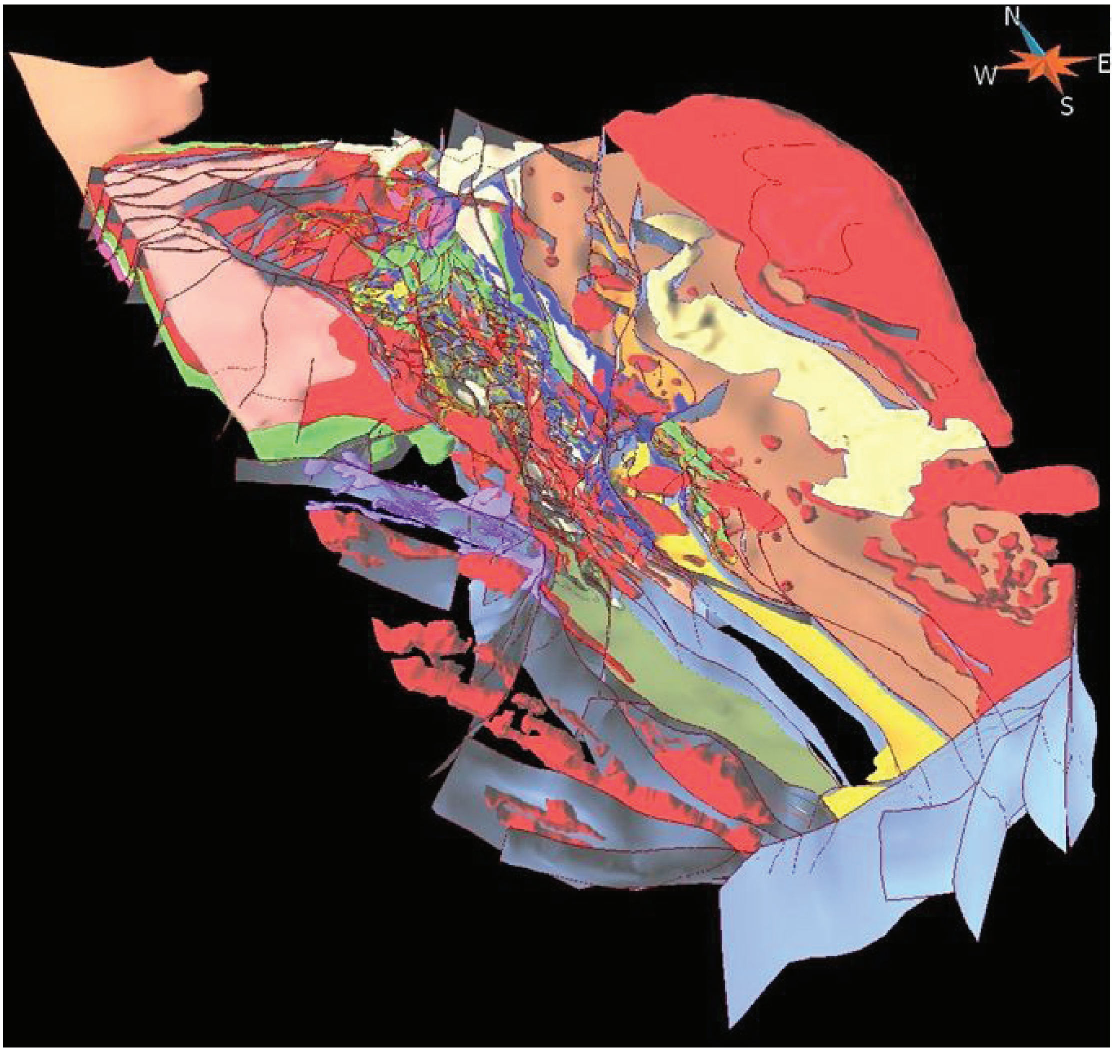

Figure 1: North-West Queensland 3D model viewed from south-west

The district-scale studies workflow that has been adopted by the Geological Survey of Queensland involves geological surface modelling in GOCAD and SKUA leading to the production of a 3D discretised volume model (or voxet model). This voxet model is used as an input for potential field inversions using gravity and magnetic data (and electromagnetic data if available) to create geologically constrained density and magnetic susceptibility models.

The available data, geological and geophysical models are combined into a Common Earth Model which is then used to assist with regional targeting. This targeting process defines discrete areas of higher mineralisation potential predicted to exist at a range of depths throughout the project area. These can be used as a guide for tenement selection or for drill targeting by greenfields explorers.

Mount Dore

The Mount Dore Project Area is a 175km x 70km block located immediately south of Cloncurry within the NWQMEP study region (Figure 2). The area is dominated by copper ± gold ± iron oxide mineralisation and hosts significant copper-gold producers

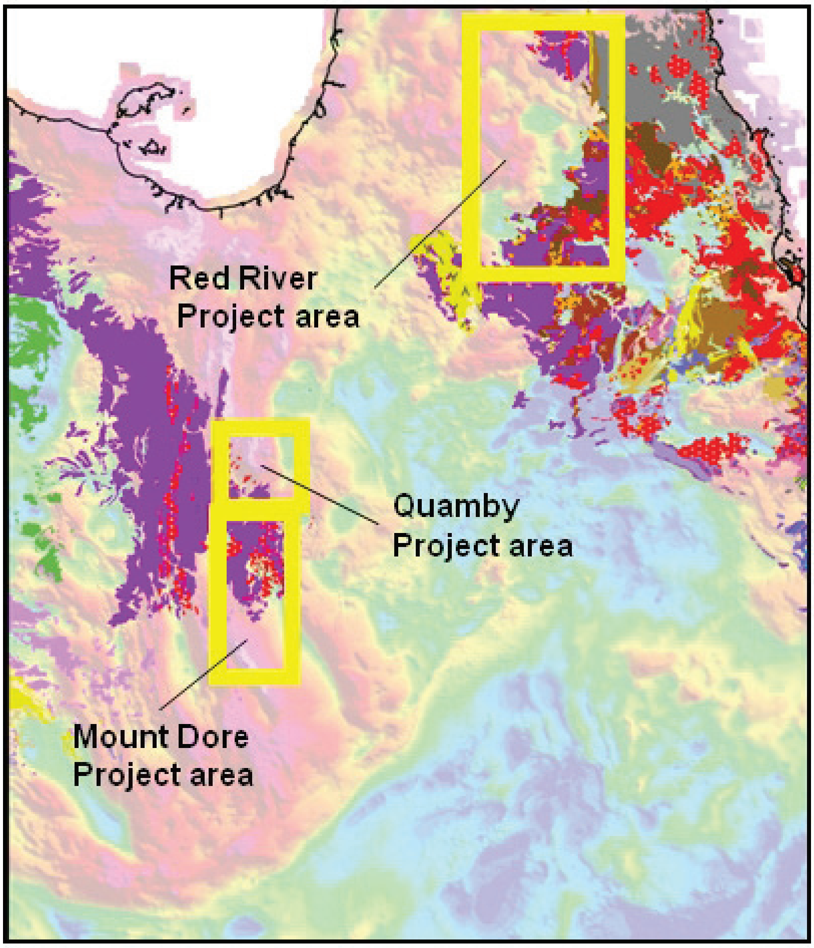

Figure 2: Location of district-scale 3D prospectivity studies

such as Osborne, Mount Elliott-Swan, Mount Dore, Selwyn, Kuridala-Hampden and Greenmount. Significantly, the area also includes Merlin, the world's highest grade molybdenum and rhenium deposit.

A Weights-of-Evidence (WoE) modelling approach was chosen to assess the potential for further economic mineralisation in the project area. Key targeting or exploration criteria were selected outlining the controls on IOCG mineralisation in the Mount Dore area. Examples of targeting criteria used include: proximity to crustal structures, zones of coincident high susceptibility and density, geological complexity and geochemical anomalism. The targeting workflow in GOCAD was used to assess weights for each property in relation to the training data to find relationships between the proposed exploration criteria and actual mineral occurrences. Exploration criteria with large weights in the WoE study can be used as an exploration tool, increasing predictive capabilities by increasing the understanding of specific district controls on the ore forming system. The final result of the WoE modelling, the Mineral Potential Index, represents the relative chance of each individual cell within the model hosting IOCG mineralisation (Figure 3) with prospective regions (areas with multiple overlapping favourable exploration criteria) shown as hot colours and areas of low prospectivity as cooler colours.

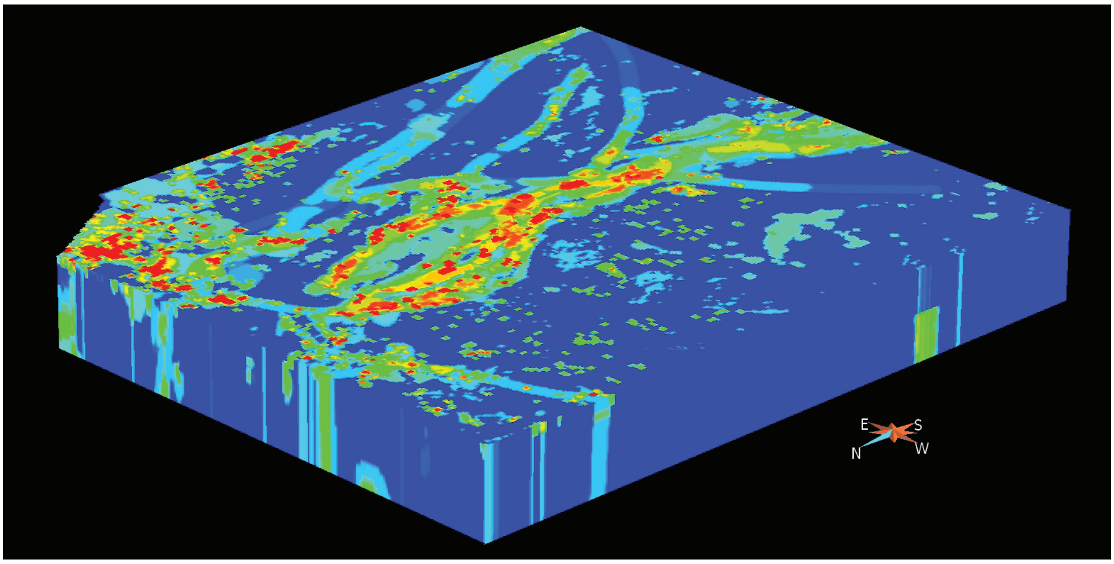

Figure 3: Mineral potential index for the northern section of the Mount Dore region where hot colours represent high mineral potential derived from the Weights of Evidence modelling.

Quamby

The Quamby project area covers an area 95km long by 80km wide, extending east from the Mount Rose Bee Fault and north from Cloncurry in north-west Queensland, lying immediately north of the Mount Dore project area (Figure 2). 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.

Two WoE models were created in the Quamby region to account for the two distinct geological domains (Canobie and Mary Kathleen Domains) and mineralisation styles present in the project area. In each model key targeting criteria were tested to ascertain controls on mineralisation. The final 3D mineral potential models (Figures 4 and 5) 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.

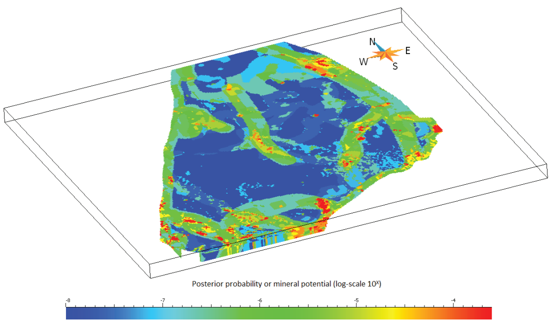

Figure 4: 3D view of a horizontal slice (200 metres below Australia Height Datum) of mineral potential model of Canobie Domain viewed from south-west

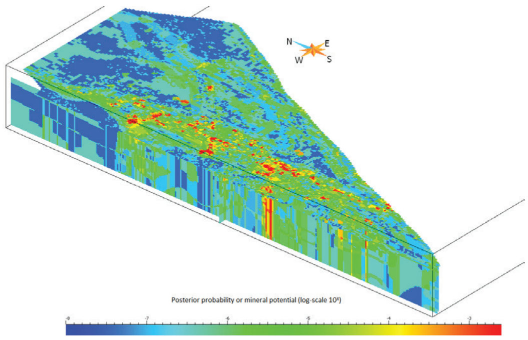

Figure 5: 3D view of horizontal slice (200 metres below Australia Height Datum) and north–south section of mineral potential model of Mary Kathleen Domain viewed from south-west

Red River

The Red River Project area is the current 3D district-scale model in process. The Red River Project covers an area of about 300km long by 170km wide extending west from Chillagoe in north Queensland and north from Georgetown. Proterozoic and Palaeozoic outcrop varies from very good to poor in the east and south to concealed in the west and north. The area is prospective for multiple styles of mineralisation including intrusion-related gold (including epithermal styles) related to the Permo-Carboniferous magmatism of the Townsville-Mornington Island Igneous Belt.

Initial work on the Red River Project has included a depth to basement map (Figure 6) for the undercover region and a solid geology for the 3D model (Figure 7). Field work was undertaken in June 2013 to collect field samples for magnetic susceptibility and density measurement, and to gain further understanding of the geology of the area. During this trip samples were also collected for magnetic remanence testing to understand the magnetic signature of the intrusive bodies in the area.

The Red River Project plan is similar to that completed for the Mount Dore and Quamby project areas with a geological model, geophysical inversions and mineral potential model to be created. Results from the Red River project will be released in 2014.

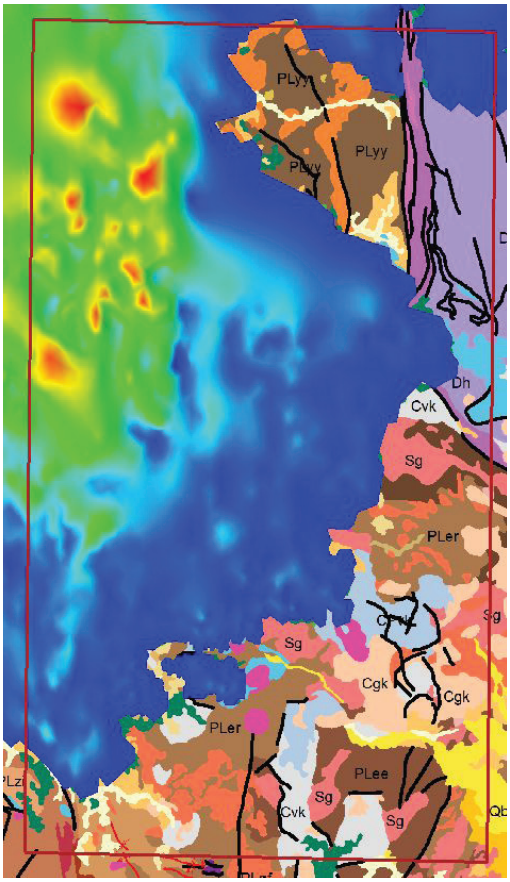

Figure 6: Depth to basement map of Red River Project area overlain on outcropping geology. Blue areas indicate shallow cover and red areas indicate thick cover (1200 metres).


Figure 7: Solid geology map for 3D modelling created from outcropping geology and geophysical interpretation of covered regions.

Basement geology of the southern Thomson Orogen region in Queensland

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The Thomson Orogen is the largest but least understood element of Queensland geology. It occupies the vast region between the North Australian Craton and the New England Orogen (Figure 1) and records the enigmatic time period following Rodinia break-up. Only a small proportion of the Thomson Orogen crops out at the surface with the remainder covered by a series of sedimentary basins. The small outcrop area is relatively rich in mineralisation with several different styles and time periods represented (Purdy & others, 2013). Additionally, much of the Thomson Orogen is coincident with a major temperature anomaly and is prospective for geothermal energy resources. These factors, and the constraints that the Thomson Orogen can provide to models for the tectonic development of eastern Australia, prompted the GSQ to begin a new project in 2012 with the broad aims of increasing knowledge and encouraging further research and exploration (Purdy & Brown, 2011). This project has so far resulted in extensive compilations of existing data (Brown & others, 2012), a major review document (Purdy & others, 2013), and large amounts of new data (e.g. Carr & others, 2012) including geochronology which is yet to be fully published.

