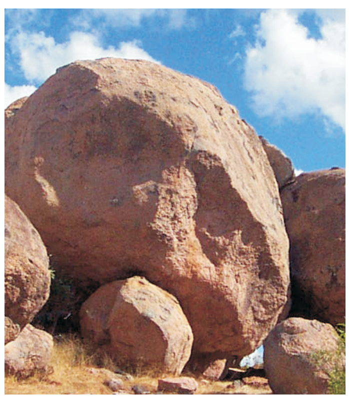
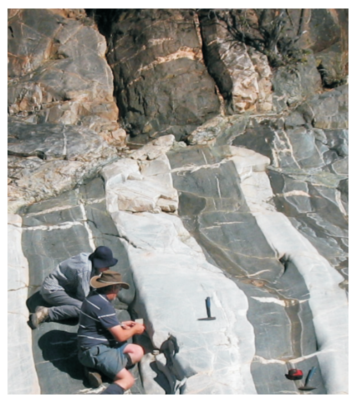
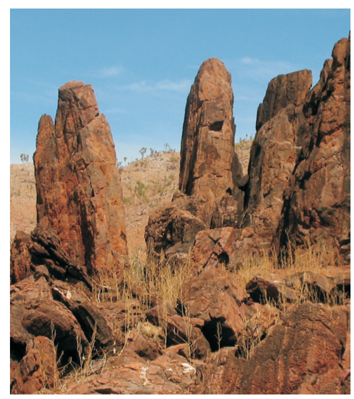
Department of **Employment, Economic Development and Innovation**
Geological Survey of Queensland

Queensland Geological Record 2010/04

Digging Deeper 8 seminar
Extended abstracts

Geological Survey of Queensland

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Cover photographs: L to R; Carboniferous granite, Sundown area near Mount Garnet; Examining Proterozoic metamorphic rocks, Einasleigh area; Calc-silicate rocks in the Corella Formation north of Kajabbi; Abandoned pit, Dobbyn copper mine; High-grade gneiss and amphibolite, Einasleigh (Photographer: Ian Withnall, GSQ)

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GEOLOGICAL SURVEY OF QUEENSLAND, 2010: Digging Deeper 8 Seminar extended abstracts. *Queensland Geological Record* **2010/04**.

CONTENTS

QUEENSLAND GOVERNMENT EXPLORATION GRANT INITIATIVES

Simon Crouch

Geological Survey of Queensland

Since 2006 the Queensland Government has committed over $10 million to directly support exploration through the grant initiatives under the Smart Mining – Future Prosperity and Greenfields 2020 programs.

The Smart Mining – Future Prosperity program was a 2006 Election Commitment of $29.08 million over four years to increase and accelerate investment in exploration, address skill shortages and promote the involvement of women in mining.

Of this, $7.28 million of grants under the Collaborative Drilling, Cluster Formation and Industry Network Initiatives were provided to directly stimulate exploration in Queensland.

The Collaborative Drilling Initiative of $6 million provided grants of half the drilling costs up to $150 000, to support industry in the testing of new exploration targets by drilling.

The Cluster Formation Initiative of $800 000 provided grants of up to $50 000 to share drilling and geophysical resources in the state.

The Industry Network Initiative of $480 000 provided grants of up to $40 000 to encourage the growth of junior mineral exploration companies by supporting access to technical and ancillary services that develop or help to develop deposit models and generate drilling targets.

As of October 2010 over $3.62 million has been paid to companies successfully completing 52 projects across all three initiatives. Twenty-seven of these projects were technical successes.

There are two types of technical success defined, either the discovery of new mineralisation or a newly acquired understanding of the geological causes of the geophysical anomalies.

Currently $0.56 million is committed to projects planned for completion in 2009 and 2010.

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.

Round 3 is complete with 12 projects successful and $0.99 million in grants paid to companies. Eight projects were technical successes.

As of October 2010 all projects under the three rounds of the Cluster Formation and Industry Network initiatives were completed with $0.32 million paid to companies.

For Round 4 of the Collaborative Drilling Initiative 33 submissions were received with 11 projects from 9 companies successful. Two projects have been completed. It is anticipated this round will be completed by early 2011.In July 2010 a further $3.0 million was assigned to exploration grant initiatives under Greenfields 2020. Three rounds have been planned to date, with the $2.2 million Round 5 closing on 19 November 2010.

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

Round 5 is planned to finish in early September 2012.

UPDATING THE NORTH-WEST QUEENSLAND MINERAL AND ENERGY PROVINCE STUDY REPORT

Laurie Hutton, Ian Withnall, Terry Denaro, Sarah Sargent, Jim Beeston and Joseph Tang

Geological Survey of Queensland

The North-West Queensland Mineral and Energy Province study report will be released at the end of this year. The report will consist of several components:

- An A3 book which will display, in a highly visual way, different aspects of the Mount Isa Minerals and Energy Province. This book, which will comprise figures, diagrams, tables and summary text, will be backed up by detailed reports which will be included on a DVD.
- A 3D model of the geology of the Mount Isa region, including an extension of the geology under cover surrounding the outcropping part of the Inlier. This will be discussed in a paper by Ben Jupp and Matthew Greenwood (this volume).
- A GIS including a seamless geology of the region stitched together from 1:100 000 Geology maps which have been updated during the remapping of the Inlier since 2006, as well as detailed studies carried out by mineral exploration companies, university researchers, and government agencies. The GIS will also include geophysical images of the latest potential field data collected over the last 10 years.
- Two reports commissioned by GSQ and compiled by researchers from GSQ and PGN Geoscience, on the geodynamics of the Mount Isa Inlier, and the relation of the Mount Isa Inlier to adjacent Proterozoic terrains in Australia. This will be discussed in a separate paper by Paul Donchak (this volume).
- A report, commissioned by GSQ and compiled by Mira Geoscience, on a mineral systems analysis of the Mount Dore region, as an example of how the data can be used in mineral exploration. This will be discussed in a paper by Ben Jupp and Matthew Greenwood (this volume).
- A mineral systems analysis of the major deposit styles
- A database and report on geochemistry collected during mineral exploration in the Mount Isa Region
- An analysis of sedimentary basins overlying the Proterozoic rocks of the Inlier and their potential for energy resources
- An analysis of the geothermal potential of the region.

The purpose of the report is multifold:

- Provide a compilation of the latest knowledge, models and geological and geophysical data available for the Mount Isa Inlier and surrounds.
- Provide a seamless geology, compiled from 1:100 000 scale mapping, of the Inlier and surrounds.
- Develop a geodynamic framework for the Inlier and links to other Proterozoic terrains in Australia. This will provide input into understanding the mineral systems operating in the Inlier.

- Provide information of potential energy resources as a regional planning tool.
- Provide a high quality document to promote the Mount Isa region as a preferred exploration location at national and international venues.

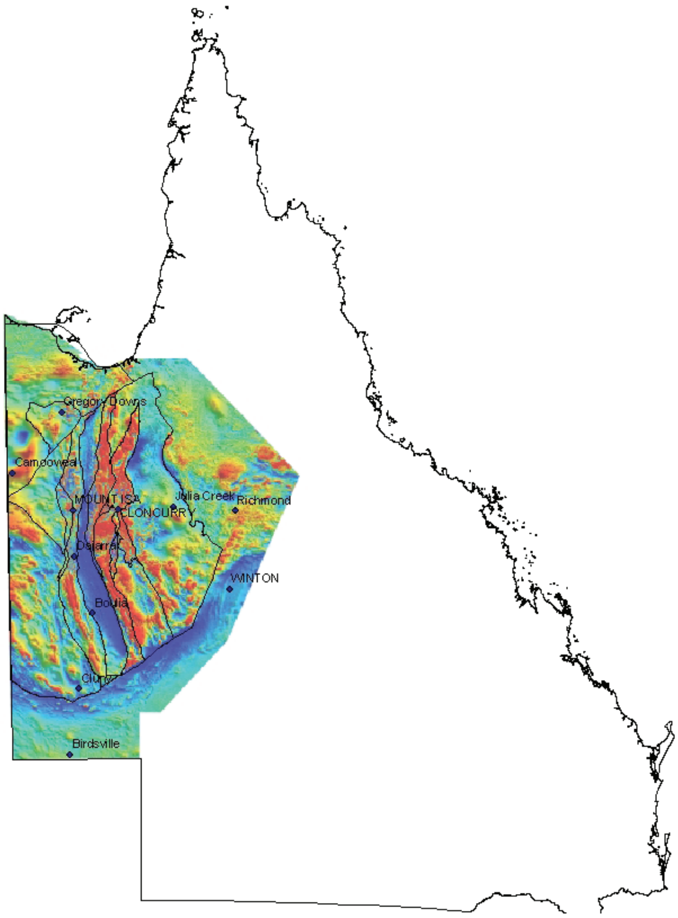

Figure 1: Map of Queensland showing the extent of the North-West Queensland Mineral and Energy Province Study underlain by a regional total magnetic intensity image and showing geological domain boundaries used in the report

SEAMLESS GEOLOGY

The core of the new North-west Queensland Minerals and Energy Province product is the detailed revision of the surface geology and interpretation of the solid geology, and this was the largest component of the study. It includes the areas under Phanerozoic cover as well as the outcropping Mount Isa Inlier, and is based on integration of the following key datasets:

- Digitised versions of the published geology from a range of sources, but particularly from the BMR-GSQ 1:100 000 map series (as described by Blake, 1987) into which were stitched the detailed mapping conducted by BMR in conjunction with various university researchers and students in the late 1980s (Blake & Stewart, 1992).

- Digitised versions of the published geology at 1:250 000-scale over the surrounding covered areas from joint BMR-GSQ surveys in the 1950s to early 1970s.
- These data sets were reinterpreted and validated generally in a GIS environment by comparing them with a range of imagery, including:
  - » Stitched regional high resolution aeromagnetic and radiometric survey data acquired by MIM Holdings Ltd (and now available in the public domain), the Springvale-Boulia survey by Geoscience Australia and surveys flown for GSQ as part of the Smart Exploration and Smart Mining Initiatives. Flight spacing ranges from 200m over the outcropping Mount Isa Inlier to 400m over covered areas.
  - » Landsat and Aster multispectral satellite data
  - » Hymap Hyperspectral data over selected swathes flown for GSQ as part of the Smart Exploration and Smart Mining Initiatives
  - » Google Earth imagery
  - » Coloured aerial photography, mostly at 1:80 000 scale acquired by the Department of Natural Resources (now Department of Environment and Resource Management)
  - » The gravity database compiled from GSQ and GA data and augmented by new surveys carried out for GSQ as part of the Smart Exploration and Smart Mining Initiatives. Station spacing ranges from 2 to 4km.
- Significant departures from the existing mapping of the outcropping Proterozoic rocks were flagged for follow-up field checking in four main field seasons in 2006–2009.
- The surface geology of the areas of Phanerozoic cover was extensively modified from interpretation of Landsat and radiometric data, but no follow-up checking was done.
- The changes to the geological arcs and polygons were passed to the Spatial and Graphics Unit of the GSQ and manipulated in ArcInfo in separate map tiles before being edge-matched and stitched together as a seamless dataset.

Each polygon is tagged with two separate numeric keys corresponding to the Surface Geology and the basement unit respectively. This necessitated interpretation of all concealed Proterozoic boundaries and faults across the entire area from gravity and magnetic datasets or simple interpolation across narrower areas of cover. Obviously for polygons of outcropping Proterozoic rocks, both keys will be identical.

In the GIS, the full detailed subdivision of the geological units is preserved, but by assigning different attributes to the polygon keys, a variety of simplified and generalised thematic maps can be generated.

All arcs have been attributed with the ID description, method of interpretation and source as well as names for some faults and folds.

- Faults have been extracted as a separate dataset and the segments of through-going faults have been merged into a single feature. For comparison purposes they have been attributed with the kinematic interpretation from the NWMPS (2000), although in many cases this may not necessarily reflect current views.

Discussion of the geology of the Mount Isa Inlier

The outcropping part of the Mount Isa Inlier, as well as the adjacent under cover areas, have been divided into fifteen domains (Figure 1), based on combinations of basin evolution, structural grain, metamorphic grade and geochronology. This provides a more flexible manner to describe variations in the geology between different parts of the belt. Although most are based on outcropping characteristics, geophysical characteristics have also been used, particularly for those largely under cover. The domains are a modification of those of previous workers, such as the three-fold division of Carter & others (1961), and the eight fold subdivision in the North-West Queensland Mineral Province Study (1st edition, QDME, 2000). In the new North-West Queensland Mineral and Energy Province Study, the geology of the inlier has been described on a domain by domain basis. The domains are also used as a subdivision on the time-space plot of the inlier.

The domains are descriptive and do not imply geodynamic relationships, and the relationship between the domains is not always clearly understood. Many boundaries are defined along mapped faults, making it difficult to ascertain the original geometric relationships.

In the book, geological descriptions of the domains are not intended to be comprehensive, but to convey key relationships. In particular, recent geochronology is highlighted as this represents new knowledge and establishes new relationships both within and between domains. Each domain is discussed under the following headings:

- Extent/distribution
- Principal geological components
- Age
- Structure/deformation history
- Inter/intra province relationships.

MINERAL SYSTEMS OF THE MOUNT ISA INLIER

(T.J. Denaro)

Classifications of mineral deposits have traditionally followed two alternative approaches, focusing either on descriptive features of the mineralisation such as host rock type and ore body morphology, or on genetic aspects. However, there are limitations in the application of this and other empirically-based classification schemes where there is a need to predict the location of undiscovered resources, such as in greenfields exploration (Skirrow & others, 2009).

An alternative classification approach is to describe mineralisation in terms of mineral systems that emphasise similarities in the processes of ore formation and take account of the crustal- to deposit-scales of the mineralising processes. This approach has been adopted for this study.

Wyborn & others (1994) defined a mineral system as "all geological factors that control the generation and preservation of mineral deposits, and stress the processes that are involved in mobilising ore components from a source, transporting and accumulating them in more concentrated form, and then preserving them throughout the subsequent geological history". Wyborn & others (1994) proposed that a mineral system has seven geological factors:

1. sources of the mineralising fluids and transporting ligands
2. sources of the metals and other ore components
3. migration pathway
4. thermal gradient
5. energy source
6. a mechanical and structural focussing mechanism at the potential depositional site
7. chemical and/or physical mechanisms for ore precipitation.

The original mineral systems approach was adapted by the Australian Geodynamics Cooperative Research Centre into a set of five questions (Walshe & others, 2005) and later adopted by the Predictive Mineral Discovery Cooperative Research Centre (Barnicoat, 2008; Murphy & others, 2008). Huston (2010) adapted these and added an additional question on post-depositional processes, as well as stressing the need to determine "essential components" and "mappable criteria" that can be used in a GIS environment to indicate mineral potential. The mineral systems questions used in the North-West Queensland Mineral and Energy Province Study analysis are:

1. What are the geodynamic and P-T histories (including timing of mineralisation) of the system?
2. What is the structural and lithological architecture of the system?
3. What and where are fluid reservoirs and metal sources for the mineral system?
4. What are the fluid flow drivers and pathways?
5. What are the metal (and ligand) transport and depositional processes?
6. What are the effects of post-depositional processes on metal accumulations?

Mineral systems have been analysed by reviewing literature on the significant mineral deposits, geology, tectonics and mineralisation of north-west Queensland. Mineral systems analysed are structurally-controlled epigenetic Cu±Au±iron oxide deposits in the Eastern Fold Belt, structurally-controlled epigenetic Cu±Au deposits in the Western Fold Belt, Ag-Pb-Zn in high-grade metamorphic terrains in the Eastern Fold Belt, and stratabound sediment-hosted Zn-Pb-Ag in the Western Fold Belt. A key output of the models is sets of measurable targeting criteria that can be used in quantitative assessments of mineral potential.

GEOCHEMICAL MODELLING

(J. Tang)

The Queensland exploration geochemistry and drill hole database for the NWQMEP comprises 1 374 000 well-attributed data points which are made up of 4 data categories — stream sediments (16.9%), rock chips (7.9%), soils (30.0%) and drill hole information (45.2%). The data are compiled from the open-filed exploration company reports submitted to the Geological Survey of Queensland as part of the reporting requirement for mineral exploration in Queensland. The vast spatial distribution of data and the range of elements assayed are utilised as an important exploration tool to:

- Identify regions of data-gap in intensely explored areas that may offer further exploration opportunities
- Establish mineral potentiality map by discovering areas with elevated elemental concentrations above the statistical mean
- Identify geochemical anomalies using multi-data types and multi-elements appraisal.

ENERGY RESOURCES

Sedimentary basins overlying the Proterozoic rocks of the Mount Isa Inlier have been described. The distribution of facies as well as their energy potential have been assessed. The following basins are included in the study:

- The Neoproterozoic to Palaeozoic (Ordovician) carbonate-dominated marine sediments of the Georgina Basin formed in a shallow sea that transgressed from the south across the north-western region of exposed ancient crust. It has been explored for petroleum and large deposits of phosphate.
- Following a mid-Palaeozoic hiatus, Late Carboniferous/Early Permian fluvioglacial and fluvial sediments were deposited during a post-Thomson Orogen sagging episode, culminating in the Aramac Coal Measures in the Galilee Basin.
- After another hiatus, widespread deposition resulted in further coal measures including the Betts Creek beds during the Late Permian Early Triassic. Current exploration in the Galilee Basin includes petroleum, coal and coal seam gas.
- During the Jurassic/Cretaceous a succession of sag events led to shallow depressions filled with continental and shallow marine deposits. Terrestrial coal measures (Birkhead Formation) and marine oil shale deposits (Toolebuc Formation) were variably deposited in the Eromanga and Carpentaria Basins within a major sedimentary system that currently forms part of the Great Artesian Basin.
- Apart from fossil fuels, the area is also a target for geothermal energy, including the newly identified Millungera Basin beneath the Carpentaria Basin to the east of the Mount Isa Inlier.

GEOTHERMAL MODELLING

The following criteria were used to assess the geothermal prospectivity for Hot Sedimentary Aquifers (HSA) and Enhanced Geothermal Systems (EGS) within the North-West Queensland Minerals and Energy Province. The table below summarises the important criteria required to evaluate an area for EGS and HSA and highlights the thickness of overlying sediments as the critical factor when assessing these two geothermal systems.

HS A	EGS
1. Sediment thickness greater than 1000m with sufficient thermal resistance 2. Sufficient thermal resistivity and low thermal conductivity of overlying sediments < 3.0W/mK 3. Regional aquifers and seals above potential heat source 4. Elevated temperatures measurements 5. Any other indicators of geothermal systems eg. Fluoride anomalies, hot springs	**1. Sediment thickness greater than 3500m with sufficient thermal resistance** 2. Sufficient thermal resistivity and low thermal conductivity of overlying sediments < 3.0 /mK 3. Target heat source with heat production values > 5µW/m^3 4. Calculated geothermal gradients > 40°C/km from temperature measurements 5. Any other indicators of geothermal systems eg. Fluoride anomalies, hot springs

Using a basin by basin geothermal assessment of the Georgina, Millungera, Galilee, Carpentaria and Eromanga Basins, an overarching geothermal prospectivity analysis was undertaken to delineate areas with potential for HSA and EGS.

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GEODYNAMIC EXPLORATION FRAMEWORKS FOR THE MOUNT ISA REGION

Paul Donchak

Geological Survey of Queensland

INTRODUCTION

One of the key considerations for assessment of the exploration potential of any region is its geodynamic setting. The geodynamic setting is a primary constraint on commodity type and mineralisation style which in turn must be taken into account if an effective exploration strategy is to be implemented. The recognition of the full range of geodynamic settings represented within any terrane during its tectonic evolution expands the range of possible mineralisation styles and opens up new exploration possibilites. The integration of new and innovative exploration models based on updated geodynamic interpretations with appropriate exploration strategies is a primary driver for greenfields exploration success.

MOUNT ISA GEODYNAMICS IN AN AUSTRALIAN CONTEXT

The Mount Isa Inlier forms part of what is now generally termed the North Australian Craton (NAC), which together with the South and West Australian Cratons (SAC and WAC) constitute the main crustal elements of Proterozoic Australia (Figure 1).

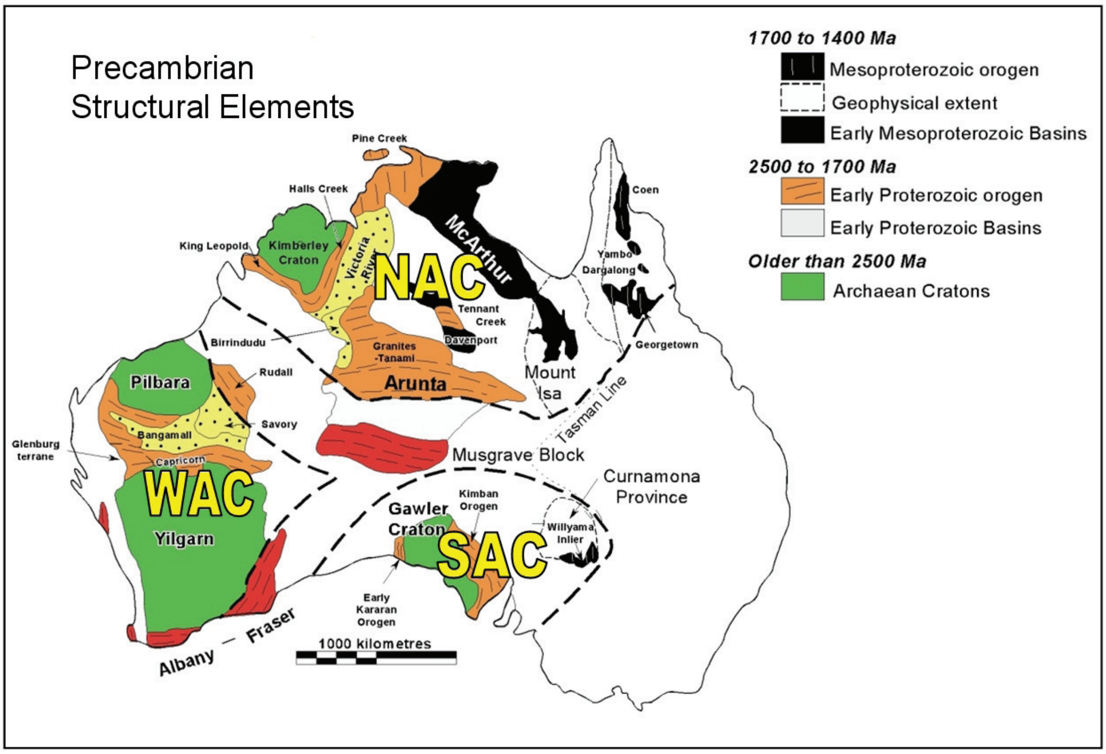

Figure 1

1900–1870 Ma Barramundi extension

The earliest known sequences within the exposed Mount Isa Inlier are basement rocks deposited prior to 1860Ma. These include sequences now assigned to the Kurbayia Metamorphic Complex, Yaringa Metamorphics and Saint Ronans Metamorphics exposed as remnants within younger basement rocks forming the central spine of the Inlier. Deposition within the NAC to the west at this time was controlled by the 1900–1870Ma Barramundi Extensional Event characterised by a NW-tending normal fault array offset by orthogonal NE-trending transfer structures. Similar NE-trending faults which compartmentalise Mount Isa geology are thought to be reactivated Barramundi Extensional Event transfer features. Higher degrees of extension during this event may have split Mount Isa basement crust away from the rest of the NAC during this time.

1870–1840 Amalgamation of the NAC

This time period represents the largest continental amalgamation event recorded in the geological evolution of the Australian continent. The early onset of this amalgamation in the Mount Isa Inlier is recorded in the deformation of the basement protolith sequences prior to the intrusion of the Kalkadoon-Ewen Batholiths and eruption of the Leichhardt Volcanics around 1860Ma. These events are interpreted to record sequential stages of accretion of the Mount Isa terrane with the rest of the NAC to the west. At some stage during during this process, the Mount Isa continental ribbon was sutured to the Arunta/Tennant Creek terrane along a broad arcuate front (possibly an easterly-dipping subduction segment) largely concealed under shallow cover in the southwest corner of the Mount Isa region (Figure 2).

