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

North-West Queensland Mineral and Energy Province Report

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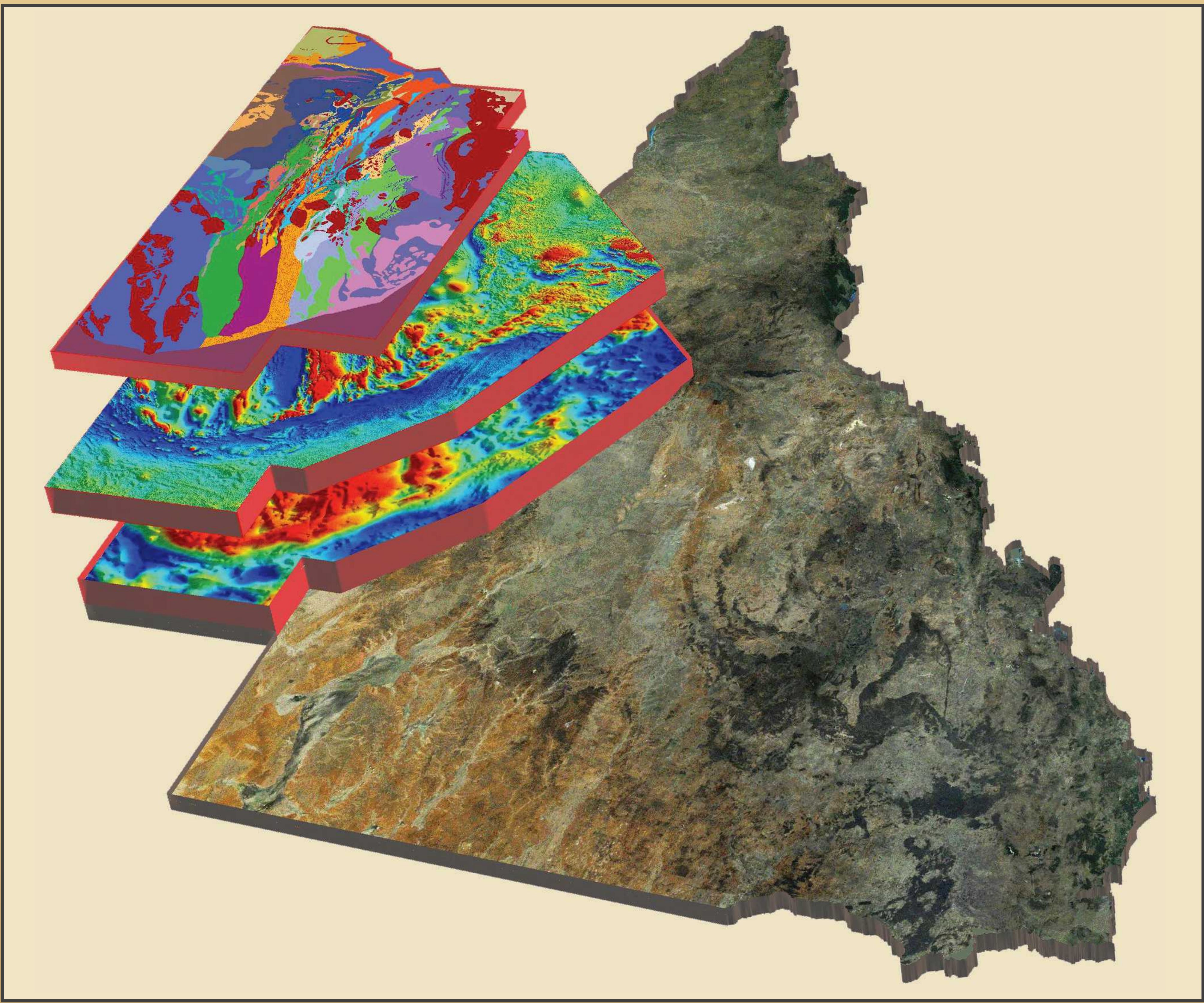

Queensland Government

North-West Queensland Mineral and Energy Province Report

compiled by

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

CONTRIBUTORS

Geoscience
H.F. Baker
J.W. Beeston
P.R. Blake
D.D. Brown
K.L. Crosby
L.G. Culpeper
T.J. Denaro
C.R. Dhnaram
P.J.T. Donchak
S.P. Faulkner
M.L. Greenwood
L.J. Hutton
M.R. Jones
B.J. Jupp
J.L. McKellar
A. Parsons
W.G. Perkins
S.N. Sargent
M. Scott
J.M. Simpson
B.D. Stockill
E.H. Tang
A.J. Troup
I.W. Withnall

Production Editor
J.W. Beeston

Desktop Publishing
S.A. Beeston

Maps/Graphics
P.E. Deacon
G.L. Nuttall

Cartography
R.K.J. Blight
B.K. Hauser
C.D. MacWhirter
D. Nieuwenburg
G.S. Pascoe
S.M. Turner
L.J. Young

GIS
P. Lin

With contributions from:

PGN Geoscience
L. Ailleres
R. Armit
P.G. Betts

Mira Geoscience
T. Chalke
G. Pears

ADDRESS FOR CORRESPONDENCE:
Department of Employment, Economic Development and Innovation, Queensland
Geological Survey of Queensland
PO Box 15216, City East, Qld 4002
Telephone: (07) 3006 4666; International +61 7 3006 4666
Email: geological_info@dme.qld.gov.au
Web: www.deedi.qld.gov.au

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North-West Queensland Mineral and Energy Province Report

The North-West Queensland Mineral and Energy Province (NWQMEP) study (Figures 1.1 and 1.2) represents the culmination of the 2006–09 regional mapping program by the Geological Survey of Queensland (GSQ) that focussed on a revision of the surface geology of the Proterozoic Mount Isa Inlier. This new information, in combination with new geophysical data and interpretations, forms the foundation from which geological interpretation has been extended into the surrounding areas covered by Phanerozoic sedimentary rocks. This report includes new information about this world-class resource province and new insights concerning the geological evolution of the region and how this has resulted in its mineral and energy prospectivity.

The last major synthesis of this region is the North-West Queensland Mineral Province Report (Queensland Department of Mines and Energy & others, 2000). Since 2000 there has been a significant body of work undertaken in the Mount Isa Inlier and equivalent Proterozoic Australian sequences warranting a review of the evolution of the region and its role in continental amalgamation. Major advances have also taken place in technology and work processes that have impacted on the processing, integration, visualisation and analysis of geological and geophysical data.

During this time new high quality airborne magnetic and radiometric surveys have been flown at a maximum line separation of 400m over almost 430 000km^2 of north-western Queensland (Plates 8 and 10–17). Gravity surveys at two and four kilometre station intervals were also undertaken over a similar area (Plates 9 and 18–19). These regional geophysical surveys have targeted under-cover areas adjacent to the Mount Isa Inlier, providing information to support geological interpretations in areas with very limited outcrop.

The goals of this report are to synthesise this information and apply modern technologies to provide fresh insights into the tectono-stratigraphic evolution, 3D architecture and controls on the distribution of mineral and energy resources, and thus enhance the effectiveness of exploration activity to realise the resource potential of this fertile region.

The report was prepared over the period February to November 2010, using public domain geological, geophysical and geochemical data, and the latest publications. Analysis phases of the project involved interdisciplinary studies requiring the reconciliation of diverse data sets to produce more robust geological interpretations.

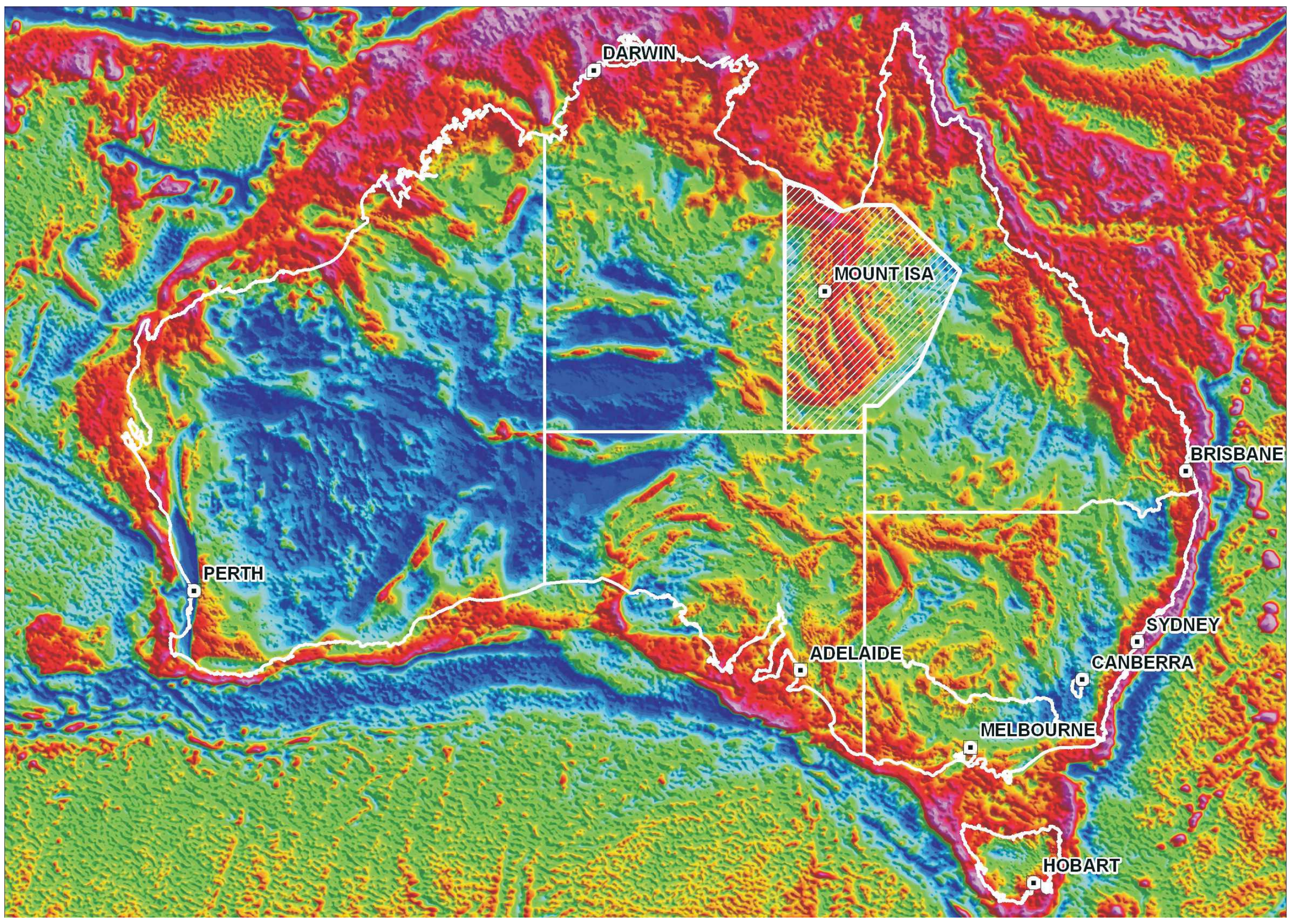


Figure 1.1: Bouguer gravity image of Australia showing the location of the North-West Queensland Mineral and Energy Province

Philosophy and approach

The NWQMEP is Australia's largest lead, zinc and silver producer, hosting almost 30% of the world's lead-zinc reserves, as well as being a significant producer of copper. The region continues to produce new world-class discoveries such as the Merlin Cu-Au-Mo-Re deposit. The discovery of Merlin, as well as the Kalman Cu-Mo-Re-Au deposit, heralds potential for more diversity in the range of commodities in the region, which will soon produce for the first time in its history magnetite iron ore, molybdenum and rhenium. North-West Queensland also has significant energy potential, including non-traditional geothermal and shale gas. Non-metallic and industrial minerals are a valuable resource for the region, but only phosphate has been included in this report, the main focus being on metallic minerals and non-traditional energy resources.