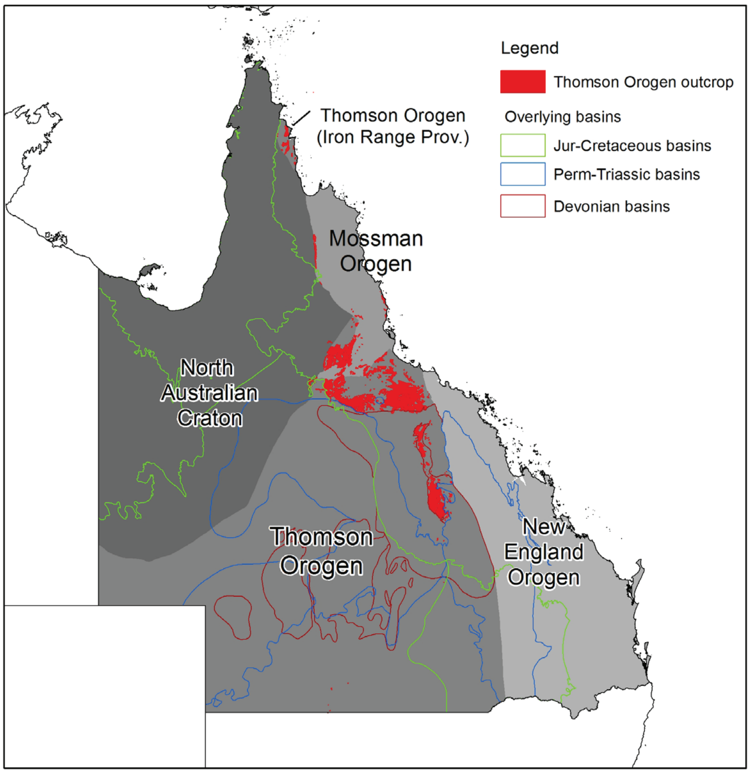

Figure 1: Distribution of the Thomson Orogen and overlying basins in Queensland

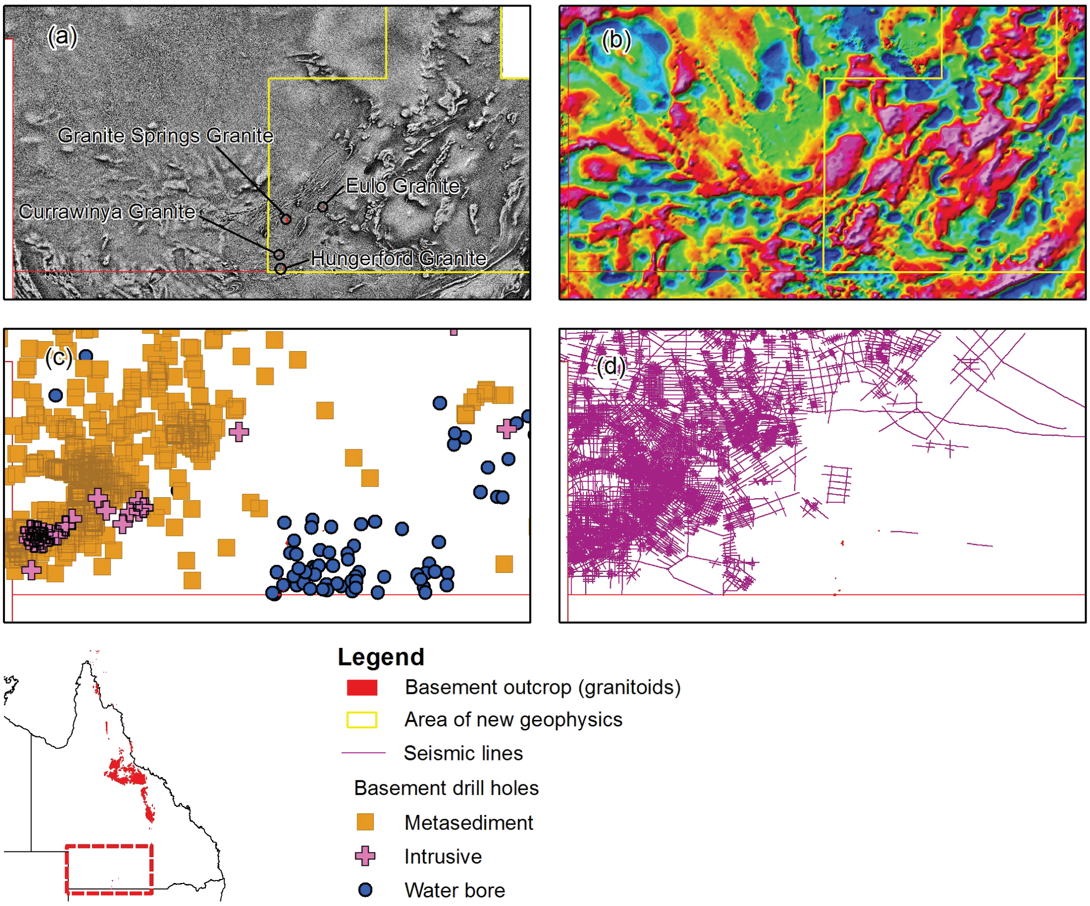

Figure 2: Datasets used in interpretation and compilation of the basement geology map. a) Magnetics (including new data) and distribution of outcropping rocks, b) gravity (including new data), drill holes, d) seismic lines

The southern part of the Thomson Orogen in Queensland, around Eulo and Hungerford, includes an area of relatively shallow cover (see Simpson & Cant, 2012) and scattered, small areas of granitoid outcrop (Figure 2). This general region and its extension into northern New South Wales is a greenfields mineral province and is gaining interest from some explorers. Additionally, the area is a focus of current investigations including a collaborative data acquisition project involving GA, GSQ and GSNSW, and potential collaborative research projects involving the state surveys and several universities.

A major goal of the GSQ project which falls in line with these newer initiatives is to interpret the basement geology of this “southern Thomson region”. The basement geology map, described and shown here as a first draft, is intended to form a base to be tested with further work and which may be expanded to larger areas of the Thomson Orogen.

Data sources

The basement geology map draws upon several data sources (Figure 2) and builds from a recent interpretation in the New South Wales part of the Thomson Orogen (Hegarty, 2010).

Outcrops

Four small areas of granite outcrop exist within the Queensland part of the southern Thomson region at Eulo, Granite Springs, Currawinya, and Hungerford (Figure 2). Field observations and petrographic descriptions are made for these granites with particular attention paid to the more extensive and mineralised Granite Springs Granite. These outcrops are all dated by U-Pb SHRIMP (zircon) and provide important age constraints on the adjacent geology. Outcrops of granite and metasediments in the Tibooburra area of north-west New South Wales provide additional constraints and are described in detail (Greenfield & others, 2010).

New geophysics

The GSQ has acquired new gravity, magnetic and radiometric data over part of the southern Thomson Orogen region (Figure 2). Magnetics and gravity images are fundamental to the basement interpretation map. Magnetics images in particular reveal significant complexity in the area of shallow cover with several domains of differing magnetic character easily divided along with intrusive phases and major structures. Gravity when overlaid transparently on magnetics images is particularly useful to define features in areas of deeper cover and to define large-scale structures.

Petroleum drill holes

Most petroleum drill holes are outside of the area of shallow cover and provide the only physical constraints on the geology of these areas (Figure 2). Mostly drilled in the 1950s and 60s, they are an extremely valuable resource. Details of basement intersections from these drill holes are compiled in a database of general information (e.g. hole location, drilling date, total depth) and basement information (e.g. depth to basement, lithological description, material available) (Brown & others, 2012 following the work of Murray, 1994). All drill holes with core available have been logged, described and photographed, with samples (for petrography, geochemistry and geochronology) taken from selected holes as part of the GSQ project. Several cores (both intrusive and metasedimentary rocks) are dated and all of this information will be compiled into a final database product.

Water bores

Many water bores in the southern Thomson Orogen are deep (up to ~600m) and descriptions indicate that they may intersect basement rocks (Figure 2). However, lithological information from these bores is generally limited to single word descriptions (e.g. ‘bedrock’, ’granite’, ‘slate’). Although the information is basic, treated with caution, these water bores provide some constraints on the basement geology and depth to basement.

Seismic

Similarly to petroleum drill holes, seismic data is abundant in the north-western part of the southern Thomson region where cover depth is greater and petroleum prospectivity is higher (Figure 2). In general, seismic surveys in this area were designed to image targets in overlying basins. Because of this, and also due to general nature of the rocks (i.e. comprised dominantly of steeply dipping metasediments and intrusions), the Thomson Orogen component is poorly imaged. Despite this, some seismic data may help to constrain the orientation of major structures.

GSNSW map

A basement geology interpretation map has been produced by the GSNSW (Hegarty, 2010) and is constrained by outcropping areas (particularly around Tibooburra), existing water bore data and samples, new cores from water bores, and results of mineral exploration drilling. This provides a useful starting point for areas adjacent to the Queensland/New South Wales border, and by working with the GSNSW the basement interpretation map is now seamless across jurisdictions.

Interpreted geology

Metasediments are clearly the dominant lithology in the southern Thomson Orogen region. However, new geophysics reveal that intrusions are more abundant than indicated by petroleum drill hole intersections. Although direct observations of the basement geology are limited, several observations and interpretations can be made. Future data acquisition as part of planned collaborative projects can test these interpretations.

Metasedimentary rocks

The only direct observations of metasedimentary rocks within the undercover Thomson Orogen in Queensland come from basement intersections in petroleum drill holes. Basement cores have been studied in detail by the GSQ team and broad lithological groupings are defined (Figure 3). Within the southern Thomson Orogen region, intersections are dominated by the turbidite/mass flow and distal starved turbidite groupings (Figure 3). The turbidite/mass flow deposits are widespread and comprise finely interbedded and interlaminated siltstone and sandstone with graded bedding, cross bedding and rip-up clasts common and rare pebbly horizons. The distal starved turbidites comprise laminated fine-grained carbonaceous and quartz-rich mudstone with steep dip and minor deformation. They are rhythmically laminated or exhibit graded bedding with minor ripple marks and cross bedding. Both groupings are metamorphosed to a low grade and exhibit a single slaty cleavage parallel to, or at a shallow angle to bedding. The Nebine Ridge is an exception and metasediments in drill cores here exhibit multiple deformations. Some metasediments are higher grade adjacent to intrusions and exhibit spotting (representing retrogressed porphyroblasts), although this is not ubiquitous.

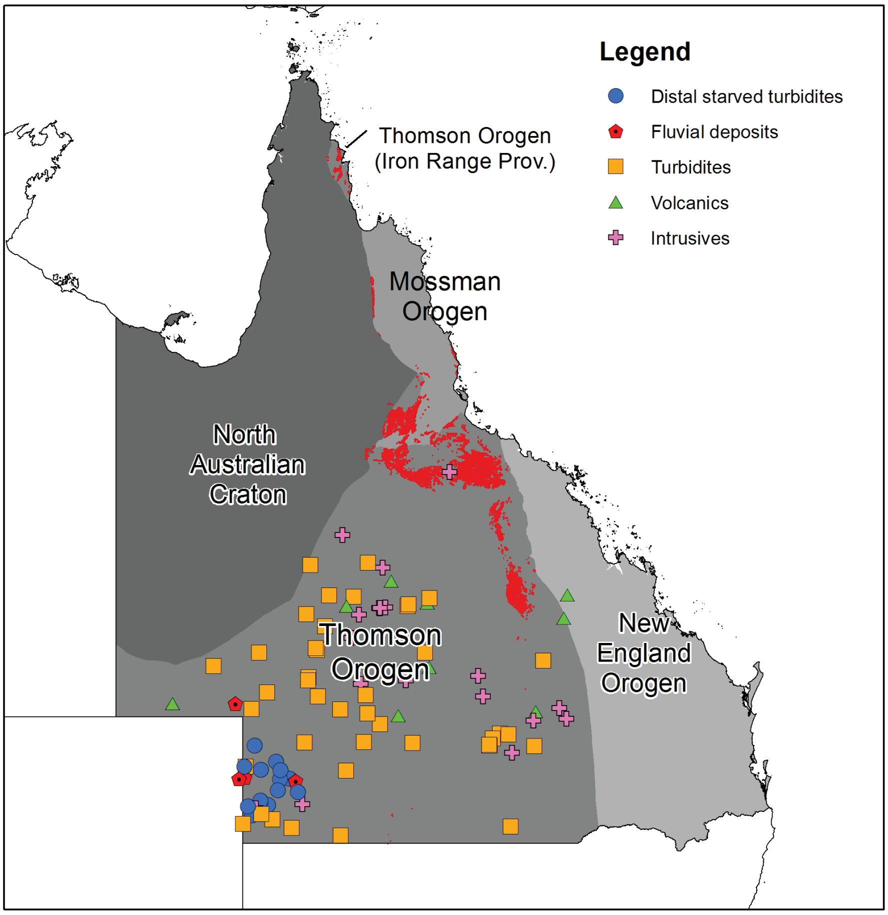

Figure 3: General lithological groupings of basement cores from petroleum drill holes

Maximum depositional ages for the deposits are commonly around 490–500Ma, with significant populations in the Grenvillian (1000–1300Ma) bracket. This correlates well with exposed Thomson Orogen metasediments to the north (e.g. Fergusson & others, 2001; 2007; 2009) and may also correlate with the Warratta Group defined in the New South Wales part of the Thomson Orogen (Greenfield & others, 2010).

Although the area of shallow cover around Eulo and Hungerford lacks information from petroleum drill holes, the basement geology is imaged well in new geophysical data. This data suggests the presence of at least four metasedimentary-dominated units/domains with differing magnetic and gravity character. The most extensive unit is characterised by relatively bland or even magnetic response and is herein informally referred to as the Strathmore formation (Figure 4; 4a;4b). Slightly elevated magnetic response is noted adjacent to some interpreted intrusive units suggesting the effects of contact metamorphism and therefore indicating relative age constraints. Despite the widespread distribution of this unit there is no/little evidence of its composition. However, given the relatively consistent geophysical response characterised by relatively low magnetic intensity, we suggest that it most likely comprises monotonous sequences of metasediments, possibly quartz-rich sandstones.

Adjacent to the Strathmore formation is another metasedimentary unit that appears relatively featureless in geophysical images apart from a few roughly defined trends.