The eastern margin of the Mount Isa crustal fragment is interpreted to represent an ancient west-dipping subduction zone, with associated arc magmatism represented by the ~1860Ma Leichhardt Volcanics and Kalkadoon-Ewen Batholiths. In the Gawler Craton to the south, a similar linear magmatic belt defined by the ~1850Ma Donington Suite is thought to represent the southward extension of subduction-related magmatism (Figure 2). The Australian continent at this time was transected by paired NE-dipping and SW-dipping subduction zones flanking the narrow Central Australian craton, resulting in a complex pattern of orogenic collision and backarc extension throughout the continent .

Convergence during Kalkadoon-related subduction is interpreted to be the driving force behind the 1870–1850Ma Barramundi Orogeny in the Mount Isa region. This orogeny culminated in ocean closure and subsequent accretion of the Numil and Abingdon Province crustal blocks to the east of Mount Isa. The existence of subduction at this time has important implications for later mineralisation as the crust is effectively fertilised by metals extracted from the downgoing slab by advecting hydrothermal fluids.

Equivalent amalgamation events elsewhere in Australia include the Cornian Orogeny in the Gawler Craton and the collision between the Kimberley Craton and the NAC

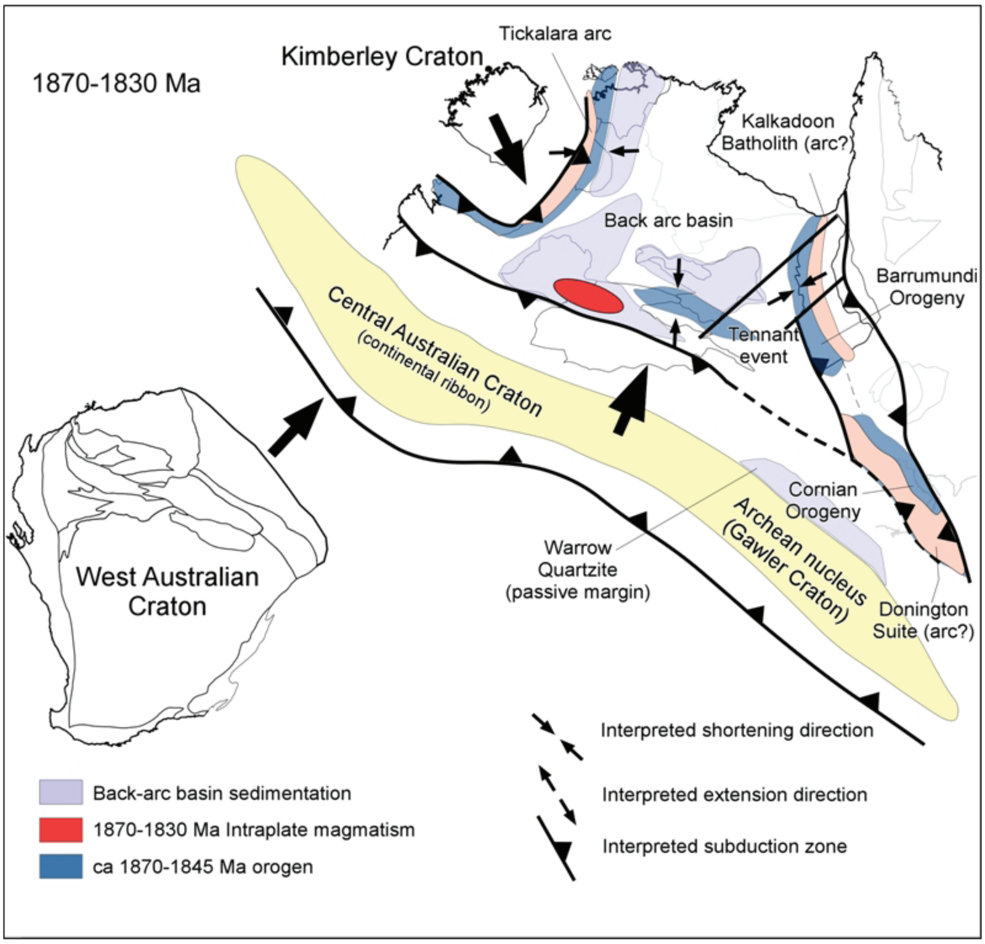

Figure 2

along the King Leopold and Halls Creek Orogens. These events are thought to have completed assembly of the NAC by around 1840Ma, also including the continent of Laurentia to the east. This process of amalgamation was a significant step forward in the formation of the supercontinent Columbia (Nuna).

1820–1795Ma Localised granite emplacement

This period saw collision of the Central and West Australian Cratons with major deformation (the Stafford Event) along the Paterson Orogen (Ruddall Complex) at ca 1795Ma (Figure 3). Hinterland sedimentary packages in the NAC were deposited in a continental back-arc setting. Significant granitic plutonism occurred in the Arunta Inlier and Granites-Tanami Province, and felsic volcanism in the Arunta Inlier and Davenport Province. In the Mount Isa region, local magmatic activity resulted in intrusion of the Yeldham Granite (~1820–1800Ma) and Little Toby Granite (~1800Ma) in the western part of the Inlier. The Mount Isa granite systems are the same age as Au deposits of the Tanami (e.g. Coyote, Callie, Sandpiper ~1800–1810Ma) and may have unrecognised Au exploration potential.

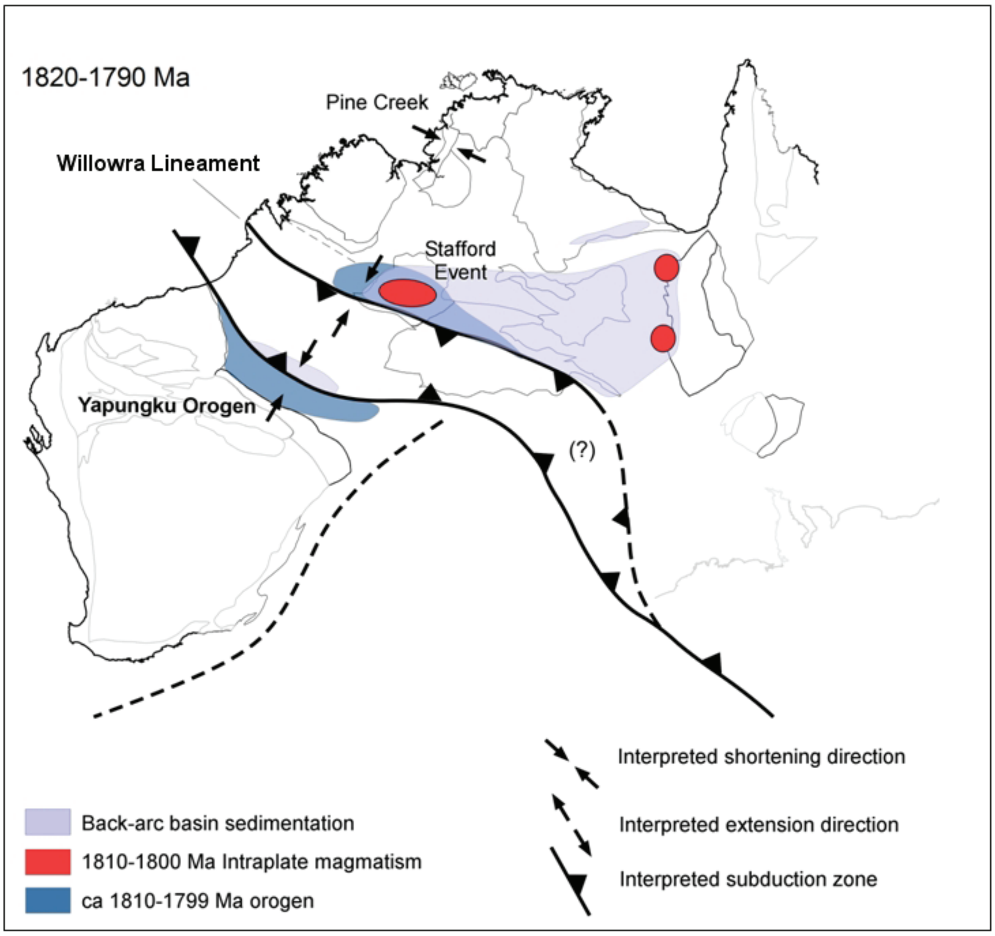

Figure 3

1790–1760Ma Leichhardt Superbasin Development

By this time, SW-dipping subduction had ceased leaving one major NE-dipping subduction zone transecting the Australian continent. Subduction-related orogenic convergence (the Yambah Event) characterised the Arunta Inlier and adjacent Tennant Creek/Davenport Inliers at his time while further to the east and north-east backarc extension predominated (perhaps related to rollback of the southern segment of the subduction zone) (Figure 4). Extensive bimodal volcanism was associated with this inboard extensional regime.

In the western half of the Mount Isa region, this extensional event was associated with the deposition of the marine Mount Guide and Leander Quartzites followed by eruption of voluminous continental tholeiitic basalt in the Leichhardt River, Mount Oxide and Century Domains. Deposition of these successions is interpreted to have occurred during approximate ENE-WSW crustal extension. The Leichhardt River Domain is interpreted to be a remnant continental rift axis. Basaltic magmatism was followed by deposition of the Myally Subgroup.

In the central part of the Mount Isa region, this period saw eruption of the Magna Lynn Metabasalt followed by voluminous eruption of felsic-dominated volcanics

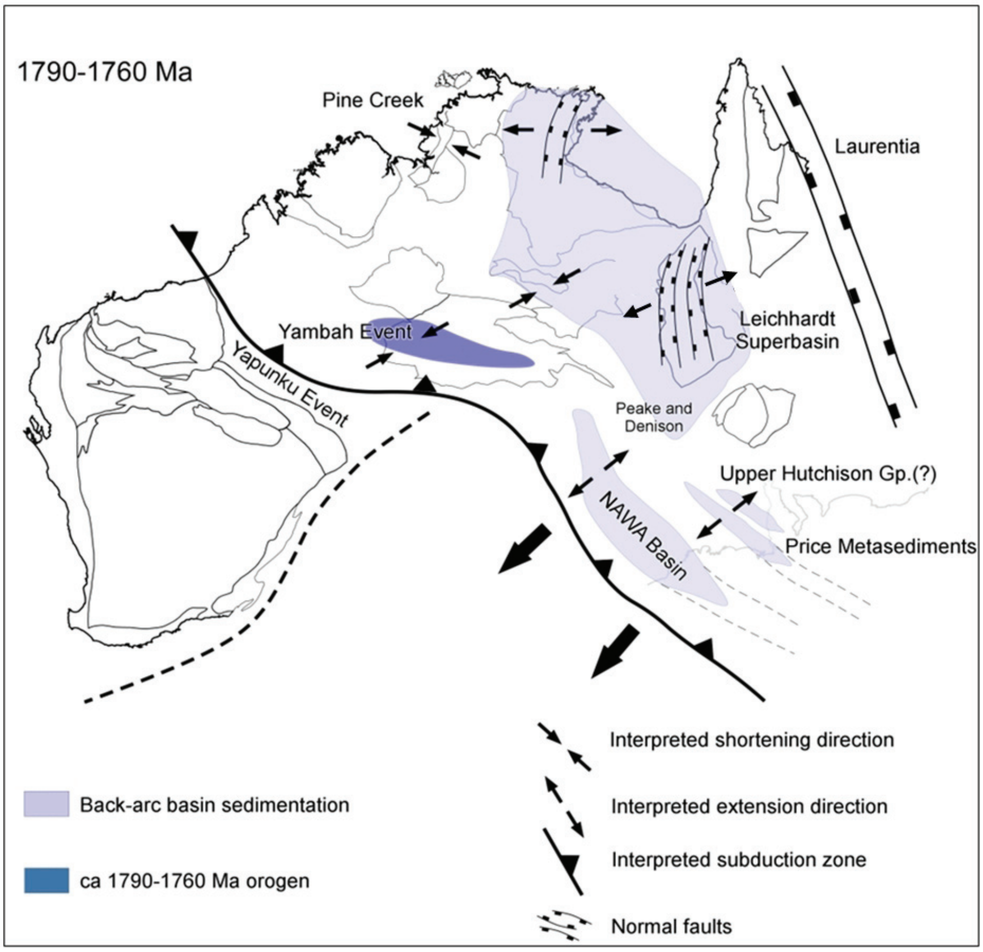

Figure 4

rocks of the Argylla Formation, succeeded further east by eruption of the felsic ~1760Ma Bulonga Volcanics and mafic Marraba Volcanics.

1760–1740Ma Backarc Extension and Detachment Formation

The presence of arc-related magmas in the southern Arunta lnlier suggest that the southern margin of the continent was an active convergent margin between ca 1760Ma and ca 1740Ma. Extensive basin systems developed across large parts of the NAC and the SAC at this time, indicating that they formed part of the same contiguous continent by this time. The development of extensional basins is interpreted to reflect roll-back of a north-dipping subduction zone between major accretionary events at ca 1800–1780Ma and ca 1740–1690Ma (Figure 5).

Basins of this age are extensional and characterised by a dominantly clastic basal succession followed by carbonate dominated upper successions. This pattern is evident in the Mount Isa Region, where protracted extension begins with broad sag-phase clastic successions of the lower Quilalar Formation in the Leichhardt River, Mount Oxide and Century Domains correlating with the deposition of the Ballara and Mitakoodi Quartzites in the centre and east of the region. These sequences were succeeded by shelfal carbonates of the upper Quilalar and Corella Formations.

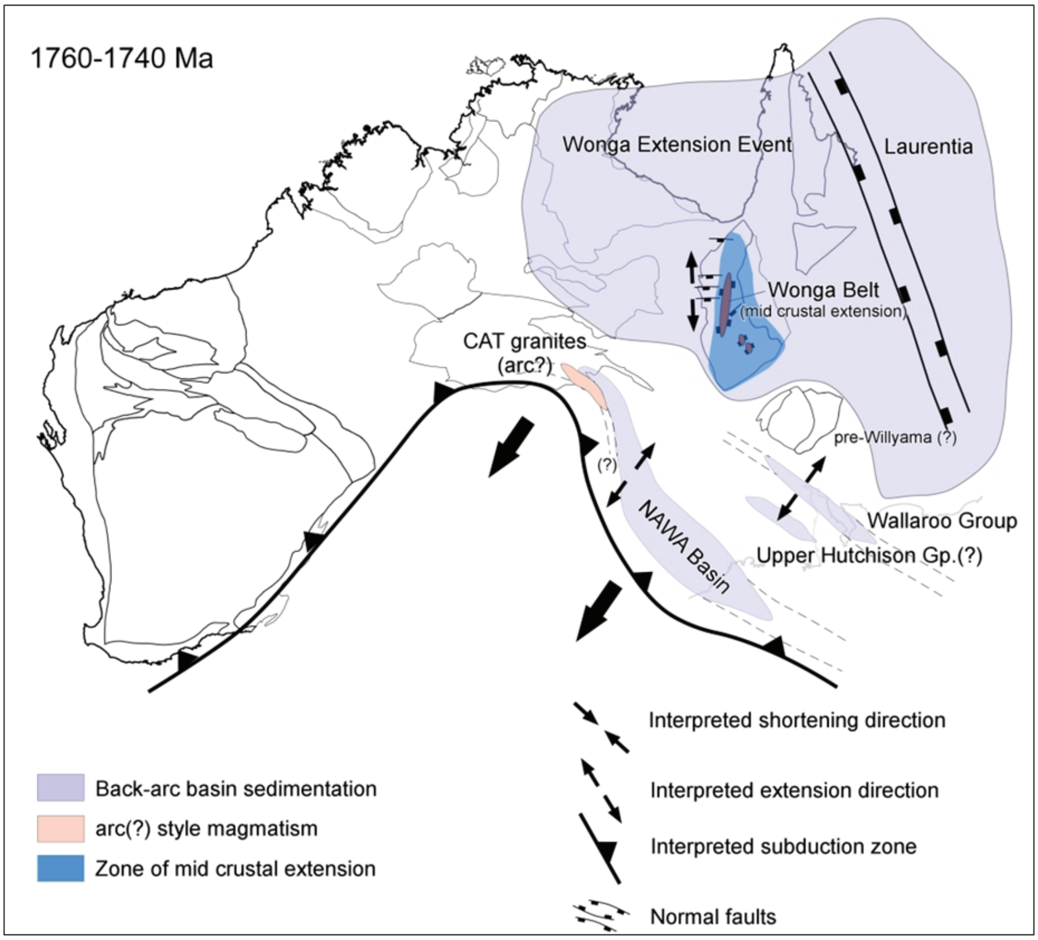

Figure 5

This time slice culminated in an episode of rapidly accelerating broadly N-S extension (the Wonga Event) accompanied by the development of a mid-crustal detachment extensively intruded by syntectonic granitoids now exposed in the Mary Kathleen Domain. No evidence of sediment deposition during this extensional event has been preserved.

1735–1725Ma Continental Shortening

Subduction related convergence propagated orogenic stresses into the over-riding plate resulting in depositional hiatus or basin inversion in the continental interior. Adjacent to the plate margin the stresses were at their most intense, resulting in the 1740–1725Ma Kimban Orogeny in the Gawler Craton and the 1735–1725Ma Strangways Event in the Arunta and Tennant Creek/Davenport Inliers associated with greenschist to granulite facies metamorphism and multiple phases of deformation (Figure 6).

At this time in the Mount Isa region, these events were expressed as broadly east-west shortening producing inversion of the Leichhardt Superbasin at 1730–1725Ma. Inversion was associated with localised folding in the Mount Oxide Domain, and southern Leichhardt River Fault Trough. This inversion may have been associated with uplift and erosion along the eastern Leichhardt River Domain, resulting in

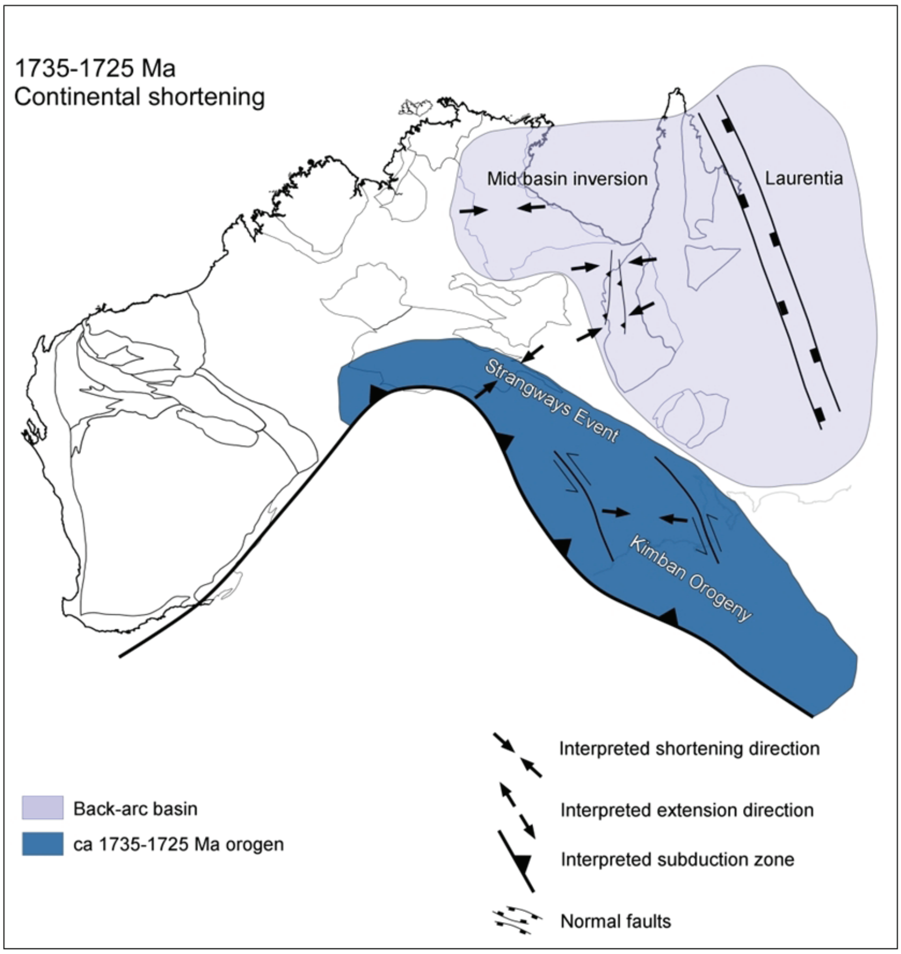

Figure 6

the development of the Mount Gordon Arch. Around 1740–1710Ma a depositional hiatus occurred in the Leichhardt River Domain and further east where no further sedimentation followed deposition of the Corella Formation.

1725–1690Ma Continental Extension

This time period was marked by syn-extensional basin development throughout the North Australia Craton and the Curnamona Province, following the termination of the major phase of the Kimban Orogeny (Gawler Craton) and Strangways Event (Arunta lnlier).

Extensional basin formation is interpreted to record roll-back of the north-dipping subduction zone along the southern margin of the craton and may have resulted in protracted high temperature metamorphic conditions after the main stages of crustal shortening associated with the Kimban Orogeny and the Strangways Event (Figure 7).

This period marked the deposition of the Curnamona Group in the Olary Domain, the Thackaringa Group and the Broken Hill Group in the Broken Hill Domain (lower Willyama Supergroup), and the Einasleigh Metamorphics, Bernecker Creek Formation, and Daniel Creek Formation in the Georgetown Inlier.

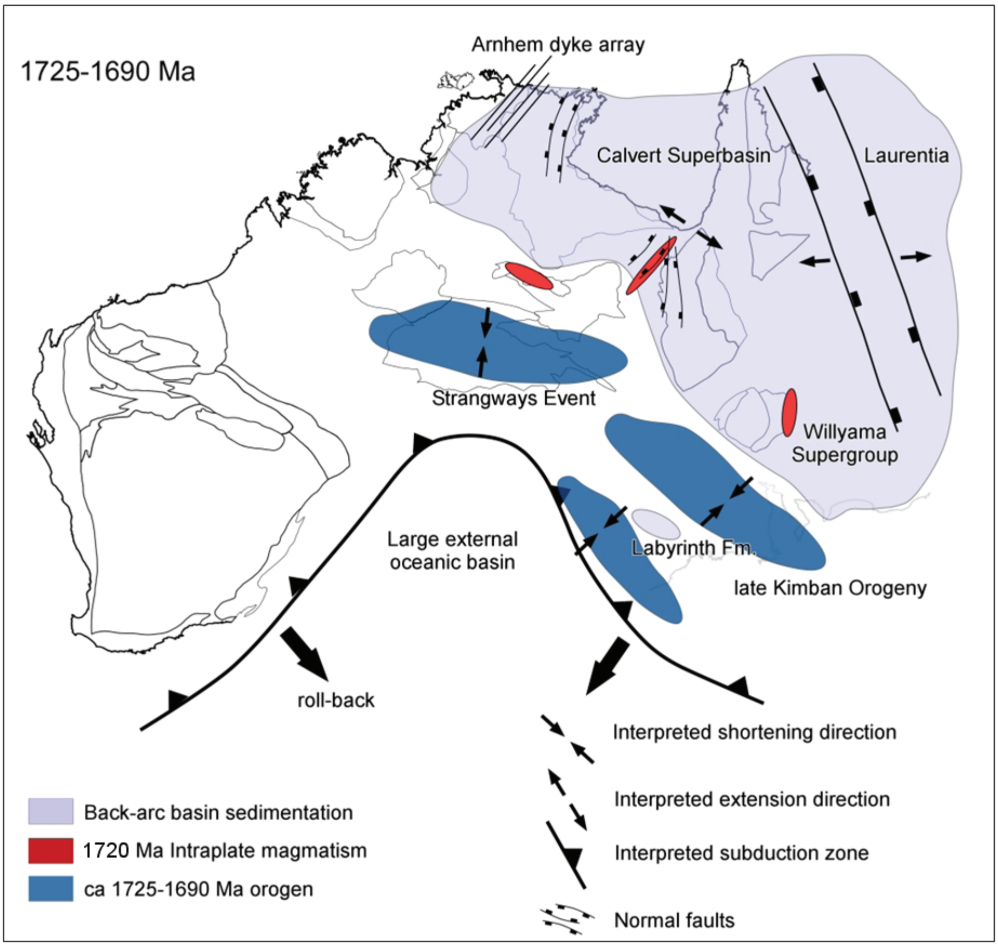

Figure 7

In the Mount Isa region, evidence for extension at this time was first recorded in the northern Camooweal-Murphy Domain where the 1725Ma Peters Creek Volcanics were erupted. This was followed by initiation of the ***Calvert Superbasin*** which developed across the Leichhardt River, Mount Oxide and Century Domains. The onset of Calvert Superbasin sedimentation occurred at 1720–1710Ma with the deposition of fluvial conglomerates and feldspathic sandstones of the Bigie Formation and eruption of the bimodal Fiery Creek Volcanics during north-west–south-east directed extension. Associated deposition also occurred in south-east-thickening half grabens in the Mount Oxide, Century and Leichhardt River Domains. Further east around 1710Ma, deposition of the sandstone-dominated Mount Albert Group occurred in the Kalkadoon-Leichhardt and Mary Kathleen Domains and the calcareous to quartzose sediments of the Staveley Formation and Roxmere Quartzite were deposited in the Marimo-Staveley Domain.