The resource endowment of the province is striking considering that over 50% of the north-west's 500 000km^2 is concealed by post-Proterozoic cover and, as a result, has not been adequately defined and remains under-explored in terms of the latest exploration technologies. Discoveries such as Ernest Henry, found under less than 60m of Mesozoic cover, attest to the significant greenfield potential of this region. As a consequence, a major focus of this study has been on extending the search area for new mineral and energy resources.

The revision of the surface geology integrated new field observations with existing mapping from a range of sources and interpretation of a range of remote sensing datasets, including traditional aerial photography, Landsat and Aster satellite data, airborne magnetics and radiometrics, and gravity data. SHRIMP U-Pb zircon geochronology in conjunction with Geoscience Australia (GA) also contributed significantly to our new understanding of the geology.

The NWQMEP has experienced a long and episodic history of basin formation, deformation and associated structural complexity, and repeated crust-mantle interactions — key factors for the mineral and energy wealth of the region. However, the absence of exposed plate boundaries in the Mount Isa Inlier has led to a large amount of speculation regarding the geodynamic context in which the inlier has evolved.

One objective of this study therefore, has been to reconcile new data into a coherent geological history and to develop an understanding of the structural architecture in terms of earth processes, recognising that tectonic setting and associated architecture are first-order controls on resource distribution.

A tectonic analysis was commissioned by the GSQ and carried out in association with PGN Geoscience to provide: (i) a uniform tectonic interpretation of major deformation events and responses across the region, and (ii) a model of the geodynamic evolution of the inlier considering the relationships and correlations with other Australian Proterozoic provinces.

A new subdivision of the province into domains is presented that reflects combinations of basin evolution, structural grain, metamorphic grade and geochronology and provides a more flexible framework for describing variations in the geology and deformational responses between different parts of the region. Space-time-plots have also been constructed that include new information on the geochronology of igneous rocks, changes to geological contacts and unit designations, the timing of mineralisation, and an overview of the major tectonic events affecting the region.

A solid geology interpretation has been produced (Map 1 and Plate 5) integrating new geological mapping of outcropping areas, interpretations based on potential field data in association with drillhole data, and interpretations of recent regional seismic data acquired by GSQ and GA. This interpretation has been used to extend the geological understanding from the best known outcropping areas out under Phanerozoic cover. It depicts the

Figure 1.2: Map showing the extent of the North-West Queensland Mineral and Energy Province study area

lithology of the concealed basement, delineates major crustal structures and boundaries, and identifies major intrusive bodies, all of which are significant in terms of resource prospectivity.

These data, along with field observations and processed geophysical data, (including seismic, airborne magnetic, gravity and magnetotellurics) have been integrated and reconciled in the development of a 3D model of the crustal architecture of the province. This model was constructed as a visualisation tool for displaying the spatial associations of geological features at depth and beneath cover, as well as providing a conceptual framework for more specific basin evolution, deformation, fluid flow and mineral systems studies.

The 3D product includes geophysically modelled regions of the deep crust to provide an appreciation of whole-of-crust processes affecting the region. A detailed depth-to-basement surface has been constructed to assist explorers in initial tenement selection. These new data and the rigour in data integration have resulted in significant developments in the interpretation of structures, stratigraphy and magmatism in the region.

Knowledge about significant known mineral deposits types and occurrences in the north-west has been compiled and synthesised as a series of tables that emphasise the processes of ore formation and take into account the crustal- to deposit-scale aspects of the mineralising systems for each of the major mineralisation styles in the inlier. Ore deposits, however, are highly variable in their local characteristics. A scale-integrated study is provided as an example of how open-file geological and geophysical data can be used to develop more robust workflows and produce district-scale 3D models that can be used for predictive investigations in greenfields areas. In this example the GSQ commissioned Mira Geoscience to develop a Common Earth Model and use Bayesian statistics to quantitatively evaluate associations and define patterns, effectively 'testing' the significance of features identified through the regional mineral systems analysis at district-scale.

Current knowledge of the energy resources in Palaeozoic strata that overlie and surround the Mount Isa Inlier have been compiled and summarised by Energy Geologists of the GSQ. Sources have included company reports of early petroleum drilling, water drilling, and government stratigraphic bores, surface geological mapping, and reviews of the basins in a variety of geoscience society and conference proceedings and journals. These summaries are focussed on exploration potential for conventional oil and gas, coal, coal seam gas, and shale gas. The area is considered under-explored.

The geological setting of the NWQMEP suggests that this region should be prospective for geothermal energy. Using a basin by basin geothermal assessment of the Carpentaria, Eromanga, Galilee, Georgina and Millungera Basins, an overall geothermal prospectivity analysis has delineated areas with potential for 'Hot Sedimentary Aquifers' and 'Enhanced Geothermal Systems'.

Key products

The following products of the study are aimed at increasing the confidence of exploration decision-makers and assisting in the discovery of the next generation of world-class mines in the region.

- An overview of the characteristics of the Proterozoic geological domains — Chapter 2
- Synthesis of geodynamic evolution of the Proterozoic Mount Isa Inlier, including eleven time-slices of the Mount Isa Inlier — Chapter 3; a more detailed report is included as Appendix 1
- A summary of the geodynamics of the Mount Isa Inlier from a Proterozoic Australian perspective, including eleven geodynamic evolution maps of eastern Proterozoic Australia — Chapter 4; a more detailed report is included as Appendix 2
- Two time-space plots detailing the chrono-stratigraphy and tectonic events for: (1) the Mount Isa Inlier and (2) Proterozoic Eastern Australia — Maps 2 and 3 and Appendixes 3 and 4
- A 3D model covering the entire NWQMEP study area including depth to basement surface and 5 gravity 2.5D forward model transects focussing on structures in the lower crust. An overview of the model is presented in Chapter 5, but the detailed interpretation and data is given as Appendix 12.
- Mineral systems analysis of:
  (1) structurally-controlled epigenetic Iron oxide-Cu-Au (IOCG) deposits and Ag-Pb-Zn in high-grade metamorphic terranes east of the Kalkadoon–Leichhardt Domain, and
  (2) stratabound sediment-hosted Zn-Pb-Ag and structurally-controlled epigenetic Cu±Au deposits west of the Kalkadoon–Leichhardt Domain. Chapter 6 contains an overview of these systems, with more comprehensive reports on each of them in Appendix 5a–d.
- The global significance of the NWQMEP in terms of its mineral endowment and production for base metals and silver — Chapter 7
- Exploration geochemistry and drillhole database comprising over 1.3 million attributed data points representing stream sediment, rock chip, soil and drillhole information. The database is presented as Appendix 13, but a brief overview is given in Chapter 8.
- A district-scale iron-oxide-copper-gold predictive study of the Mount Dore region which includes a 3D geology model, 3D Common Earth Model, pseudo-lithology block model, ranked district target criteria and a 3D mineral potential index model. An overview of the results of this study is given in Chapter 9, but the detailed report by Mira Geoscience is contained in Appendix 6.
- An overview of multispectral data available for the region — Chapter 10
- The energy resources in Palaeozoic strata that overlie and surround the Mount Isa Inlier have been investigated by Energy Geologists of the GSQ. Summaries of these investigations are given in Chapter 11, focussing on the exploration potential for conventional oil and gas, coal, coal seam gas, and shale gas.
- A summary of the geothermal potential of the region — Chapter 12
- Attributed GIS dataset in ArcGIS and MapInfo formats that includes the following layers:
  - detailed surface and solid geology as arcs and polygons and various derived layers including an attributed fault array
  - infrastructure
  - topography
  - mineral occurrences
  - geophysical images
  - satellite images.

Key bibliographic references

The emphasis of this study has been on new knowledge and adding value to mineral exploration, and on highly visual products that can be interrogated in the digital GIS environment. As a result, it does not include a systematic, detailed description of all facets of the geology of the NWQMEP. Publications from government, research and industry geoscientists provide comprehensive coverage of most aspects of the geology and evolution of the province. A comprehensive bibliography is available as Appendix 14, but the main sources are listed below:

- Overall descriptions of Proterozoic geology — Blake (1987); Stewart & Blake (1992)
- 1:100 000 scale geological maps and accompanying reports — Alsace (Derrick & Wilson, 1982); Ardmore (Bultitude, 1982); Cloncurry (Ryburn & others, 1983); Coolullah (Wilson & Grimes, 1986); Dajarra (Blake & others, 1982); Duchess Region (Bultitude & others, 1982; Blake & others, 1984); Hedleys Creek (Sweet & others, 1981); Kennedy Gap (Wilson & others, 1979a); Kuridala Region (Donchak & others, 1983); Lawn Hill Region (Sweet & Hutton, 1982); Mammoth Mines Region (Hutton & Wilson, 1985); Marraba (Derrick, 1980); Mary Kathleen (Derrick & others, 1977); Mount Isa (Hill & others, 1975); Mount Oxide Region (Hutton & Wilson, 1984); Myally (Wilson & Grimes, 1984); Prospector (Wilson & others, 1977); Quamby (Wilson & others, 1979b); Selwyn Region (Blake & others, 1983)
- Sequence stratigraphy and basin analysis —
  - Various papers in Stewart & Blake (1992)
  - Various papers resulting from the North Australian Basins Resource Evaluation (NABRE) Project in the *Australian Journal of Earth Sciences*, Volume 47, No. 3, June 2000 Thematic Issue — Carpentaria – Mount Isa Zinc Belt: basement framework, chronostratigraphy and geodynamic evolution of Proterozoic successions
  - Chapters and appendixes in the reports of the *pmd**CRC I1 and I7 Projects (Gibson & Hitchman, 2005; *pmd**CRC I7 project Team, 2008)
- Geochronology — Connors & Page (1995); Page (1983a,b; 1988); Page & others (2000); Page & Sun (1998); Page & Sweet (1998); Perkins & Wyborn (1998); Southgate & others (2000); Giles & Nuttman (2003); Neumann & Fraser (2007); Neumann & others (2006b; 2009a,c); Carson & others (2008a, and in preparation); Magee & others (in preparation)
- Structure, tectonics and metamorphism — Blenkinsop & others (2008); Connors & Lister (1995); Drummond & others (1998); Foster & Rubenach (2006); Giles & others (2006); Holcombe & others (1991); Laing (1998); O'Dea & others (1997a,b,c); Pearson