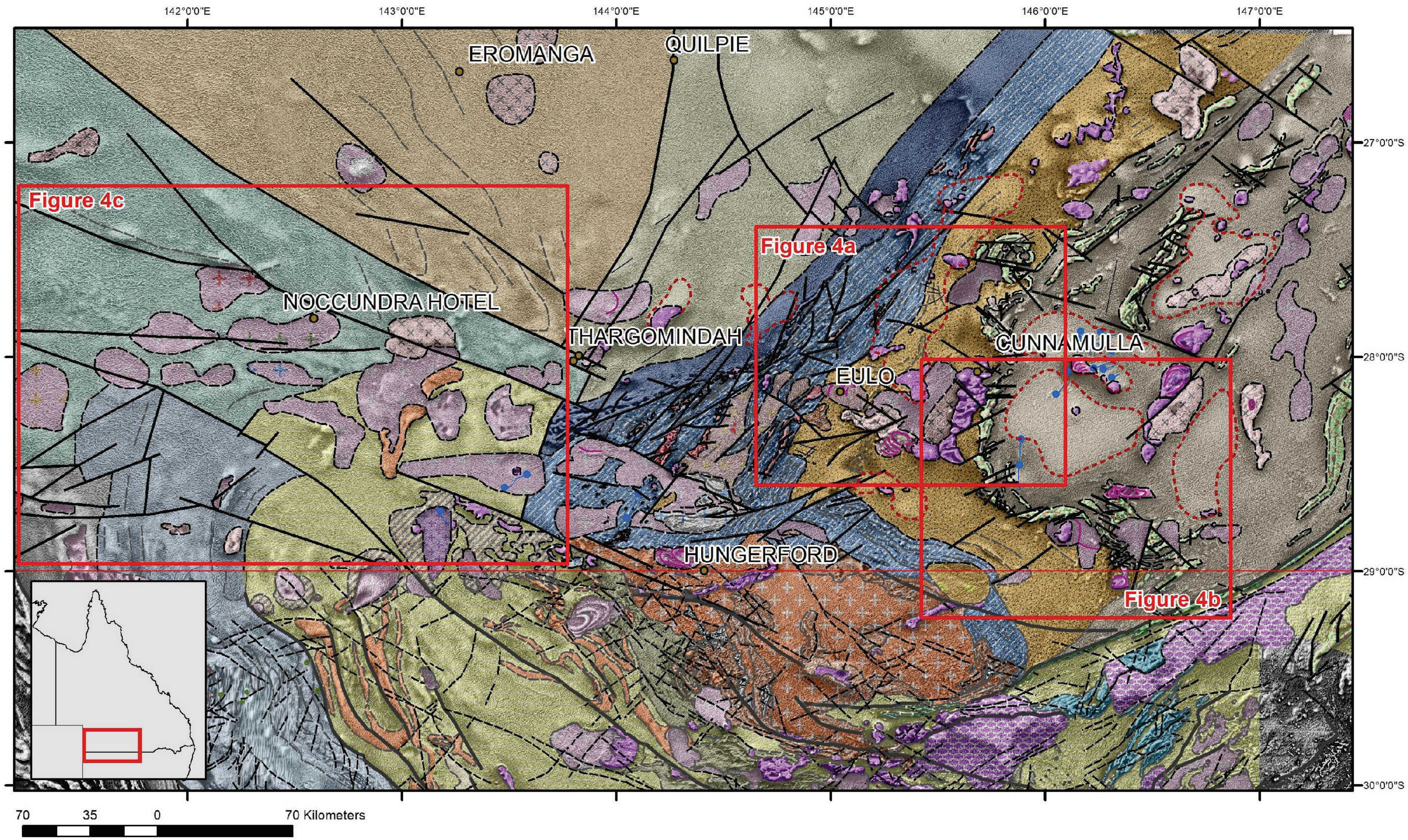

Figure 4: Basement geology map on greyscale 1VD magnetics image

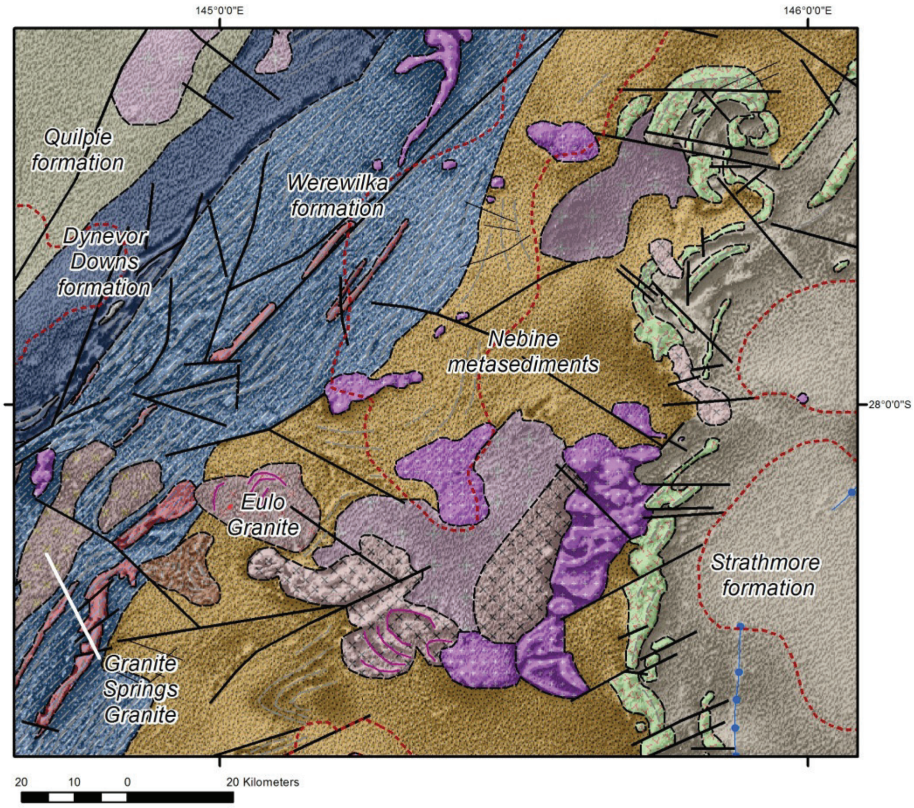

Figure 4a: Geophysical (magnetic) character of key metasedimentary units and some granites in the southern Thomson Orogen

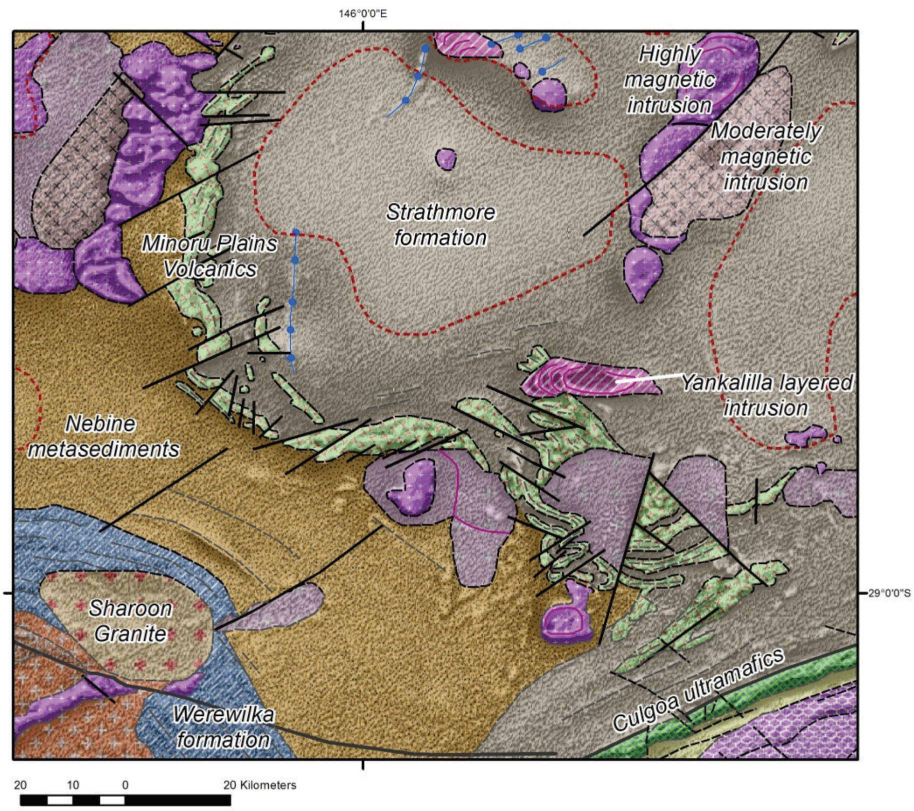

Figure 4b: Possible volcanic unit (Minoru Plains Volcanics) forms a marker horizon and is deformed into large-scale open folds. Moderately and highly magnetic intrusions also observed in this area

This unit may correlate with multiply deformed metasediments intersected in drill holes on the Nebine Ridge and hence is informally called the Nebine metasediments.

The most striking unit in terms of geophysical appearance is referred to informally as the Werewilka formation (Figure 4; 4a). This unit exhibits a strong stripey appearance relating to alternating high and low magnetic horizons and serves somewhat as a marker unit. As such the unit appears to define a broad antiform with a north-west trending axis and faulted hinge zone. Although this unit does not outcrop and is not intersected in petroleum drill holes, it may be sampled by xenoliths which are abundant in the S-type Granite Springs Granite. Detrital zircon dating is planned for these xenoliths. The origin of the distinct magnetic signature is unknown but may relate to the presence of pyrrhotite in carbonaceous parts of the sequence as observed for units with a similar magnetic character in New South Wales (Hegarty, personal communication). Alternatively, highly magnetic horizons may relate to relatively thin volcanic deposits.

A fourth geophysical domain that may represent a metasedimentary unit occurs to the west of the Werewilka formation and is marked by large areas of reverse magnetisation (Figure 4a). This unit extends into an area of deep cover where it becomes poorly defined in geophysical images. The distribution of this unit, particularly to the west and north is therefore relatively unknown. The unit is informally named the Dynevor Downs formation and designated as a metasedimentary sequence because internal trends parallel those in the adjacent Werewilka formation. However, little is known about the composition of the unit and it remains somewhat mysterious.

To the west of the Dynevor Downs formation, large areas of turbidites are informally mapped as the Quilpie formation and Thargomindah formation. Further west again, distal starved turbidites observed in drill cores are used to roughly define a separate unit. Due to lithological correlation with the Warburton Basin, this is referred to as the Lycosa formation (Sun & Gravestock, 2001).

Metavolcanic? rocks

While some of the metasedimentary units described above may contain minor volcanic horizons, a more significant and clearly defined unit can be mapped to the east around Cunnamulla. This unit may form an important marker horizon and is informally named the Minoru Plains Volcanics. No direct information is available for this unit and the distribution is entirely based on geophysical images where it forms clear, magnetic high domains truncated and displaced by interpreted minor faults. Given the highly magnetic character and linear distribution, it is likely that these features represent mafic to intermediate volcanic-rich intervals. The volcanics are potentially a correlative of the Warraweena Volcanics interpreted in New South Wales (Hegarty, 2010) but may also be an entirely separate volcanic unit (a cohesive stratigraphy is yet to be defined).

On a large scale, the unit is broadly deformed into open folds with north-east trending axes paralleling the Werewilka formation (Figure 4b). It is an obvious target for any potential future drilling programs and may include lithologies/environments prospective for mineralisation. Additionally, the age and geochemistry of the unit may provide important constraints for the tectonic development of the Thomson Orogen.

Intrusive rocks

Intrusive rocks in the southern Thomson Orogen are observed in basement intersections of petroleum drill holes and small areas of outcrop on the Eulo Ridge. Many are also clearly apparent in magnetic and gravity data. Descriptions from petroleum drill cores are compiled in a recent database product (Brown & others, 2012) and suggest that intrusive rocks exhibit a wide range of textures (fine-grained and equigranular to coarsely porphyritic), compositions (quartz diorite to monzogranite), and degree of alteration. They have recently been resampled and dated by the GSQ and also as part of a collaborative project with QUT. Ages range from ~400–480Ma. New gravity data has helped to define the distribution of these intrusions.

Outcropping intrusions form the only exposed basement rocks in the southern Thomson region. As such they are valuable resources and are described and dated (~380–456Ma, Bultitude & Cross, 2013). Each of the outcrops have different characteristics and are considered separate bodies. Interestingly, areas of outcrop do not correlate with obvious plutons in geophysical images making them difficult to map and raising the possibility that more ‘geophysically invisible’ granites exist through the region. The most extensively outcropping unit is the S-type Granite Springs Granite. This is a very distinctive coarsely porphyritic biotite, muscovite, alkali feldspar granite to monzogranite with abundant alkali feldspar phenocrysts ranging to 10cm length and common metasedimentary enclaves. Phenocrysts are locally strongly aligned parallel to a regional north-east fabric revealed in magnetics images (Figure 4a). Shear zones and thin aplitic dykes and quartz veins are also common and have the same trend.

The new gravity and magnetic data acquired in the southern Thomson Orogen region reveal that intrusions are far more abundant than originally thought. Intrusions occur throughout the region, but on a broad scale appear to be concentrated in wide but distinct bands or linear belts (Figure 4). One belt extends in a north-east orientation parallel to the regional trend of metasedimentary units. This belt is marked by a distinct gravity low and numerous distinct plutons. The other belt extends from the vicinity of Hungerford north-west and west to the South Australia border where it curves to the south-west. This belt of intrusions essentially truncates the northerly regional trends of metasedimentary units and is dominated by ovoid-shaped non-magnetic intrusions (Figure 4c).

On a smaller scale, intrusions exhibit a wide range of sizes, shapes, and geophysical characteristics reflecting different compositions, compositional variation, styles of emplacement, and ages. Some broad categories of intrusions are defined (Table 1).

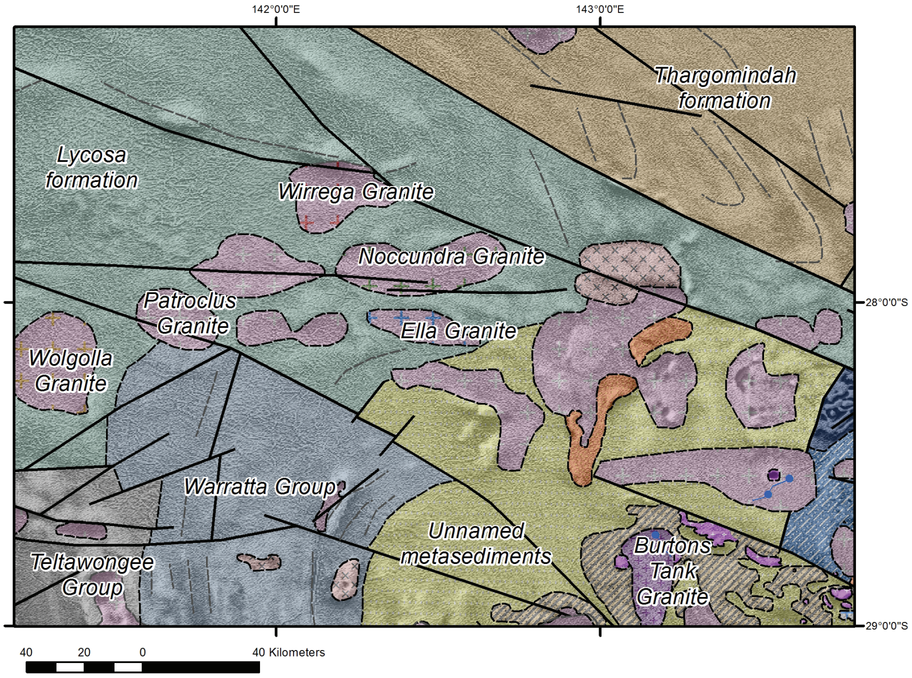

Figure 4c: Roughly east–west trending belt of non-magnetic intrusions (Wolgolla-Ella suite)

Table 1: Broad categories of intrusions in the southern Thomson Orogen

Category	**Description**	**Example**
Non-magnetic	Most abundant/voluminous type of intrusion. Commonly ovoid-shaped bodies marked by distinct gravity lows. Often surrounded by narrow magnetic high zones interpreted as contact aureoles. Some exhibit more distinct magnetic rims or cores indicating zonation/ internal compositional variation. Very abundant in the broad linear belts. Probably represent individual granitic or alkali granite plutons. Many appear relatively young.	Wolgolla-Ella suite of intrusions. 418.8±2.8Ma; 428±5Ma (Figure 4c)
Moderately magnetic	Less abundant than non-magnetic intrusions. Generally occur as well-defined, large oval or irregularly-shaped bodies. Some clearly represent single individual plutons while others appear to be multiphase bodies associated with more felsic and more mafic phases. May represent intermediate composition (granodiorite) plutons.	Figure 4b
Highly magnetic	Abundant but generally small-sized and irregularly-shaped bodies. Occur both as discrete individual bodies and in association with larger less magnetic (more felsic) plutons. Some areas of broad/ vague magnetic high domains may represent larger highly magnetic intrusions at depth (i.e. not on the basement surface). Some bodies exhibit internal banding/zoning. Interpreted as gabbroic or dioritic composition intrusions.	Yankalilla layered intrusion (Figure 4b)
Diatremes	Small, circular, normal or reversely magnetised bodies. Commonly occur in clusters of >5 individual bodies. Interpreted as diatremes.	
Gneiss/S-type	Highly irregular-shaped domains comprising curved to vaguely linear low to moderate magnetic trends. Difficult to define. Some are clearly part of the regional fabric and may represent interleaved granite and metamorphics. Probably relatively old.	Granite Springs Granite (~456Ma) (Figure 4a)

Where possible, intrusions are given informal names based on drill holes that intersect them or nearby towns or homesteads.