1690–1670Ma Calvert Superbasin extension

At this time, large regions of the continent underwent extension resulting in deposition of dominantly fluvial sedimentary successions in central and northern regions, and uplift (and associated erosion and depositional hiatus) throughout eastern and north-eastern Australia.

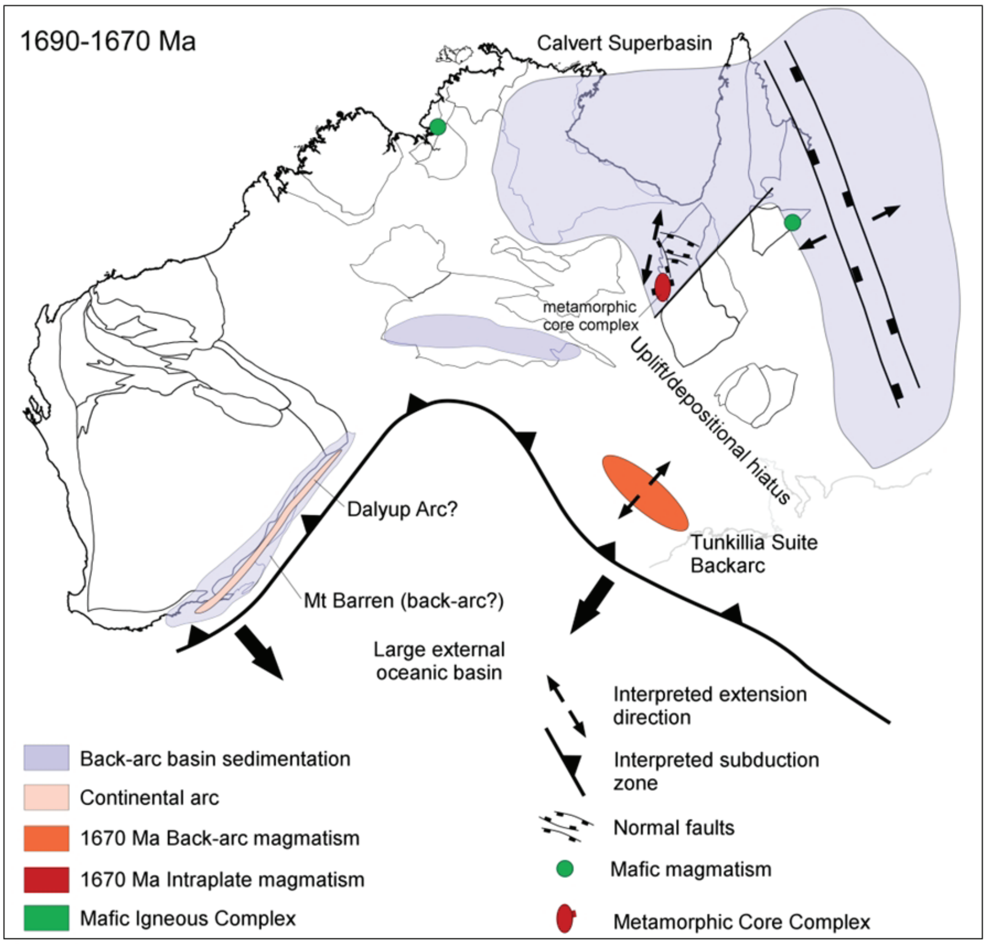

Figure 8

Extensional tectonism was driven by roll-back of a north-dipping subduction zone accompanied by back-arc magmatism in the Gawler Craton, and felsic and mafic magmatism and basin development along the eastern margin of the Yilgarn Cration. Backarc extension was expressed far into the interior and nascent rifting at the proto-Laurentian margin was initiated east of the Georgetown Inlier (Figure 8).

In the Mount Isa region, this era is interpreted to mark continued development of the Calvert Superbasin (Surprise Creek Formation and Torpedo Creek Quartzite) and is characterised by fluvial to shallow marine sedimentation in the western parts of the Mount lsa lnlier, metamorphic core complex development in the Sybella Domain and a regional depositional hiatus in the eastern parts of the inlier, until deposition of the lower Soldiers Cap group (the Llewellyn Creek Formation) within the Soldiers Cap Domain.

1660–1645Ma Isa Superbasin extension

This period marks the transition from rift-related sedimentation of the Calvert Superbasin to sag-phase-dominated sedimentation of the ***Isa Superbasin***. This transition is interpreted to reflect the opening of a small ocean basin along the eastern margin of the Australian continent. Australia is interpreted to have occupied the lower

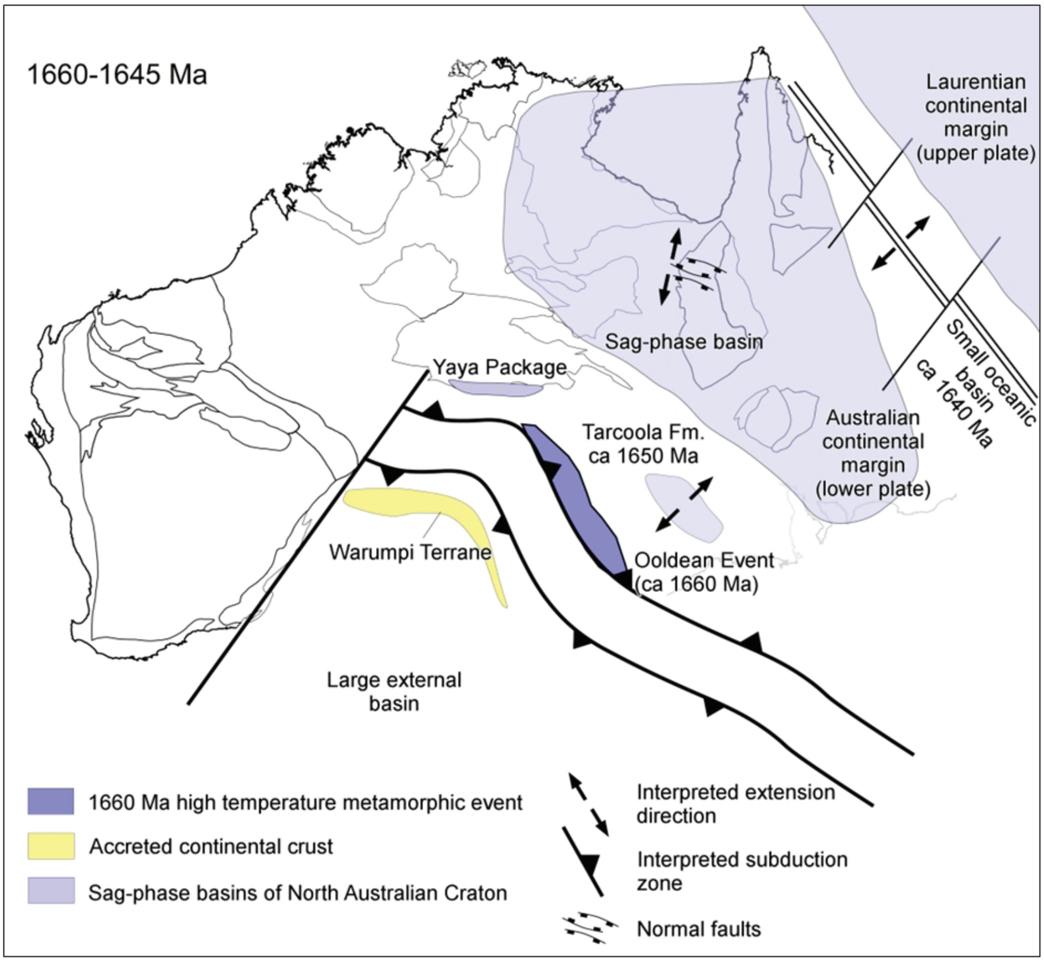

Figure 9

plate and underwent continental thermal subsidence. Laurentia occupied the upper plate and underwent regional uplift, depositional hiatus and erosion (Figure 9).

Along the southern margin of the Australian continent, continued subduction transported the Warumpi terrane towards the southern margin of the Australian continent. Roll-back of this subduction zone led to intermittent extension and inversion during post-rift sag-phase basin development.

During this phase, the Isa Superbasin sequences of the lower Mount lsa Group were deposited in the Leichhardt River Domain as well as the McNamara Group in the Century, Mount Oxide, and Ardmore Domains. Sag-phase sedimentation in the west was punctuated by periods of NNE-SSW directed extension (e.g. Myally Sub-basin).

Deposition in the eastern Mount Isa Inlier at this time included the upper Soldiers Cap Group (Mount Norna Quartzite, Toole Creek Volcanics) in the Soldiers Cap Domain and the Answer Slate in the Marimo-Staveley and Kuridala-Selwyn Domains.

Equivalent sequences to the east in the Georgetown Inlier include the Dead Horse Metabasalt and Cobbold Metadolerite, as well as the pelitic Corbett and Lane Creek Formations.

1645–1630Ma Collision and Extension

A major accretionary event (~ 1640Ma Leibig event associated with Warumpi terrane collision) occurred along the southern margin of the North Australian Craton, resulting in inversion of many of the interior basins (Figure 10). This event coincided with a major inflection in the Australian Apparent Polar Wander Path.

Continued ocean development occurred between Australia and Laurentia, maintaining Isa Superbasin sag-phase depocentres in the Mount Isa region. In particular, between 1650–1630Ma, McNamara Group elements continued to be deposited in the Century and Murphy-Camooweal Domains (Loretta, River, Term Supersequences). However, at around 1640Ma, the Riversleigh basin inversion event saw reverse reactivation of east-west to east–north-east faults on the northern Lawn Hill Platform.

The upper Etheridge Group was deposited far to the east during this time period in the Georgetown Inlier.

The Isa Superbasins' lower plate extensional or far-field back-arc environment during this and earlier periods provided a favourable environment for the accumulation of shale-hosted massive sulfide Pb-Zn-Ag deposits in anoxic subbasins in an

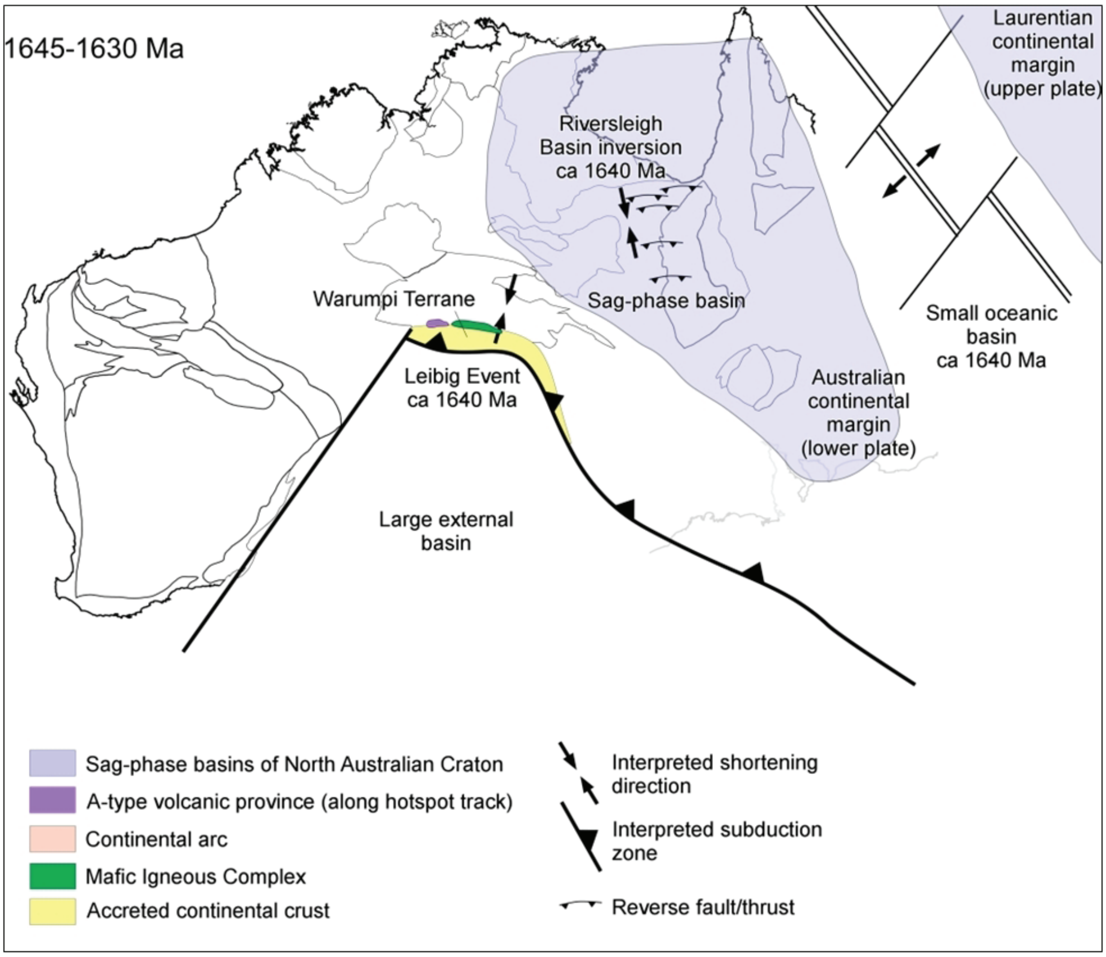

Figure 10

environment of long-term elevated heat flow. Episodic changes in extension rate and direction over this time period combined with intermittent periods of inversion drove circulation of mineralising fluids sourcing metals from volcanic and clastic basement sequences. These Pb-Zn-Ag deposits also accumulated in an environment favourable for long-term preservation, as they were isolated from collisional margins where any mineral deposits are lost to erosion associated with crustal thickening, uplift, denudation and recycling.

1640–1570Ma cessation of sedimentation and beginning of orogenic deformation

This time period saw waning sedimentation in the face of increasing deformation and arc magmatism throughout the southern convergent margin of the Australian continent. Closure of the small ocean that had developed between Laurentia and Australia also began to take place at this time, possibly associated with the Ewamin Orogeny affecting the Georgetown Inlier.

Early in this time period at Mount Isa, sedimentation continued with deposition of the ~1640–1595Ma upper McNamara Group on the Lawn Hill Platform (Lawn, Wide, and Doom Supersequences), and the ~1610Ma deposition of the calcareous Milo beds in the Tommy Creek Domain. However, sedimentation was brought to a halt soon after by the ~1600–1570Ma Early Isan Orogeny. This orogenic event is characterised N-S to NW-SE directed crustal shortening. In the Leichhardt River Fault Trough deformation is characterised by inversion of east–west trending normal faults inherited from the pre-Isan basin evolution. In the Mitakoodi Domain and Soldiers Cap Domain crustal shortening was accommodated by movement along shallow, west dipping decollements (e.g., Overhang Shear Zone) and nappe development in the hanging walls of the decollements . The peak of the high temperature, low pressure metamorphism occurred around 1580Ma.

Elswhere, equivalent major orogenic episodes affected the southern continental margin and environs, including the ~1610–1575Ma Chewings Orogeny in the Arunta Inlier, the 1610–1590Ma Wartaken Orogeny affecting the Gawler Craton, and the 1610–1590Ma Olarian Orogeny affecting the Curnamona Province. The subduction-related Saint Peter Suite magmatic arc was active along the length of the Gawler Craton at ~1620–1610Ma.

A unique feature at this time is thought to be the interaction of a mantle plume with a north-dipping subduction zone resulting in orogenesis and north-south crustal shortening throughout the eastern parts of the Australian continent between ca 1610Ma and ca 1570Ma. The plume is interpreted to have interacted with Gawler Craton and Curnamona Province lithosphere at ~1590–1570Ma resulting in the development of a large felsic igneous province dominated by A- and I-type granitoids and volcanics (e.g. Hiltaba Suite granitoids and Gawler Range Volcanics in the Gawler Craton). As the continent moved south, a northward migrating hotspot track was generated (Figure 11).

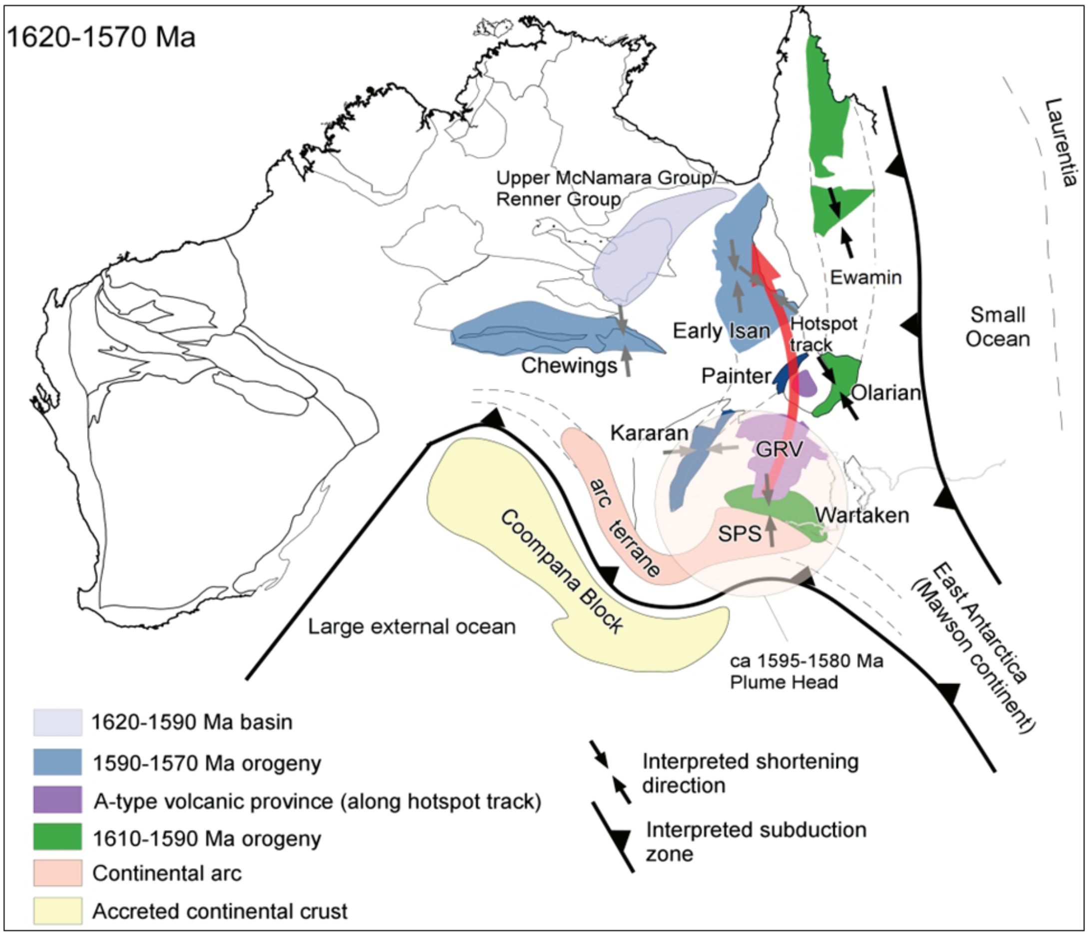

Figure 11

1570–1500Ma Isan Orogeny and late Magmatism

Intraplate shortening predominated during this period, with deformation in the NAC related to collision of Laurentia with the Australian continent. In the Mount Isa Inlier, extensive east–west shortening during this period occurred as two episodes — (i) major north–south oriented folding during the 1570–1550Ma Middle Isan Orogeny, and (ii) brittle wrench style faulting during the Late Isan Orogeny. The Middle Isan Orogeny was expressed as the Jana Orogeny in the Georgetown Inlier. Australia continued to migrate over a mantle plume resulting in the emplacement of TTG and A and I-type granitoid suites in the Mount Isa lnlier (the Williams and Naraku Batholiths) (Figure 12).

The systematic decrease in the width of the hotspot track from ~500km in the Gawler Craton to ~80km in the Mount Isa Inlier reflected the transition from plume head to plume tail interaction with continental lithosphere. The introduction of plume-related metal-bearing mantle melts at this time added to the crustal enrichment of the hanging wall of the older Mount Isa-Numil/Abingdon subduction zone. Elevated heat flow and associated crustal melting, together with hydrothermal fluid generation and re-activated brittle fault systems provided ideal mechanisms for the production, transport and concentration of the metal-bearing fluids responsible for the widespread IOCG mineralisation in the eastern Mount Isa Inlier.

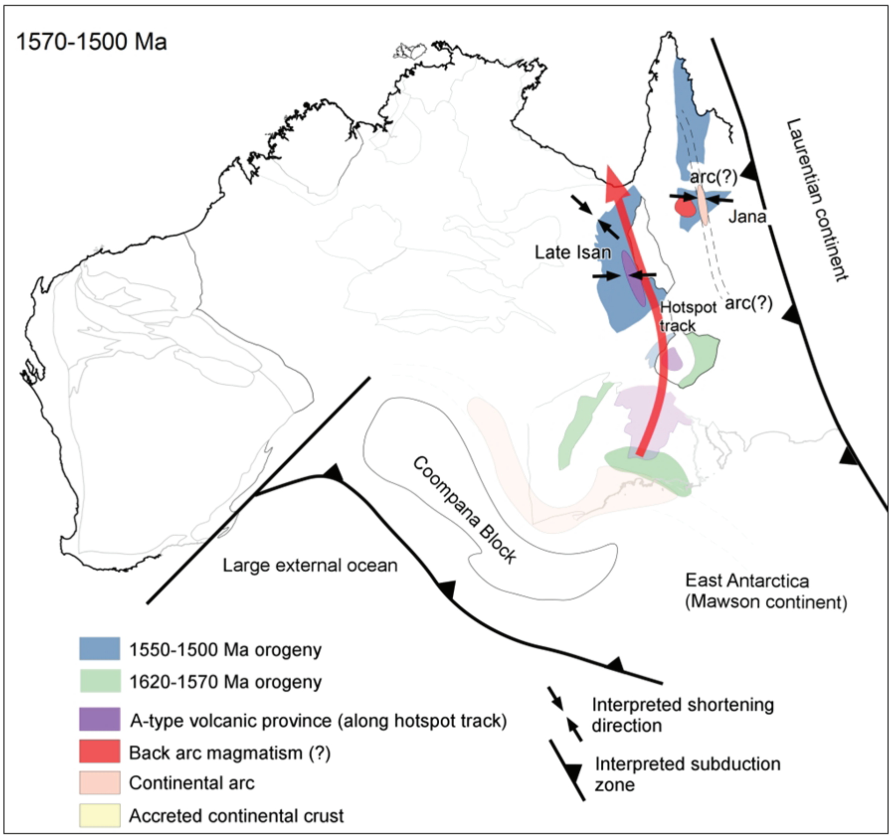

Figure 12

CONCLUSION

The geological evolution of the Mount Isa Inlier has seen the region develop through a range of geodynamic settings that were favourable for the generation, concentration and preservation of world-class mineral deposits. Recognition of these favourable settings and the spectrum of mineralisation styles that may accompany them will be vital for the generation of successful future greenfields exploration strategies.