- & others (1992); Scott & others (1998); various papers in Stewart & Blake (1992)
    - chapters and appendixes in the reports of the *pmd**CRC I1, I2+3 and I7 Projects (Gibson & Hitchman, 2005; Blenkinsop, 2005; *pmd**CRC I7 project Team, 2008)
    - papers in a special issue of *Precambrian Research*, Volume 163, on the Mount Isa Inlier
- Energy — Gravestock & others (1986); Leslie & others (1976); Moore & Mount (1982); O'Neil (1989); Petroleum Resources Assessment and Development Subprogram (1990)
- Igneous petrology and geochemistry — Mark (2001); Wyborn (1998); Wyborn & others (2001)
- Geophysical interpretation – Chopping & Henson (2009); Hutton & others (2009); chapters and appendixes in the reports of the pmd*CRC I1, I2+3 and I7 Projects (Gibson & Hitchman, 2005; Blenkinsop, 2005; pmd*CRC I7 project Team, 2008)
- Mineralisation — GSQ Mineral Occurrence reports for the following 1:250 000 Sheet areas: Camooweal (Denaro & others, 1999a); Cloncurry (Denaro & others (2004); Dobbyn (Culpeper & others, 2000); Duchess and Boulia (Denaro & others, 2003b); Lawn Hill (Denaro & others, 1999a,b); Mount Isa (Denaro & others, 2001); Urandangi (Denaro & others, 2003a); and Westmoreland (Culpeper & others, 1999); and papers in the following publications
    - *Australian Journal of Earth Sciences*, Volume 45, No. 1, February 1998: Thematic Papers — Geology and mineralisation in the Proterozoic – Carpentaria Zinc Belt of northern Australia
    - *Australian Journal of Earth Sciences*, Volume 45, No. 3, June 1998: Thematic Issue — Geological framework and mineralisation in the Mount Isa Eastern Succession, North-West Queensland
    - *Economic Geology*, Volume 93, No. 8, December 1998: A special issue on the McArthur River – Mount Isa – Cloncurry Minerals Province
    - *Geology of Australian and Papua New Guinean Mineral Deposits*. The Australasian Institute of Mining and Metallurgy, Monograph 22 (1998).
    - Papers in *Australian Journal of Earth Sciences,* Volume 53, February 2006: thematic issue — Mount Isa tectonics.

Topography

Physiographically, the present land surface reflects the structure and geological history of the region, as well as local structures and rock types. Overall, the region can be described as a highly dissected peneplain with lesser relief and greater alluviation on the inland (southern and south-western) side of the divide than on the northern and eastern side. The average altitude of the Barkly Tableland along the south-western margin of the Proterozoic upland is 240 to 300m. The Gulf Country, to the north, has an average altitude of 60 to 120m at the foot of the upland. The western edge of the plains to the east has an average altitude of 105 to 210m.

The study area can be subdivided into the following general physiographic units (Stewart, 1954; Twidale, 1964) that broadly correspond to major geological subdivisions:

- Isa Highlands — this upland block projects in a north-north-westerly direction to within 50km of the Gulf of Carpentaria. It is a complex ridge that averages about 360m above sea level but locally exceeds 500m, and is coincident with the area of outcropping Proterozoic rocks, and associated Mesozoic and younger outliers. The complex geological structure is expressed in the topography and drainage patterns. The topography comprises homoclinal ridges and hogbacks, some with truncated crests, small plateaux, and alluvial deposits in the valleys. Present topographic levels indicate that the highlands have been truncated by a post-Mesozoic planation surface.
- Georgina Basin — drained by the southward flowing Georgina River and its tributaries. In the north-west it consists of black soil plains and a gently sloping topography, but becomes progressively more dissected near the Isa Highlands.
- Carpentaria Plain — this broad plain between the Isa Highlands and the Gulf of Carpentaria is essentially depositional, with an alluvial cover, braided stream channels and an uneven slope, and is drained by streams that flow into the Gulf of Carpentaria. It has a low gradient, with a rise of only 210m from the Gulf of Carpentaria to the divide between the Gulf and inland drainages. Several low lateritic plateaux occur within the plain. Broad expanses of bare mudflats, crossed by belts of sandy beach ridges, extend as coastal deposits around much of the Gulf.
- Inland Plain — the flat-lying plain of the Eromanga Basin is drained by the Diamantina River and its tributaries. Low lateritic plateaux occur within the plain.
- Simpson Desert — occurs in the south-western part of the study area and consists of innumerable longitudinal sand dunes that trend north-north-west separated by interdune clay pans. Several large salt-pans and ephemeral lakes, such as Lake Machattie, occur in the area.

The outcropping Proterozoic rocks form a watershed or divide of continental importance. South and west of the divide, streams drain inland as part of the Georgina–Diamantina system that terminates in Lake Eyre in South Australia. However, water only reaches Lake Eyre at intervals of several years. Even within the area of outcropping Proterozoic rocks, these streams are braided and heavily alluviated.

Streams north of the divide, such as the Leichhardt, Flinders, Cloncurry, Gregory and Nicholson Rivers, drain into the Gulf of Carpentaria. These streams are more or less entrenched in the plains of the Gulf Country, but develop complex distributary systems in their lower courses (Carter & others, 1961).

Only four watercourses in the study area, the Gregory and O'Shannassy Rivers and Lawn Hill and Widdallion Creeks, are perennial. These are fed from springs tapping underground water in Palaeozoic limestones. Of the remainder, smaller watercourses only flow for a few days or weeks each year; larger ones may flow for several months. All of the larger watercourses and some of the smaller ones have a number of permanent waterholes. Surface water is fairly easy to find in most parts of the area for two to three months after the end of the 'wet season'. Large areas become essentially devoid of surface water later in the year. Much of the study area is reliant upon groundwater from the Great Artesian Basin and shallower sources for domestic and stock watering purposes.

Climate

The study area is almost entirely within the tropics. The climate is semi-arid to sub-humid tropical, and ranges from a tropical, moderate rainfall, coastal climate in the north to a tropical, low rainfall, continental climate in the south. As the topographic range is less than 600m it does not significantly influence climate, except perhaps for a slightly increased rainfall in the higher country.

The climate comprises a warm dry season from April to September and a hot wet season from October to March. Average rainfall ranges from 260mm per annum in the south to 770mm per annum in the north. Peak rainfall is in the summer months, with the highest rainfall in January and February, although isolated storms can bring falls of up to 50mm at any time of the year. Mean daily temperature maxima range from 23°C in June and July to 38°C in November and December; daily maxima in excess of 40°C are common between October and February. Mean daily temperature minima range from less than 10°C in June, July and August, when there are occasional frosts, to about 25°C in December to February.

Due to access problems caused by heavy rainfall, field activities are not possible throughout most of the region in January and February. Occasionally, rain delays the resumption of field activities until March or early April.

Vegetation

Because of the wide climatic range, there is a considerable diversity of vegetation throughout the study area, but in general the vegetation cover is sparse and does not cause any major access problems or impediments to exploration activities.

The stony hill country, formed by outcropping Proterozoic rocks, supports mainly eucalypts, including snappy gum, mountain gum and stunted box 3 to 7.5m high. There is commonly a moderate to heavy cover of low scrub, consisting mainly of acacia (including 'turpentine bush') and ti-tree.

Varieties of the needle-sharp resinous grass spinifex thrive throughout the region, wherever the soil is poor or scanty and is well-drained. Spinifex forms as clumps that are generally 0.3 to 0.6m high but may grow to more than 1.5m high, presenting an obstacle to travel.

The plains are generally sparsely timbered, except in the far north, where extensive tropical savannah with eucalyptus, scrub ti-tree and acacias provide moderate tree cover. Black soil plains support Mitchell grass and Flinders grass. In these areas, trees are confined to sandy rises and the margins of watercourses, where coolibah and similar mallee-type eucalypts grow to 3 to 10m in height.

Land Use

The NWQMEP is a large and relatively remote part of Queensland. In terms of land area, grazing (particularly beef cattle) is by far the major land use. However, most of the Province's economic activity centres upon Mount Isa.

Apart from mining and associated down-stream processing and service industries, the major industries in the Province are:

- beef production
- wool production
- fishing and aquaculture
- transport and freight services
- engineering services
- tourism.

Administration

The NWQMEP encompasses ten local governments (nine shires and one city council, see Figure 1.2) and an independent Land Council (Mornington Island). The region has links with Townsville, on the Queensland coast to the east. The Gulf communities, namely Burke, Carpentaria, Mornington and Doomadgee, also have links with Croydon and Etheridge shires (particularly through the Gulf Local Authority Development Association).

The region has a total population of approximately 35 000 of whom approximately 63% are based in Mount Isa. It has very high population mobility due to the large number of itinerant workers, employees on contracts (such as mining workers) and fly-in fly-out workers. Approximately 15% of the population in the region are temporary residents.

Infrastructure

Because it is a long-established mining district, the NWQMEP is served by a sound framework of local infrastructure, including good road, rail and air connections with the major population centres and ports in Queensland (Figure 1.2 and Plate 1).

Key aspects of the general infrastructure relevant to the mining industry are as follows:

- Mount Isa has an established urban centre (population 22 000) with a broad range of business and community facilities and services, including specific exploration/ mining support groups.
- A major regional airport at Mount Isa with daily flights to and from Brisbane and Townsville and regular connections with Cairns; the airport at Cloncurry handles additional air traffic associated with the Ernest Henry and other mines in the local district. Private airports have also been constructed to serve the Century and Osborne mines.
- A good local network of State and Council-maintained sealed and unsealed roads as well as station and mineral exploration vehicle tracks
- Road and rail access to the deep water port of Townsville, which has nine operational berths equipped with bulk handling facilities, five of which are currently being used to handle mineral and metal cargoes
- Extensions to existing mining operations and in particular, the production of bulk commodities such as magnetite and phosphate, will inevitably increase tonnages on the Mount Isa to Townsville railway.
- Implementation of the Mount Isa System Rail Infrastructure Master Plan, completed in 2009, will see the annual capacity increased in stages from 6.9Mt to more than 20Mt.
- Proximity to the general purpose port of Karumba, at the mouth of the Norman River, in the south-east corner of the Gulf of Carpentaria; the port currently handles zinc concentrates that are transported via a 310km long slurry pipeline from the Century mine. The concentrates are taken through the shallow in-shore waters of the Gulf by 5000t barges to export vessels lying some 45km offshore.
- Electricity is generated by the 325MW Mica Creek Power Station (MCPS) at Mount Isa, which supplies Mount Isa city, Cloncurry and surrounding areas. It generates electricity using gas piped 840km from Ballara in south-west Queensland.
- Xstrata (Mount Isa Mines Limited), while supplied from MCPS, also operates its own 30MW gas-fired power station on the mine site at Mount Isa.
- Many of the cattle properties are serviced from MCPS by Single Wire Earth Return (SWER) powerlines.
- With the exception of Ernest Henry and Century, which are supplied from MCPS, power for most mines is generated on-site using either diesel or natural gas (in the case of Phosphate Hill, Osborne and Cannington).
- Continued growth in energy demand in the region is likely to approach or exceed the capacity of existing supply facilities within a few years, particularly if new mines commence operations.
- Proposals to connect the Mount Isa region to the National Grid are currently being considered. One of these, the CopperString Project aims to construct a 720km-long high-voltage transmission line from Townsville to Cloncurry. It will provide approximately 400MW of transfer capacity, to complement the existing energy infrastructure in north-west Queensland, and could be extended to some of the larger mines. If all government approvals are received, the transmission line could be operational by late 2013.
- Water for the city and the mining complex at Mount Isa is supplied from two large dams on the Leichhardt River (Lake Julius and Lake Moondarra). The former also supplies water by pipeline to the Ernest Henry mine and has recently been connected to Cloncurry. Other mining operations supply their own water, either from smaller dams or bore fields.
- Secure and highly reliable telecommunications networks using the latest exchange and transmission technology, although mobile phone coverage is mainly restricted to the vicinities of Mount Isa and Cloncurry.