Conclusions

The southern Thomson Orogen basement geology interpretation map draws upon many data sources including petroleum drill hole descriptions and cores, minor outcrop, water bores, seismic, gravity, and magnetics. The map is seamless with a similar map produced for the New South Wales part of the Thomson Orogen by the Geological Survey of New South Wales. In Queensland, the southern Thomson Orogen area is dominated by metasediments. These are mostly turbidites that exhibit low grade metamorphism and a single slaty cleavage. However, several different units of differing magnetic and gravity character can be defined and are informally named. A distinctive, highly magnetic domain is interpreted as a volcanic unit and forms a marker horizon. The area is very structurally complex but may overall define a large, faulted antiform with a north-east trending axis. Intrusive units are very abundant and many different types and ages of intrusions occur. The majority appear to form broad belts although the importance of the location, orientation and age of these belts are yet to be established.

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New results, observations and future plans: The joint GSQ-GA Thomson geochronology project

Patrick Carr[2], Andrew Cross[1], David Purdy[2], Dominic Brown[2] and Natalie Kositcin[1].

[1]Geoscience Australia, [2]Geological Survey of Queensland

The GSQ-GA Thomson Orogen project aims to better understand the timing of deposition, metamorphism, provenance and source characteristics of the rocks occurring undercover throughout Queensland.

Fundamental to this investigation is multi-component, *in situ* analysis of detrital zircons. Zircons are unique in that their extreme resistance to chemical and physical abrasion safeguards their internal geochemistry and isotopic integrity. These minerals often display complex internal zoning attributed to different periods of growth and recrystallisation. Established methods use a spot (sample) size of about 30µm diameter, allowing for independent sampling of internal zoning.

The multi–component analysis involves SHRIMP U–Pb (GA), LA–ICP–MS, Lu–Hf analysis and SHRIMP O–18/O–16 analysis (ANU) of the same spots. This multi–component approach has become increasingly popular amongst researchers, as it not only provides a maximum depositional age and provenance information, but also gives further insight into sedimentary source(s).

SHRIMP U–Pb detrital zircon ages obtained during this study identify two successions within the undercover Thomson Orogen; the Cambrian–Ordovician "Gondwana succession" (n=4) and an older "?pre-Gondwana succession" (n=1).

The Gondwana succession has been identified in four widespread metasedimentary samples and is characterised by a maximum depositional age of ~495Ma, and major provenance peaks between 500–520Ma, 565–580Ma and 1050–1200Ma. This age spectra is also identified throughout central and eastern Australia, in western New Zealand and eastern Antarctica. It is believed to represent a huge depositional system forming outboard of and within Gondwana following the early Terra Australis Orogen. Locating the source of these sediments is problematic with some authors suggesting a local source (Delamerian Orogen) and others suggesting a more distant source (Kalkarindji Large Igneous Province or the Mozambique Orogenic Belt). Continuing Lu–Hf and O isotopic analysis will help to further constrain possible sources.

The older, ?pre-Gondwana succession has so far only been identified in a single quartzite unit on the north-western edge of the subsurface Thomson Orogen (Goleburra 1), however it is also recorded in numerous samples from the Anakie and Charters Towers provinces and within the Koonenberry Belt of NSW. The sample records a maximum depositional age of 1074Ma, a major peak between ~1100–1300Ma and a minor peak between ~1500–1600Ma. The source of these sediments is thought to be either the Musgrave Inlier, uplifted between ~570–530Ma, or its proposed subsurface extension into Queensland (Agwamin Seismic Province). This is further evidenced by new $\varepsilon Hf_{(t)}$ values which are broadly comparable to samples of the Musgrave Inlier.

Unlocking the southern Thomson's hidden mineral resource potential

Richard Blewett

Geoscience Australia

Due to extensive cover by Mesozoic and younger sedimentary basins and regolith, the geology of the southern Thomson Orogen is poorly understood. Small outcrops of the Thomson Orogen are exposed along the Eulo Ridge (south Qld) and in the south-west around Tibooburra (NSW). Proximal to these regions the average thickness of cover is estimated to be <200m, which is within current economic exploration and mining depths.

The southern Thomson Orogen is true 'greenfields' country. Although the mineral potential of the region is largely unknown, the north-eastern Thomson Orogen is well mineralised (e.g., Thalanga, Charters Towers), as is the similarly-aged Lachlan Orogen to the south (e.g., Cadia, Cobar, Tibooburra). In order to encourage exploration investment into the southern Thomson Orogen, Geoscience Australia, the Geological Survey of Queensland and the Geological Survey of New South Wales have commenced a three-year collaborative project to collect new (and synthesise existing) pre-competitive geoscience data.

The first year and a half of the project will synthesise existing datasets across the state borders to create a seamless solid geology map. This map will form the basis of a 3D model (map), which will utilise pre-existing government and industry seismic and drilling data. In support of the 3D map, several programmes of geophysical data acquisition, processing and interpretation will be undertaken. These include: airborne electromagnetic (AEM), broad-band magnetotelluric (MT) and gravity data, amongst others. In order to understand the nature of the cover rocks and their relationship to basement, a surface geochemical survey will also be completed to provide higher resolution infill of the existing National Geochemical Survey of Australia (NGSA) dataset.

In addition, the potential mineral systems of the region will be assessed and a gap analysis conducted, with these results and the 3D and cover maps informing a planned drilling programme to be conducted in 2014–15. The drilling methods will be informed by the results of a similar pre-competitive drilling project in the Stavely Zone of western Victoria.

Prior to drilling, a number of geophysical techniques will be applied in the vicinity of the proposed holes to aid selection and improve prediction of expected cover depths. The actual drill holes will test the predictive capacity of the various pre-drilling geophysical techniques — a useful outcome in itself. The recovered core will be analysed with a range of geochemical, geochronological, geophysical and geological techniques. The combined results will be synthesised and integrated into a pre-competitive geoscience data package to encourage exploration investment.

Interim products and datasets will be released throughout the project, with the final results delivered to industry in 2016.

Cape York Mineral Resource Assessment

Joseph Tang, Dominic Brown, David Purdy and Patrick Carr

Geological Survey of Queensland

The Geological Survey of Queensland (GSQ) within the Department of Natural Resources and Mines is evaluating the mineral resource potential of the Cape York region under the Queensland Government's Future Resource Program. With renewed support for mining from indigenous communities on Cape York, the new initiative will re-assess the mineral potential using new and existing geochemical data and new geological information and knowledge. The aims of this program are to assist with Cape York regional planning and to potentially create new opportunities in the region.

An earlier National Geochemical Survey of Australia or NGSA Program (2006–2010) undertaken by the GSQ and Geoscience Australia (GA) sampled the entire Australian continent to establish the broad scale Geochemical Atlas of Australia (report download from http://www.ga.gov.au/energy/projects/national-geochemical-survey/atlas.html). Statistical analysis of the Cape York data identified 23 major river catchments (defined as catchment >5500 sq km) as geochemically anomalous for a range of elements such as rare earth, tungsten, tin, uranium, antimony, bismuth and arsenic (Tang & Brown, 2010). A summary of anomalous riverine catchments in Cape York for the different elements is tabulated below.

Element	**Anomalous catchment in the Cape York region**
Aluminium	Pine River, Kendall River, Saltwater Creek
Antimony	Walsh River
Arsenic	**Mitchell River,** Cape Melville, Normanby River, Walsh River,
Barium	**Einasleigh River**, Smithburne River,
Beryllium	**Mitchell River**, Einasleigh River, Lynd River, Saltwater Creek, Tully River, Walker Creek, Watson River
Bismuth	Herbert River, Kendall River, Lynd River, Mitchell River, Saltwater Creek, Tully River, Walsh River
Cobalt	Watson River
Lead	Carron River, Gilbert River, Saltwater Creek, Tully River, Walsh River
Lithium	Daintree River, Kendall River, Pine River
Molybdenum	Ducie River, Jackson River, Kendall River, Pine River
Selenium	Jackson River
Tantalum	**Mitchell River**, Herbert River, Lynd River
Tin	**Mitchell River**, Herbert River, Lynd River, Walsh River
Tungsten	**Mitchell River**, Barron River, Crosbie Creek, Lynd River, Normanby River, Pascoe River, Staaten River, Walsh River
Uranium	Lynd River, Saltwater Creek, Tully River
Total REE	**Lynd River**, Carron River, Mitchell River, Palmer River, Tully River, Walker Creek, Watson River

Note: Bold highlights strong anomalies along major sections of the river.

The Cape York Resource Assessment project is a follow-up program to sample subcatchments within larger anomalous catchments. The primary aims are to establish better constraints on the anomalies and find potential causes of geochemical anomaly, which may result from localised mineralisation and/or an elevated regional background levels. The results from this project have strong implications on the mineral potential of the region as well as other practical uses in medical geology, agriculture and environmental science.

Specific objectives

The specific objectives of the mineral resource assessment project in the Cape York region are to:

- sample a total of 208 target sample sites at an increased sampling density of one sample per 500 square kilometres
- collect overbank, bank or transported regolith samples at or close to the outlet of subcatchments
- prepare and analyse the samples to extract the maximum geochemical information (68 elements) using internally consistent, state-of-the-art techniques
- appraise the mineral resource potential of the 208 subcatchments and sub-tributaries for all 68 elements
- complete a follow-up mapping program to establish a new understanding of the geology, construct a geological framework, and investigate the cause of geochemical anomalism and assess resource potential of the regions.

Catchment definition and target sample sites

The drainage subcatchments used in this project are based on digital elevation modelling using the GEODATA 9 Second Digital Elevation Model (DEM-9s) v.2. The Australian Nested Subcatchments (ANCS-C) that are used as the basis for drainage sampling in this project were generated by the Centre for Resource and Environmental Studies at the Australian National University in Canberra (Hutchinson & others, 2000).

The target sample sites are defined using a combination of digital elevation modelled ANCS-C subcatchments, the Queensland 250K drainage systems and road access. The spatial distribution of sites is based strongly on expertise from previous geochemical sampling and mineral exploration experience. Samples are targeted near the subcatchment outlets and, in poorly defined drainage, are targeted at or as close as possible to their lowest point in the subcatchment. In some instances, the configuration of drainage pattern rather than subcatchment boundary is used in site selection and such sites may fall just outside a subcatchment.

The average sampling density is aimed at 1 site per 500 square kilometres or less, and this is a practical density for explorers as well as the GSQ mappers to complete follow up investigations. The sampling program takes advantage of the natural mixing of materials derived from various source lithologies within catchments and the subsequent deposition in low-energy environments near their outlets. Ideally, the floodplain or overbank sediment chemistry can represent the average, background geochemical composition of the subcatchments.

Field Programs

The mineral resource assessment project is divided into two phases: Phase 1 is for geochemical sampling and Phase 2 is for geological mapping.

Phase 1 sampling program is divided into two stages based on geographic distribution of sample sites (Figure 1). A total of 208 subcatchment target sites are planned for stream sediment sampling. The detailed field procedures and sampling method to be used in the Cape York project is based on established methodology designed by Geoscience Australia (Lech & others, 2007). The sample collection methodology has been used in similar geochemical programs in other states and overseas and has to be strictly adhered to. Subcatchment outlet sediments are sampled at two depth intervals from 0–10 cm below the surface for the top outlet sediment (TOS) and from

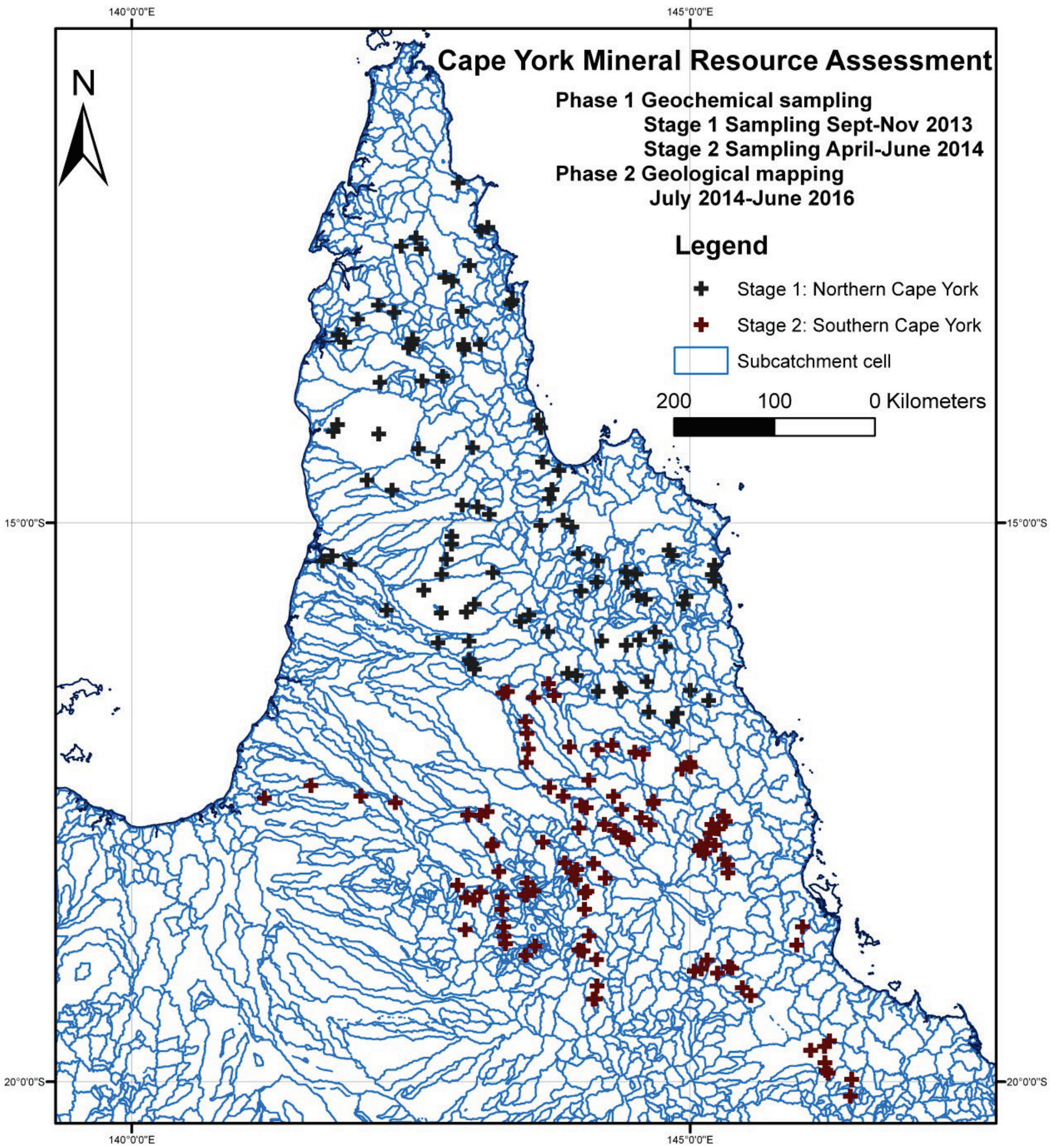

Figure 1: Target sample sites for the Phase 1 subcatchment sampling program in Cape York. Stage 1 of the sampling program has been completed

60–90 cm below the surface for the bottom outlet sediment (BOS). The fieldwork also involves recording observations of the characteristics of soil material at the surface and immediately below the surface. The maximum amount of material removed from any site will be less than 5kg and any superficial ground disturbance will be less than 2 square metres. Stage 1 involved sampling subcatchments in the Northern Cape York region and this sampling program has been completed. The second stage will sample target sites in the Southern Cape York region, and the work program is planned for May–June 2014 after the annual wet season.

Phase 2 of the program planned for July 2014 to June 2016 will involve geologic and mineral occurrence mapping for areas identified as anomalous from the earlier sampling program. The regional geology will be re-interpreted using new field observations, tectonic and geochronological understanding, and geophysical data acquired by GSQ through previous initiatives. It is estimated that approximately 200 whole rock, geochronology, isotopic and mineralised samples will be collected and assayed in Phase 2 to answer key scientific questions. A key outcome of the mapping phase is to revise the 1:250 000 scale geological maps of the Coen and Cape Weymouth areas. This mapping initiative will improve understanding of the geological history of this part of the North Australian Craton and northern Thomson Orogen. Potential quarry rock materials for Cape York will also be mapped as part of the mapping and this information is vital for future development of the region.