THE NORTH WEST QUEENSLAND 3D MODEL — UNCOVERING QUEENSLAND'S RESOURCE POTENTIAL

Ben Jupp

Geological Survey of Queensland

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 underexplored. There remains huge potential for further significant discoveries in the region.

The Geological Survey of Queensland (GSQ) has recognised the need to better aid explorers to uncover the resource potential of this underexplored region. The North-West Queensland Mineral and Energy Province (NWQMEP) Study currently approaching completion at the GSQ aims to provide valuable insights for explorers into the links between the geodynamic setting, 3D architecture, structural evolution and mineralising processes within both the exposed and covered regions of the Mount Isa Inlier (Figure 1). This study incorporates new regional scale datasets, new geological mapping, new mineral systems analyses and new 3D geological models to provide a valuable tool for explorers to better evaluate regions of interest and ultimately unlock the mineral and energy resource potential of the region.

The North West Queensland 3D model is a critical aspect of the NWQMEP Study and incorporates current geological concepts and a range of diverse data sets to form a coherent physical representation of the current state of geological understanding of the north-west Queensland region. This model has been 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.

The key aims of the model are:

- update the pmd*CRC I7 3D model of the Mount Isa region with new geological mapping results, deep crustal seismic and magnetotellueric datasets,
- link the regional subsurface architecture of the exposed Mount Isa Inlier with that of surrounding undercover regions,
- define the major crustal structural breaks and potential fluid conduits,
- address areas of uncertainty within the region, and
- provide a broad architectural framework which can be used to underpin future district or camp-scale studies.

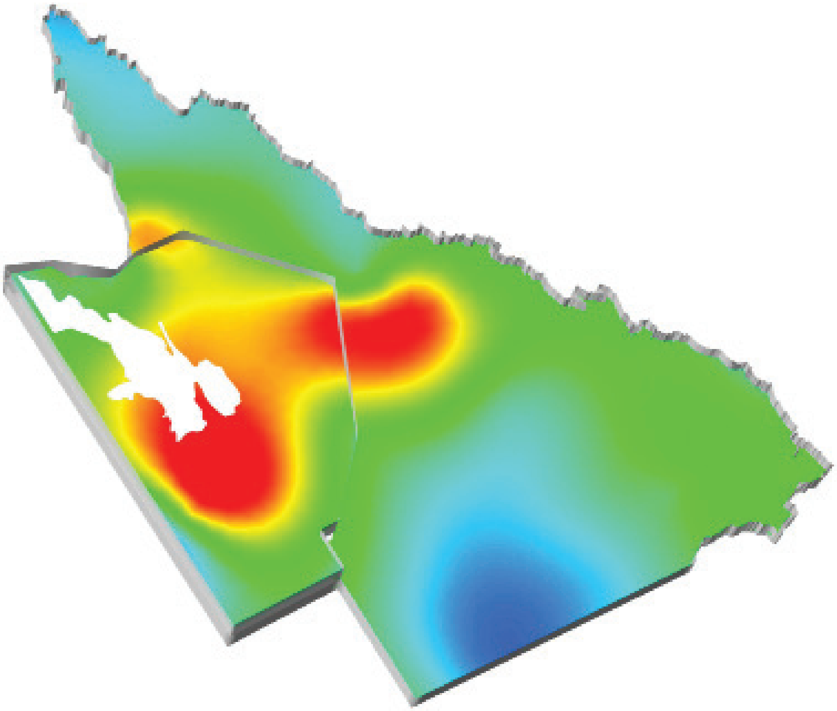

Figure 1. NWQMEPS 3D Project Area

3D MODEL CONSTRUCTION

The north-west Queensland 3D model (Figure 2) was constructed as part of the NWQMEP Study using the GOCAD 3D modelling software package. It covers an area of over 500 000km^2 to a depth of approximately 25km. The model builds on previous models which were constructed during the pmd*CRC and updates the current state of understanding of the region with new datasets.

Construction of the model was carried out using regional aeromagnetic and gravity datasets, updated geological mapping results, new deep crustal seismic, and magnetotelluric datasets (Figure 3). These datasets were used to construct serial cross sections drawn at 10km intervals. Forward modelling was carried on a number of key cross sections in order to better constrain subsurface geometries.

Fourteen major units have been correlated and constructed across the north-west Queensland region. Unit subdivisions (Table 1) were defined based on an updated Proterozoic Mount Isa Time-Space Plot which will be included within the NWQMEP Study report. The lithostratigraphic units have been modelled in a broadly sheet-like and pseudo layer-cake type geometry with relatively flat/gently inclined enveloping surfaces.

All major intrusive suites have been modelled across the Mount Isa Inlier (Figure 2). Modelled suites include the Kalkadoon, Toby-Ewan, Wonga, Weberra, Sybella and Williams suites. All intrusives have generally been interpreted as massive flat based laccolithic type bodies. Interpreted intrusive bodies have similarly been constructed in the surrounding undercover regions.

Figure 2. NWQ 3D model illustrating fault architecture and all intrusive suites

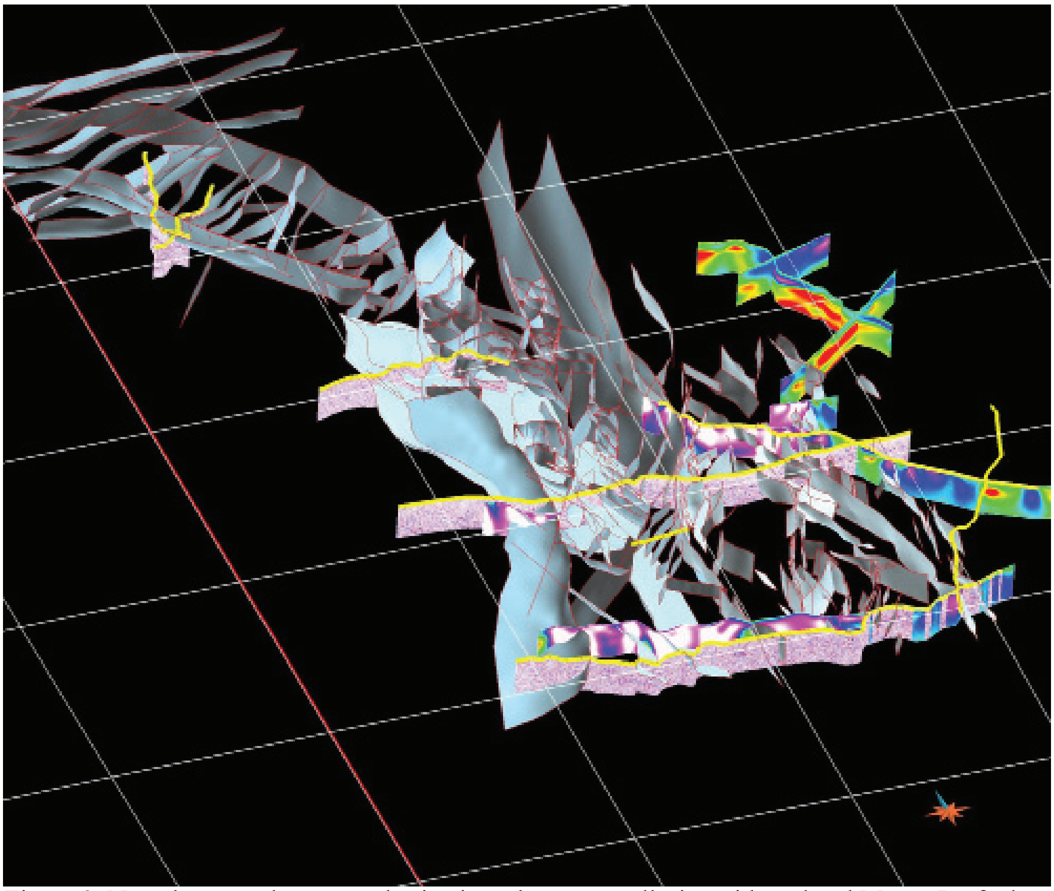

Figure 3. New datasets; deep crustal seismic and magnetotellurics with updated Mount Isa fault architecture

Table 1: Superbasins and internal lithostratigraphic units constructed within the NWQ 3D model

WEST		EAST	
3D SURFACE (GoCAD project surface nomenclature)	**MODELLED UNITS**	**3D SURFACE (GoCAD project surface nomenclature)**	**MODELLED UNITS**
		Base of Millungera Basin (base_Millungera)	Millungera Basin sequence
		Base of Tommy Creek (base_Tommy)	comprises the Milo Beds within the Tommy Creek Domain
Base of Isa Superbasin (base_Isa)	comprises the Lower and Upper McNamara Group, the Mount Isa Group and the upper Gun Supersequence		
		Base of Soldiers Cap (base_Solders_Cap)	Includes Soldiers Cap Group and Answer Slate
Base of Calvert Superbasin (base_Calvert)	comprises Big and Prize Supersequences (includes Bigie Formation, Fiery Creek Volcanics, and Surprise Creek Formation)	**Base of Calvert Superbasin (base_Calvert)**	includes Staveley and Roxere Formations
		Base of Mount Fort Constantine (base_Constantine)	comprises Mount Fort Constantine Volcanics
Base of Quilalar/Corella (base_Quilalar)	Comprises Quilalar and Corella Formation and equivalents	**Base of Quilalar/Corella (base_Quilalar)**	comprises Ballara and Mitakoodi Quartzites, Overhang Jaspilite and Corella Formation
Base of Myally (base_Myally)	comprises the Myally Subgroup of the Haslingden Group	**Base of Bulonga (base_Bulonga)**	comprises Bulonga Volcanics and Double Crossing Metamorphics
Base of Eastern Creek Volcs (base_ECV)	comprises the Eastern Creek Volcanics and lower members of the Haslingden Group		
Base of Leichhardt Superbasin (base_Leichhardt)	comprises the Mount Guide Quartzite and equivalents, Bottletree Formation, Magna Lynn Metabasalt and the Argylla Formation	**Base of Leichhardt Superbasin (base_Leichhardt)**	Includes Argylla Formation inferred to exist beneath exposed sequences
Base of Tennant Creek (base_Tennant_Ck)	Includes Bucket Hole Formation and Oroopo Metabasalt		
Base of Leichhardt Volcs (base_L_Volcs)	Includes the Leichhardt Volcanics, Candover Metamorphics, Cliffdale and Scrutton Volcanics; this surface also marks the top of pre-Barramundi Orogeny basement rocks (e.g. the Kurbayia Metamorphic Complex, Saint Ronans and Yaringa Metamorphics)	**Base of Leichhardt Volcs equivalents (base_L_Volcs_equiv)**	Includes rocks forming basement to Leichhardt Superbasin and younger sequences; includes temporal equivalents of Leichhardt Volcanics

The fault architecture (Figure 2) is a key aspect of the 3D model and is defined by a complex network of over 400 interlinking 3D surfaces. In order to limit the size of the model only faults greater than 10km strike length have been constructed except where interpretation or geological complexity required otherwise. The fault architecture is dominated by steep structures which tend to flatten toward low angle listric geometries at greater depth extents. Potential field data has been used to help identify major crustal breaks and dips of major faults undercover. Greater strike length faults have been interpreted as having greater crustal penetration and are modelled as such.

DEPTH TO BASEMENT

A regional depth to basement surface has been developed across the north-west Queensland region and constructed in GOCAD (Figure 4). This surface has been developed to aid explorers to identify zones where shallow cover places prospective basement within reach of current drilling technology. Depth information was extracted from historical company drill holes, water bores, stratigraphic drill holes and seismic profiles where available. Where hard constraints were sparse, magnetic depth source modelling was carried out using the ModelVision 2.5D modelling software. Magnetic anomaly depth estimates were calculated using 1:250000 gridded TMI images (80m grid cell). DEM and flying heights were removed from modelled depths to obtain true depth values.

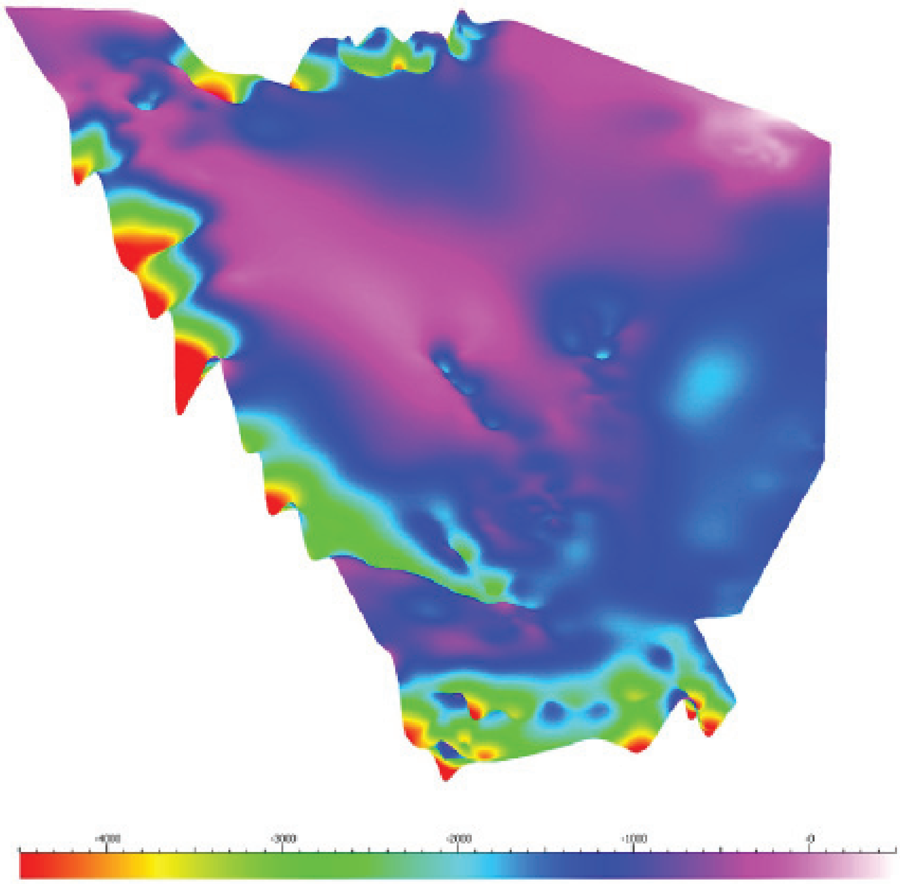

Figure 4: NW Queensland 3D Depth to Basement Surface (30x Vertical Exaggeration)

A final database was compiled and gridded in Geosoft and then exported as a .csv file for import into GOCAD. The final surface was built and interpolated to best fit all data. Due to limitations in hardware a true fit to each point was not feasible. Where data was sparse a coarse mesh was used to limit triangles required. Where data was dense a more dense mesh was used. In regions of outcrop it was assumed no cover was present and DEM values (90m resolution) were used.

CONCLUSION

The north-west Queensland 3D model provides a valuable tool for explorers to better understand the complex nature of the subsurface geology of the north-west Queensland region, from which further detailed studies can be carried out. While significant detail has been captured within this model, it should be recognised that the model represents only one possible solution to a very complex geological problem. As is the nature of geology and emphasised through by the succeeding pmd*CRC I1, I2, I4 and I7 3D models, results and understandings are in a continual refinement process. New geophysical inversion technologies, better hardware systems and ongoing data acquisition will see this current 3D model continue to be updated, revised and improved as further insight into the true nature of the geology is uncovered. This model remains a highly simplified representation of the current level of understandings of the regional geology.

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MOUNT DORE AREA 3D MINERAL POTENTIAL STUDY

Matthew Greenwood

Geological Survey of Queensland

The Mount Dore Project Area is a 175km x 70km block located immediately south of Cloncurry within the NWQMEPS (North-West Queensland Minerals and Energy Province Study). The area is dominated by copper ± gold ± iron oxide mineralisation and hosts significant copper-gold producers 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.

The purpose of the study was to investigate the geological, structural, geophysical and geochemical characteristics of IOCG mineralisation and use this data as an input into a regional Common Earth model to create a 3D mineral potential map of the Mount Dore area. The 3D Mineral Potential map represents the relative chance of each individual cell within the model hosting IOCG mineralisation and can be used to aid targeting for further mineralisation, particularly under cover, within the Mount Dore area.

The GSQ commissioned Mira Geoscience to develop a Common Earth Model and use Bayesian statistics to evaluate associations and define patterns, effectively 'testing' the significance of features identified through the regional mineral systems analysis at district scale. The newly developed workflow will be applied for future projects undertaken by the Greenfields Prospectivity Unit.

MODELLING

The initial component of the project involved creating a 3D model of the Mount Dore project area using the SKUA implicit modelling environment within the GOCAD software suite. Firstly the major structural domains were identified and divided into fault compartments which were incorporated with mapped faults to build the SKUA fault network. Ten stratigraphic packages were identified within the region, grouping together rocks of similar physical property characteristics. The stratigraphic horizons and faults were modelled in SKUA (Figure 1) using the solid geology map and seven interpreted cross-sections created from potential field, seismic and magnetotelluric data. Airborne EM data (GEOTEM) was processed and sharpened to produce conductivity depth images (CDIs) using EmaxAIR.

INVERSION

A regional voxet model (900 metre lateral resolution) was constructed from the SKUA horizon model with each geological domain populated with corresponding physical properties (density and magnetic susceptibility) based on an assessment of collected

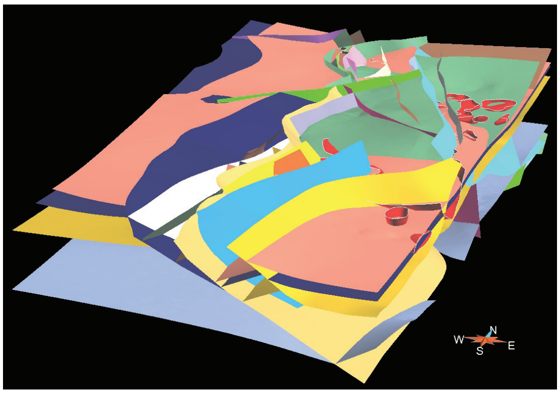

Figure 1. Fault and Horizon SKUA model of the Mount Dore region viewed from the south

rock property information. Initial potential field inversions of the gravity and magnetic data were undertaken using VPmg to refine the granite geometry and depth of cover in the south-west of the region. These results were used to improve and prepare the initial voxet model for regional potential field inversions.

A series of constrained potential field inversions of the magnetic and gravity data of the entire Mount Dore project area were conducted in 2 stages using VPmg. The first stage involved homogenous property inversion to optimise the properties assigned to each geological domain and achieve a better fit to the observed data. Homogenous optimisation of properties, especially the magnetic susceptibility, was hindered by the inherent heterogeneity created by clustering multiple lithologies into broad geological domains. A second inversion stage was implemented using the optimised densities and susceptibilities as inputs for heterogeneous unit inversions

Heterogeneous unit inversions of the gravity and magnetic data allowed the density or magnetic susceptibility of each cell to vary within the range of the constraints set by the initial modelled lithology. This stage of inversion highlighted anomalous regions within the geological domains of the 3D density model (Figure 2) and magnetic susceptibility model (Figure 3), for example, the inversion created zones of heightened density and magnetic susceptibility corresponding to mapped dolerites which were not represented in the simplified geological reference model .

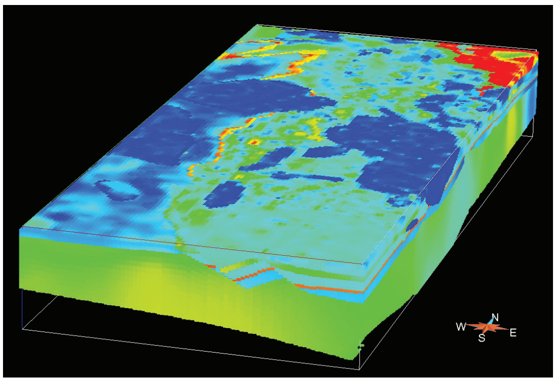

Figure 2. Regional density model of the Mount Dore region produced after VPmg homogenous and heterogeneous property inversions

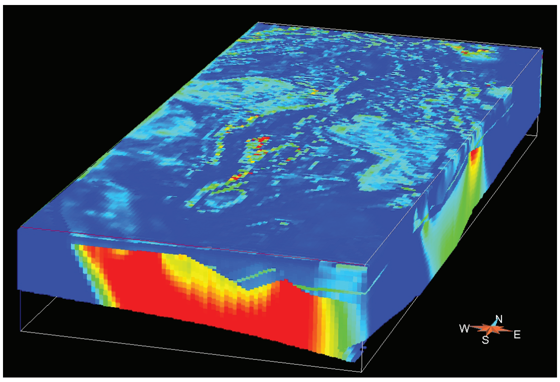

Figure 3. Regional magnetic susceptibility model of the Mount Dore region produced after VPmg homogenous and heterogeneous property inversions

The regional inversion results were interpolated into a high-resolution model of the upper 2.5 kilometres of the crust with a cell size of 300 metres laterally by 150 metres vertically. A tiled magnetic susceptibility inversion was performed on the high-resolution model with the MAG3D UBCGIF inversion program to resolve magnetic anomalies in the near-surface not accounted for by the regional VPmg inversion.

PSEUDO-LITHOLOGY

The GEOTEM CDI results were interpolated into the high resolution model and the resulting 3D density, susceptibility, and conductivity distributions were classified into a pseudo-lithology model. The pseudo-lithology uses the property distributions within each of the initial geological regions to create domains within the statistical multi-variable ‘parameter space’. The pseudo-lithology of each cell was then classified by its properties depending on its proximity to these domains in the parameter space, identifying cells which are more similar to cells in other regions than its own. The pseudo-lithology is useful in testing the validity of the starting model, allowing interpretation of additional geological complexity and to identifying areas which may represent metamorphism or alteration.

The pseudo-lithology classification corresponded with the original geological domain in 72% of cells, a good validation of the starting property model. A considerable proportion of the volume which has been reclassified from the starting model was assigned to the Double Crossing Metamorphics class, and is coincident with small areas on the map identified as intrusive which were not included in the modelling (Figure 4). Other reclassified areas can be interpreted as unidentified intrusive bodies or as a metamorphic or alteration overprint.

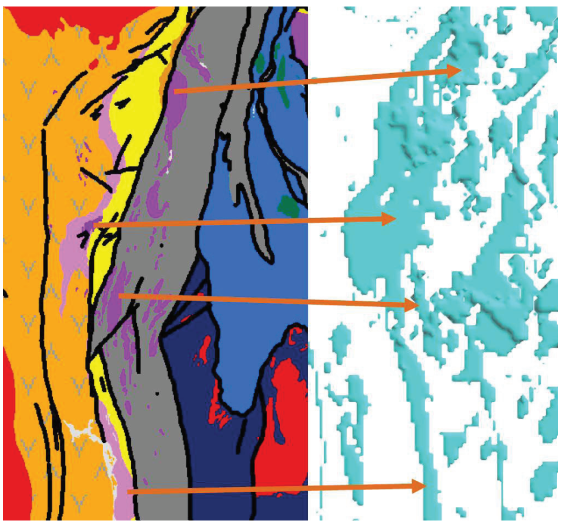

Figure 4. Geology map (left) and volumes of changed pseudo-lithology (right). The reclassification is due to small intrusives than didn’t appear in the initial regional modelling.