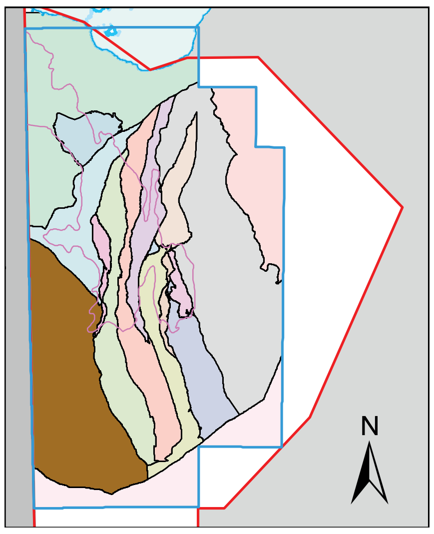
Major mining industry facilities in north-west and northern Queensland that service producers are as follows:

- **Mount Isa Copper and Lead Smelters**
  The MIM Holdings Ltd copper and lead smelters at Mount Isa smelt concentrates from the Mount Isa, Hilton, George Fisher and Ernest Henry mines to produce copper anode and crude lead containing silver.
- **Phosphate Hill High Analysis Fertiliser Plant**
  WMC Fertilizer Ltd's ammonium phosphate fertiliser plant at Phosphate Hill comprises a phosphoric acid facility, ammonia plant and granulation plant, based on the extensive phosphorite resources on site. Natural gas from the Ballara – Mount Isa gas pipeline is used for ammonia production, process drying and power generation. Sulphuric acid is generated by a plant at Mount Isa, based on scrubbing of smelter gases from the Mount Isa copper smelter; additional sulphuric acid is sourced from the Sun Metals zinc refinery in Townsville. The Phosphate Hill operation produces diammonium phosphate and monoammonium phosphate.
- **Townsville Copper Refinery**
  The MIM Holdings Ltd copper refinery at Townsville is one of the world's leading electrolytic refineries, producing 99.9% pure LME Grade A copper. It treats anode copper produced at Mount Isa, by means of the MIM-developed ISA PROCESS, which uses permanent stainless steel cathode plates in association with copper cathode-stripping machinery. The production capacity is 280 000tpa of Cu cathode.
- **Sun Metals Zinc Smelter**
  The Sun Metals Corporation (a subsidiary of Korea Zinc Company Ltd) Zinc Smelter at Stuart, 11km south of Townsville, is the first new, large-scale greenfields zinc refinery to be built world-wide for over a decade. The operation produced its first metal in November 1999, and is produces about 200 000tpa zinc metal (considerably above its nominal capacity of 170 000tpa) from ~400 000tpa of zinc concentrates sourced mainly from the north-west Queensland region. Some 360 000tpa of sulphuric acid by-product is transported mainly to the north-west Queensland region for use in fertiliser production and copper leaching plants.

Proterozoic Geological Domains

This is an overview of the Proterozoic geology of the NWQMEP. It presents a new subdivision of the province that reflects combinations of basin evolution, structural grain, metamorphic grade and geochronology and provides a more flexible method to describe variations in the geology between different parts of the belt. It largely replaces the existing Eastern Successions (Eastern Fold Belt), Western Succession (Western Fold Belt) and Kalkadoon–Leichhardt Belt nomenclature of Day & others (1983); Blake (1987) and Blake & Stewart (1992), although some elements of older subdivisions are retained. The Leichhardt Domain corresponds to the Leichhardt River Fault Trough (LRFT) of Glickson & others (1976). Other elements such as the Lawn Hill Platform and Myally Shelf (Plumb & Derrick, 1975) still have relevance in a depositional context. The domains are superimposed on the major depositional elements, the pre-Barramundi basement, Leichhardt Superbasin, Calvert Superbasin and Isa Superbasin of Southgate & others (2000) and Jackson & others (2000), and the South Nicholson Basin of Plumb & others (1980). The following text discusses the domains.

Ardmore – May Downs Domain



Extent / Distribution

- The Ardmore – May Downs Domain comprises the south-western part of the exposed Mount Isa Inlier, but the rocks are interpreted here to be the eastward continuations of the Arunta Province and Tennant Creek Provinces that lie to the west in the Northern Territory. The domain extends under cover to the south, where some poorly exposed basement rocks are known from the northern part of the Simpson Desert.

Principal geological components

- In the north the Yaringa Metamorphics are a pre-1850Ma package of metasediments which have been intruded by the Big Toby, Little Toby and Moonaghans Granites (Wyborn & others, 2001), which were intruded between ~1810–1795Ma. These granites may correlate with the Stafford Event in the Northern Territory where 1820–1790Ma granites intrude amphibolite grade metamorphics. They may also correlate with the Yeldham Granite in the Lawn Hill region, which has yielded a U-Pb TIMS age of ~1820Ma (Wyborn & others, 2001) and a TIMS xenotime age of ~1793Ma.

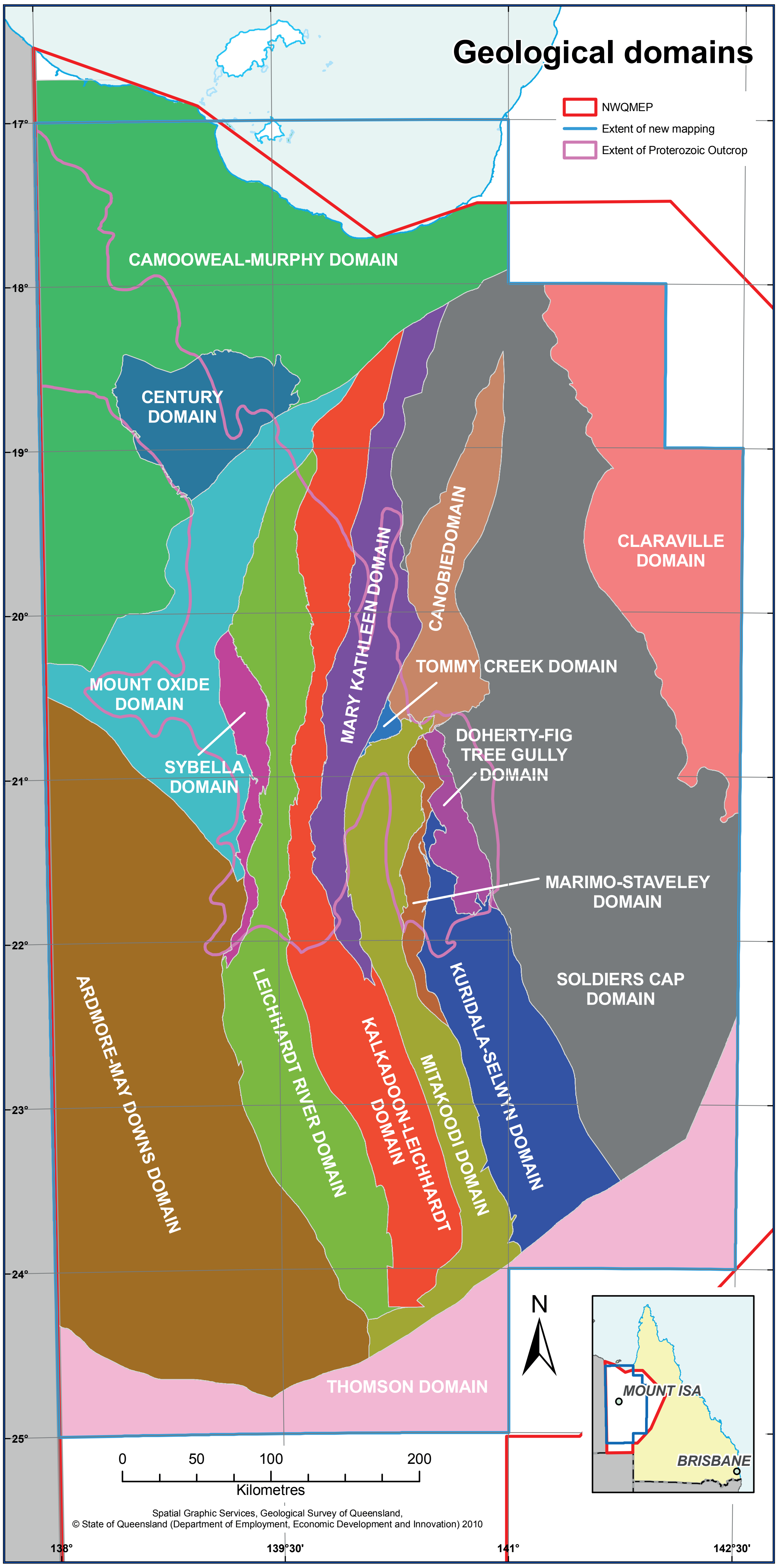


Figure 2.1: Geological domains in the main study area within the North-West Queensland Mineral and Energy Province