Sample preparation

All stream sediment samples collected for the Cape York project will be sent to the GA laboratory in Canberra for processing. The contents of the TOS sample will be thoroughly mixed during sample preparation; likewise for the BOS sample. The bulk sample will be weighed, dried (for a minimum of 48 hours at 40°C) and sieved through a 3.35mm mesh to remove any foreign material. Clay clumps or soil aggregates are gently broken up, with care being taken not to crush rock fragments or hard nodules. The bulk material is tested for:

- pH 1:5 (soil:water) and electrical conductivity (EC) 1:5 (soil:water) analysis
- X-ray diffraction (XRD) analysis.

The bulk material is sieved through a 2mm mesh, and subsequently split into two portions of approximately 20% and 80%. The <2mm fraction represents the bulk sample (minus larger rock, flora and fauna animal fragments). Sub-samples from the 20% split (i.e. <2000µm) will be used for:

- Platinum group element (PGEs) analysis
- Gold (Au) analysis after aqua regia (AR) leach and inductively coupled plasma-mass spectrometry (ICP-MS) analysis of multi-elements
- 50g of the <2000 micron TOS sample is analysed for mobile metal ion-multi element extraction (MMI ME) content.

The remaining material from 20% split (after the above analyses) is milled to a fine powder, which will be further split for:

- Fluoride (F) analysis

- Selenium (Se) analysis
- X-ray fluorescence (XRF) and inductively ICP-MS analysis.

The 80 % split of <2mm sample is further sieved through a 75µm mesh to obtain the 'Fine Fraction' stream sediments or the <75µm sample fraction. The <75µm fraction is representative of the finer (mostly silt- and clay-sized) sediment and regolith particles and exhibits a stronger geochemical contrast compared to background (signal-to-noise ratio). This fraction also requires no milling, and in most cases minimal sieving, and is split for:

- XRF and ICP-MS analysis
- Au analysis after aqua regia (AR) leach and ICP-MS analysis of multi-elements.

The complete assay result from Phase 1 geochemical sampling is anticipated in February 2015, and the data will be analysed and synthesised to establish geochemical anomalies and potential mineral systems in Cape York.

Summary

The Cape York geochemical sampling project aims to sample all 208 subcatchments in the Cape York region using an internally consistent methodology in accordance with the procedures set up by Geoscience Australia. The new geochemical data from this project will be used to appraise the mineral potentials of the region and will revitalise mineral exploration interests in Cape York leading to the possible discovery of strategic rare-earth mineral resources.

The mapping initiative will improve understanding of the geological history of this part of the North Australian Craton and northern Thomson Orogen. Mines, mineral occurrences and potential quarry rock materials for Cape York will also be mapped and this information is vital for the future development plans of the region.

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Identifying mineral and extractive resources in the land use planning system

Mal Irwin

Geological Survey of Queensland

The Queensland Government is committed to developing a planning system that delivers efficiency, consistency and certainty about the types of land uses that can occur in regions. This is a key component in planning for action to drive economic growth over the next decade. The Geological Survey has a key role in identifying resource locations and associated infrastructure needs and developing relevant planning approaches.

One key driver for the current planning initiatives is the need to balance the economic potential offered by mining and gas extraction in the major coalfields against the risk of permanent loss of agricultural land. Another matter of key economic interest for the future is striking a balance between environmental protection and access to valuable mineral or petroleum resources on Cape York and in the western rivers' catchments. Agricultural and tourism activities will offer increasingly significant economic benefits during the 'Asian century'. These examples illustrate the principle that economic development through intensification of competing land uses needs to be guided by resource data to ensure that the best opportunities for future development are identified and nurtured.

This is especially relevant for extractive materials which need to be located close to the urban markets that threaten to expand and alienate the resources which enable their construction.

The Department of State Development, Infrastructure and Planning (DSDIP) is developing a new State Planning Policy (SPP) that addresses several planning issues as matters of state interest under the government's Four Pillar economic development model. The economic development component of the new SPP will identify 157 Key Resource Areas for extractive materials, and advise local governments on planning protection for mineral and coal resources and petroleum infrastructure.

The Geological Survey of Queensland (GSQ) has developed the extractive resource KRAs and has advised DSDIP on the structure and contents of the new SPP and associated guideline. GSQ will continue to collate and develop spatial data on extractive and mineral resources to guide planning and development decisions.

Statutory Regional Plans for the Darling Downs and Central Queensland regions have recently been released. The key aim of those plans is to provide a regional context for expression of the state interests identified in the SPP, and thereby foster diverse and strong economic growth by resolving land use conflicts between agricultural and mining activities and the need for urban expansion. The regional plans also serve to identify infrastructure needs and locations.

The Cape York Regional plan, currently undergoing public consultation, will be designed to balance appropriate economic development with the protection of Cape York's iconic natural areas of high conservation value. Replacement of the Wenlock Basin, Archer Basin, Stewart Basin and Lockhart Basin Wild River Area declarations will occur as part of the regional planning process to enable appropriate development within the region and give local communities greater control of their own economic future.

Development of new regional plans for the remainder of Queensland will continue, with development of the Southeast Queensland Regional plan already commencing. The Wide Bay – Burnett, Mackay–Whitsunday and Far North Queensland regions will also be reviewed in the foreseeable future.

Most surface land resources and environmental values are readily mapped. Planning for most land use types can refer to surface features. In contrast, the subterranean nature of earth resources means that they are at risk of sterilisation by inadvertent placement of incompatible land uses over them. Extraction of resources also generates considerable impacts over areas adjacent to the resource and transport routes.

The risk of sterilisation by other land uses warrants development of specific planning tools which identify resource locations. Ancillary issues arising from extractive activities, such as transport routes, associated infrastructure and appropriate 'separation areas' to maintain buffer space around valuable resources, need to be incorporated into such tools. The 'separation area' identifies where encroachment of sensitive uses must be prevented by appropriate planning measures to allow future operations to meet environmental standards.

This is the essence of the Key Resource Area (KRA) concept as applied in the State Planning Policy 2/07: Protection of Extractive Resources (SPP 2/07). This concept was designed by the former Department of Mines during the 1990s and the current Resource Planning unit in GSQ is responsible for identification of new Key Resource Areas and other resource interests. This includes inclusion of resource interests in regional council and city planning schemes, such as granted mining tenures and KRAs from SPP 2/07.

GSQ has the sole responsibility for collating extractive resource data, assessing the planning situation for each significant resource and drafting KRAs where appropriate. GSQ may also be asked to comment on developments within KRAs.

In addition preliminary outlines of various levels of prospectivity for a wide range of mineral and energy commodities have been developed and provided to DSDIP as a key component in identifying potential for future resource discoveries. This work is based on existing mineral occurrence data held in IRTM, geological and geophysical mapping and general metallogenic principles. At this stage the work is qualitative, using GIS assisted techniques. Future iterations of these regional plans will be able to apply upgraded assessments of mineral potential based on programs planned by the GSQ over the next few years.

GSQ provides input into various levels of the planning and assessment system, including the drafting of regional council planning schemes, providing responses to Environmental Impact Statements for major projects and any new regulations and policies that may have an impact on access to resources.

Queensland's Coastal Geothermal Energy Initiative: identifying hot rocks in cool areas

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Geological Survey of Queensland

The Coastal Geothermal Energy Initiative (CGEI) drilling program commenced in November 2010 and concluded in July 2012, with the completion of 10 boreholes fully cored to depths of between 320 and 500 metres. A variety of geological settings along the State's north and east coasts had been targeted in the drilling program to collect new pre-competitive geoscientific datasets for geothermal energy.

The new datasets collected from the CGEI drilling program have indicated moderate to high heat flow values, between 71 and 113mW/m^2, which are higher than previous estimates. These values are above the global average and highlight possible geothermal energy potential across the Millungera, Surat, Hillsborough and Maryborough basins. Using the newly established heat flow data, modelled temperatures of 187–240°C are predicted at 5km depths, based on which, total thermal energy content as well as equivalent electric power generation potential has been estimated for the highlighted regions in each basin. As an example, geothermal energy assessment of the Millungera Basin is presented here in more detail. A similar approach was applied to other highlighted basins to assess their potential.

Detailed exploration programs are required to refine geothermal energy potential across the highlighted basins. The viability of exploration programs within the highlighted basins is favourable due to the close proximity to centres of population, industry including mining, or power transmission lines.

Keywords: Queensland, geothermal energy, drilling, heat flow, thermal energy, Monte Carlo simulation.

Project Background

Queensland's known geothermal energy resources are located in the far south-west of the state, beneath the Cooper and Eromanga basins. This is a long way from the existing national electricity grid and major population centres, preventing economic viability of the resources in the near term. The $5 million CGEI was established to investigate additional sources of hot rocks for geothermal energy close to existing electricity infrastructure along the State's northern and eastern coastal strips. The CGEI included a shallow drilling program to collect pre-competitive geoscientific datasets. The main purposes of this initiative were firstly to increase knowledge of the crustal temperatures along the 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.

Data Collection

A precise crustal heat flow determination program was planned as part of the CGEI drilling program to evaluate the geothermal prospectivity of selected geological provinces along the Queensland coast. Moderate to high heat producing intrusives of Proterozoic age, residual heat from Cainozoic volcanism and rifting, and younger low to moderate heat producing intrusives overlain by sedimentary basins with thick coal measures, were targeted for further investigation through the drilling program. The geological setting of the selected targets had been previously discussed in detail in several papers and is not considered further here (Fitzell & others, 2009; Talebi & others, 2010). The drilling program commenced in November 2010 and concluded in July 2012, with the successful completion of 10 boreholes fully cored to depths of 320–500 metres (Figure 1).

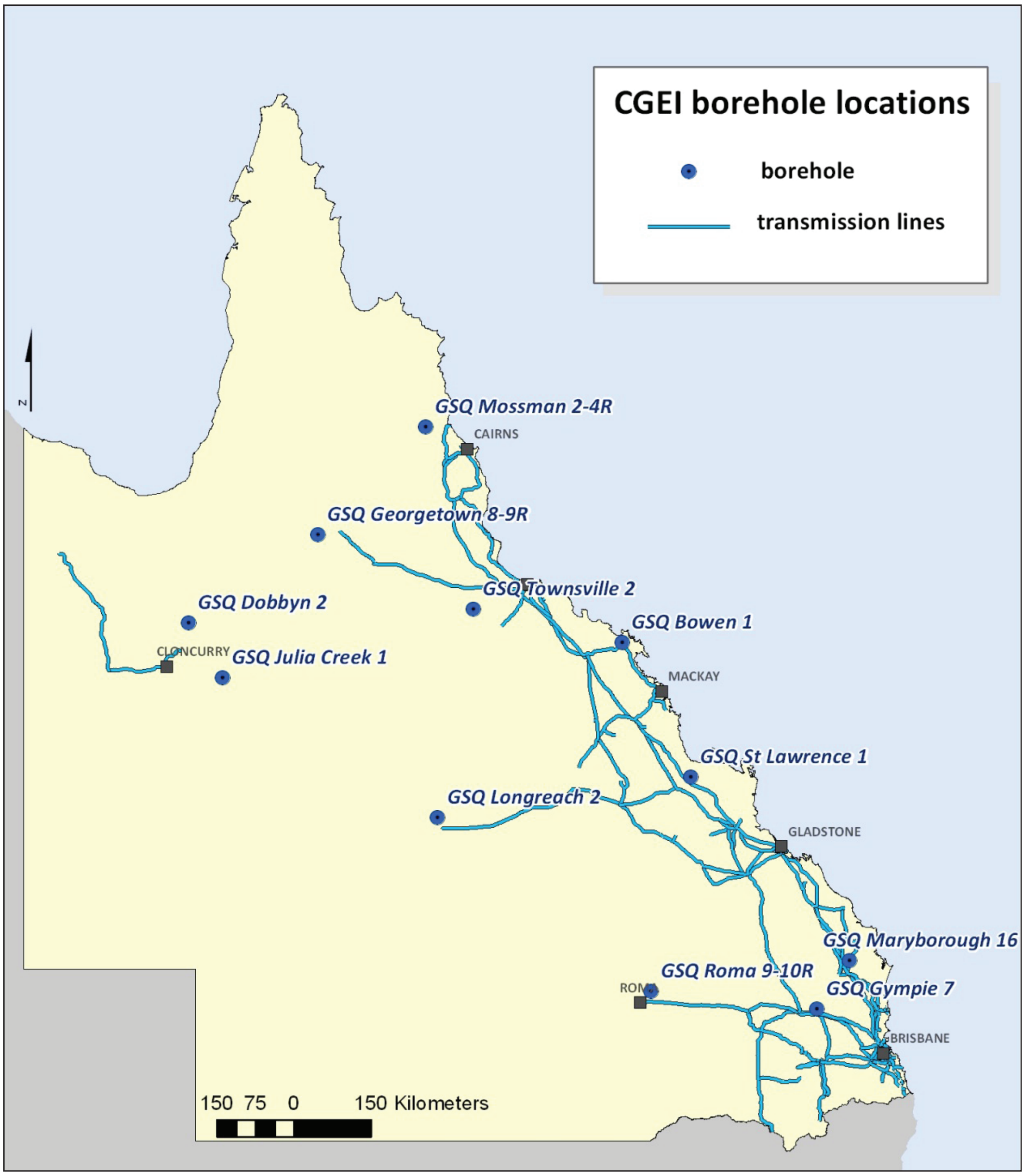

Figure 1: Location of CGEI boreholes

Precision downhole temperature logging was undertaken 6–8 weeks after hole completion, when the hole returned to its thermally equilibrated state, and detailed thermal conductivity analysis of the core samples had been completed for all boreholes. The data have been used to determine vertical conductive heat flow in each borehole using inversion modelling techniques. Temperature dependence of thermal conductivity data was also taken into account, following the method of Sekiguchi (1984). The modelling process has indicated moderate to high vertical conductive heat flow of 71–113mW/m^2, which is higher than previous estimates (Table 1). These values are above the global average and imply possible geothermal energy potential in the respective target drilled.

Table 1: A summary of all modelled heat flow values for CGEI boreholes

Tectonic Unit	Borehole Name	Total Depth (mGL)	Modelled Interval (m)	Harmonic Mean Conductivity (W/mK)	Mean temp. gradient (°C/km)	Heat Flow (mW/m^2)
Millungera Basin - south	GSQ Julia Creek 1	500	120–480	2.19±0.08	52.82	113.0±2.8
Millungera Basin - north	GSQ Dobbyn 2	500	91–500	1.68±0.04	66.31	107.0±1.7
Surat Basin – Roma Shelf	GSQ Roma 9	336	106–336	2.11±0.10	39.04	82.2±2.4
Hillsborough Basin	GSQ Bowen 1	321	89–321	2.14±0.11	33.06	71.0±2.3
Maryborough Basin	GSQ Maryborough 16	387	61–380	1.97±0.13	34.37	67.4±2.9
Eromanga Basin	GSQ Longreach 2	327	84–310	1.40±0.06	41.75	60.0±2.5
Tarong Basin	GSQ Gympie 7	338	54–337	1.18±0.08	31.78	37.5±1.5
Styx Basin	GSQ St Lawrence 1	340	90–338	1.51±0.04	42.66	64.3±1.1
Georgetown Inlier	GSQ Georgetown 8	320	43–265	3.74±0.12	16.09	56.5±1.0
Hodgkinson Province	GSQ Mossman 2	339	62–265	3.96±0.08	19.80	77.0±0.9

Uncertainty in the heat flow is calculated by propagating the relative uncertainty in the average thermal conductivity of the rock units intersected.

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 by:

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

Where λ and *d* are the thermal conductivity and thickness of the regarded interval; T_0 and T_z represent the temperature at the top and bottom of the interval, respectively. The heat flow at the top of the interval is q_0 and is assumed purely conductive and therefore constant to depth *z*. Although this linear relationship is a simplification of a

Table 2: Input parameters used in the 1D-modelling of temperature to 5km depth beneath the borehole GSQ Julia Creek 1, Millungera Basin.