EXPLORATION TARGETING

A Weights-of-Evidence (WoE) approach was chosen to assess the potential for further economic mineralisation using the existing location of known iron oxide ± copper ± gold (IOCG) mineralisation as training data. A Common Earth model (CEM) of the Mount Dore region was prepared with a cell resolution of 300m by 300m by 150m and extending to 2.5km depth. The CEM contains all available data including the SKUA modelling, the rock properties from the inversions, the pseudo-lithology and points of known mineralisation.

Key targeting or exploration criteria were selected in consultation with the GSQ and in light of published and unpublished literature, including the Mineral systems Analysis undertaken as part of NWQMEP study, 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. Initially 22 exploration criteria were identified and populated into the CEM as continuous or discrete properties. 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. Eleven of the exploration criteria exhibited significant correlation with mineralisation in the Mount Dore area and were used to calculate a Mineral Potential Index which represents the relative chance of each individual cell within the model hosting IOCG mineralisation (Figure 5). A separate Mineral Potential Index was created for undercover greenfields regions as several of the exploration criteria, such as surface geochemistry, require outcropping geology.

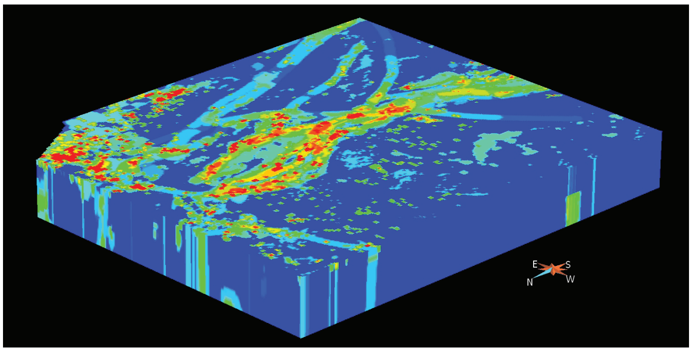

Figure 5. Mineral potential index for the nothern section of the Mount Dore region where hot colours represent high mineral potential derived from the Weights of Evidence modelling.

NEW SHRIMP GEOCHRONOLOGY FOR THE CONNORS ARCH, NORTHERN NEW ENGLAND OROGEN

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The late Paleozoic Urannah Batholith forms the core of the Connors Arch in the northern New England Orogen (NEO). The batholith consists of rocks ranging from granite to gabbro, but is composed mainly of granodiorite. Recent mapping of the Urannah Batholith (by R. Bultitude), combined with new SHRIMP U-Pb zircon data, has expanded the known age of magmatism in the batholith, as well as characterised a previously unrecognised metamorphic complex. We also report some ages for igneous units in the overlying lower part of the Bowen Basin succession, and in the adjacent Thomson Orogen to the west.

The Connors and Auburn Arches in central Queensland are the northern and southern parts respectively, of what was considered by Day & others (1978) to be a late Devonian – early Carboniferous volcanic arc. This model has had widespread support. Some researchers however, have suggested that the Connors and Auburn Arches were probably not the site of arc volcanism but more likely represent magmatism related to backarc extension (e.g. Holcombe & others, 1997; Allen & others, 1998; Bryan & others, 2001).

Recently published SHRIMP U-Pb data indicate the oldest granites in the Auburn Arch range in age from ~349Ma to ~320Ma (Withnall & others, 2009). SHRIMP U-Pb zircon data collected by Allen & others (1998) for the Urannah Batholith, led these researchers to suggest that the bulk of the batholith was emplaced between ~306Ma and ~286Ma. Allen & others (1998) also suggested that the lower age limit for the Connors Arch may be ~322Ma, based on K–Ar hornblende ages reported in Malone (1970) for rocks south of the Urannah Batholith.

Our new SHRIMP U-Pb results have identified the oldest unit found so far in the Urannah Batholith—a granite at Bowen, which has yielded an age of 341.3±2.4Ma (early Carboniferous). It intrudes rhyolitic ignimbrite of the Edgecumbe beds which has given a SHRIMP U-Pb age of 347.3±2.2Ma. Additionally, foliated granodiorite west of Proserpine has yielded a SHRIMP U–Pb age of 327.9±2.4Ma and two granites south-west of Bowen have identical ages of ~322Ma. Besides these older igneous rocks, our recent dating has also identified other intrusives ranging between ~305Ma and ~292Ma—i.e., broadly similar to the range of ages identified in the Urannah Batholith by Allen & others (1998).

One of the most interesting aspects of the recent mapping has been the identification of an extensive metamorphic complex, roughly in the centre of the Urannah Batholith. These rocks are mainly upper amphibolite-grade paragneisses, with a distinctive elevated Th response on radiometric images. SHRIMP U-Pb zircon dating, as well as

ID-TIMS U-Pb monazite analyses, indicate the metamorphism took place between ~298Ma and ~291Ma. Field evidence, coupled with the new age data, also suggests that at about 291Ma there was widespread emplacement of granites of mainly intermediate composition, as well as some volcanic activity; a sample of Connors Volcanics has yielded a SHRIMP U-Pb age of ~291Ma. Igneous units of the lower Bowen Basin succession were subsequently emplaced; two samples of Lizzie Creek Volcanics have yielded ages of 286.5±2.0Ma and 283.6±2.1Ma, and the Mount Wickham Rhyolite ages of 285.9±2.0Ma and 284.9±1.7Ma.

Late Carboniferous – early Permian magmatic activity was also widespread in the adjacent Thomson Orogen (Oversby & others, 1994). Virtually identical SHRIMP U–Pb ages of ~292Ma were obtained from a rhyolitic ignimbrite of the Bulgonunna Volcanic Group and a granodiorite that intrudes it.

SHRIMP U-Pb detrital zircon provenance spectra were also obtained from two samples of paragneiss collected from the newly-defined metamorphic complex. Although both samples are dominated by early to mid-Paleozoic zircons, they generally have different age spectra. The gneiss from East Creek has age components at ~1220Ma, ~650Ma, ~570Ma, ~500Ma, ~425Ma and ~380Ma as well as a series of mostly discontinuous individual ages that extend back to ~3480Ma and a single grain at ~320Ma. In contrast, the other gneiss sample, from the Normanby area, has age components at ~1620Ma, ~1135Ma, ~575Ma, ~510Ma, ~440–400Ma and ~325Ma as well as individual grains at ~1710Ma, ~1790Ma, ~2630Ma and ~3180Ma. Both samples show common age clusters of between ~575Ma and ~500Ma, and between ~325Ma and ~320Ma; the latter represents the youngest detrital age component in both.

Between about 305Ma and 285Ma, the NEO underwent a period of major extension which resulted in the development of the Bowen and Gunnedah Basins (Korsch & others, 2009) and, west of the Connors Arch, the eruption of the ~305Ma to ~292Ma Bulgonunna Volcanic Group (this work; Black, 1994). The identification of a widespread magmatic event at about 292Ma in the northern NEO suggests that extension in the region may have reached a peak at about this time.

Our identification of an early Carboniferous magmatic event within the Connors Arch broadly coincident with forearc rocks to the east, lends weight to the interpretation of Day & others (1978) that the Auburn and Connors Arches represented an Andean-style volcanic arc during the late Devonian – early Carboniferous. Youngest inherited zircons found within the two samples of paragneiss at about 325Ma, may also support this argument. This age is similar to that obtained for the youngest detrital zircons found in NEO accretionary rocks by Korsch & others (2009), who suggested they were derived from an active continental-margin magmatic arc. The ~325Ma detrital zircons in the two samples of paragneiss may have a similar provenance, and represent younger components of the arc. The major inherited zircon age components in the two samples of paragneiss analysed, at ~425Ma, and ~500Ma, are consistent with derivation mainly from the Georgetown and Charters Towers regions where granites of a similar age are exposed. The source of the inherited ~570Ma age component is more uncertain as there are no well documented igneous events of that age in the Bowen region. Rocks with similar-age zircon populations have been found in the Anakie Metamorphic Group (Fergusson & others, 2001), as well as in igneous rocks from the Thomson Orogen in north-western New South Wales (Glen & others, 2010).

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TO SEAL OR NOT TO SEAL — THE WALLOON SUBGROUP, EASTERN SURAT BASIN

Micaela Grigorescu, Jonathan Hodgkinson and John Draper

Geological Survey of Queensland

A comprehensive gap analysis, undertaken by the Carbon Geostorage Initiative group (Dixon & others, 2009), analysed all the available departmental open-file databases (petroleum and stratigraphic wells, geophysics and seismic data) in order to identify geostorage 'plays' in Queensland. One of the concepts explored by the gap analysis was the existence and significance of unconventional seals. In the context of carbon geostorage in sedimentary reservoirs, an unconventional seal is a fine-grained low permeability unit with heterogeneous lithology and thickness greater than 200m that would be able to inhibit the vertical migration of CO_2 under buoyancy forces. In the Surat Basin, the Walloon Subgroup is considered to have the properties of an unconventional seal and the capacity to prevent vertical migration of CO_2 from the underlying potential carbon geostorage reservoirs, the Hutton Sandstone and the Precipice Sandstone.

This study builds on the previous work of Clark & Cooper (1985) and Hamilton (2007) with the aim of identifying the mineralogy of the Walloon Subgroup, to ascertain some of the units' sealing properties in the eastern Surat Basin. The initial sedimentological work (Clark & Cooper, 1985; Hamilton, 2007) was largely based on two fully cored stratigraphic wells, GSQ Chinchilla 3 and GSQ Dalby 1. Our study focuses on the mineralogy of the Walloon Subgroup over a larger area and incorporates a total of 125 samples from 9 wells (Figure 1). Only 75 samples from the GSQ Dalby 1 well (150.739° / -27.3392°, total depth 858m, drilled in 1980) will be presented and discussed in this publication to provide a preliminary hypothesis.

METHODOLOGY

Rock samples (core and drilling chips of Walloon Subgroup) from the GSQ core library were analysed using X-ray diffraction (XRD). Mineral identification was conducted using both rock powder samples and clay extracts; of note is that the XRD method does not allow for the unequivocal identification of certain series compositions (e.g. feldspars) or between detrital and authigenic clays.

Hydrochemical analyses from the Department of Environment and Resource Management Groundwater Database (DERM GWDB) provided major ion compositions and pH, which were important for establishing the physico-chemical character of groundwater stored within the Walloon Subgroup.

The rock compositions were used in conjunction with groundwater hydrochemical data to run basic geochemical simulations, using the Geochemist's Workbench (GWB) software package (Bethke & Yeakel, 2007). The aim was to examine the possible water-rock reactions that may take place subsequent to CO_2 injection. The simulation consisted of 1 litre of groundwater water of a representative composition being reacted with 100g of rock of representative mineral composition and a 1 molar CO_2 solution.

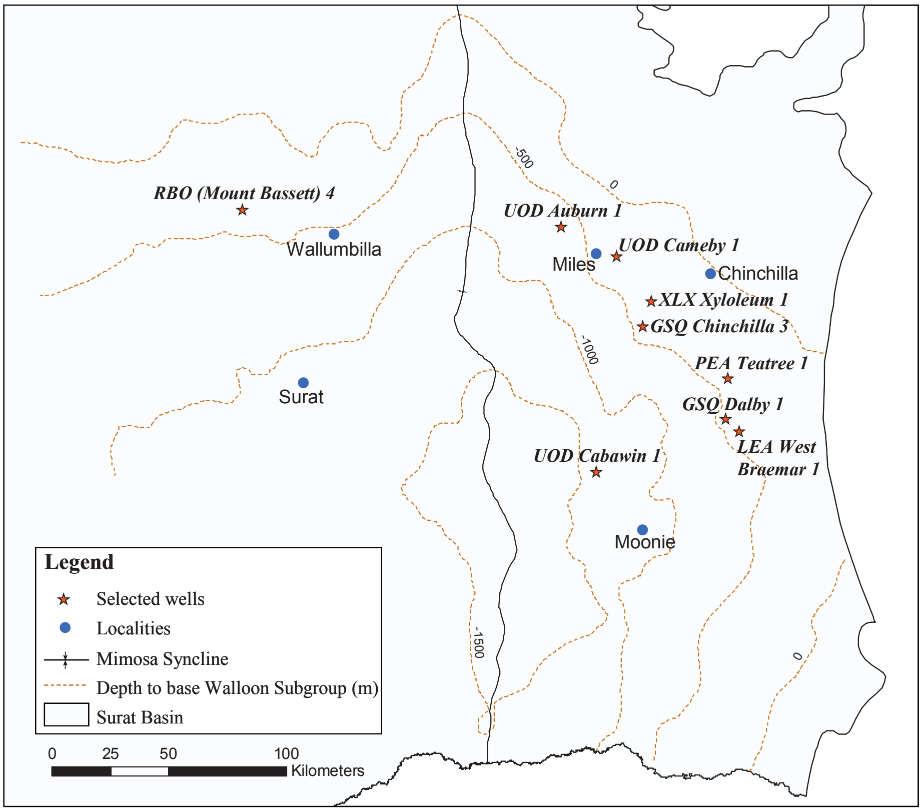

Figure 1. Location of petroleum and stratigraphic wells analysed in this study

To determine the most representative mineral and water compositions suitable for geochemical simulations, a non-traditional unsupervised analysis method, based on the principles of vector-quantisation was employed to process both the mineral and groundwater datasets. The self organising maps (SOM) method is an approach capable of clustering any type of numerical or textual data. It is well suited for non-normal distributions and non-linear relationships, which is mostly the case with geochemical datasets. The SOM method separated the mineral data into 9 clusters (a 3x3 matrix), of which only 7 were populated. The hydrochemical data was divided into only 4 clusters (2x2 matrix).

RESULTS AND DISCUSSION

Mineralogy of the Walloon Subgroup in GSQ Dalby 1

The Walloon Subgroup has been interpreted as a series of alternating channel and floodplain environments of deposition, with episodes of mire development (Hamilton, 2007). Conditions favourable to carbonate precipitation (predominantly siderite, occasionally calcite and rarely magnesian carbonates such as ankerite and dolomite) have also been encountered. High hematite concentrations have also been identified, suggesting short-lived episodes of exposure and weathering.

In GSQ Dalby 1, several cycles of sedimentation have been previously described (Hamilton, 2007); these include, from the oldest to the youngest: The Durabilla Formation, Taroom Coal Measures, Tangalooma Sandstone, Lower Juandah Coal Measures, Juandah Sandstone and the Upper Juandah Coal Measures (Figure 2).

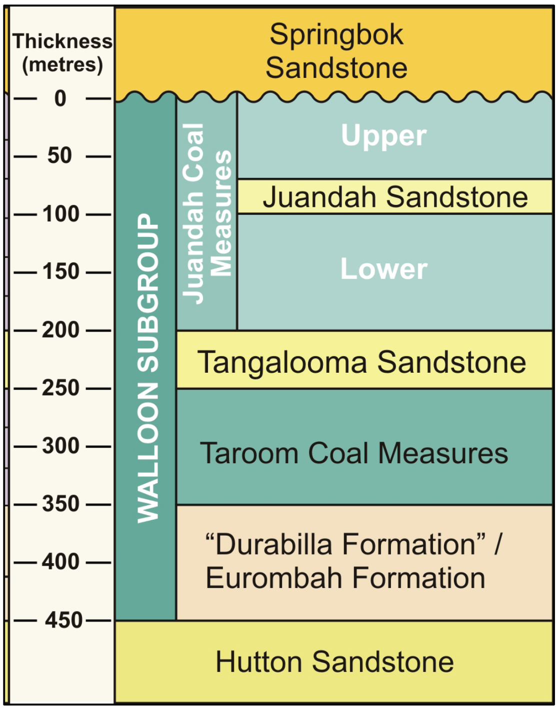

Figure 2. Stratigraphy of the Walloon Subgroup (Hamilton, 2007)

Regardless of the cycle of sedimentation, the mineral composition is quite consistent with respect to primary minerals: quartz ~ 40%, plagioclase = 15–19% and K-feldspars ~ 5%. An exception is the Juandah Sandstone, where some intervals contain feldspar concentrations greater than quartz, suggesting close proximity to the sediment source. Sodic plagioclase (low albite) is generally dominant, with small localised exceptions when high albite is prevalent. K-feldspars are quite constant and no vertical trends have been observed.

Chlorite varies largely from traces to a few percent; it correlates well with the coal measures and it is absent in the Juandah Sandstone and the Durabilla Formation. The upper section of the Juandah Coal Measures and lower section of the Taroom Coal Measures are also void of chlorite.

Kaolinite is the dominant clay mineral, but its concentration can vary substantially throughout the formation. The most frequent concentration is 18%. Localised conditions of low energy deposition or poor drainage of the floodplain lead to the formation of smectite-illite mixed layer clays. The dominance of such mixed layers does not correlate with the development of mires, in the case of coal-rich units. In the Durabilla Formation and the Juandah Sandstone, however, mixed layer clays dominate over kaolinite in mires.

The smectite-illite mixed layer clays can be divided into two populations in relation to their d-spacing. One population has a d-spacing of around 11Å, which suggests an illite-rich mixed layer. This type correlates well with the presence of chlorite and occurs in the lower section of the Juandah Coal Measures, throughout the Tangalooma Sandstone and in the upper section of the Taroom Coal Measures. The second population has a d-spacing of around 12.5Å, suggesting a smectite-rich mixed layer. This type was found in Juandah Sandstone, upper section of Juandah Coal Measures and in the Durabilla Formation.

Siderite is by far the most abundant secondary mineral, occurring as massive veins in all cycles of sedimentation. Calcite is also identified with or without an association with siderite. Ankerite and dolomite are rare. Occasional weathered horizons are rich in hematite.

In summary, no particular mineral markers were found in the Walloon Subgroup formations (Figure 3).

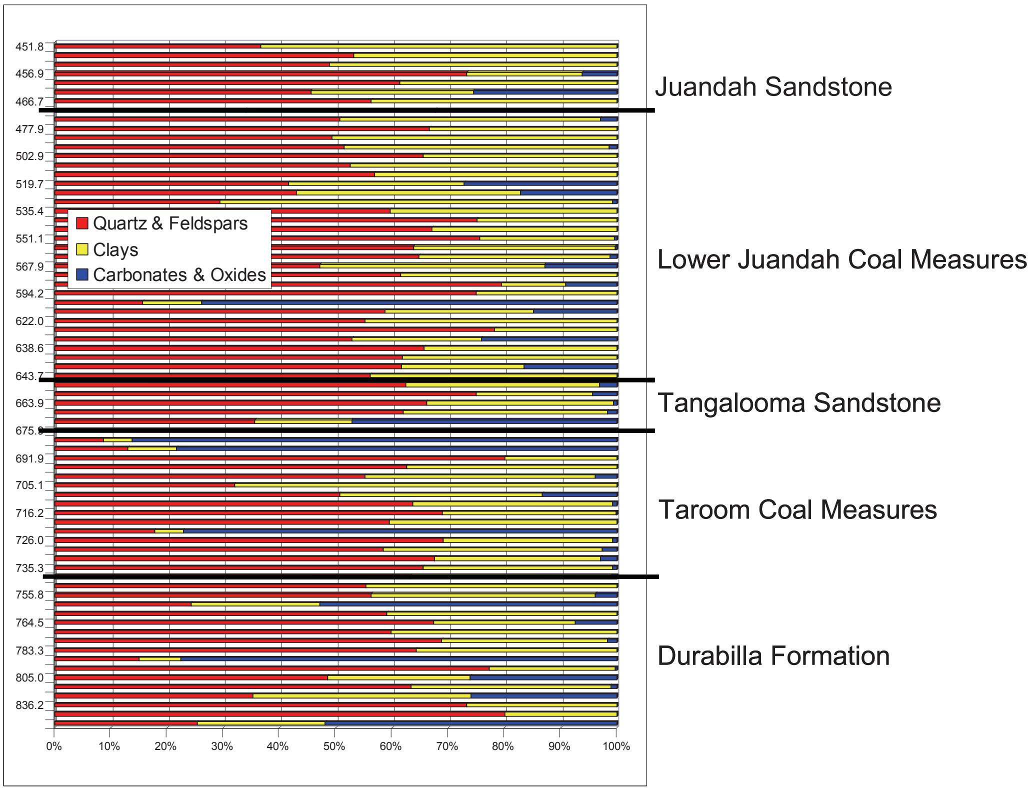

Figure 3. Vertical distribution of main mineral groups in the Walloon Subgroup, GSQ Dalby 1

Representative mineral character determined using SOM

The clustering of mineral data produced 9 groups (note that clusters 2 and 3 do not contain any samples, Figure 4) of which only three, located in the south-western corner of the matrix, are well populated and include 81% of all samples analysed. The samples included in the clusters located on the right side of the matrix represent rare outliers with high concentrations of siderite, calcite, and/or hematite. It is considered that the three south-western clusters (detailed composition in Table 1) are the most representative of the mineral character of the Walloon Subgroup and were used in the geochemical simulations.

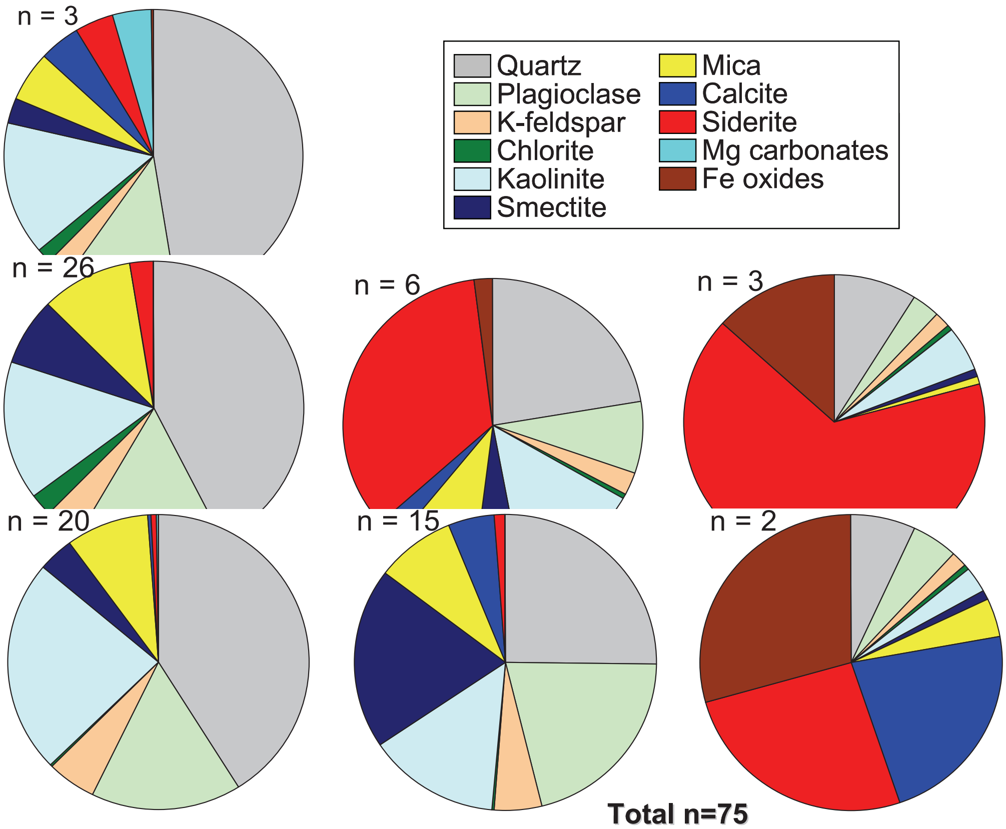

Figure 4. SOM clusters of mineral composition

Table 1. Mineral composition (%) of representative SOM clusters

Quartz	Plagioclase	K-feldspar	Chlorite	Kaolinite	Mixed layer	Mica	Calcite	Siderite
42	16	4	3	15	7	10	0	2
41	16	5	0	23	4	9	0	1
25	21	5	0	14	20	9	5	1

Note: Due to the limitations of the geochemical database, chlorite was not included in the simulations. The mixed layer was replaced by nontronite-Na and mica by muscovite.