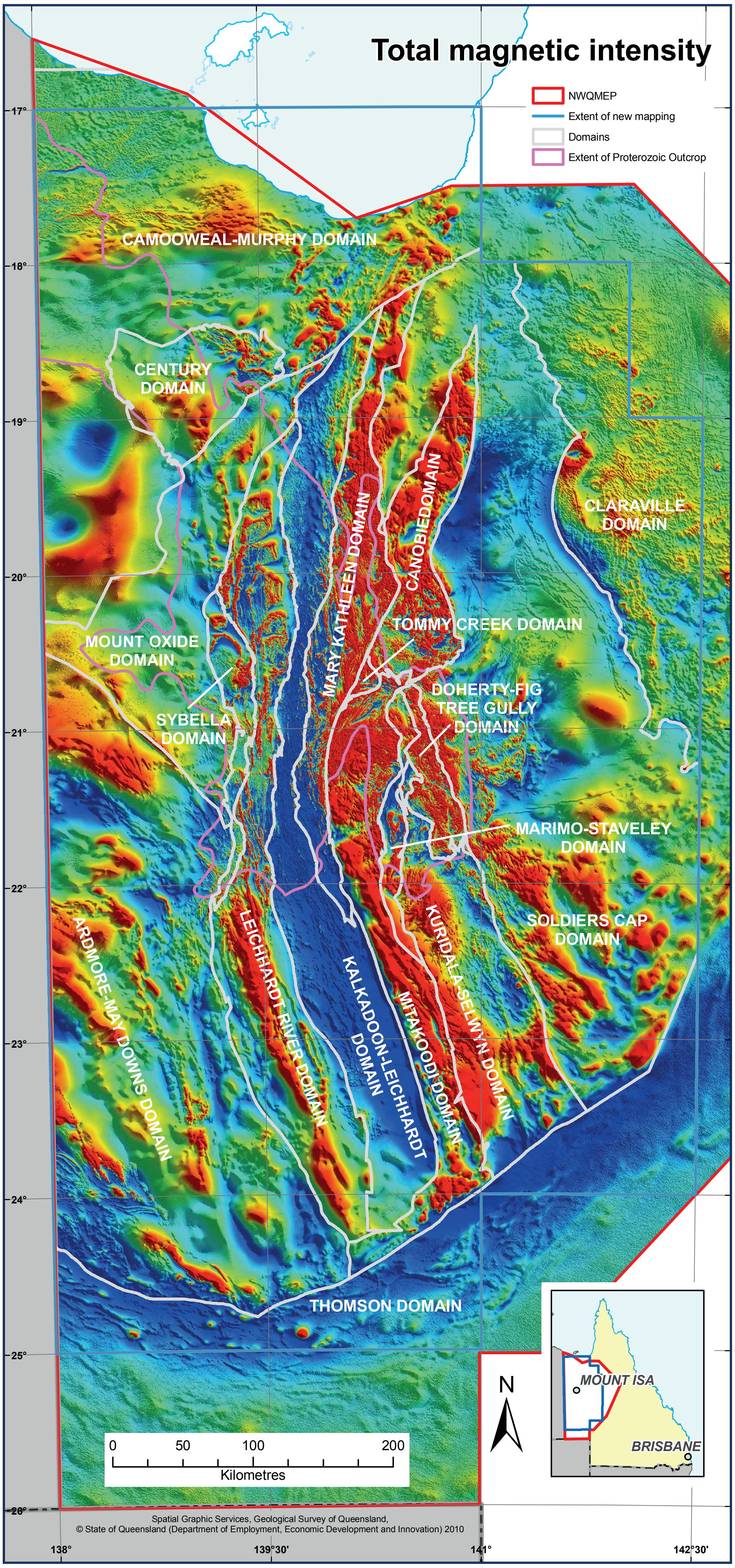


Figure 2.2: Geological domains superimposed on a total magnetic intensity image

- Farther south in the Ardmore area, rocks include the Saint Ronans Metamorphics, Bucket Hole Volcanics (Carson & others, 2008a), and the Oroopo Metabasalt. The Oroopo Metabasalt is intruded by the Yarrie Rock Waterhole Granite of unknown age.
- Small outliers of sedimentary rocks assigned to the Mount Isa Group unconformably overlie the Oroopo Metabasalt adjacent to the Rufus Fault, and at several other places along the fault.

Age

- The ages of rocks in the Ardmore and May Downs Belts are poorly constrained. All of the following ages are from west of the Rufus and May Downs Faults.
- Two gneissic rocks from the Yaringa Metamorphics west of the May Downs Fault have yielded TIMS ages of 1900±14Ma and 1885±10Ma (Page & Williams, 1988), which are interpreted as the age of amphibolite facies metamorphism associated with the Barramundi Orogeny. SHRIMP dating of granitoids intruding the Yaringa Metamorphics have given crystallisation ages of ~1858Ma (Bierlein & others, in press).
- A 'felsic' rock within the Oroopo Metabasalt has yielded a maximum depositional age of 1857±7Ma (Magee & others, in preparation).
- An intrusive rock within the Saint Ronans Metamorphics yielded an age of 1787±4Ma (Carson & others, 2008a).
- Mafic and felsic volcanics and meta-sedimentary rocks adjacent to the Saint Ronans Metamorphics, the Bucket Hole Volcanics, have yielded a maximum depositional age of 1823±8Ma, which is thought to approximate the age of the felsic volcanics (Carson & others, 2008a).
- The Moonaghans Granite, which has yielded a TIMS age of 1805±15Ma (Wyborn & others, 1988), intrudes the Yaringa Metamorphics.
- Samples from two isolated granites in the Simpson Desert have yielded ages of 1736±6Ma (outcrop at Merrica Bore) and 1769±6Ma (GSQ Mount Whelan No. 1 well). Both of these samples show disturbance of the isotopic system during the Alice Springs Orogeny (Carson & others, in preparation) and may have affinities with magmatic events in the Northern Territory.

Geophysical characteristics

- The linear magnetic and gravity anomalies within the central and southern parts of this domain predominantly trend north-north-west. In the north of the domain this trend swings around to the north-west, which is the predominant direction of the anomalies of the Tennant Creek – Davenport Provinces in the Northern Territory.
- In the north of this domain, the strongly magnetic linear anomalies and coincident moderate-to-strong linear gravity anomalies are interpreted to be associated with mafic units, such as post-Barramundi Bucket Hole Metavolcanics and Oroopo Metabasalt. In the central and southern parts of the domain, the linear highs are attributed to mafic units within the pre-Barramundi Basement. Many of these inferred mafic units appear to be folded.
- The more moderate magnetic anomalies covering larger areas in the north of the

domain are attributed to magnetic units within the pre-Barramundi basement.

- A large north-westerly trending gravity low in the central south of this domain corresponds with Arunta Block granitoids (interpreted from magnetic data) and a thick succession of overlying Cambrian/Ordovician sediments in the Toko Syncline (Georgina Basin).
- Other Arunta Block granitoids, inferred from the magnetic data, near the south-eastern boundary and in the north of this domain are not supported by corresponding gravity lows. Similarly, some of these granitoids inferred in the far north of this domain are associated with positive gravity anomalies. The source of the moderate to strong gravity anomalies here is unknown.

Structure / Deformation History

- Ages of metamorphism in the Yaringa Metamorphics suggest that granitoid emplacement and volcanism in the Kalkadoon Leichhardt Belt may postdate the peak of metamorphism during the Barramundi Orogeny by as much as 30 million years.
- The Mount Isa Group west of the Rufus Fault overlies the Oroopo Metabasalt with a strong angular unconformity, suggesting a major deformation between these two successions. Locally, a massive conglomerate wedge, unconformably overlain by the Mount Isa Group, may be equivalent to the Surprise Creek or Bigie Formations.
- Deep seismic reflection profiling shows a change in polarity in thrust faults across the region and into the Leichhardt River Fault Trough (Korsch & others, 2009). The Rufus Fault and other faults to the west dip westwards, whereas structures which define the western margin of the Leichhardt River Fault Trough dip to the east.

Inter/Intra province relationships

- Easterly magnetic trends within the Arunta Province and Tennant Creek Province in the Northern Territory, rotate to south-east adjacent to the Mount Isa Block in this domain. This suggests that a collision may have occurred between the two blocks, but its age is unclear. It must postdate the Oroopo Metabasalt because its magnetic response defines the trends. However, there is no increase in intensity of deformation associated with the Isan Orogeny adjacent to the contact suggesting any collision is unrelated and predated the main phase of that event.
- The Rufus Fault is taken as separating the Mount Isa Province from the Arunta Province and Tennant Creek Province in the west. This fault is a west dipping thrust fault based on deep seismic reflection profiling (Korsch & others, 2009). It appears to have been active during the Isan Orogeny but timing and nature of its original movement are unclear. Similarly, the age of juxtaposition of the Mount Isa Block and the rest of the North Australian Craton is unknown, but may be pre- ~1850Ma (P.G. Betts, Monash University, personal communication, 2010).

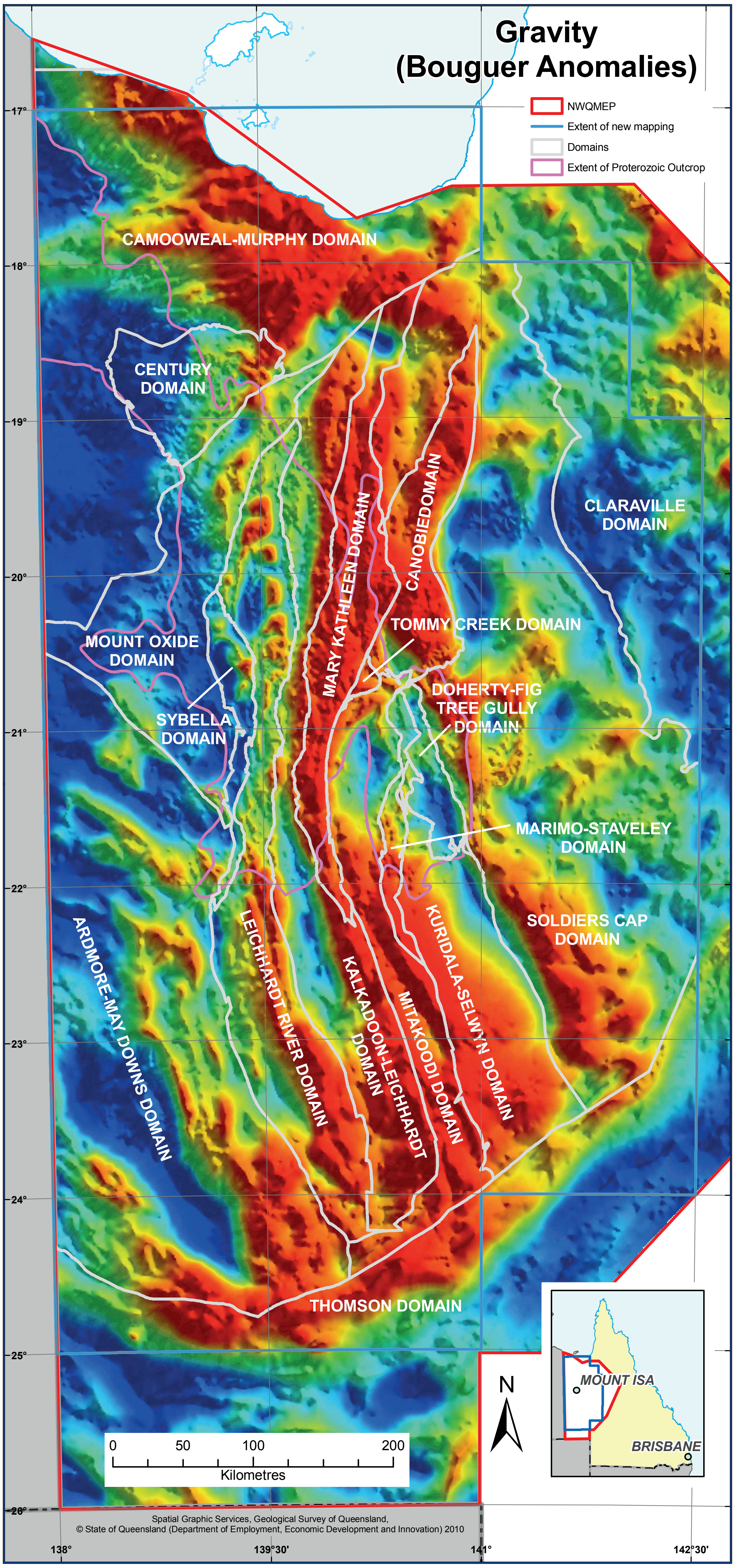
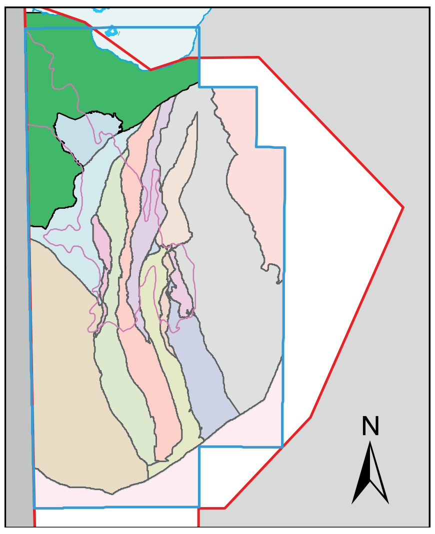


Figure 2.3: Geological domains superimposed on a gravity image

Camooweal / Murphy Domain



Extent / Distribution

- The Camooweal region forms a large area in the southern part of this domain consisting largely of Cambrian sedimentary rocks of the Georgina Basin, interpreted to be underlain by the South Nicholson Basin and rocks assigned to the Lawn Hill Platform. These rocks extend north to the Murphy Tectonic Ridge.
- The Murphy Tectonic Ridge forms the northern part of this domain and is an east–west trending feature forming basement to the Lawn Hill Platform (LHP) and Westmoreland Region succession to the south and north. The east–west trend of the basement is typical of trends in this region.
- The area to the north of the Murphy Tectonic Ridge is referred to as the Westmoreland Region.