Tectonic Unit	Age	Bulk lithology	Bulk thermal conductivity (W/mK)	Depth interval (m)
Eromanga Basin	Jurassic–Cretaceous	Mudstone	1.37±0.06	120–236
		Mudstone	1.53±0.05	236–310
Millungera Basin	Palaeo-Mesoproterozoic	Quartzose Sandstone	5.43±0.16	310–1500
Williams Supersuite	Mesoproterozoic	Granitoid	3.20±0.73	1500–3500
Soldiers Cap Group	Palaeoproterozoic	Metasediment	3.26±0.87	3500–5000

Table 3: Temperature and depth projections for CGEI boreholes, based on the established heat flow data from Table 1

Tectonic Unit		Borehole ID	Modelled temperature at 5000m	Depth to cut-off temperature 150°C
Millungera Basin — south		GSQ Julia Creek 1	238 ± 18	3190
Millungera Basin — north	Area A	GSQ Dobbyn 2	232 ± 17	3239
	Area B	GSQ Dobbyn 2	240 ± 15	3098
Surat Basin (Roma Shelf)	Area A	GSQ Roma 9-10R	187± 14	4041
Hillsborough Basin		GSQ Bowen 1	204 ± 16	3880
Maryborough Basin	Area A	GSQ Maryborough 16	205 ± 14	3362
	Area B		209 ± 13	3360
Galilee Basin		GSQ Longreach 2	140 ± 13	5407
Tarong Basin		GSQ Gympie 7	106 ± 9	8063
Styx Basin		GSQ St Lawrence 1	171 ± 16	4235
Georgetown inlier		GSQ Georgetown 8-9R	109 ± 5	7574
Hodgkinson Province		GSQ Mossman 2	138 ± 1	5462

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. It

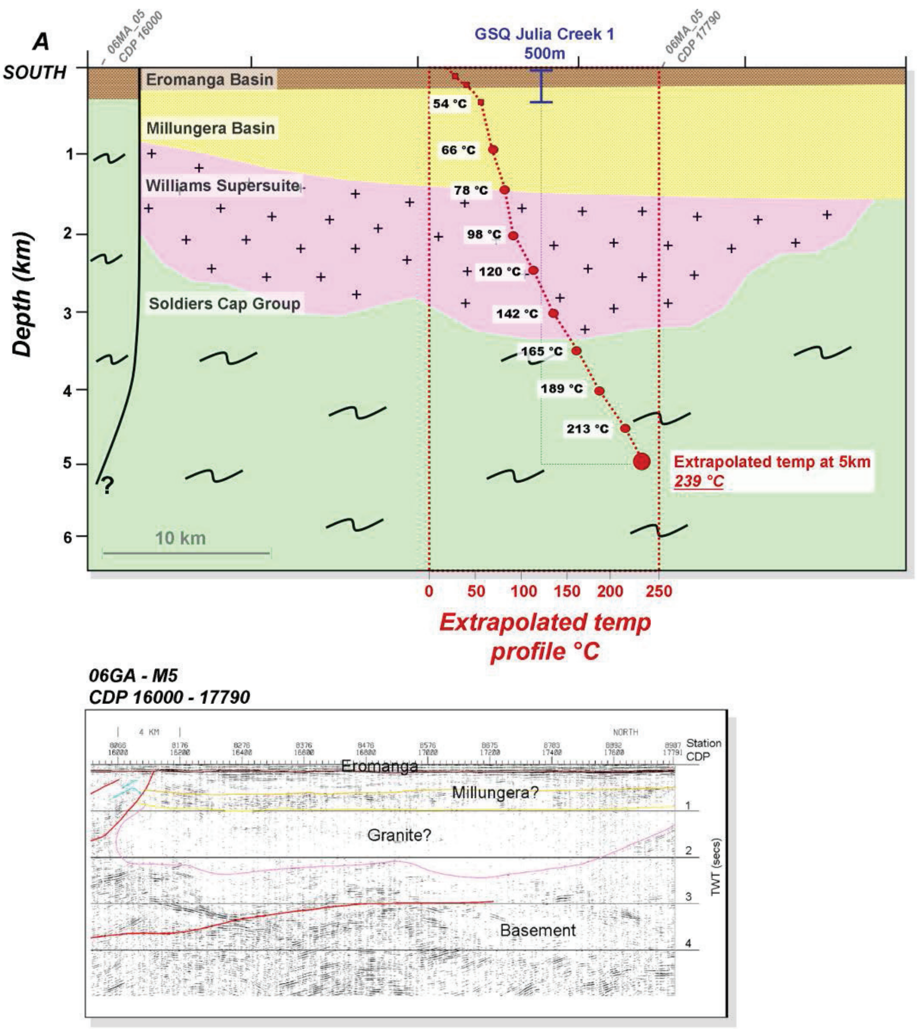

Figure 2: Temperature extrapolation at 5km depth beneath Julia Creek 1, Millungera Basin, based on heat flow of $113 mW/m^2$, in conjunction with geological and seismic cross sections.

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. Table 2 shows the input parameters used in the temperature modelling at 5km depth for the Millungera Basin in the vicinity of borehole GSQ Julia Creek 1. Figure 2 is plot of the modelled temperatures at depth beneath the same borehole in conjunction with the geological cross section of the inferred resource area.

The modelled temperatures at 5km depth range from 187 to 240°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 in the next section. Results of temperature projection at 5km, and depth estimation to the cut-off temperature, are summarised in Table 3. Uncertainty in the projected temperatures was 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 may not produce accurate results. 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.

Geothermal Energy Assessment

An important factor in the assessment of 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 energy assessment. This method is patterned from the works applied by the United States Geological Survey (USGS) on the assessment of geothermal energy resources of the United States (Muffler, 1979). In the application of the volumetric method, it is assumed, for simplicity, that the volume is a box, with a surface area A in the *x-y* plane and thickness z_1-z_0 along the z-axis, where z_1 and z_0 are the lower and upper limits of the geothermal system, respectively. Again for simplicity, it can be assumed that the heat capacity and temperature are homogeneous in the *x-y* plane and are only dependent on depth. The thermal energy content of the system can then be calculated by integrating the product of the estimated heat capacity per unit-volume, C_z, and the difference between the estimated temperature curve, T_z, in the system and the reference temperature, T_0, i.e.:

$$Q = A\int_{z_0}^{z_1} C_z[T_z - T_0]d_z$$

If one assumes that the temperature curve is close to being linear then calculation of the thermal energy is based on the assumption that the temperature is also homogeneous in the *z* direction and therefore constant over the whole system. This constant would then be the mean temperature of the resource, the average between the cut-off temperature and the temperature at the base of the system. Thus, the thermal energy content of the geothermal system containing single phase liquid, say water, can be estimated by the equation below:

$$Q = [(1-\Phi).\rho_r C_r + \Phi\rho_w C_w].V.(T_R - T_r)$$

where:

Q	Total thermal energy, Joule (J)
Φ	Rock porosity, (%)
ρ_r	Rock density, kg/m^3
ρ_w	Water density, kg/m^3
C_r	Rock specific heat capacity, J/kg°C

C_w	Water specific heat capacity, J/kg°C
V	Rock (resource) volume, m^3, (=AH) where A=Rock (resource) surface area, m^2 H=Rock (resource) thickness, m
T_R	Rock (resource) average temperature, °C
T_r	Reference (rejection) temperature, °C

For the highlighted CGEI regions, porosity and presence of fluid (water/steam) at depth are unknown. Furthermore, Sanyal & Sarmiento (2005) indicated that heat in the rock is known to strongly dominate the above equation, even for high porosity rocks with fluid contents. Therefore, it is assumed that the inferred resource rocks of the CGEI targets have negligible porosity, hence negligible fluid content, thus a more simplistic equation is adopted for the thermal energy estimates presented here, in the following form:

$$Q \approx \rho_r C_r V (T_R - T_r) \tag{1}$$

Thermal energy assessment

There are a number of input parameters and assumptions which need to be defined for a thermal energy assessment effort. These parameters and assumptions have been rationalised for the highlighted areas as follows:

Resource mean temperature, (T_R), is 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 3. Currently, there is not enough information to conclude that there is significant lateral temperature variation in the highlighted areas so the resource mean temperature, for simplicity, is assumed to be homogeneous and constant in the entire volume of the respective area.

Reference temperature, (T_r), is the temperature relative to which the thermal energy will be estimated. The choice of the reference temperature is very important since it has a large effect on the estimation of thermal energy. Some choose a reference temperature equivalent to the minimum temperature of the geothermal fluid for the intended utilization. For the purposes of this assessment and in the absence of any more definitive information, it is assumed to be the average temperature between the cut-off temperature (150°C) and the rejection temperature, the temperature of the geothermal fluid after the heat extraction process in the power plant, which is set at 70°C as a typical temperature for rejected fluid by an ORC binary plant with an air cooling system. Therefore, the reference (base) temperature is assumed to be 110°C for the purposes of this assessment.

Specific heat capacity, (C_r), of the CGEI inferred resource rocks at the cut-off temperature of 150°C and above is estimated between 900 and 1000 J/kg°C for plutonic/metamorphic or sedimentary rocks, based on an interpretation of the data presented by Vosteen & Schellschmidt (2003) in Figure 3.

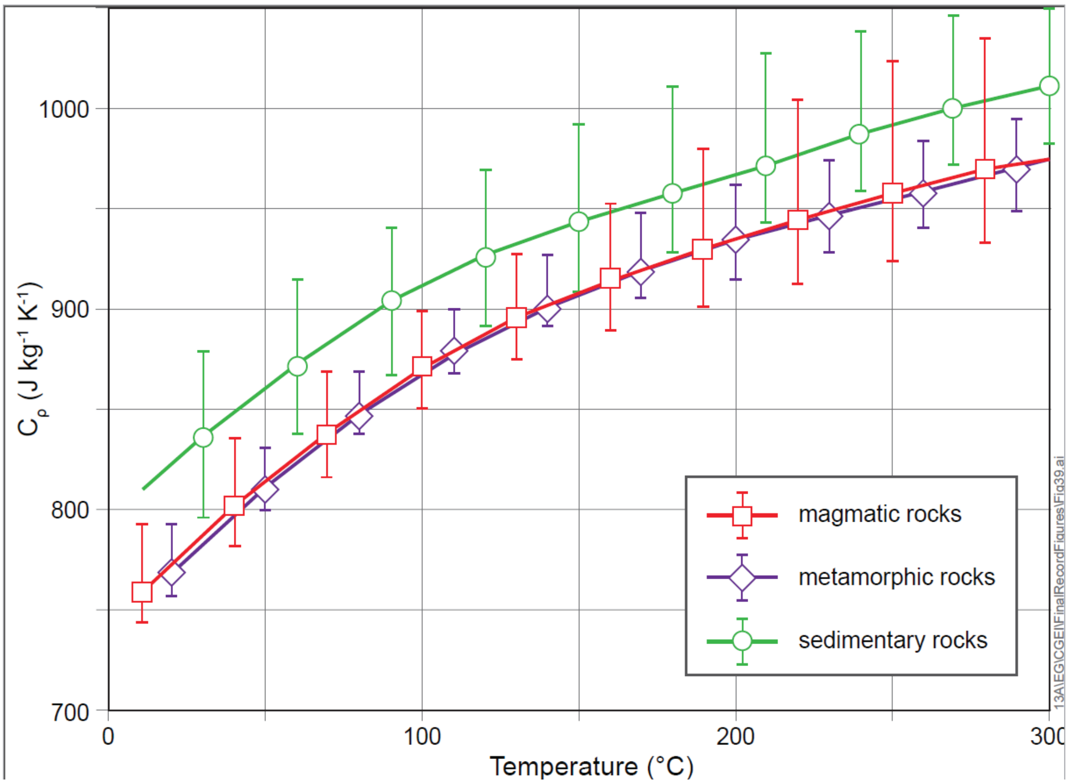

Figure 3: Mean values and ranges of variation of specific heat capacity (C_r) at constant pressure as a function of temperature for magmatic, metamorphic and sedimentary rocks (Vosteen & Schellschmidt, 2003).

Density, (ρ_r), of the CGEI inferred resource rocks is taken between 2600 and 2900kg/m^3 which, based on the GSQ database, is a reasonable approximation for many quartzo-feldspathic rocks within the highlighted areas.

Surface area of the resource, (A), is often defined from available geophysical surveys. For a hot rock project, the area of the resource is defined by the lateral extent of the granitic basement. Both inferred geology and surface development constraints (such as topography and land-use) have been given consideration in the estimation of the surface area of the inferred resources for the highlighted areas. Figure 4 shows the surface area of the resource in the Millungera Basin inferred from the integration of available geophysics data including gravity, MT and seismic.

Resource thickness, (H), is estimated by the depth at which the cut-off temperature of 150°C is exceeded to the base of the resource i.e. to 5km depth.

Using the above parameters and simplified equation (1), total thermal energy content of the highlighted areas has been estimated and reported in petajoules (PJ) in this paper. Both the input parameters and estimated thermal energy are presented in Table 4.

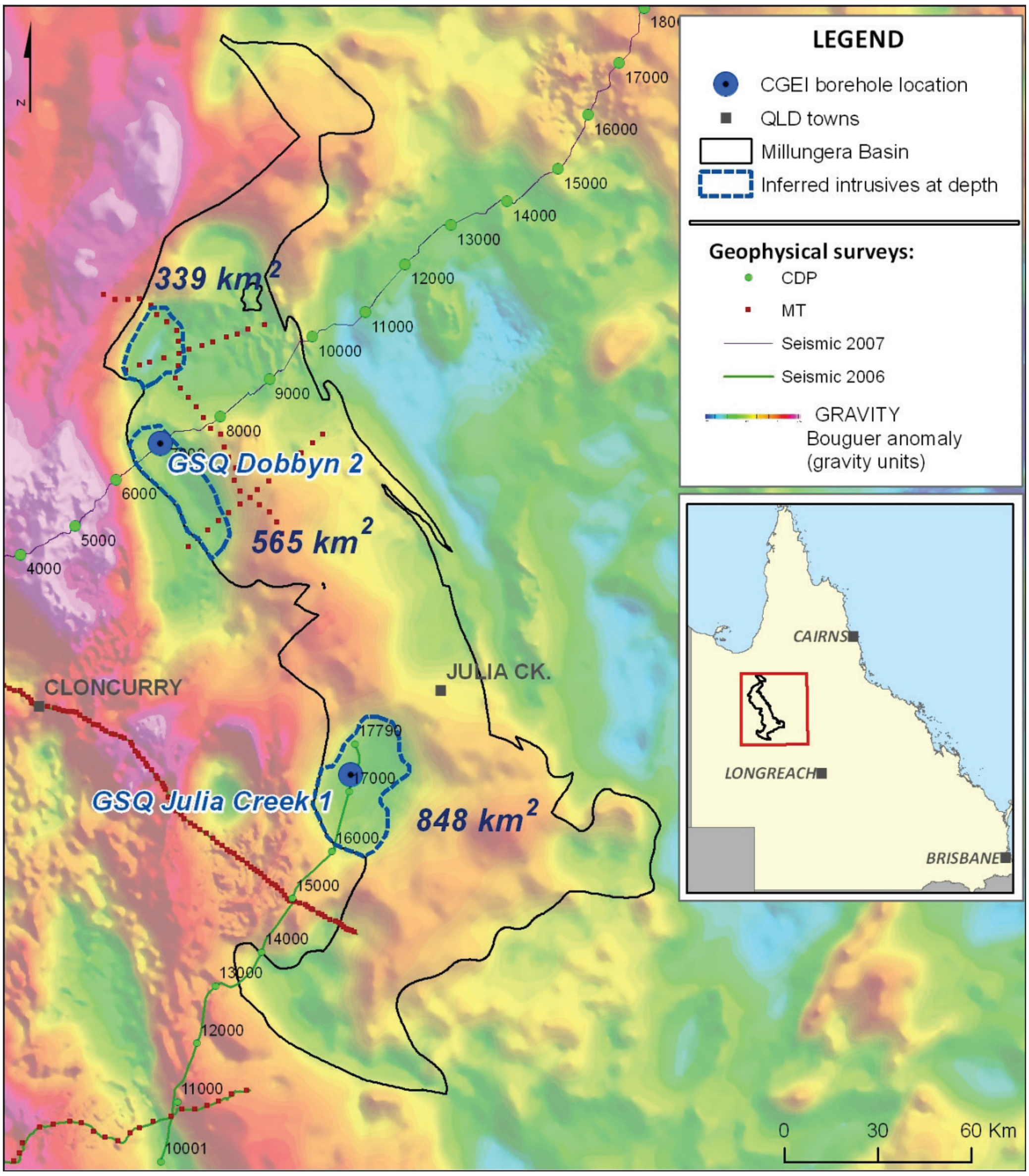

Figure 4: Inferred intrusive (resource) from gravity, seismic and MT surveys in the Millungera Basin

Electric power generation potential

For comparative purposes and to present a more tangible figure, the estimated thermal energy of CGEI inferred resources is reported in terms of equivalent electric power generation potential. There are a few parameters that govern the conversion process of thermal energy to electricity. These parameters are discussed and rationalised below for the highlighted areas.