Representative hydrochemical character determined using SOM

No groundwater bores are located in the immediate vicinity of the well GSQ Dalby 1 and no groundwater samples were ever analysed from this stratigraphic well. The closest groundwater hydrochemical data is from 50km north-east of GSQ Dalby 1; the dataset consists of 133 samples collected from numerous bores, but from shallower depths than 450m, the upper limit of the Walloon Subgroup in GSQ Dalby 1. Whether this Walloon water is representative of the formation intersected by GSQ Dalby 1 remains uncertain, but it was considered as the best data alternative to allow geochemical modelling.

Four SOM clusters were identified (Figure 5), of which two (clusters 1 and 3), representing a brackish Na-Cl water and a brackish Na-HCO_3 water, were deemed to be representative (70% of the total dataset) and used in geochemical simulations (Table 2).

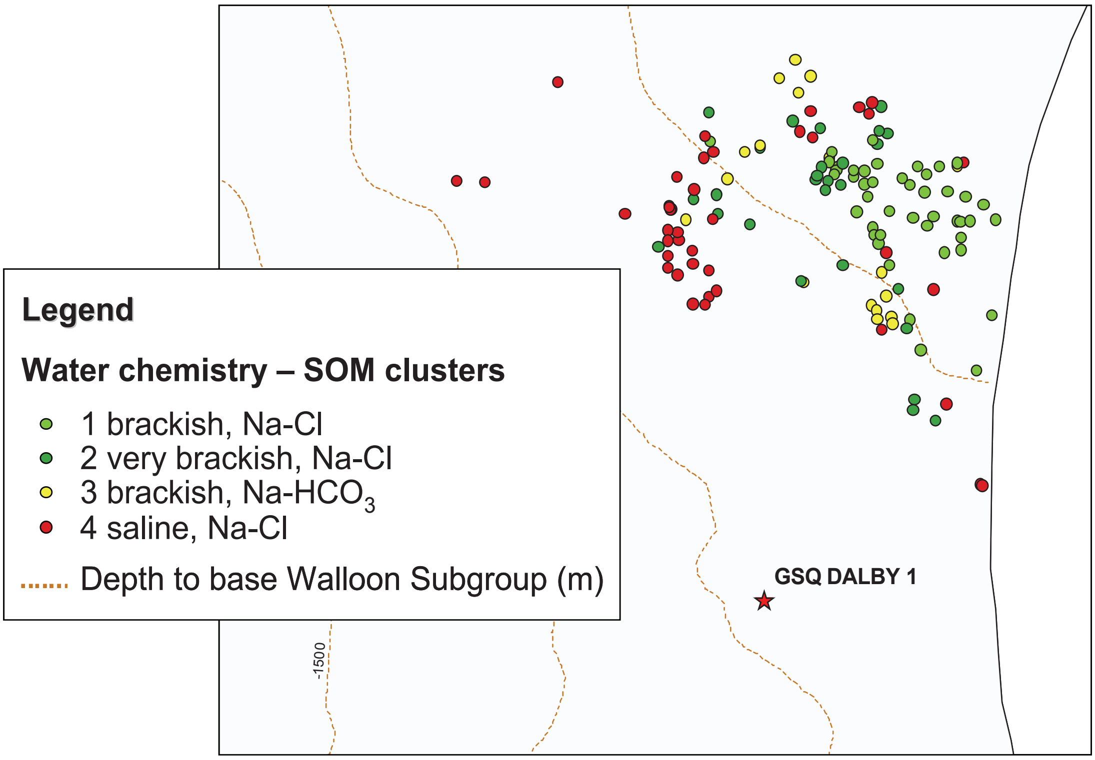

Figure 5. Location of groundwater bores, and the hydrochemical character and spatial distribution of SOM clusters

Table 2. Hydrochemical character of representative SOM clusters

pH	Na	K	Ca	Mg	HCO_3	Cl	SO_4	SiO_2	Al	Fe
7.5	986	0	81	105	458	1593	140	20	0.01	0.01
8.5	618	1	16	16	810	484	14	10	0.01	0.01

Note: Due to the limitations of the hydrochemical dataset, the values for SiO_2, Al and Fe were inferred, based on the authors' general knowledge of hydrochemistry.

Geochemical simulations

Three types of mineral compositions were reacted with two types of water compositions and 1 mol of aqueous CO_2. The resultant six simulations produced similar results with respect to the overall trends. The initial composition of the media did not significantly influence the trends, but it dictated the concentrations of the final products. Figure 6 presents the overall processes taking place when a groundwater-saturated sedimentary material typical of the Walloon Subgroup reacts with CO_2. The pH usually drops 2 units and the quartz and clay content (kaolinite and mixed layer) increases. Siderite is initially dissolved, but reprecipitates along with dawsonite, provided that the ratio of Na/Al allows that to occur. Similar trends were also observed when such simulations were run for the Evergreen Formation (Preda (Grigorescu) & Hodgkinson, 2009), a proven seal in the Surat Basin.

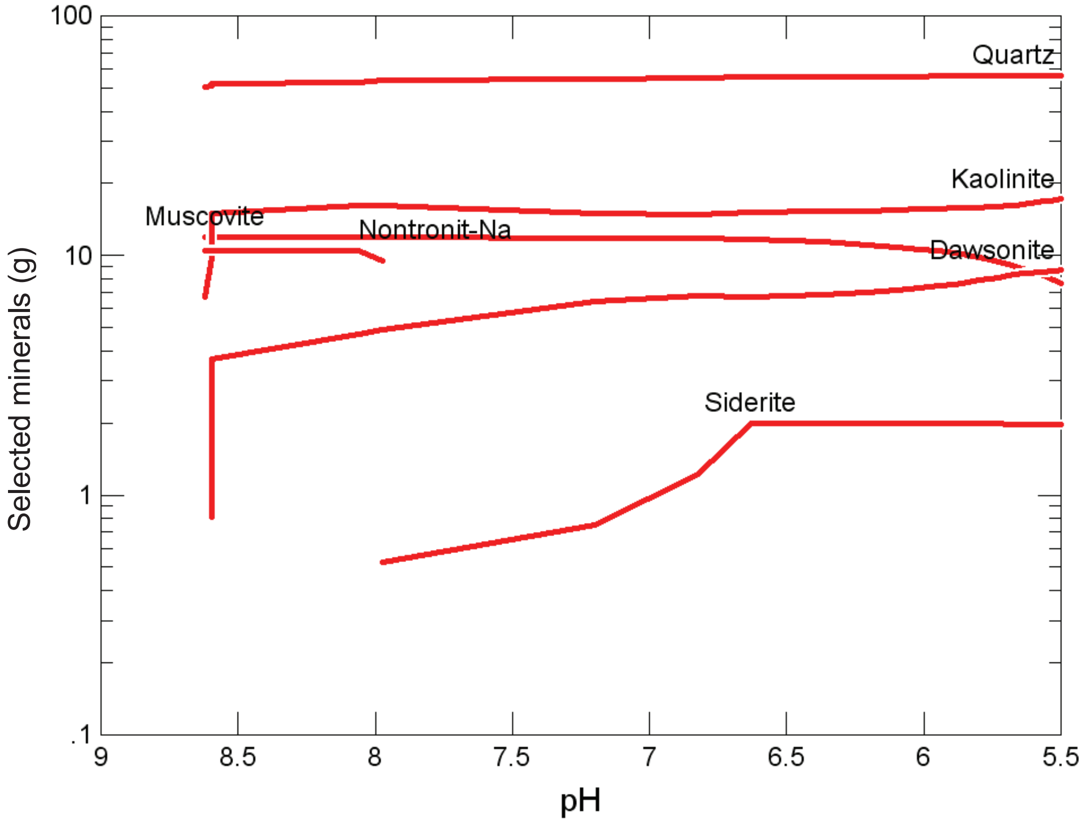

Figure 6. Indicative geochemical trends when Walloon-type formations are reacted with their typical groundwater and CO_2

CONCLUSIONS

Seventy-five samples of rock material were analysed from GSQ Dalby 1 using XRD to determine the mineral character of the Walloon Subgroup. One hundred and thirty-three groundwater samples were also analysed to determine the typical hydrochemical character of water hosted by the Walloon Subgroup.

Both datasets were clustered using self organising maps. The mineral character appears to be homogenous with no clear stratigraphic signatures. The composition is largely the following: 40% quartz; plagioclase (15–19%) > K-feldspars (5%); kaolinite (18%) > mixed layers > illite; siderite is ubiquitous. Outliers can have the following character: feldspar concentrations are larger than quartz concentrations; mixed layers dominate over kaolinite; high concentrations of siderite ± calcite ± hematite.

The water is generally brackish to saline and of Na-Cl type. Localised Na-HCO_3 type waters have also been identified.

The geochemical simulations revealed similar trends of geochemical behaviour in case of CO_2 impact. The pH typically drops 2 units and the quartz and clay content increases. Siderite and dawsonite may precipitate.

Considering its mineral character and the geochemical behaviour when reacting with CO_2, the Walloon Subgroup has good sealing properties from a mineral stability/reactivity perspective (similar to those of a proven seal like the Evergreen Formation). This study cannot, however, ascertain the regional sealing capacity of the Walloon Subgroup or its mineral homogeneity elsewhere in the Surat Basin. Future work will combine the results of this study with petrographic analysis and stratigraphic modelling in an interdisciplinary approach to unconventional seal rock characterisation.

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COASTAL GEOTHERMAL ENERGY INITIATIVE UPDATE

Steve Bowden and Sarah Sargent

Geological Survey of Queensland

CGEI UPDATE

The CGEI team has spent the year undertaking government procurement processes, target assessments, safety training, site inspections, site pegging, landholder discussions, cultural heritage clearances, site preparation, sample collection and core logging.

Government procurement process requires that contracts valued over a certain threshold such as the CGEI drilling contract must be advertised for companies to put in an offer. Supporting documents that potential contractors would use to establish their offer were also made available. These included a detailed description of the planned CGEI drilling activities and the roles and responsibilities of the contractor. The process is called an 'Invitation to Offer (ITO)'. The procurement process also required an auditable assessment process to be undertaken using various criteria (e.g. cost, capability, competency). Due to supervisor competency constraints under the Geothermal Exploration Act, the first ITO was prohibitive to all contractors applying. A second ITO was drafted and a successful contractor was chosen from the new pool.

The drilling contract was finalised between DEEDI and Gerald Spaulding Drillers Pty Ltd in early October 2010. Gerald Spaulding Drillers Pty Ltd have previous experience in geothermal exploration drilling programs.

The drilling program has been broken into phases based on the priority of the target. Phase 1 drilling will cover the highest priority drill targets and is anticipated to be complete around the middle of next year (approximately July 2011).

Site inspections led by Mark Maxwell (CGEI Project Leader — Drilling) have been carried out for all 32 proposed sites. Sites have now been pegged and are undergoing cultural heritage surveys as required. The regional nature of the CGEI adds to the complexity of these tasks. Many cultural heritage groups have been engaged to undertake cultural heritage surveys. Figure 1 shows the cultural heritage groups for the Phase 1 drilling.

The drilling program kicked off in November 2010, the beginning of the wet season. The current climate situation indicates that this is a period of above average rainfall. Wet weather will hopefully be avoided by starting the drilling program in the south (during the wet season) and working northwards (during the dry season). Monitoring of weather throughout the program will also be undertaken to enable any strategic shifts in rig logistics due to weather.

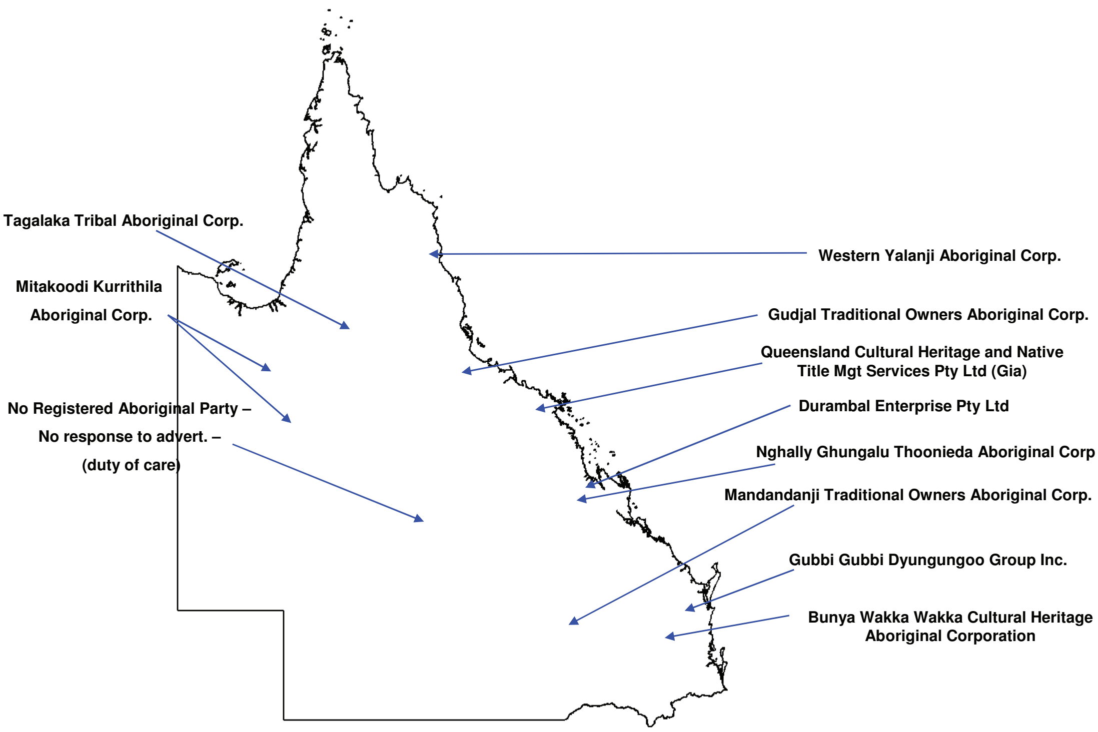

Figure 1. Cultural heritage groups associated with Phase 1 drilling

The GSQ geologist on site during drilling will be sampling 150mm of core from each distinct lithological unit. Samples are preserved immediately in zip lock bags, wrapped in tape and stored in a shady area prior to dispatch to the laboratory. The core will also be logged using ‘in house’ software based around Microsoft Access. Touchscreens are used for efficient data capture and the data is validated real-time against customised codes in the CGEI logging dictionary. The field data collected (including wireline logs) is imported into the post production database (gINT) at the completion of drilling to generate lithological, geothermal, geophysical and other logs.

In areas where hydrocarbons are expected to be intersected, the CGEI wells will have steel casing grouted into the hole and aquifers below casing depth will be sealed off using pressure grouting. The wells will be cased with 65mm Bore Class 18 UPVC to total depth to keep the hole open for the duration of the temperature stabilisation period. The wells are estimated to reach thermal equilibrium within 6-8 weeks from the completion of drilling. A steel monument is erected at the surface with a lockable cap to enable secure and easy access for temperature logging personnel.

CGEI SITE SELECTION: WHAT’S HOT AND WHAT’S NOT

PHASE 1 site selection

The selection of targets for the CGEI drilling program required a multifaceted approach to delineating geothermal potential across Queensland. Areas of geothermal potential were assessed using regional geology, existing well data, geochemistry,

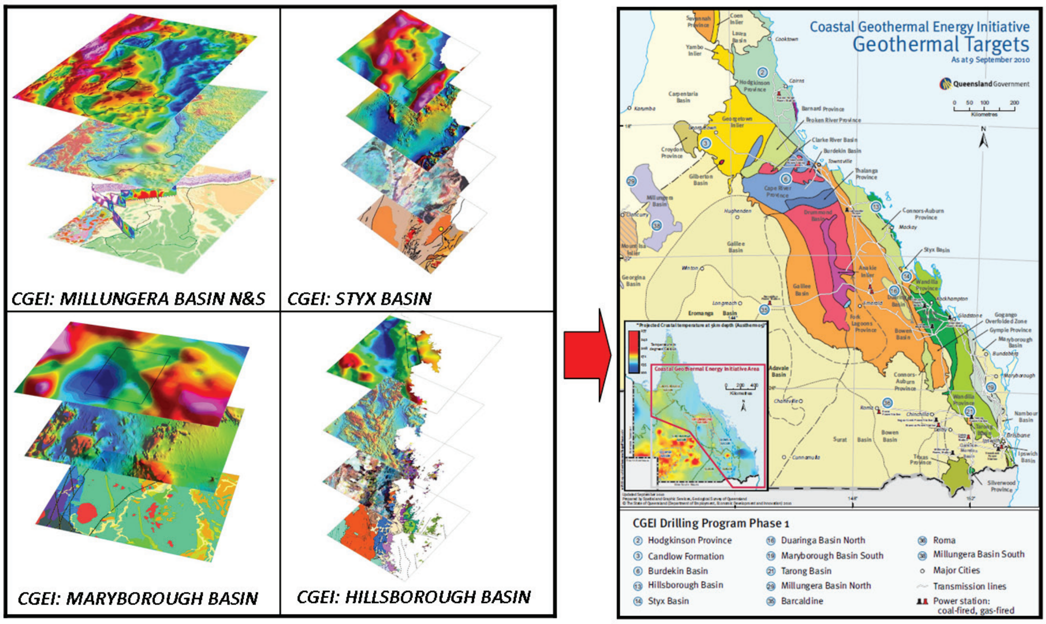

Figure 2. CGEI Phase 1 site selection

calculated heat production values, radiometrics and existing temperature measurements. Geophysical datasets such as gravity, Magnetotellurics (MT), seismic, Total Magnetic Intensity (TMI) and Reduced to Pole (RTP) were also used to postulate geothermal targets at depth. From 32 target assessments, 12 sites were selected with the highest geothermal potential to be drilled during CGEI: Phase 1 (Figure 2).

Intrusive age vs. geological setting

The 12 geothermal intrusive targets to be drilled as part of Phase 1 fall into five age groupings, correlating to major tectonic events in Queensland's geological history, summarised in Figure 3.

- The Millungera Basin and Candlow Formation CGEI targets aim to assess the heat producing capacity of the Proterozoic Williams, Naraku and Forsayth Batholiths. These intrusives have heat production values > 5µW/m^3 and the Mount Isa Inlier is an area of elevated heat flow 82mW/m^2 (Cull, 1982).
- The Burdekin Basin will target Ordovician–Silurian granites intruded into the Lolworth–Ravenswood Block. The Lavery Creek and Blisters Swamp granites show white tones on composite radiometrics image indicating high concentrations of radiogenic uranium, thorium and potassium.
- Four CGEI sites will target Early Carboniferous – Early Permian intrusives such as the Wypella Supersuite and Roma Granite with heat production values up to 5µW/m^3.
- Two sites will target inferred Late Permian – Triassic intrusions. The radiometric signature of the outcropping Boondooma Igneous Complex (the geothermal target for Tarong Basin) shows white tones, indicating high concentrations of radiogenic uranium, thorium and potassium. The Permian–

Triassic saw the onset of the Hunter–Bowen Orogeny and was accompanied by multiple stages of granite emplacement.
- Cretaceous intrusives form the geothermal target at Hillsborough Basin and Maryborough Basin South.

INTRUSIVE AGE	CGEI TARGETS	TECTONIC SETTING
Proterozoic	Candlow Formation, Millungera Basin **(3 targets)**	Intercontinental rifting and Orogeny
Ordovician-Silurian	Burdekin Basin **(1 target)**	Thomson Orogen
Early Carboniferous–Early Permian	Hodgkinson Province, Roma Granite, Styx Basin, Duaringa Basin North, **(4 targets)**	Tasman Orogenic Zone
Late Permian – Triassic	Barcaldine, Tarong Basin, **(2 targets)**	Hunter Bowen Orogeny
Late Cretaceous - Tertiary	Maryborough Basin South, Hillsborough Basin, **(2 targets)**	Cretaceous rifting

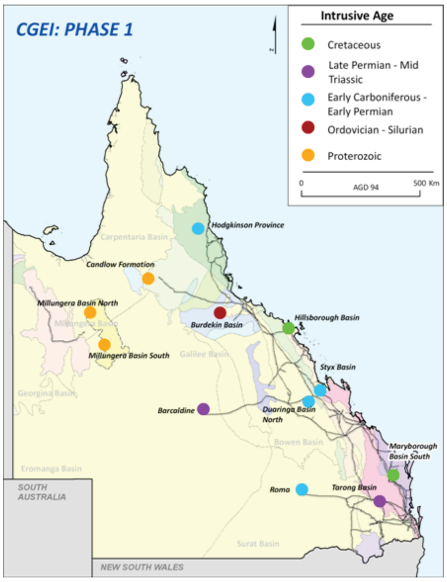

Figure 3. CGEI: Phase 1, geothermal intrusive target vs. tectonic setting

So where is the source of heat in Queensland? Preliminary assessment suggests that granites emplaced within multiple geological settings in Queensland could have geothermal potential.

Additional factors to assessing geothermal potential

Thermally insulating sedimentary cover

- >3.5km for enhanced geothermal systems (EGS)
- Insulating rock units including coal, siltstone and shale with thermal conductivity values <3.0W/mK.

Tertiary Volcanism

- Intraplate volcanism occurred along east coast, possibly contributing to an elevated heat flow
- Examples include the Chudleigh Basalt, Nulla Basalt and Main Range Volcanics

Tertiary Rifting

- Rifting of the Coral Sea off the State's north-east coast resulted in the opening of Tertiary Basins
- Some examples are Narrows Graben, Nagoorin Graben and Duaringa Basin.

CGEI DELIVERABLES

The CGEI is on track to deliver a variety of geoscientific outputs that could effectively be used by geothermal explorers for planning, executing, analysing and reporting their exploration activities. Outputs should comprise feasibility assessments; detailed well completion reports; desktop evaluation of heat flow across Queensland; documented precision heat flow investigation; documented drilling methodology and a preliminary economic assessment of Queensland geothermal potential from an exploration and production perspective.

Preliminary desktop site assessments were carried out for 32 areas/targets within the CGEI area of interest. They were used to determine the order of priority and prospectivity of the drill targets. They cover regional geology, geophysics, temperature data, heat production values, 2D gravity modelling, topography, target rationale and regulatory considerations for each target. It is intended that these documents are released publically to assist potential explorers with site specific information and assessment methodology.

As part of the legislative reporting requirements, CGEI will be preparing a well completion report for each of the wells drilled in the program. Stratigraphy, lithology, drilling details, geophysics, test results, heat flow modelling, analysis and a discussion of results are intended to be reported on top of the general metadata requirements. These reports will be stored in QDEX and provide examples that future companies undertaking the geothermal reporting process can utilise.

In order to generate a revised temperature at 5km map of Queensland, it is essential that the CGEI undertakes a detailed desktop study of all available data including that retrieved from the CGEI program. Available continuous wireline temperature data and petroleum/stratigraphic well temperature measurements are being combined with stratigraphy (using estimated thermal conductivities) to generate hundreds of one-dimensional heat flow models. The models are constrained / influenced by many other factors including weighted lithological composition, groundwater movements / convective systems, porosity and estimated curie depth. Some effort will also be made to integrate the relationship between whole rock geochemistry and subsurface temperature. Existing geophysical, geochemical and downhole temperature data enables the development of a customised approach to picking modelling points. These indicators can help capture likely peaks, troughs and plateaus that would assist in more accurate contouring when developing the temperature at 5km map of Queensland.

Precision heat flow investigation is a specialised geoscientific activity requiring a particular set of hole conditions and data tolerances. The CGEI program endeavours to undertake a 'best practice' approach including thermally equilibrated holes with greater than 200m of continuous core recovery for thermal conductivity measurements. Temperature profiles of reasonable accuracy are collected after six to eight weeks in the initial downward run of the probe. Thermal conductivity will be measured on each distinct lithological unit using two different methods of the divided bar apparatus technique (‘wet and dry’ and ‘*in situ*’ moisture content). In house software will be utilised to model temperature / heat flow down to 5km using the CGEI data and other nearby data sources. By undertaking ‘best practice’ heat flow investigations in different locations across Queensland, CGEI will contribute to the development of this specialised field of science. Also, the combined thermal conductivity and temperature profile datasets will be a great resource for researchers in the field.