Principal geological components

- The Murphy Tectonic Ridge is an east–west trending feature, consisting of pre-Barramundi metamorphic rocks (Murphy Metamorphics) overlain by the Cliffdale Volcanics and intruded by the Nicholson Granite, which are equivalent in age to the Leichhardt Volcanics and Kalkadoon Granite in the central part of the Mount Isa Block.
- Rocks assigned to the LHP occur to the south of the basement ridge. Correlations with rocks mapped in the Leichhardt River Domain to the south are difficult as few isotopic dates are available.
- Rocks of the South Nicholson Basin unconformably overlie the LHP succession.
- Rocks in the Westmoreland region are equated with similar successions on the LHP to the south, but there are significant differences in both thickness of units and rock types, suggesting different depositional environments.
- A new unit, the Augustus Igneous Complex, which is dated at ~1700Ma is now recognised from drilling in the eastern part of this domain. Altered granite which may have been originally marginally peralkaline, intrudes comagmatic fluorine-bearing rhyolite. The Augustus Igneous Complex forms basement to the Isa and Calvert Superbasin sequences in this area.

Age

- The age of units within the Murphy Tectonic Ridge such as the Murphy Metamorphics are uncertain, but the rocks are intruded by and therefore constrained by ages for the Nicholson Granite — 1856±3Ma and 1845±3Ma (Page & others, 2000; Neumann & Fraser, 2007). This granite is coeval with the Kalkadoon Granite farther south in the Kalkadoon–Leichhardt Domain.
- The overlying Westmoreland Conglomerate is correlated with the Wire Creek Sandstone on the LHP and the Mount Guide Quartzite (Guide Supersequence — Jackson & others, 2000) farther south. A maximum depositional age for the conglomerate is 1814±14Ma (Magee & others, in preparation). This is older than maximum depositional ages for the Mount Guide Quartzite from the LRFT of 1793±9Ma and 1773±16Ma (Neumann & others, 2006b).
- Ages of mafic units overlying the basal clastic units in both the Westmoreland region and LHP are poorly constrained. These are traditionally correlated with the Eastern Creek Volcanics in the LRFT (Neumann & Fraser, 2007) but there is no continuity of outcrop between the two areas and correlations are speculative.
- The Peters Creek Volcanics on the LHP are correlated with the Calvert Superbasin (Southgate & others, 2000). Ages are 1729±4Ma and 1724±2Ma (Page & Sweet, 1998; Page & others, 2000), significantly older than ages for the Fiery Creek Volcanics in the LRFT (1709±3Ma, Page & Sweet, 1998).
- Isotopically dated rocks from the Isa Superbasin sequence in the domain, occur within the upper part of the succession. These rocks only occur on the LHP and appear to correlate well across the region (Neumann & Fraser, 2007).
- The age of the South Nicholson Group is not certain. Ages of 1492±4Ma and 1493±4Ma (Jackson & others, 1999) have been obtained for the Mainoru Formation in the Northern Territory, which is correlated with the South Nicholson Group in Queensland. Detrital ages of 1591±10Ma (Page & others, 2000) and more recently 1577±29Ma (Hedleys Sandstone), 1600±21Ma (Burangoo Sandstone) and 1616±16Ma (Tidna Sandstone) (Magee & others, in preparation), all point to derivation from tuffaceous units in the LHP sequence. An age for the South Nicholson Group of ~1500–1400Ma is therefore considered likely.

Geophysical characteristics

- This large domain is characterised by generally low magnetic anomalies. Trends in both the aeromagnetic and gravity data in the northern half of the domain are east–west, reflecting the orientation of the Murphy Tectonic Ridge. This orientation lies at right angles to the general north–south trends in the magnetic and gravity data associated with the rest of the Mount Isa Block.
- Within the Murphy Tectonic Ridge high frequency, low magnitude magnetic anomalies dominate the data. The outcropping Nicholson Suite, by contrast, is seen as low quiet zones in the data and could be more extensive under cover.
- North of the Murphy Tectonic Ridge, a small outcrop of the Packsaddle microgranite is reflected by a very intense positive magnetic anomaly. To the north-east of this outcrop a large ring-dyke has been inferred from the magnetic data and is tentatively assigned to the Packsaddle microgranite.
- High frequency magnetic anomalies in the north-west of this domain are associated with the Cliffdale Volcanics of the Tawallah Group. There are numerous north-westerly, and some north-easterly, trending dykes evident in the magnetic data in this part of the domain.
- South of the Murphy Tectonic Ridge, the Peters Creek Volcanics can be traced in the aeromagnetic data as an area of generally higher frequency anomalies, with the strongest response associated with the Buddawaddah Basalt Member along the northern margin. These anomalies are cross-cut by multiple north-west trending linears. The Peters Creek Volcanics can be traced continuing from outcrop under cover to the east, but they cannot be traced with certainty to the south-east under the eastern part of the Lawn Hill Platform.
- South of the Peters Creek Volcanics, in the central region of this domain, two strong magnetic anomalies approximately 100km apart are connected by a weak ridge. The source of these anomalies is unknown.
- In the eastern part of this domain a zone containing strong positive, linear magnetic anomalies are inferred to be due to the magnetic felsic volcanics of the Argylla Formation. The trend of these is north-north-east, more like the rest of the Mount Isa Block, suggesting that this area could be assigned to another domain.
- In the far south-west of this domain, two large magnetic lows lie immediately west of a broad, linear magnetic high. The source of these anomalies is deep and unknown.
- There is no obvious correlation between the gravity data and the units within this domain. The large region of positive gravity anomalies in the north-east of the domain may be associated with the Murphy Tectonic Ridge. Most of the western half of this domain is characterised by low gravity response.

Structure / Deformation history

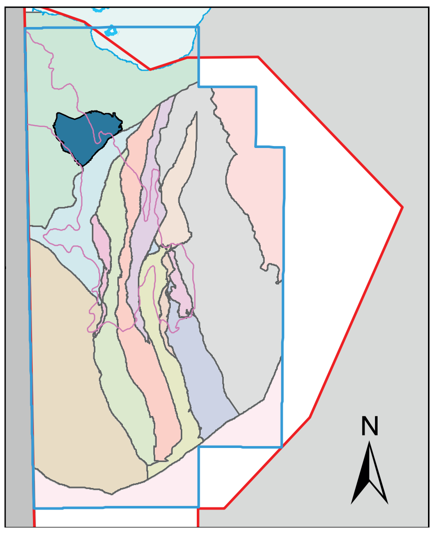
- Early formed extensional structures in the area east of the Murphy Tectonic Ridge are interpreted as being east–west oriented (pmd*CRC. I7 Team, 2008).
- A change in sedimentary style interpreted during Riversleigh Siltstone time can be seen in seismic profiles in the eastern LHP (McConachie & others, 1993). They interpret the change in sedimentary style from extensional to foreland basin across this boundary. The timing of this change in sedimentary style is coeval with a hairpin bend in the apparent polar wander path (Idnurm, 2000) and also with the collision of the Warumpi Terrain with the North Australia Craton (Scrimgeour & others, 2005).
- Three unconformity-bounded sequences, the Lawn Supersequence, Wide Supersequence and Doom Supersequence, are recognised within the Nathan Group in the Northern Territory (Jackson & Southgate, 2000). These low angle unconformities can be traced onto the LHP south of the Murphy Tectonic Ridge in Queensland (Krassay & others, 2000). Ages for the three supersequences are consistent across the LHP.
- The main compressive event here is north–south, at a high angle to the east–west compression in the Leichhardt River Domain. The cause of this discrepancy is unclear.

- East–west faults such as the Little Range Fault and Elizabeth Creek Fault, which are interpreted to have been active during the Isa Superbasin time, also show marked changes in the sedimentary sequence during South Nicholson time. It is not known if the changes relate to original depositional environments or subsequent deformations.

Inter/Intra province relationships

- The LHP is separated from the Leichhardt River Domain and Kalkadoon–Leichhardt Domain to the south-east across an extension of the Fiery Creek Fault which is interpreted as an early formed (Barramundi Orogeny) structure which has a fundamental control on post-Barramundi geology in the region.
- East–west trends in the Murphy Tectonic Ridge are continuous with trends in the Northern Territory to the west. The age of the north–south compressive event is not known, nor is its relationship to the better dated east–west compression further south in the Mount Isa Inlier.
- Current constraints place a time break of 30 million years between 1740Ma and 1710Ma in the Calvert Superbasin in the Mount Oxide Domain and Leichhardt River Domain. In contrast, there is abundant felsic magmatism (Peters Creek Volcanics) in this time range in this domain (Neumann & others, 2006b). Although they are 15 million years older than the felsic volcanics in the Fiery Creek Volcanics and clearly represent a separate event the Peters Creek Volcanics are included in the Calvert Superbasin (Jackson & others, 2000).

Century Domain



Extent / Distribution

- The Century Domain is defined as the region surrounding the Century mine. It encompasses part of the Lawn Hill Platform, but is distinguished from the equivalent rocks in the Camooweal/Murphy Domain to the north-west in having north-east trending structures (basins and domes) as distinct from easterly trends.
- This domain is separated from the Mount Oxide Domain to the south, by the Fiery Creek Fault Zone. The Mount Oxide Domain is dominated by north–south structures related to compression during the Isan Orogeny.
- Much of the region lies under cover and the geology is poorly known. The principal geological components are from the outcropping regions.