Recovery factor: 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%

Table 4: Input parameters used to estimate stored thermal energy in the inferred resources of CGEI targets. Reference temperature is assumed 110°C in all cases.

Tectonic unit		Inferred resource thickness (m)	Resource mean temp. (°C)	Resource surface area (km^2)	Rock density (kg/m^3)	Rock specific heat capacity (J/kg°C)	Thermal energy estimate (PJ)
Millungera Basin — South		1811	194	848	2880	1000	372 499
Millungera Basin — North	Area A	1761	191	565	2880	1000	231 433
	Area B	1902	195	339	2880	1000	157 805
Surat Basin (Roma Shelf)		959	169	2621	2680	900	355 057
Hillsborough Basin		1120	177	456	2870	900	88 591
Maryborough Basin	Area A	1638	178	933	2680	910	252 146
	Area B	1640	179	329	2680	910	91 189

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). In 2007, Williams used a theoretical approach and suggested a range of 5–20% as recovery factor for both natural fracture dominated resources and EGS systems. At this stage there is no sound basis for predicting the net recovery factors for the thermal energy estimates of the highlighted areas. Therefore, a conservative value of 5% has been assumed as the recovery factor in the calculations for the areas.

Thermal conversion efficiency: 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 at over 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.

With the low temperatures generally around 150°C and the use of ORC binary power plants, the conversion efficiency of geothermal plants can typically vary between 7% and 12%. For higher temperatures, the conversion efficiency can reach well over 12% (Figure 5). Given the fact that the inferred resource temperature of the highlighted areas has not been measured directly, the net thermal conversion efficiency can not be determined at this stage, however, 7% has been assumed as a conservative value for thermal conversion efficiency in the calculations for the areas.

Plant capacity factor: 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. It

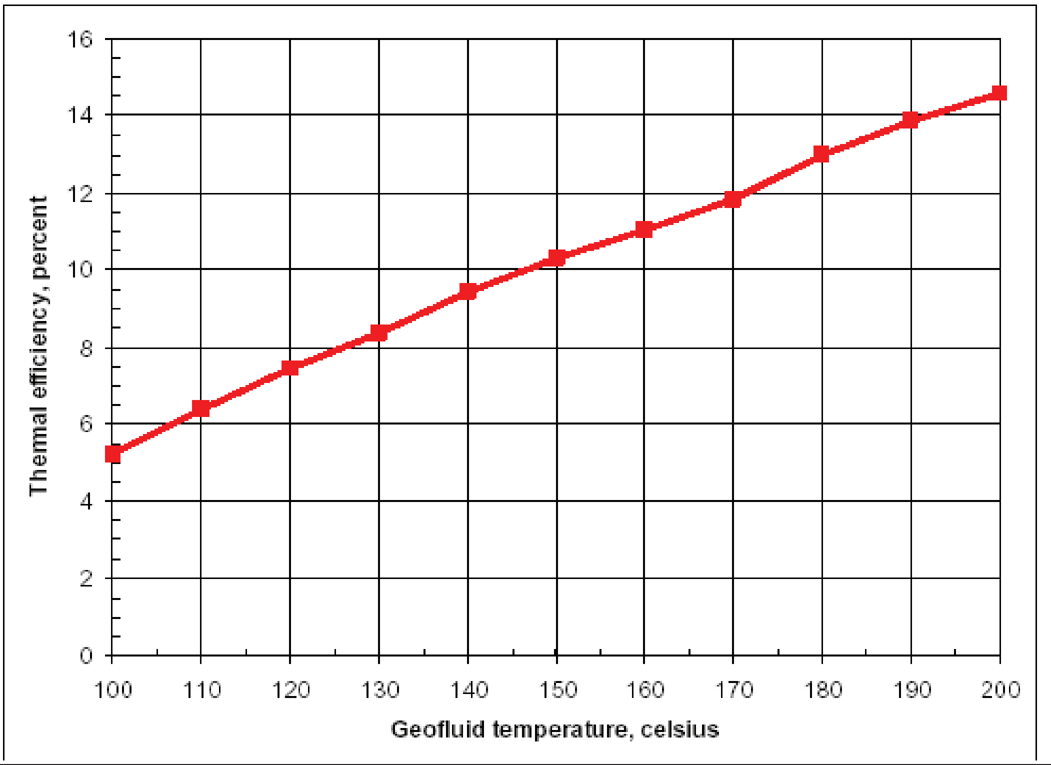

Figure 5: Level of typical thermal efficiencies for electricity generation of ORC binary plants (Bertani, 2010).

is assumed that 90% would be reasonable capacity factor when calculating electric power potential of the highlighted areas from the estimated recoverable thermal energy.

Plant/project economic life: 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. Therefore, it is a common practice to assess potential of a geothermal resource over an economic life time span of 25 years.

In summary, the assumptions used to convert the estimated thermal energy to equivalent electric power generation potential in the highlighted areas 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 437 and 1837MWe for the highlighted areas (Table 5).

Obviously the estimates are purely based on a hypothetical case, and therefore should not be taken as an implication that the authors endorse the parameters and assumptions for using in any decision making effort or practical application. These parameters, assumptions and estimates should be revised once detailed exploratory

Table 5: 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)	Estimated annual electricity generation (GWh)
Millungera Basin — South		18 625	1837	14 483
Millungera Basin — North	Area A	11 572	1142	9004
	Area B	7890	778	6134
Surat Basin (Roma Shelf)		17 753	1751	13 808
Hillsborough Basin		4430	437	3445
Maryborough Basin	Area A	12 607	1244	9806
	Area B	4559	450	3546

work is undertaken in the future and when more direct measurements at subsurface conditions are available for the highlighted regions.

Uncertainty Distribution

Because of the limited data and large uncertainty on the assumptions used, some degree of caution and conservatism has also been taken into account in the estimates. This approach, which accounts for the risk factor, can be quantified with reasonable approximation using the Monte Carlo simulation. It applies a probabilistic method of evaluating the estimated thermal energy or equivalent power output that captures uncertainty. Given the complexity and heterogeneity of the geological formations of most geothermal systems, this method is preferred over the usual deterministic approach which assumes a single value for each parameter to represent the whole system. Instead of assigning a "fixed" value to an input parameter, numbers within the range of the distribution model are randomly selected and drawn for each cycle of calculation. The Monte Carlo simulation performs the calculation and determines the estimate based on frequency distribution of the random variables. The distribution is dependent on the number of times a value is extracted from the uncertainty models of the input parameters. To obtain a good representation of the distribution, sampling is usually done through 1000 iterations with continuous calculation. The results are then analysed in terms of the probability of occurrence of the estimated thermal energy or equivalent power output in the range of values over the resulting population.

Availability of sufficient quantitative data is required to justify application of the probability approach in estimating thermal energy content of the highlighted areas. However, to provide an indication of likely uncertainties in the estimates, the assigned input parameters have been categorised as "most likely", "Minimum" and "Maximum" scenarios for the Monte Carlo simulation. The assumed input parameters used in the simulation for the Millungera Basin beneath the GSQ Julia Creek 1 borehole are summarised in Table 6.

Table 6: Input parameters used in the Monte Carlo simulation to estimate thermal energy in the Millungera Basin, vicinity of borehole Julia Creek 1

Input parameters	Minimum	Most likely	Maximum	Unit
Resource surface area	763	848	933	km^2
Resource thickness	1630	1811	1992	m
Resource mean temperature	179	194	209	°C
Rock density	2592	2880	3168	kg/m^3
Rock specific heat capacity	900	1000	1100	J/kg°C

Table 7: Result from Monte Carlo simulation, estimation of stored thermal energy and equivalent power output for the highlighted areas with 90% probability

Tectonic unit		Total stored thermal energy — PJ (90% probability)	Electric power potential — MWe (90% probability)	Annual electricity generation — GWh (90% probability)
Millungera Basin — South		>296 000	>1460	>11 510
Millungera Basin — North	Area A	>185 000	>912	>7190
	Area B	>130 000	>641	>5054
Surat Basin (Roma Shelf)		>280 000	>1,380	>10 880
Hillsborough Basin		>69 000	>340	>2680
Maryborough Basin	Area A	>205 000	>1010	>7963
	Area B	>73 000	>360	>2838

Figure 6 shows the result of the Monte Carlo simulation for the estimated thermal energy in the vicinity of GSQ Julia Creek 1 drilled in the Millungera Basin. The simulation result is presented as a plot of relative and cumulative frequency distribution against the estimated thermal energy. In fact, it shows that the probability that thermal energy could be greater than 296 000 PJ is 90%. In other words, the risk that the inferred resource could not sustain 296 000 PJ is less than 10%.

The results of the simulation for all the highlighted areas are summarised in Table 7. There is no doubt that the reliability of results from Monte Carlo simulation highly depends on the type, amount, and quality of geoscientific data, which are also dependent on the stage of development and maturity of the target area. Generally, the reliability increases as the target area is drilled with direct measurements and more quantitative data becomes available.

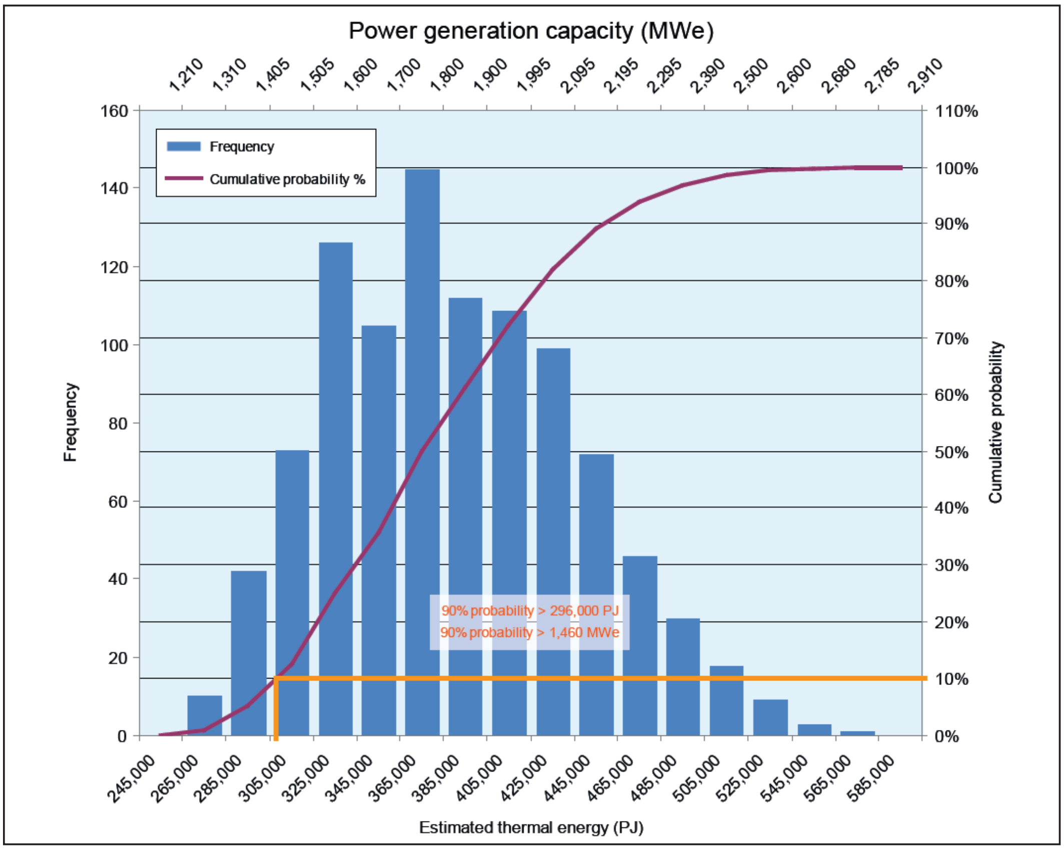

Figure 6: Result from Monte Carlo simulation, probability of stored thermal energy within the Millungera Basin, vicinity of borehole Julia Creek 1

Discussion and Conclusion

The CGEI was established to investigate geothermal energy potential close to potential market and the electricity network where electricity demand is increasing significantly and geothermal energy has been less investigated to date. Ten higher ranked geological settings were selected along northern and eastern Queensland to determine vertical conductive heat flow through a shallow drilling program. The newly established heat flow data ranges from 71 to 113mW/m^2 across Millungera, Surat, Hillsborough and Maryborough basins implying possible geothermal energy potential within these basins. These were previously considered to have a normal crustal heat flow with low geothermal energy potential. Using the new heat flow dataset, temperatures of 187–240°C have been predicted at 5km depth in one-dimension in the selected regions. Due to the lack of information and for simplicity, it was assumed that the heat flow remains relatively constant with depth, and that the modelled temperatures are homogeneous in the vertical direction and therefore constant over the entire system. Based on the modelled temperatures at greater depths, total thermal energy content is estimated between 88 000 and 372 000PJ at the selected targets using the volumetric approach under stated assumptions. The distribution of the heat per unit volume ranges between 140 and 240PJ/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 risk factors such as poor permeability.

Equivalent gross electric power generation potential of the highlighted areas has been estimated from the recoverable thermal energy based on certain assumptions. The estimates show power generation potential of 437–1837MWe in the highlighted regions. The Monte Carlo analysis has indicated that the electric power generation potential of 340–1460MWe can be expected from the highlighted basins with 90% probability. Obviously, the estimates are purely based on a 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, the 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.

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 in early 2014. All the reports will be publically available through the Queensland Government's Digital Exploration Reports (QDEX) on-line system.

Recommendations

Following recommendations are made in order to refine 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 evaluate commercial viability of geothermal energy development programs in the highlighted basins individually.

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Unconventional petroleum resources in the Toolebuc Formation, western Queensland

Alison Troup, Sally Edwards, Micaela Grigorescu, Owen Dixon and Suraj Gopalakrishnan

Geological Survey of Queensland

Petroleum exploration has targeted nearly every sedimentary basin in Queensland, with varying degrees of success. With recent developments in unconventional petroleum extraction in the United States of America, there has been renewed interested in assessing hydrocarbon occurrences that were considered to have unfavourable reservoir characteristics in the past. As part of a collaboration with Geoscience Australia and other state and territory surveys to examine Australia's unconventional petroleum potential, the Geological Survey of Queensland has been assessing the Toolebuc Formation.

These assessments will be based on mapping the criteria used by the United States Geological Survey (USGS) to screen formations for unconventional petroleum assessment (Charpentier & Cook, 2011:

- total organic carbon > 2 wt%
- type I, II or type IIs kerogen
- thermal maturity > 1.1% Ro; <3.5% Ro
- net reservoir thickness >15m
- evidence of thermogenic gas stored in the formation.

The Early Cretaceous Toolebuc Formation is a regionally extensive unit within the Eromanga and Carpentaria basins in western Queensland, where it has been intersected in petroleum exploration wells, and water and mineral bores. It comprises laminated calcareous and kerogen-rich mudstone with minor coquinite, limestone and sandstone.

Data in petroleum exploration reports and water and mineral bore information has been used to map out possible 'sweet spots' or a 'fairway' on which to define an assessment unit. The assessment has consisted of:

- defining a three-fold lithological framework using fifteen fully-cored GSQ stratigraphic bores
- applying this stratigraphic framework throughout the Eromanga and Carpentaria basins using wireline logs in petroleum wells
- mapping depth to top of formation based on the stratigraphic framework
- 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

- determining mineralogical variation using X-ray diffraction (XRD) and hyperspectral logging across the selected stratigraphic drillholes
- mapping of gas composition, based on chromatography results presented in mudlogs
- characterisation of hydrocarbons based on gas wetness ratios calculated from mudlog data.