The drilling and data capture operation would also be documented and should include information on consumables used, drilling conditions encountered, rates of progress, hole completion specifics, data capture systems and a summary of operational methodology. This information will be presented in the well completion report in part and summarised as a whole in the final CGEI report. Such information should assist future explorers with planning their field projects.

The final CGEI report will also include a preliminary economic assessment of geothermal potential for QLD from an exploration and production perspective. This high level information is useful to policy and business decision makers.

PATTERNS IN HISTORICAL PETROLEUM EXPLORATION IN QUEENSLAND

Alison Troup

Geological Survey of Queensland

Early exploration for oil and gas in Queensland was disappointing with the earliest discoveries fortuitous, such as the discovery of gas in a water bore near Roma in 1900. Until 1960 exploration was sporadic, with no commercial discoveries being made. Since 1959/60, conventional petroleum exploration has endured four cycles of exploration and discovery; 1959–1974, 1979–1989, 1990–1999, 2000–present.

This exploration resulted in the discovery of the main petroleum regions in Queensland, being the Cooper, Eromanga, Bowen and Surat Basins. Some exploration has occurred in other basins, however, with the exception of the Gilmore gas field in the Adavale Basin, no other basin has reported reserves or production.

The data used in this assessment are supplied by the companies under the legislative reporting requirements. Figure 1 shows the number of exploration wells and discoveries by financial year from 1959/1960 to 2009/2010.

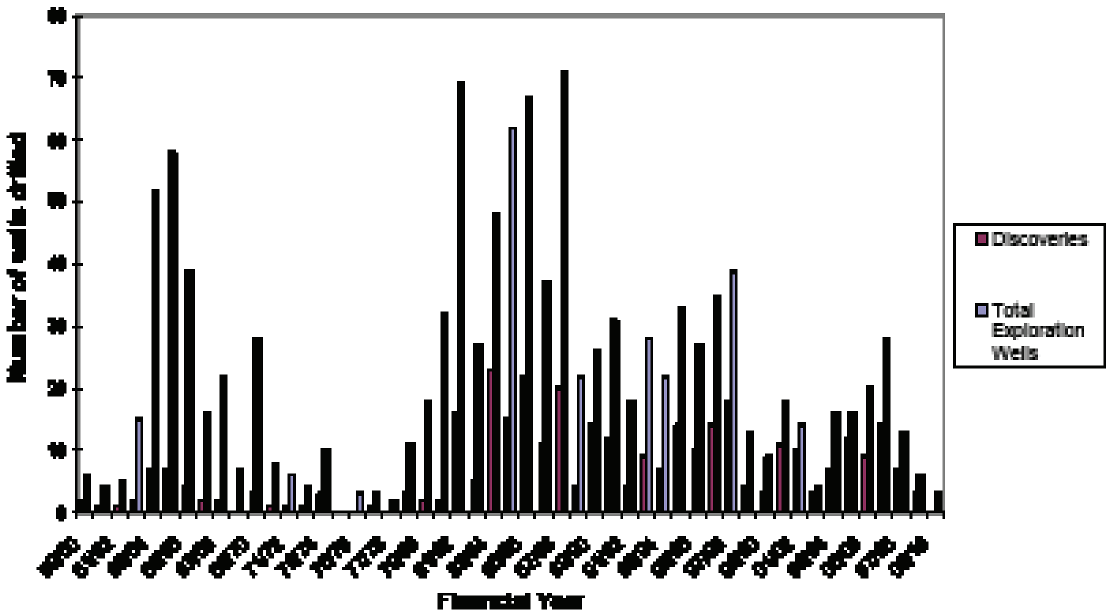

Figure 1. Number of wells drilled per year and number of reported discoveries per year

CYCLE 1 1959–1974

Interest in exploring for petroleum in Australia received a significant boost via the Commonwealth Government's Petroleum Search Subsidy Scheme, which was extended to cover the cost of drilling in 1957. The effect of this scheme in Queensland was to encourage exploration throughout the state. The first discoveries were the gas fields at Timbury Hills and Pickanjinnie in 1960, which were overshadowed by the discovery of Australia's first commercial oil field at Moonie in 1961. Interest in exploring in the Bowen-Surat region was triggered by these discoveries. During the first cycle, 252 exploration wells were drilled in the region, with 33 discoveries being made. Early in this cycle, exploration focussed on the Jurassic reservoirs of the Surat Basin. Only small discoveries were made in older reservoirs until the discovery of the Silver Springs gas field at the end of the first cycle, in the Triassic Showgrounds Sandstone.

The Cooper-Eromanga region received only cursory exploration during the first cycle; 25 exploration wells were drilled with 7 discoveries.

CYCLE 2 1979–1989

During the second cycle, exploration in the Bowen-Surat region focussed on the Triassic-aged reservoirs with 264 conventional exploration wells being drilled for 54 discoveries. Coal seam gas exploration began early in the second cycle, but met with little success. This exploration focused mainly on the coal measures in the northern Bowen Basin where maturation levels were higher and hence high gas contents.

Activity in the Cooper-Eromanga region was much higher during the second cycle, after the discovery of the Jackson oil field in 1981 and the Challum gas field in 1983. A total of 226 wells were drilled in the Cooper-Eromanga region resulting in 79 discoveries.

CYCLE 3 1990–1999

During the third cycle, the exploration focus in the Bowen-Surat region began to shift away from conventional targets and towards coal seam gas. There were 101 conventional exploration wells drilled during this cycle with 29 successful results. In comparison, 170 coal seam gas exploration wells were drilled. Conventional exploration continued to target the Triassic reservoirs. There was also a shift in the coal seam gas exploration from the northern to central and southern Bowen Basin. Coal seam gas discoveries at Moura were followed by Peat, Scotia and Fairview. Production of coal seam gas from these areas resulted in a beginning of a new facet of the petroleum industry in Queensland.

Exploration in the Cooper-Eromanga region slowed slightly with 179 exploration wells being drilled for 65 discoveries. During this period, there was a significant change in exploration emphasis from oil to gas. This coincided with gas becoming an important part of the energy mix in Queensland as well as gas being exported to Moomba in South Australia for the first time.

CYCLE 4 2000–PRESENT

During the fourth cycle, exploration for conventional targets in the Bowen-Surat region decreased significantly. Only 37 wells were drilled with 20 discoveries. All of the conventional discoveries made during the forth cycle in the Bowen-Surat region were made in reservoirs of Permian age. There were 617 coal seam gas exploration wells drilled in the Bowen-Surat region during the fourth cycle, with an additional 36 wells drilled into the Eromanga or Galilee basins, testing new plays. These totals show the strength of the switch from conventional petroleum to coal seam gas exploration in Queensland. In particular, the Walloon Coal Measures became a key focus of for coal seam gas exploration. Figure 2 highlights this switch to a coal seam gas focus during the fourth cycle.

Exploration rates in the Cooper-Eromanga region continued to decline during the fourth cycle, though the success rates increased. To date, 101 exploration wells have been drilled with 56 discoveries. During this period, the emphasis change yet again with oil being targeted in response to higher world oil prices. The relatively high success rate is probably a reflection of the use of 3-D seismic as an exploration tool enabling better target definition.

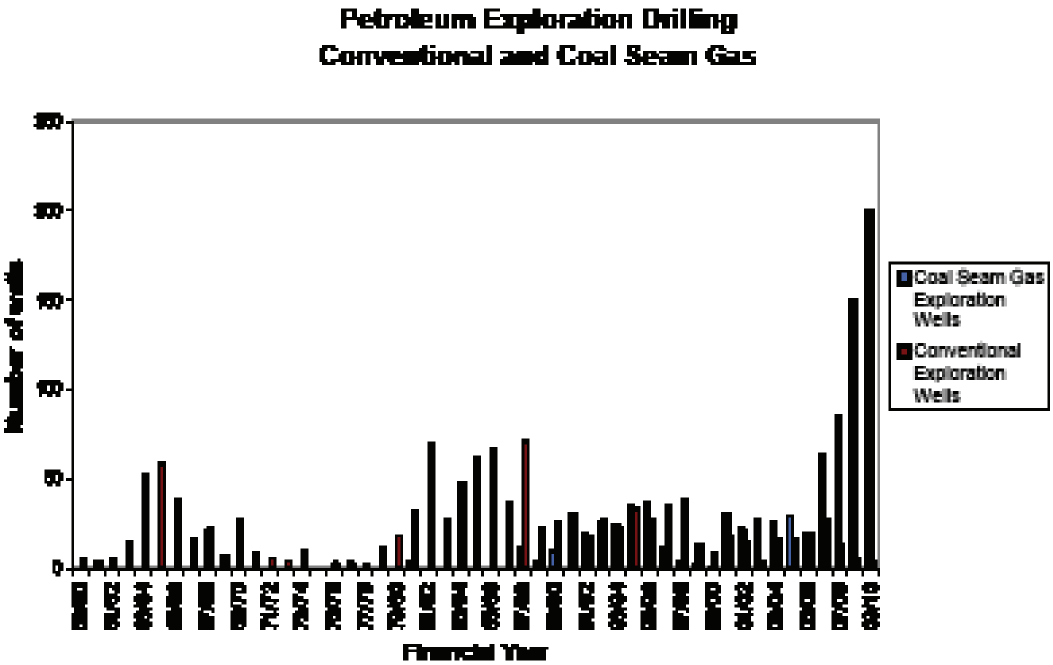

Figure 2. Total number of exploration wells drilled showing those targeting coal seam gas compared with those targeting conventional plays.

RESULTS

Exploration for petroleum in Queensland has resulted in the discovery of approximately 70 380 million cubic metres (2.5 TCF) of gas, 616 206 million cubic metres (21.76 TCF) of coal seam gas and 8 148kL (51 249 863bbls) of liquids. Production to the end of December 2009 totalled 59 543 million cubic metres (2.1 TCF) of gas, 14 856 million cubic metres (0.5 TCF) of coal seam gas, and 5 760kL (36 233 901bbls) of liquids.

Despite all the exploration and the discoveries in Queensland, there are still many opportunities for further exploration. Under-explored basins provide potential for discovery of new conventional targets, or development of new unconventional possibilities. Exploration for unconventional targets other than coal seam gas is yet to begin.

GSQ GEOCHEMICAL ASSETS

Joseph Tang

Geological Survey of Queensland

The geochemistry group of the Geological Survey of Queensland (GSQ) started in July 2003 with the purchase of 1 415 053 data from Terra Search Pty Ltd that formed the Queensland Exploration Geochemistry and Drill hole database. Since 2006, funding from the Queensland Government Smart Exploration initiatives has enabled the geochemistry group and the database to expand. Collaborations with Queensland universities, Geoscience Australia and the mining industry resulted in a more diverse geochemical dataset that included exploration-, whole rock-, isotopic- and baseline-geochemistry, and geochronology and diamond indicator mineral databases.

THE DATA ASSETS

The Queensland Exploration Geochemistry and Drill Hole database (QEGD)

Systematic geochemical sampling is an exploration technique that has been used in Queensland since the 1950s, and approximately 22–25% of Queensland has some form of geochemistry coverage, particularly in the areas of well-exposed geology over mineral prospective regions of Mount Isa, Georgetown, Ravenswood and Drummond, and along the coastal fringe. Mineral exploration in Queensland has targeted primarily base and/or precious metals; and also included strategic and industrial minerals; oil shale and gems particularly in and around known mineral fields but rarely in areas under post-Mesozoic cover rocks.

As part of Queensland's reporting requirements in accordance with the Mineral Resource Act 1989, companies undertaking exploration have to submit exploration reports to the GSQ. Data from open-file company exploration reports are compiled by Terra Search Pty Ltd and by a GSQ team to form the QEGD. The QEGD has expanded to 2 909 063 publicly available open-file data (current to June 2010), representing approximately 60% of all data held in company reports (Figure 1). The main data types are stream sediments (26.3%), rock chips (9.6%), soils (36.1%), drill cores (27.9%) and whole rock chemistry (<0.1%).

Whole rock and isotopic geochemistry and geochronology data

Whole rock geochemistry was routinely collected during geological mapping programs and the chemistry was used as an investigative tool to understand rock formation, classification, source, paragenesis and conditions of emplacement. The GSQ has compiled 15 000 whole rock geochemistry data (containing up to 45 trace elements of varying precisions) representing 1464 geological units. A data scoping exercise undertaken by the GSQ estimated that the ~2000 geoscientific theses held

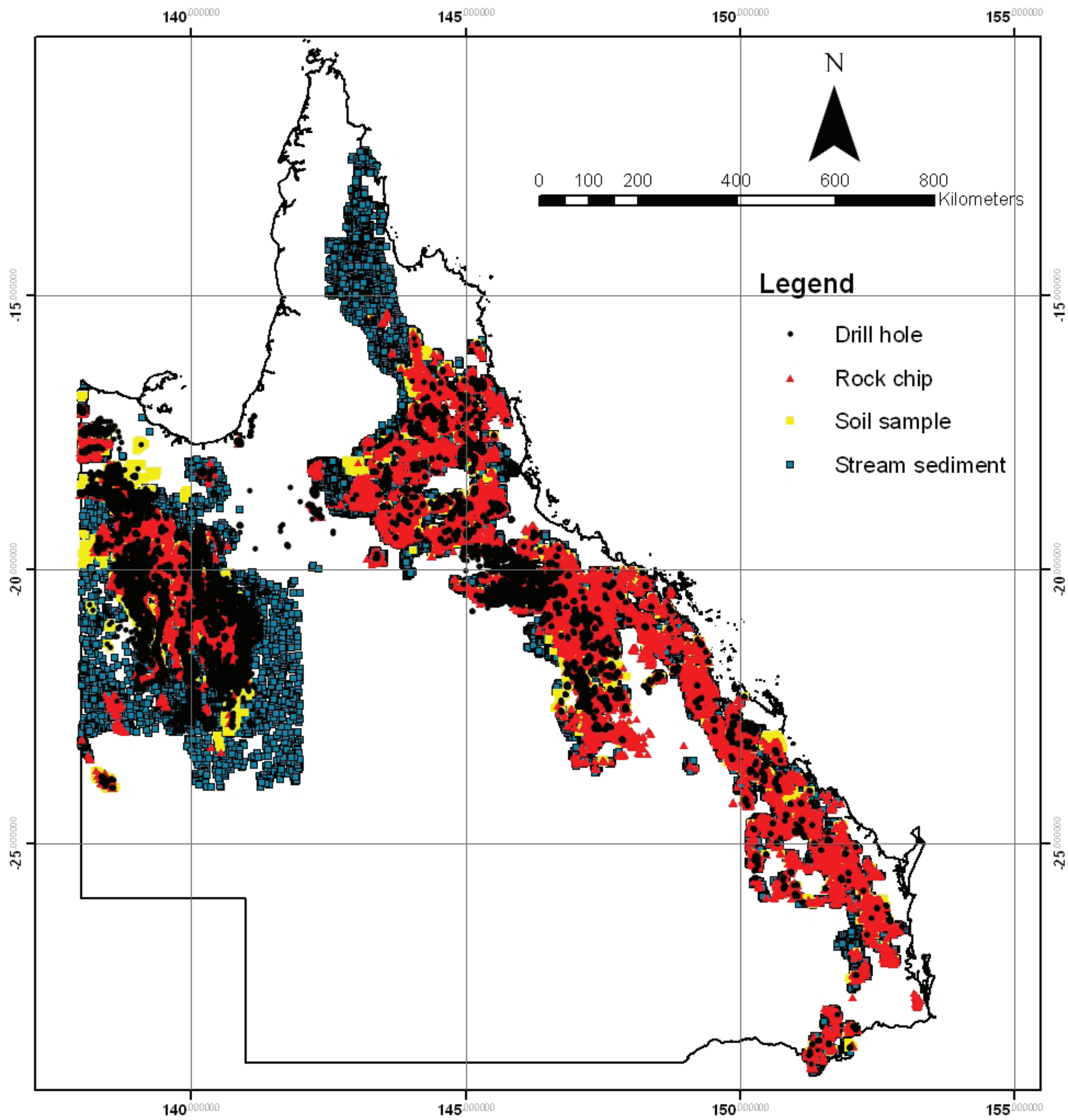

Figure 1. The distribution of the different sample types extracted from the Queensland Exploration Geochemistry and Drill hole database: (data current to June 2010).

at the University of Queensland (UQ), the Queensland University of Technology and the James Cook University contain approximately 22 000 whole rock analyses and 35 000 mineral chemistry, fluid inclusion, geochronology, regolith chemistry and isotopic data. These high quality data will provide crucial geochemical platforms for detail geological and ore systems researches. The GSQ has collaborated with staff from the universities to compile the hard copy data into a digital database. The work aims at making all geochemical data held at universities accessible to the geoscientific community, and progress with the various universities is ongoing and at different stages (Figure 2).

The GSQ, Geoscience Australia (GA) and the various Queensland universities have amassed an approximate total of 40 000 whole rock geochemical analyses in respective databases and hard-copy theses. To date, a total of 21 000 whole-rock geochemistry data are available to the public from:

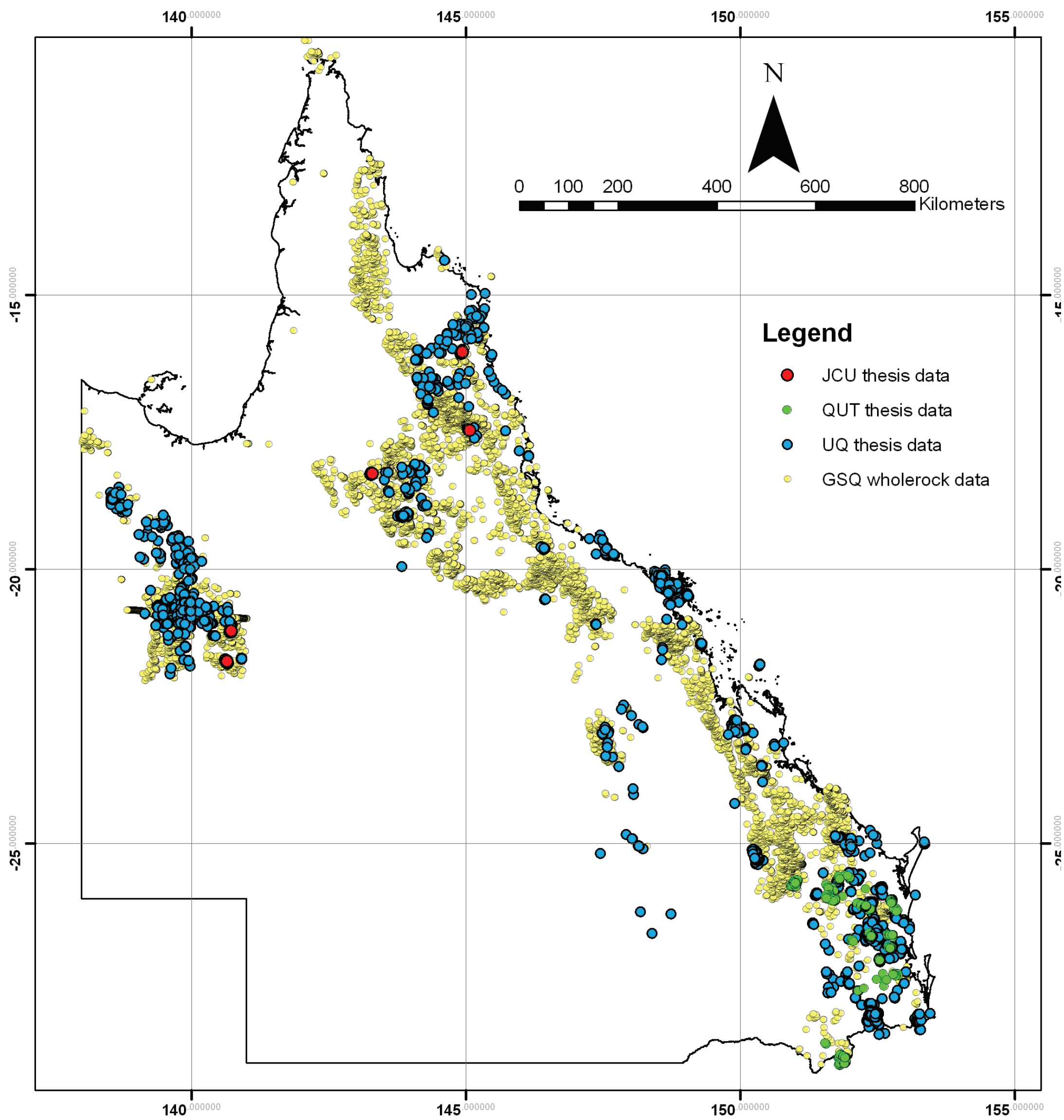

Figure 2. The distribution of whole rock and basic geoscientific data types from the Geological Survey of Queensland and the various academic institutions in Queensland.

- GSQ 2010: Mineral Occurrence and Geology Observations 2010, Department of Employment, Economic Development and Innovation, digital data released on DVD
- GA OZCHEM database at http://www.ga.gov.au/gda/
- An interim database from the GSQ and UQ collaborative project is available at https://espace.library.uq.edu.au/view/UQ:185174.

The National Geochemical Sampling of Australia (NGSA)

GSQ has completed a collaborative program with GA to sample all major river catchments in Queensland as part of the National Geochemical Sampling of Australia project (Lech, 2007). The project aims to establish the baseline geochemistry of Australia using a consistent geochemical dataset (up to 60 elements). In Queensland, a

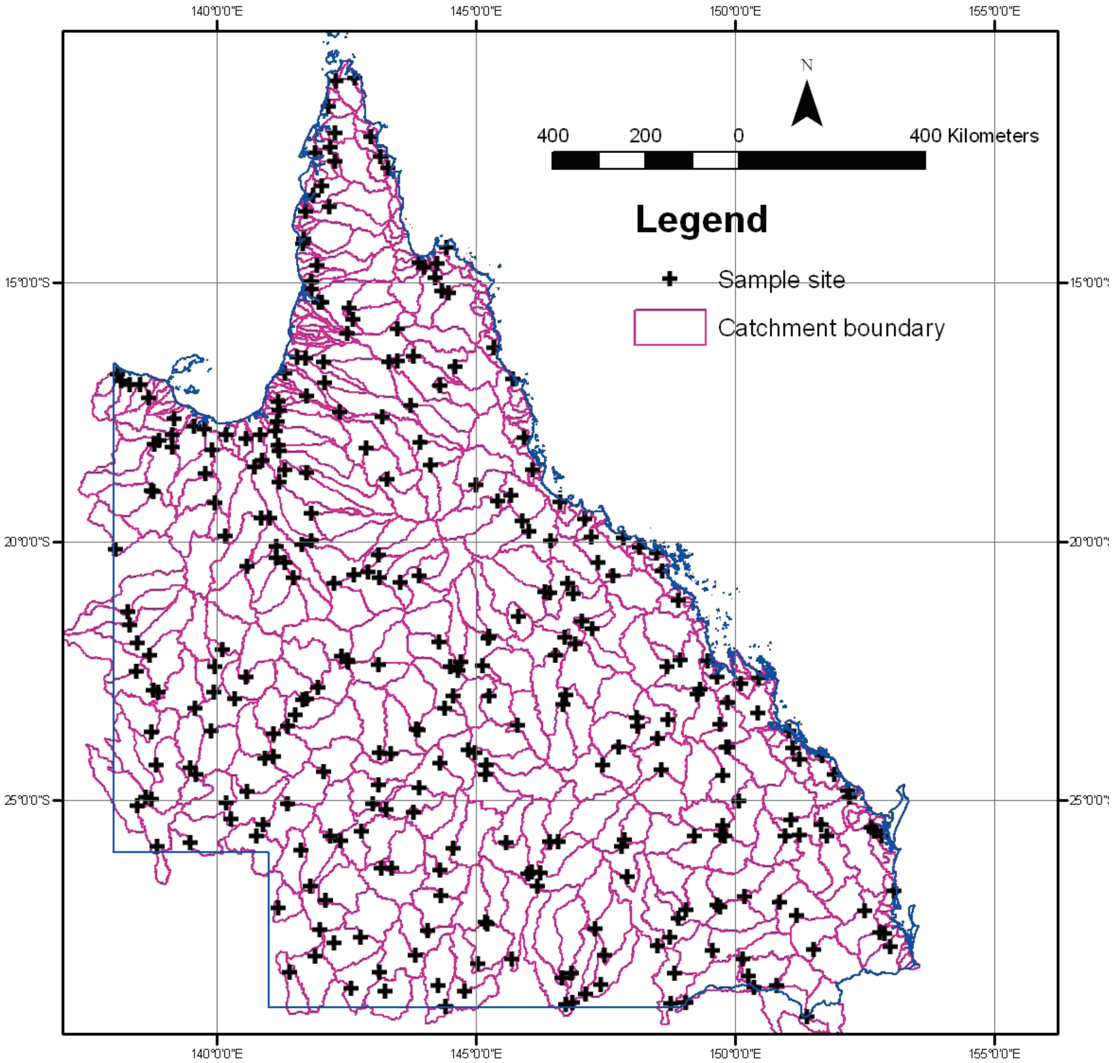

Figure 3: The 311 alluvial sediment samples collected from major catchments in Queensland as part of the National Geochemical Sampling of Australia project. Two samples (0–10cm and 60–80cm depths) are taken at each site and are analysed for 60 elements using various analytical methods.

total of 311 major catchments have been sampled (Figure 3). The NGSA program will conclude in June 2011 and a report with accompanying data will be released at both state and national levels. This database can be used to complement other geochemical databases in future mineral exploration.