Principal geological components

- Basement is represented by the Kamarga Volcanics (pre ~1810Ma), which are intruded by the Yeldham Granite (1796±3Ma) (Wyborn & others, 1988).
- Where exposed, the Kamarga Volcanics are overlain directly by the Isa Superbasin sequence, indicating that the Calvert and Leichhardt Superbasin successions are not present.
- Elsewhere in this domain the Calvert and Leichhardt Superbasin successions, when present, are of variable thickness. Calvert Superbasin rocks (Peters Creek Volcanics) occur south of the Murphy Tectonic Ridge in the Camooweal Domain and extend to the east under cover. However, they appear to thin to the south, although other Calvert Superbasin rocks are known from the eastern part of the Century Domain.
- Mount Isa Superbasin rocks appear to be continuous across this domain. The Lawn Hill Formation, the youngest unit in the Isa Superbasin Sequence, which hosts world-class Zn-Pb mineralisation at the Century mine (Broadbent & others, 1998), is best developed within this region.
- The domain includes an interpreted Cambrian impact structure adjacent to Century mine (Salisbury & others, 2008). Similar features, which are under cover within the Camooweal region are also interpreted as impact structures (Salisbury & others, 2008).

Age

- The age of Kamarga Volcanics is not known precisely, but they are intruded by the Yeldham Granite which has an age of 1796±3Ma (Wyborn & others, 1988; Neumann & Fraser, 2007). This granite is similar in age to the Big Toby and Monaghans Granites west of Mount Isa (Wyborn & others, 1988) and the Stafford Event granites in the Northern Territory. Granites of this age are not known from the rest of the Mount Isa Inlier.
- Ages of the sedimentary succession on the Lawn Hill Platform are well constrained (Southgate & others, 2000). Ages from different parts of the Lawn Hill Platform both within and outside the Century Domain, indicate a sedimentary and igneous package of rocks ranging from 1694±3Ma for the lower Gunpowder Creek Formation in the Calvert Superbasin to 1595±6Ma for the Lawn Hill Formation at Century mine (Southgate & others, 2000; Broadbent & others, 1998).

Geophysical characteristics

- The bulk of this domain is characterised by background magnetic anomalies.
- The Yeldham Granite in the central part of this domain is reflected by distinct low amplitude, high frequency magnetic anomalies giving rise to a ‘mottled appearance’ in the data. The data indicate that the Yeldham Granite is a much more extensive batholith beneath the McNamara Group. In the east of this domain, strong magnetic highs appear to form rims to the Yeldham Granite and may represent a more mafic phase of the intrusion.
- The Fiery Creek Volcanics are represented by high frequency, moderate positive magnetic anomalies.
- Where the Kamarga Volcanics outcrop in the central portion of the domain, they are associated with high frequency, moderate positive magnetic anomalies giving rise to a ‘mottled appearance’ in the data, very similar, but higher in amplitude, to the Yeldham Granite. However Kamarga Volcanics, inferred under cover near the eastern boundary of this domain and in the central north, are reflected by weaker magnetic anomalies.
- Several very extensive (over 100km) dykes represented by narrow north-east trending features in the aeromagnetic data traverse this domain and continue at depth into the Camooweal–Murphy Domain. These dykes have not been deformed or faulted suggesting a young age.
- There are two distinct gravity zones within this domain — high to the east and low to the west — marked by a distinct north-north-east boundary. Most of the granitoids within this domain have associated gravity lows. Positive gravity anomalies in the north-eastern corner of this domain appear to be an extension of the ridge located further north-east.

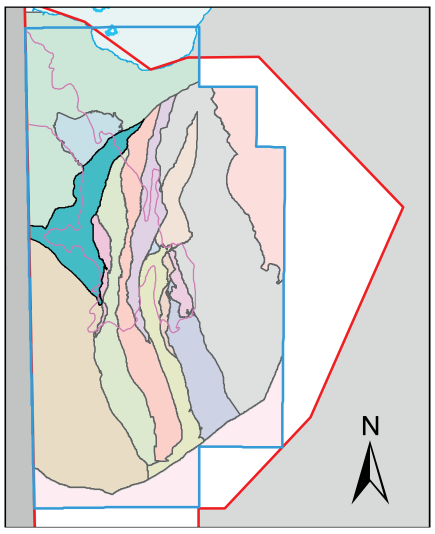
Structure / Deformation history

- The Fiery Creek Fault Zone has been defined from surface mapping, and has been extended by geophysical interpretation. The fault zone was interpreted in the first North-West Queensland Mineral Province Study (Queensland Department of Mines and Energy & others, 2000) as having been initiated during the ~1870–1850Ma Barramundi Orogeny. The structure truncates the Kalkadoon–Leichhardt Domain and delineates the southern boundary of the Century Domain.
- The Century Domain lies between the northern Lawn Hill Platform in the Camooweal–Murphy Domain that has east–west extensional and compressive structures, and the Leichhardt River Domain to the south that has north–south extensional and compressive structures. This change in orientation may be due to reorientation of stresses across the Fiery Creek Fault Zone, particularly during the Isan Orogeny. Basin- and dome-style folding in the northern part of the adjacent Mount Oxide Domain may reflect interaction of these two compressive regimes.
- In the western part of the domain, deep seismic reflection profiles show a large east-dipping normal fault, the Riversleigh Structure, which is overlain by sedimentary rocks of the South Nicholson and Georgina Basin (Hutton & others, 2009). There is significant growth across the Riversleigh Structure during both Mount Isa and Calvert Superbasin time.
- The north-north-west-trending Termite Range Fault is a major structural feature with surface expression in the Century Domain. The fault has been interpreted as a wrench fault (Hutton, 1973) and, in part, as an east-dipping normal fault. Deep seismic profiles show both an east-dipping thrust and possibly a steep westerly dipping fault near Century mine. This fault has been modelled as a conduit for fluids feeding the Century mineralisation (Zhang & others, 2010).

Inter/Intra province relationships

- As noted above, the Fiery Creek Fault Zone defines the boundary between Lawn Hill Platform rocks of the Century Domain with east–west compressive structures and the rocks with north–south compressive structures in the domains to the south. However, the reason for the change in structural trends across the fault zone remains enigmatic.
- Within the domain, rocks of the Lawn Hill Platform are overlain by rocks of both the Mesoproterozoic South Nicholson Group and the Cambrian rocks of the Georgina Basin.

Mount Oxide Domain



Extent / Distribution

- The Mount Oxide Domain is defined as lying south of the Fiery Creek Fault Zone, and west of the Mount Gordon Fault Zone. The south-western margin is the northern limit of prominent north-west-trending magnetic highs which can be traced into the Northern Territory.
- It includes the southern part of the Lawn Hill Platform (Hutton & Sweet, 1982).
- Much of the western part of the domain is covered by younger rocks, mostly Cambrian rocks of the Georgina Basin.

Principal geological components

- Basement to the Mount Oxide domain is unclear. A deep seismic profile indicates that mafic rocks of the Eastern Creek Volcanics underlie the McNamara Group in the eastern part. Tighter folding within the McNamara Group east of the Russell Creek Fault suggests that there may be a different (less compressible?) basement to the west.
- Mafic volcanics assigned to the Eastern Creek Volcanics crop out in the cores of the Fiery Creek Dome in the north-east of the domain. The Eastern Creek Volcanics are overlain by a thick succession of clastic sedimentary rocks assigned to the Myally Subgroup.
- The Quilalar Formation, an equivalent of the Ballara Quartzite and Corella Formation in the Mary Kathleen Domain (Derrick & others, 1980; Neumann & others, 2006a), is thickest around the Weberra Granite in the north-east of the domain. To the south and west, the overlying Surprise Creek Formation incises through thinner successions of the Quilalar Formation and directly overlies the Myally Subgroup.
- The Big Supersequence, comprising the Bigie Formation and Fiery Creek Volcanics, is best preserved in the Fiery Creek area of the Mount Oxide domain. Deposition is controlled by north-east-trending, north-west-dipping growth faults (Betts & others, 2000) In the Fiery Creek / Mellish park area, a 90° angular unconformity is mapped between the Quilalar Formation and Fiery Creek Volcanics. This unconformity is referred to as the 1740–1730Ma mid-basin inversion. It is interpreted as both a compressional event (Betts, 1999) and an extensional event (Gibson & others, 2008). The Fiery Creek Volcanics, particularly the mafic phase, are highly altered, in places comprising hematite and sanidine (Hutton & Wilson, 1984).
- The McNamara Group (Isa Superbasin) crops out over much of the southern and central parts of the domain. It is overlain by the South Nicholson Basin and Georgina Basin over most of the western parts of the domain.

Age

- The oldest dated rocks in the Mount Oxide domain are the Fiery Creek Volcanics (felsic phase) which are dated at 1709±3Ma (Page & Sweet, 1998). These rhyolites are coeval with the Weberra Granite (1711±3Ma; Neumann & others, 2009c). The Bigie Formation, a coarse clastic sequence underlying the Fiery Creek Volcanics has a maximum depositional age of ~1760Ma (Neumann & Fraser, 2007), which clearly is much older than the depositional age.
- The Surprise Creek Formation, which, together with the Fiery Creek Volcanics and Bigie Formation, makes up the Calvert Superbasin sequence in the domain, has ages of 1694±3Ma and 1688±5Ma (Page & others, 2000; Jackson & others, 2005).
- The Gunpowder Creek Formation has not been dated within the domain. However dates from adjacent terranes have yielded ages of 1658±3Ma and 1653±7Ma from peperites along Gunpowder Creek (Page & others, 2000; Neumann & Fraser, 2007).

Geophysical characteristics

- The majority of this domain is characterised by background magnetic response and a predominantly low gravity response. With the exception of the Big Toby Suite, there is very little correlation between the mapped units and the aeromagnetic data. The Big Toby Suite has a featureless, low aeromagnetic response.
- Small, positive anomalies in the north of the domain may reflect magnetic units within the lower Haslingden Group beneath cover.
- In the far north of this domain, positive gravity anomalies underlie the Myally Subgroup and may reflect mafic volcanics of the Eastern Creek Volcanics.