Lithological framework

Lithological logging of the uppermost Wallumbilla Formation, Toolebuc Formation and lowermost Allaru Mudstone was completed on fifteen GSQ stratigraphic boreholes across the extent of the Toolebuc Formation in the Eromanga and Carpentaria basins. Based on this logging, the Toolebuc Formation can be sub-divided into three lithofacies:

- an upper calcareous mudstone interval with or without calcite laminae
- a middle calcareous kerogenous mudstone interval with high abundance of calcite laminae, which are shells of *Inoceramus* and *Aucellina* (Ozimic, 1986)
- a basal highly kerogenous, slightly calcareous mudstone interval with no calcite laminae. Fish scales, phosphatic fish debris and pyrite framboids are also common.

The Toolebuc Formation has a distinct, serrated gamma ray anomaly and may exhibit multiple peaks. The peak of this anomaly typically coincides with the top of the basal kerogenous mudstone facies. Wireline log picks have been used to identify the top and bottom of the Toolebuc Formation in petroleum wells in the Eromanga and Carpentaria basins.

Mineralogy

XRD analysis has been conducted across the formation on samples taken from eight GSQ stratigraphic boreholes. The mineral composition (wt%) has been compared with gamma ray logs for these wells and it has been noted that high gamma ray values (>150 API) are indicative of zones of high calcite (>50%).

The XRD analyses have also been compared with Hylogger™ data for these wells and have been used to constrain the minerals identified using hyperspectral logging.

Source potential

The Toolebuc Formation is rich in organic matter, with TOC contents up to 30 wt%. The highest TOC values are associated with the high gamma ray peak. Analytical TOC results were supplemented with TOC values calculated from the Δ log R technique (Passey & others, 1990).

Vitrinite reflectance for the Toolebuc Formation has been modelled based on Rv_{max} profiles established from petroleum wells across the Eromanga Basin (Smith, 1987, 1989; Hawkins & others, 1991). From this data, Rv_{max} ranges from 0.20 to 0.78%, indicating that the Toolebuc Formation is immature to mature for hydrocarbon generation, and is within the oil window where the formation is deeper.

T_{max} data from pyrolysis analysis has also been used to examine the thermal maturity of the Toolebuc formation. The area where the T_{max} exceeds 435°C is much smaller than the area where the Rv_{max} exceeds 0.6%. However, it has been noted that the T_{max} values are suppressed where the TOC values are high. Thus, the modelled Rv_{max} is likely to be a better indicator of the maturity of the formation.

Gas composition

The Toolebuc Formation, and to a lesser extent the lowermost Allaru Mudstone and uppermost Wallumbilla Formation, has a consistent gas kick. Methane has been recorded in mudlogs, typically where the depths are greater than 300m. Butane and pentane are present in the Eromanga Basin, where depths are greater than 600m. However, butane and pentane have also been detected in desorption samples taken from GSQ Julia Creek 1, where the Toolebuc Formation is much shallower.

Desorption samples from GSQ Julia Creek 1 in the northern Eromanga Basin produced small volumes of gas on crushing. Isotopic analysis of this gas suggests an immature thermogenic origin (Boreham, *in* Faulkner & others, 2012). This is in an area of the formation that has been mapped as thermally immature and suggests that there may be greater potential for oil and gas generation in areas that have undergone deeper burial and higher temperatures. Given its proximity, the Toolebuc Formation is the likely source for gas shows in the underlying Wallumbilla Formation and overlying Allaru Mudstone.

Mudlogs from conventional exploration wells have been used to broadly map out gas composition, based on the presence or absence of methane to pentane (C1 to C5) detected using gas chromatography. Following this, wells with mudlogs showing C1 to C5 over the Toolebuc Formation were selected for digitisation, based on one to two wells per 1 degree grid spacing over the Eromanga Basin. Wells with mudlogs containing records up to propane (C3) were used as additional data points where logs showing C5 were not available.

The digitised logs have been used to calculate Gas Wetness Ratios, Light to Heavy ratios and oil character quotients using the equations of Haworth & others (1984) for the characterisation of hydrocarbons in a reservoir, based on relative concentrations of hydrocarbon components. Interpretation of these ratios is based on visual study of the relationships of the three curves. These ratios suggest that the Toolebuc Formation may contain oil in the deeper, more mature areas.

Unconventional hydrocarbon prospectivity

Regional maps have been used to delineate an area of the Toolebuc Formation that may have greater potential for unconventional hydrocarbon prospectivity.

- Total organic carbon > 2 wt%. Based on rock eval-pyrolysis and calculated TOC, the Toolebuc Formation averages greater than 2 wt % TOC across most of its extent.
- Type I, II or type IIs kerogen. The Toolebuc Formation is known to contain type II kerogen.
- Thermal maturity > 1.1% Ro and <3.5% Ro. This has been modified for shale oil assessment based on a cut off of 0.6% Ro. For the Toolebuc Formation, this is constrained to the deeper area in the south-western Eromanga Basin.
- Net reservoir thickness >15m. This has been adjusted to a gross formation thickness of 30m to account for the uncertainty in the definition of the reservoir interval. The Toolebuc Formation is thickest along a belt through the central Eromanga Basin.
- Evidence of thermogenic gas stored in the formation.

Based on these criteria, a fairway for the Toolebuc Formation has been mapped out in the south-western Eromanga Basin.

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Creating SEGY digital data from scanned images of seismic sections – making old data live again.

Owen Dixon

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The Geological Survey of Queensland undertakes regional studies of the prospectivity of areas of Queensland in order to assist in the orderly management of our natural resources and assist industry in efficient use of those resources for the benefit of the people of Queensland. The assembly of seismic data over regional areas produces one of the major bottlenecks in these studies. Vintages of seismic data vary greatly, but most regional lines were shot in early exploration phases, and consequently the archived data available are quite variable.

Hard-copy seismic sections are generally available as scans. Field data is often available, but support data may be missing. Digital stack data in SEG-Y format is often not available.

Even if digital stack data is available it still requires considerable housekeeping to make it useable on a workstation. The headers need to be checked, and edited if required. The hard-copy or scanned section is generally still needed to determine the CDP-shotpoint relationship and trace sequence. The trace headers also require review, and coordinate data have to be created for modern datums. Reprocessing of field data to a common standard is desirable, but the required data is often missing or incomplete.

Seismic interpretation workstations can usually display scanned images, but these lack the full utility of SEG-Y data in terms of horizon tracking etc. Commercial sources of converting the scanned images to SEG-Y are available, but GSQ has developed a quick and easy method of producing SEG-Y data using freely available software.

The method uses imaging software (we use the GNU Image Manipulation Program (GIMP), but multiple packages are suitable) and Seismic Unix.

The format of scanned images held by GSQ is commonly single bit TIFF. The images are converted to 8-bit grey-scale and then manipulated to align the image (using the rotation, skew and distort function), and to crop the image to the extent of the traces.

The resulting image is then passed to a Seismic Unix script with appropriate processing parameters:

- remove bitmap headers and trailing bytes
- recast 8-bit binary data to floating point
- rotate resulting grid to set fast dimension in time
- resample in the time dimension to an even, high sampling rate

- resample in the trace dimension to an even number of stripes per data trace
- optional timing line and noise reduction by blurring and threshold
- add trace headers with proper CDP relations
- stack on CDP
- apply time-variant filter matching that of original data
- resample in time to final sample rate
- optional amplitude adjustment to recover relative amplitudes
- wave-shaping to account for distortion from only using positive wave data
- final time-variant filter pass
- populate coordinate data in trace headers
- create ebcdic and binary headers
- output final SEG-Y file.

Useful seismic data for workstations can be readily derived from scanned seismic sections with little more overhead than if original SEG-Y data were available. This is a very useful tool to provide a consistent dataset in a time and cost-efficient manner.

Seismic expression of northern Hutton-Wallumbilla Fault system

Hagay Haviv

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Scanned, processed profiles of historic seismic lines are being used to develop a better understanding of the geological structures related to the Hutton-Wallumbilla Fault system in the Surat and Bowen basins by using them as the basis for a conceptual model. The methods used are both time and cost effective when examining sub-surface stratigraphy as they negate the need for new exploration or sophisticated processing. This technique is especially useful for assessing the current model of this area, helping to develop a better understanding of fluid flow processes and hydrocarbon accumulations in the region.

Fault systems commonly consist of multiple structural complexities. The accumulation of strain and its subsequent release controls the propagation of broad fault zones, which may evolve over time. To get further insight into fault mechanisms, a small area in the south-eastern Denison Trough was investigated in detail. This study attempted to determine whether the Hutton-Wallumbilla Fault system is composed of a single fault generated instantaneously, or is the product of several smaller faults generated over a longer period of time. It also examines the relationship between the Hutton-Wallumbilla Fault and hydrocarbon accumulations.

Seismic lines recorded close to the fault were used in the velocity analysis. The data was categorised by source type (vibroseis or dynamite), record length and sample rate. Datum and projections were matched with selected petroleum wells to allow for correlation with the geological formations in the wells. This correlation enabled the design of filters, which produced a unified seismic dataset.

Well logs were correlated with interval velocities from the scanned profiles in order to develop characteristic velocities, which were then used to define a three-dimensional velocity gradient for the area.

The correct interpretation of geological structures on a seismic profile requires the velocity analysis to be conducted accurately. Some structures in seismic profiles may be the result of lateral variations in velocity, giving a misleading view of the real structure. Extra caution should be taken with the depth as the velocity profile increases, and false structures may become more important.

The strong seismic reflectors were correlated to formation intersections in wells. This correlation provided better understanding of the relationship between rock properties and seismic reflection, resulting in a more accurate finer detailed model.

The surveys conducted in the area of interest varied in age, and for some of the surveys the only data available are scanned sepia sections. These scanned images were converted to SEGY data for use on a workstation.

The role of Queensland Government initiatives in exploration success

Joshua Leigh

ActivEX Limited

Overview

ActivEX Limited have been involved in three Collaborative Drilling Initiatives (CDI's) and two Industry Network Initiatives (INI's), all of which have been technical successes. The initiatives are primarily to encourage growth of junior exploration companies by supporting companies with high risk exploration &/or innovative drilling, throughout areas of Queensland. They've played a crucial role in allowing ActivEX Limited as a junior exploration company, to pursue and press the edges of mineral exploration, challenge current models and concepts, and advance the overall geological understanding of the target areas.

Mount Agate CDI

The most recent CDI was carried out over the Mount Agate Exploration Permit for Minerals (EPM) 14955. The program was designed to test Sub-Audio Magnetic (SAM) conductivity targets associated with numerous, partially outcropping and highly mineralised haematite breccias, hosted within the Wimberu Granite of the Mount Isa block's Eastern Succession.

The results confirmed the association of significant copper, gold, molybdenum & rare earth mineralisation with SAM conductivity anomalism, although the extent

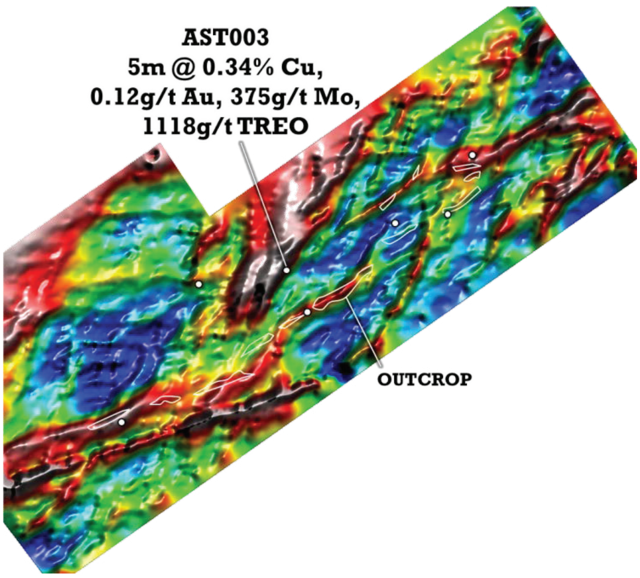

Figure 1. SAM conductivity response over the Mount Agate EPM

of mineralisation at depth was not as well developed as ActivEX Limited expected. However, drilling improved the geological understanding of the target area and highlighted the significant rare earth mineralisation, possibly related mineralisation in adjacent tenements. Research into the nature of rare earth mineralisation is underway.

Esk Trough INI

The Esk Trough INI was completed over nine ActivEX Limited EPMs, extending for more than 160km of strike in the Esk Trough region, with the aim of determining the most fertile ground for porphyry style mineralisation. The initiative implemented geological mapping, NIR mineral spectroscopy (PIMA), portable XRF (pXRF), leading to the development of conceptual models with the aid of a number of specialist consultants.

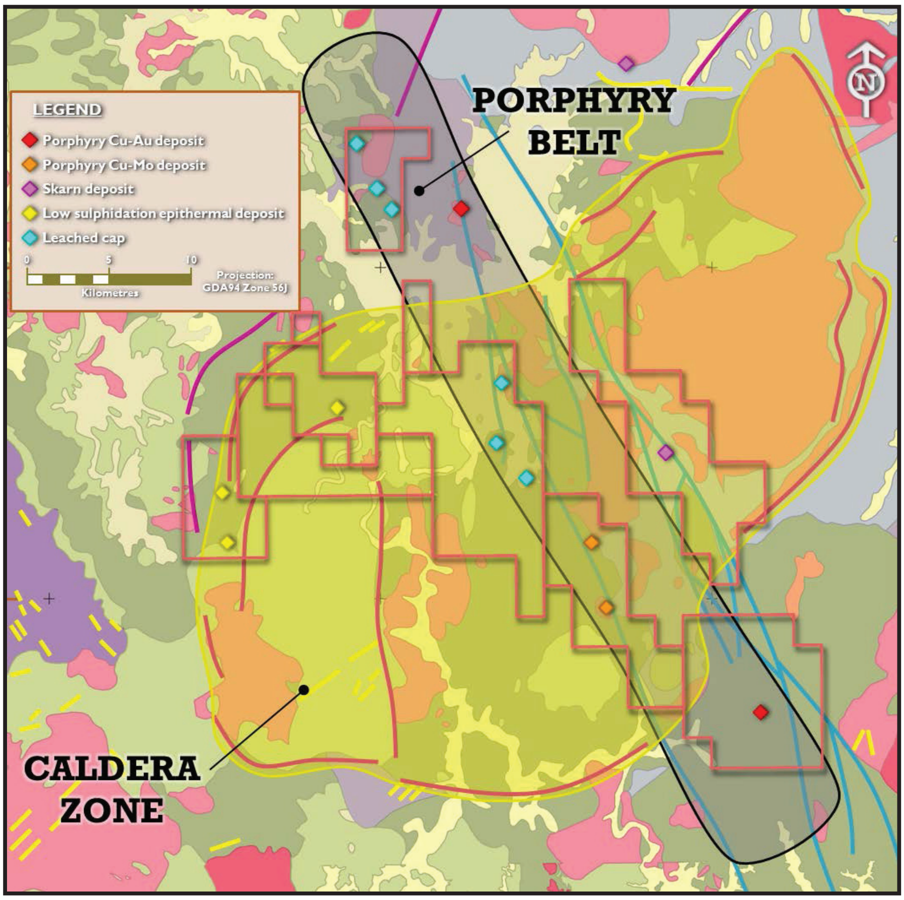

Figure 2. Regional 250k geology in the northern Esk Trough with deposit locations and interpretations

Thorough research and conceptual model development carried out during the Esk Trough INI has broadened the local and regional geological knowledge of the Esk Trough area, as well as directing ActivEX Limited's exploration to the northern part of the Esk Trough. The implementation of numerous techniques and subsequent interpretation, has allowed ActivEX Limited to delineate a NNW trending porphyry belt associated with Permo-Triassic westward convergence, highlighted by exposed Cu-Au mineralisation at surface and leached caps believed to be associated with porphyry mineralisation at depth. Low sulphidation epithermal mineralisation has been correlated with late Triassic extensional tectonics and caldera development. Exploration driven by these interpretations, have led ActivEX Limited to a number of prospects, some of which are advancing to resource stage. ActivEX Limited's exploration efforts persist today in the fertile terrain, where the company continues to pursue mineral resources, backed by thorough research, understanding and innovative techniques.