Diamond Indicator Mineral Database

A diamond indicator mineral database (Queensland Geological Record 2008/04) has been compiled and is available through the DEEDI Information Centre.

USAGE OF ARCHIVAL GEOCHEMICAL DATA IN MINERAL EXPLORATION

A cost effective geochemical exploration technique is to integrate archival geochemical data (exploration geochemistry and whole rock geochemistry) with high precision and multi-element geochemistry (REE and trace element chemistry, stable, and radiogenic data of selected samples). Appropriate processing and combination of the various exploration geochemical data types could potentially delineate areas of geochemical anomalies that warrant follow-up work.

Usages of Exploration geochemical data in mineral exploration

- Identify areas of data-gap by highlight area of intense exploration activities and areas of data lapses that offer further exploration opportunities.
- Establish mineral potentiality map — plots of high precision data will establish a mineral potentiality map. Areas with elevated elemental concentrations above the statistical mean can be regarded as mineral potential regions.
- Identifying geochemical anomalies using multiple element assays of multi-data types e.g. anomaly plots, and factor and cluster analyses.
- Provide a regional geochemical overview for mineral prospectivity by integrating processed geochemical grids with other data sets such as geology, geophysics and known mineral occurrences.

Usage of whole rock and trace element geochemistry in mineral exploration

There are close links between ore deposits, tectono-magmatic associations and geology. The correct interpretations of major elements, trace elements and isotopic geochemistry, radiometric ages, petrography and geology can be used as exploration tools to identify:

- Magmatic and fluid sources (igneous, sedimentary, crustal or mantle material)
- Tectonic settings
- Magma generation
- Differentiation processes
- Conditions of emplacement (pressure-temperature-chemistry).

RECOMMENDATIONS AND FUTURE DIRECTIONS

1. The integration of archival information with trace elements and isotope geochemistry data will give explorers crucial information on mineral potentiality, tectonic setting, source signatures, fluid migration, mineralisation environment and the timing of mineralisation events. Such information is crucial for ore modeling and target generation, particularly for concealed ore systems.

2. Areas with low precision data should be reinvestigated and re-sampled.

3. Assays using high precision trace element geochemistry techniques (e.g. ICP-MS analysis) will better define the geochemical background.

4. In greenfield exploration, high precision analyses are recommended to detect traces of mineralisation under the post-Mesozoic cover.

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UPDATE ON HYLOGGER™ PROGRESS

Suraj Gopalakrishnan

Geological Survey of Queensland

In Digging Deeper 2009 we introduced the HyLogger™, a new advanced non-destructive, scanning technique for mineralogically logging an entire drill hole in its original tray, without tedious sample preparation and in much shorter time frames. This year, we would like to update you with the activities associated with HyLogging™ at the Geological Survey of Queensland (GSQ).

In 2009, GSQ acquired HyLogger 2-5 from the Commonwealth Scientific Research Organisation (CSIRO), as part of the AuScope National Virtual Core Library (NVCL) research infrastructure roll out funded by the Federal Government's (Department of Industry Innovation Science and Research [DIISR]) National Collaborative Research Infrastructure Strategy (NCRIS) program.

The HyLogger™ is a robotic hyperspectral scanner, capable of quantitative mineral identification in the visible-near infrared (VNIR) and shortwave infrared (SWIR) regions of the electromagnetic spectrum (400–2500nm). It has a spatial resolution of 8mm and a spectral resolution of 8nm, together with depth-referenced high resolution digital imagery (~0.1mm resolution), it derives a valuable spatially-referenced dataset, suitable for higher level modelling applications, making it a valuable tool in deciphering the salient mineralogy of the cores.

The data is interpreted using "The Spectral Geologist" (TSG) software suite, also developed by CSIRO. The TSG software produces detailed mineralogical logs, spatially-registered images of the core and core trays, and other standard scalars stored in relational databases allowing these products to be interrogated remotely, via the AuScope NVCL Internet Portal. Spatially referenced external data can also be imported into TSG and compared with existing scalars.

The high quality of the HyLogger™ data is assured by performing a series of calibrations along its measurements. Data are radiometrically calibrated to an absolute standard before each tray-run and to a common set of standard minerals 1–2 times a day. Spectral comparison is also made against known Mylar (Standard) features. Instrumental variations are also monitored regularly, noting negligible variations in the initial 6 months (variation = 0.2nm at 2155nm).

AuScope's NVCL is part of the National GeoTransects Program (see picture below), whose ongoing goal is to image the top 2km of the earth's crust under the Australian continent. The Geological Survey of Queensland has a priority to HyLog both mineral and stratigraphic core in our core libraries that fall within the assigned geotransects. To date, we have covered most of the mineral core from our drill core facility at the Exploration Data Centre (EDC), Zillmere that falls within (and adjacent to)

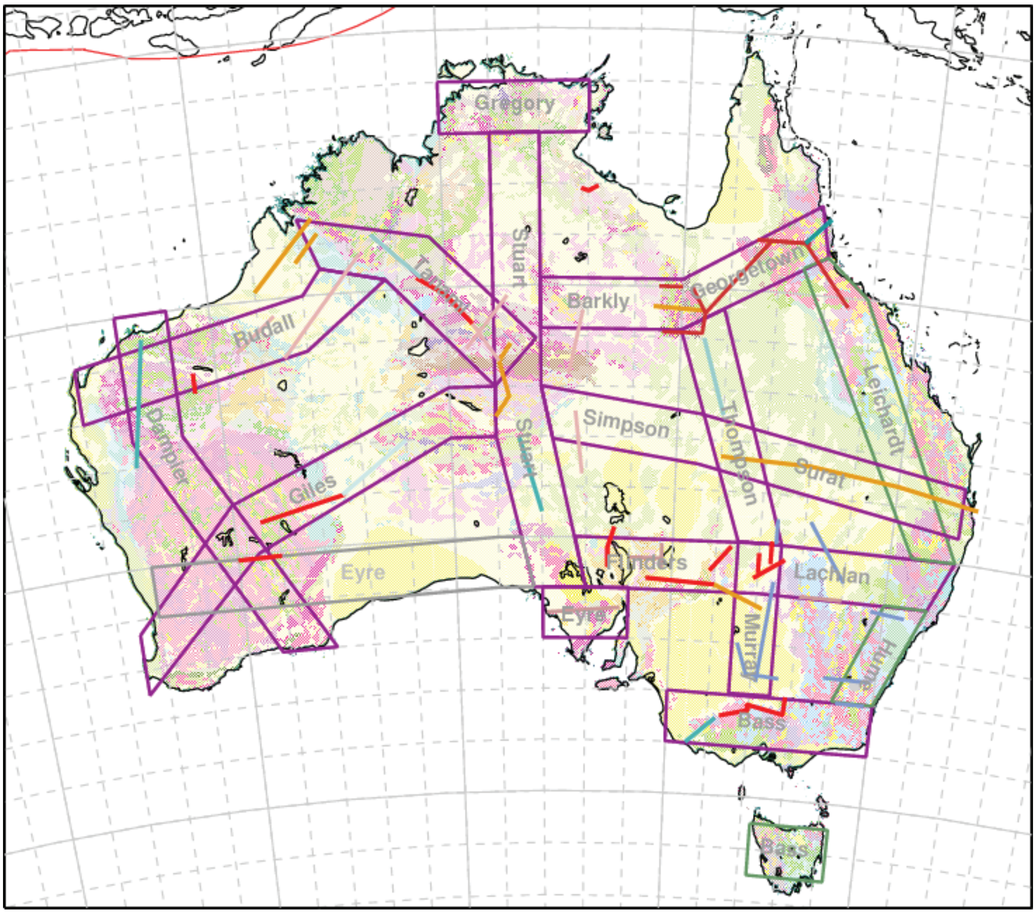

Figure 1. Configuration of Geotransects across Australian continent based on the seismic reflection profiles. (Ref.: http://rses.anu.edu.au/seismology/ANSIR/AuScope/transect.html)

the geotransects and are continuing with stratigraphic core. Since its delivery to the GSQ in September 2009, 37 500m of core have been scanned at the EDC Drill Core Facility, which amounts to 11 300 trays covering 166 holes (see Figure 2 for locations).

The AuScope/GSQ NVCL program also allows external/industrial clients to use this facility. Recently there has been a steady increase in industry requests for HyLogging™; 389m of mineral core from the Kilkivan region, 140m of core from Cloncurry/Mount Isa region, 3500m from the Kalman region, Mount Isa, 934m from Merlin, Mount Isa, 500m from Bluebush, Mount Isa, to name a few.

This facility is also supporting university research. 1530m of stratigraphic core from the Taroom region in the Galilee basin was scanned for the University of Queensland and 428m of Coalstoun-19 core was scanned for the University of Tasmania. Several internal requests were also scanned to support existing GSQ projects.

The AuScope NVCL infrastructure is also intended to facilitate undergraduate, postgraduate, public sector and industrial level research into the mineralogy of the top 2km of the earth's crust. There are research opportunities available for research projects in mineral systems, alteration signatures, mineralogy, petrological studies, fluid-rock interactions or petroleum and geometallurgical characterisation. Other

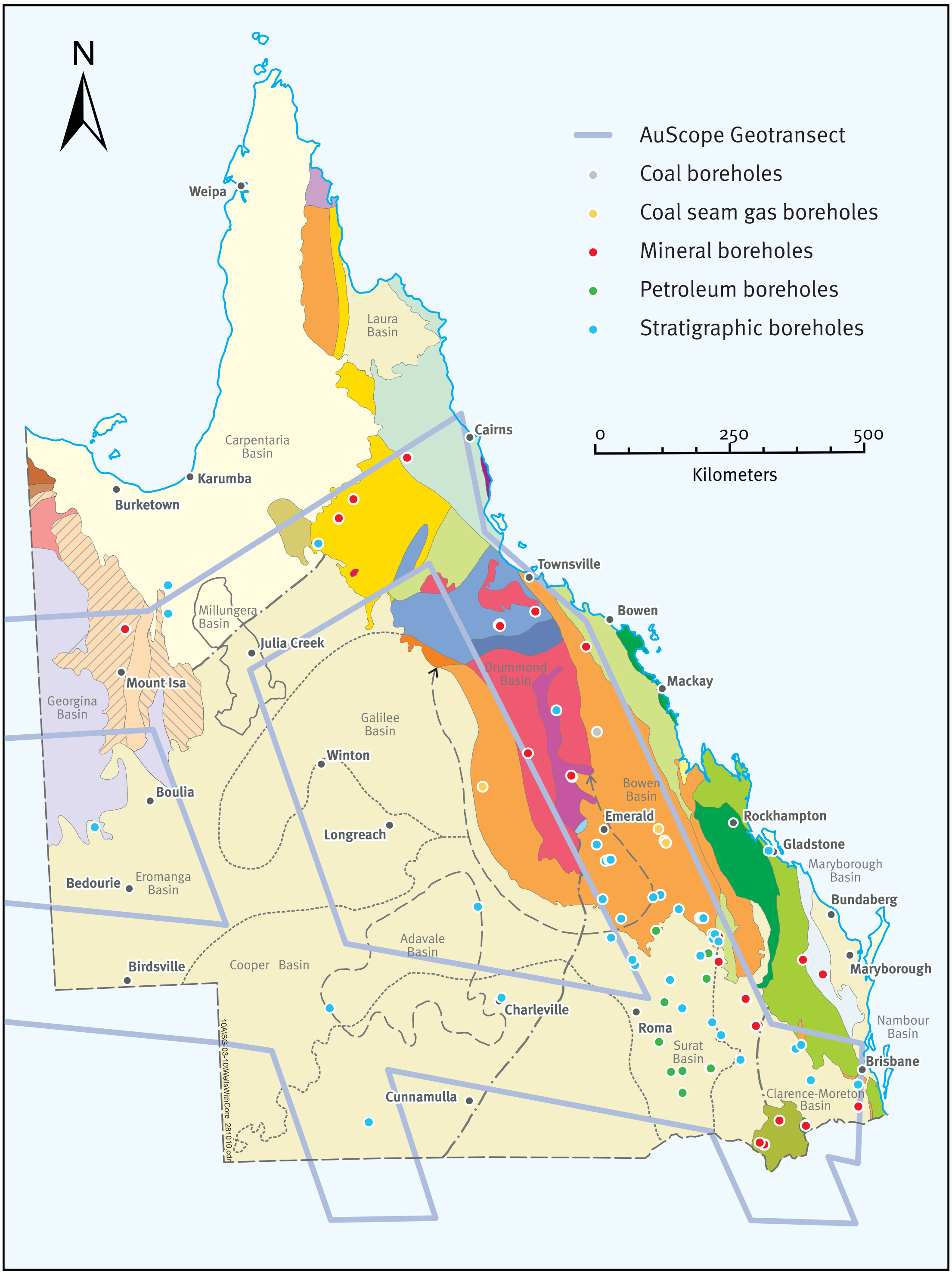

Figure 2. Location of drill holes scanned using HyLogger™ up to October 2010

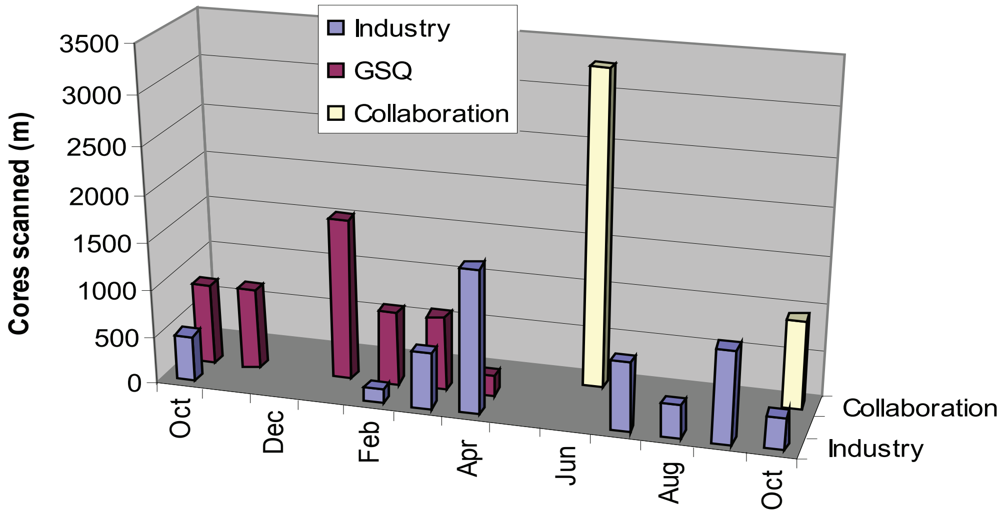

Figure 3. Core scanned by GSQ as part of the HyLogging™ project

ideas that can enhance or make valuable use of the HyLogging™ infrastructure and its published outputs are also encouraged.

HOW IT WORKS

High resolution spectrometers within the HyLogger™ detect reflectance spectra formed due to the preferential absorption at energies corresponding to the stretching and bending of molecular bonds (e.g. O-H, Al-OH, H-O-H) in the visible to short and mid-infrared regions within the electromagnetic spectrum. These absorption features are characteristic of individual minerals. Each reflection spectrum is matched to a library of mineral spectra to find the best combination of up to 3 minerals, with a minimum contribution being 15% of a single mineral. Validation of the collected data forms another integral part of NVCL program. Even though the HyLogger™ has many quality checks in place, a secondary form of validation using standard analytical methods supplements the quality of the data derived using this procedure. Minerals identified using classical characterisation methods like X-ray diffraction, Scanning Electron Microscopy, etc. were compared with the HyLogger™ generated mineral indices to validate the HyLogger™ results.

GSQ has also value added HyLogger™ data with a hand-held X-ray Fluorescence (XRF) spectrometer (Niton XL3T-500), which can measure elemental composition with accuracy in the parts per million (ppm) ranges. An experimental exercise incorporating Niton data with HyLogger™ data helped to decipher some interesting anomalies in the Iron Oxide Copper Gold Deposits (IOCG deposits) of the Kalman region, Queensland.

THERMAL INFRARED (TIR) UPGRADE

The existing HyLogger™ system scans the range of VNIR/SWIR regions within the electromagnetic spectrum giving information mostly on iron oxides, OH-bearing minerals and carbonates. CSIRO is developing a TIR upgrade to use with the existing HyLogger™ suite that could discriminate anhydrous silicates such as quartz, feldspar, garnet or pyroxenes by their mineral specific spectral features shown only in the TIR wavelength (8000–12000nm). With this upgrade, the HyLogger™ system will have the capability to capture spectra in the range of VNIR/SWIR/TIR, deriving valuable information on the entire geological spectrum. The TIR remote sensing is generally done by measuring the emitted radiation from the outdoor target against a cold sky. But the indoor TIR has a source much hotter than the room environment and hence corrections from room radiation and target emission are necessary. Ideally, having the room and target (core) at the same temperature works efficiently with the corrections applied. GSQ has a setup inside the core shed where the HyLogger™ is located next to the core with the ambient conditions similar to that of core, which is the ideal condition for TIR. It is expected to have our system upgraded with the TIR facility by January 2011.

ACKNOWLEDGEMENT

The research infrastructure support provided by the Federal Government funded NCRIS/ AuScope/CSIRO through the AuScope National Virtual Core Library project is gratefully acknowledged.

KALMAN DEPOSIT CHARACTERISATION USING HYLOGGER™

Mal Jones[1] and Carsten Laukamp[2]

[1]Geological Survey of Queensland, [2]CSIRO

The Mount Isa region has attracted mineral exploration since the late 1860s when explorers such as Ernest Henry first arrived in the Cloncurry district (Blainey, 1960). Recent discoveries such as Kalman underline the continuing prospectivity of the region. The Kalman Cu-Au-Mo-Re prospect lies on the Pilgrim Fault south-west of Cloncurry. Mineralisation is considered to be intrusion-related and is hosted by Corella Formation rocks (1742–1750Ma (Geoscience Australia Geochronology Laboratory, 2007)). This project entailed the spectral logging of ten holes from Kalman, using the HyLogger™ Visible to Short Wavelength Infra Red logging system. The total core length amounted to approximately 3200m. Additional downhole assays were conducted using a hand held Niton XRF analyser. Company assay data and lithological logs also contributed to the study.

The close proximity of the drillholes within an area of 500 x 600m enables the geology to be visualised in 3D using software such as Gocad. This aspect of the study is still in progress.

The Kalman prospect lies within the footprint of the Geological Survey of Queensland (GSQ) - CSIRO Hyperspectral survey of 2006–07 which provides a number of image maps characterising the surface materials (Cudahy & others, 2008). The airborne surveys of the surface and HyLogger™ data from the subsurface complement each other in providing perspectives of mineral distribution in 3D. The project has also enabled an investigation of the benefits of portable XRF (P-XRF) analyses for deposit characterisation.

The aims of the project are to:

- Report results of investigation to wider exploration community to publicise as a valuable tool to support exploration in Queensland;
- Publicise its capabilities via an integrated project based on a Cu-Au-Mo-Re prospect. The project also enabled an evaluation of the Niton portable XRF (P-XRF) analyser;
- Display the data from HyLogger™, P-XRF, assay, and lithological logging investigations in 3D. Interpret patterns of alteration associated with mineralisation and display these as 3D surfaces and or volumes;
- Determine spectral signatures of mineralised zones and use these to calibrate equivalent zones on surface Hyperspectral images;
- Determine spectral signatures of zones adjacent to mineralisation to infer ‘near miss’ intersections in cores;
- Determine ‘near miss’ equivalent spectral signatures for surface Hyperspectral imagery for mineral exploration targeting; and
- Provide a report to project sponsors (Kings Minerals NL).

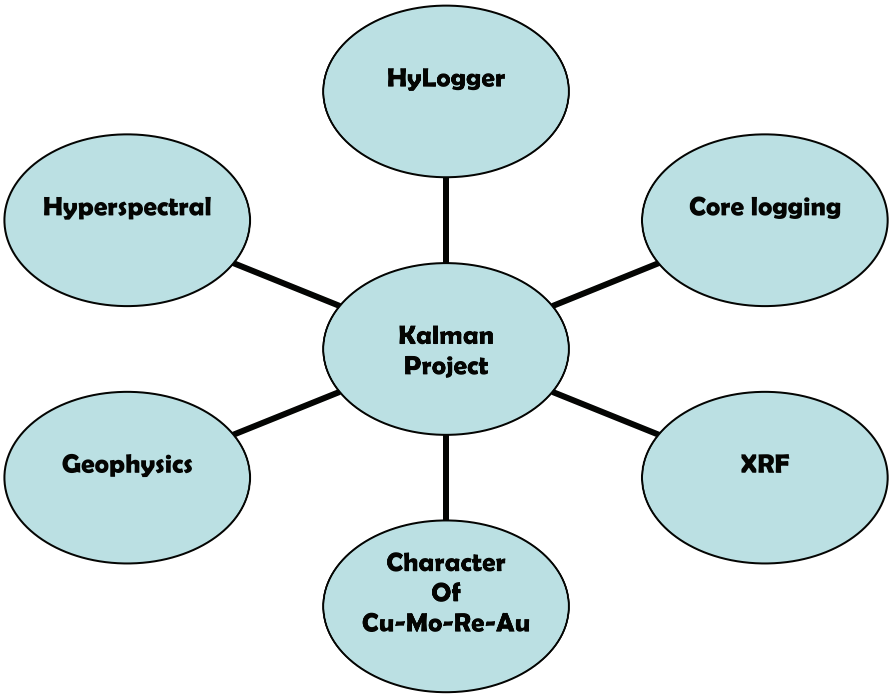

Figure 1. HyLogger™ is one of several datasets that contribute to characterising metallic mineralisation at prospect and region scales

The Kalman investigation has generated a large amount of data that is yet to be fully investigated. Ongoing studies are in progress at the GSQ and CSIRO, and the results will be made public via conference presentations and published papers. This talk provides some examples of how HyLogger™ data can be used to assist mineral exploration through a better understanding of the metallic mineral-bearing rocks, and the contrasts with the surrounding unmineralised geology.

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