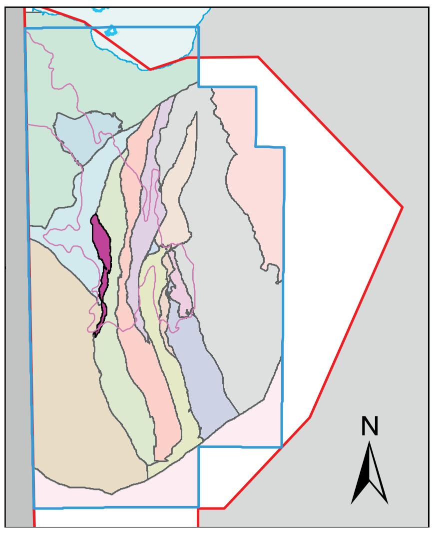
Structure / Deformation history

- Two regional unconformities are mapped in the domain. The main deformation (mid-basin inversion) occurs between the top of the Quilalar Formation and the Bigie Formation (1740–1720Ma). This is best displayed to the north of Fiery Creek where a right angle unconformity is mapped between the two sequences. Compressional direction of the mid-basin inversion is east–west from folding in the Mellish Park syncline (Betts, 1999).
- A second regional unconformity occurs between the Fiery Creek Volcanics and basal Surprise Creek Formation. This unconformity is less well exposed but the Surprise Creek Formation incises down through the Fiery Creek Volcanics into the underlying Quilalar Formation.
- Deposition during the period from 1690–1640Ma, which covers much of the Surprise Creek Formation and lower McNamara Group, is interpreted to have been controlled by east–west oriented normal faults (O'Dea & others, 1997b). Many of these structures have been inverted during north–south compression early in the Isan Orogeny.
- The Mount Gordon Fault Zone separates south-dipping normal faults in the Leichhardt River Domain from mainly north-dipping normal faults on the Lawn Hill Platform, suggesting the fault may have been a transfer fault accommodating a shift in half graben polarity between 1690–1640Ma.
- At about 1640Ma, a regional inversion is recorded within the Riversleigh Siltstone and is coeval with a hairpin bend in the Apparent Polar Wander Path recorded from rocks in the Mount Isa and McArthur Basins (Idnurm, 2000).
- The main east–west compressive phase of the Isan Orogeny is mapped throughout the Mount Oxide domain. Elevated strain, which resulted in the development of slaty cleavage and tight to isoclinal folds, is evident between the Lady Loretta Pb/Zn deposit and the Russell Creek Fault. It may reflect buttressing against a more stable basement craton to the west. Strain reduces markedly to the east away from this zone.
- In the east of the domain, tight folding (e.g. Boomerang Anticline) adjacent to the Mount Gordon Fault is interpreted as buttressing against thicker development of the Eastern Creek Volcanics in the Leichhardt River Fault Trough.
- Broad folding and doming, with localised thrusting, results from east–west compression during the middle Isan Orogeny.

Inter/Intra province relationships

- The northern boundary of the Mount Oxide domain is defined as the Fiery Creek Fault Zone.
- North of the Fiery Creek Fault Zone, the fold orientation changes to north-east and east–west. Within the Mount Oxide Domain, structural style changes from basins and domes in the north to north–south oriented fold axes in the south.
- The eastern boundary of the Mount Oxide Domain (and the Lawn Hill Platform) with the Leichhardt Domain is the Mount Gordon Fault Zone. Relationships across the Mount Gordon Fault Zone reflect a change in basement. Changes in the polarity of half grabens across the fault, as well as dramatic thinning of units suggest that the Mount Gordon Fault Zone was active during sedimentation in Isa Superbasin time (McNamara and Mount Isa Groups).

Sybella Domain



Extent / Distribution

- The Sybella Domain forms a northerly-trending linear belt west of Mount Isa and is up to 20km wide and ~180km long.
- It occurs along the western edge of the Leichhardt River Fault Trough, a north–south trending 1790Ma – 1750Ma extensional feature.
- To the north, the rocks plunge under the Isa Superbasin succession and their northern continuation is unknown.
- In the south, the domain is covered by younger sedimentary rocks and its southern continuation is also unknown.

Principal geological components

- The domain is mainly defined by the distribution of the Sybella Batholith, which crops out over ~1600km^2 and was subdivided into 12 different plutons by Wyborn & others (2001).
- The geochemistry of the Sybella Batholith was summarised by Wyborn & others (2001), who described the granites as fractionated I types, with the variation due to fractional crystallisation from a dominantly liquid magma. Intercalated with the granite are diorite and gabbro bodies suggesting the magmatism was bimodal (Gibson & others, 2008).
- Country rocks comprise calc-silicates (well-bedded, metasediments?), amphibolite (fine grained, metamorphosed mafic rocks?), and quartzite. This sequence was previously mapped as Eastern Creek Volcanics but is lithologically different to the main belt of this unit in the Leichhardt River Fault Trough and has been renamed Alpha Centauri Metamorphics in this report. Aeromagnetic images show the granite contacts parallel the stratigraphy. Metasedimentary xenoliths of country rocks are common in some phases of the granite. A complex fault zone separates the intrusive complex and the amphibolite facies country rocks (Alpha Centauri Metamorphics) from greenschist facies rocks of the Leichhardt Superbasin (Gibson & others, 2008).
- The granite is interpreted to have been intruded into an active extension zone (Gordon, 2004; Gibson & others, 2008), and emplaced into a dilational jog in a sub-horizontal shear zone as sill-like bodies. This interpretation is supported by granite contacts which are parallel to stratigraphy.
- As well as these deeply intruded sills, the Sybella Batholith includes microgranite of different geochemistry (Wyborn & others, 1988), and emplaced at a higher crustal level (Gordon, 2004). Beryl-bearing pegmatites within the batholith are linked to peak Isan metamorphism at about 1570–1580Ma (Rubenach & others, 2008).

Age

- The age of the Sybella Batholith is tightly constrained between 1675–1670Ma. The Carters Bore Rhyolite is also considered part of the event at 1678Ma (Neumann & Fraser, 2007). The tight age grouping of the granites also supports the model of their intrusion during an active extension event.
- ϵ_{Nd} values for the Sybella Granite are +1.8 (Wyborn & others, 1988). This value is more primitive than values from granites in the Western Fold Belt at Mount Isa and suggests little crustal input into the granites derivation.

Geophysical characteristics

- The Sybella Domain is characterised by complex magnetic anomalies but generally low gravity responses associated with the lower density rocks of the Sybella Batholith. The latter generally have low, featureless aeromagnetic responses. Some of these intrusions, although relatively low in magnetic response, exhibit a distinct north-westerly trending linear 'fabric'. Examples are the Keithy, Widgeewarra, Hay Mill, Kitty Plain and Steeles plutons. The Widgeewarra, Queen Elizabeth plutons and southern half of the Khako Granite are characterised by a featureless low magnetic region. Stronger magnetic rims observed around parts of these intrusions are attributed to the fact that the granite contacts parallel the magnetic volcanic stratigraphy in these areas, rather than a contact metamorphic effect.
- By contrast, the Alpha Centauri Metamorphics have a high magnetic response, which is mostly parallel to the granite contacts suggesting the latter are sills intruded parallel to the stratigraphy. These magnetic highs at the contacts between the granites and the metamorphics have corresponding increases in gravity response, particularly the strongly magnetic 'arc-shaped' feature along the northern margin of the Keithy Granite.
- The Easter Egg Diorite is represented by a coincident, strong positive magnetic and gravity anomaly. A small, circular coincident magnetic and gravity high to the north of the Keithy Granite may represent a small diorite intrusion similar to the Easter Egg Diorite.

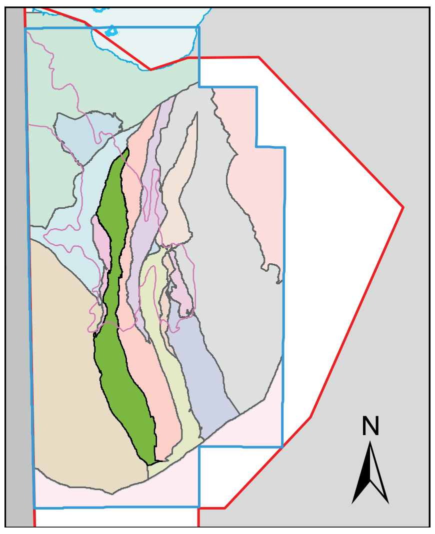
Structure / Deformation History

- The Sybella Batholith was 'syntectonically emplaced' during a 'basin forming' (extensional) event. The main phase of the granite was emplaced as sills at about 15km below the basal Mount Isa unconformity (Gordon, 2004).
- Metamorphism/metasomatism of the Alpha Centauri Metamorphics occurred during intrusion of the granite (Rubenach & others, 2008). Two metamorphic events are recognised by Rubenach & others (2008), an earlier cordierite – K-feldspar assemblage (which records temperatures of ~650–700° at 15km depth) and a younger migmatitic sillimanite – biotite- K-feldspar assemblage. These two events are synchronous with intrusion of the granite at 1670–1675Ma.
- The granite sills which were later structurally emplaced into higher crustal levels during the main east–west compressive phase of the Isan Orogeny (Gordon, 2004).

Inter/Intra province relationships

- The Sybella Domain lies parallel to the western margin of the Leichhardt River Domain.
- The domain also lies along the contact between the Mount Isa Block and other North Australian Craton rocks to the west which are here considered to be extensions to the Arunta and Tennant Creek Provinces which lie mostly in the Northern Territory.
- Highly deformed zones within the Sybella Domain may have resulted from the buttressing of Mount Isa Terrain to the east and the North Australian Craton to the west.

Leichhardt River Domain



Extent / Distribution

- The Leichhardt River Domain is a narrow meridional belt, gently concave to the east.
- In the north, the belt terminates on a NE-SW magnetic lineament (a continuation of the Fiery Creek Fault) about 45km north of the limit of outcrop.
- Based on geophysical interpretation, the belt extends under cover from 22°S for about 250km south to the Cork Fault.
- East of the belt is the Kalkadoon–Leichhardt Domain. The boundary is generally represented by a fold zone incorporating sequences from the Myally Subgroup through to the Moondarra Siltstone of the Mount Isa Group. South of the Rifle Creek Antiform, the eastern boundary is represented by the contact between the Bottletree Formation and the Kalkadoon Granite.
- In the north, the western boundary is the western margin of the Mount Gordon Arch/Fault Zone which contains sequences from Fiery Creek Volcanics through to the Gunpowder Creek Formation.
- Farther south, extending north and south of Mount Isa, the western boundary is the Judenan fold belt, west of the Paroo-Basement Fault.
- South of 21°50' the western margin is the Rufus Fault and it changes trend to become NNW-SSE towards the Cork Fault.

Principal geological components

- The Leichhardt Superbasin, Calvert Superbasin and Isa Superbasin, which are

separated by angular unconformities, lie within this domain.
- Throughout the northern half of its length, the domain is characterised by a series of fault blocks dominated by mafic volcanics of the Eastern Creek Volcanics.
- Although the Leichhardt/Calvert Superbasin boundary is at the base of the Bigie Formation, the main angular unconformity in the north in the Myally area is at the base of the Fiery Creek Volcanics. The direction of extension changed from ENE-WSW to NE-SW leading to a rejuvenation of rifting, bimodal volcanism and associated granite intrusion and the development of the new Calvert Superbasin.
- In the fault block north of the Paroo Range, the unconformity at the base of the Bigie Formation truncates an anticline-syncline pair showing that there is a period of aborted inversion prior to the unconformity.
- Similarly at the base of the Prize Supersequence there is locally a high angle unconformity again indicating a period of shortening. This unconformity locally truncates that at the base of the Calvert Superbasin.
- In the Paroo Range a series of smaller unconformities have been mapped above the Prize unconformity.
- The Mount Gordon Arch is better regarded as a series of basin and dome folds which are cut downwards by the unconformities (Derrick,1982). The Bonus 'Basin' represents the maximum erosion with about 8km of Calvert and Leichhardt Superbasin removed.
- Modern day analogues for the Leichhardt Superbasin include the North American Rio Grande and East African rift systems.

Age

- The oldest unit is the Bottletree Formation which occurs in a strip south of the Rifle Creek antiform. Ages range from 1808±19Ma to 1790±9Ma.
- Two ages for the Mount Guide Quartzite which is the lowest unit of the Leichhardt Superbasin are 1773±16Ma and 1793±9Ma. These are interpreted to represent maximum depositional ages (Neumann & others, 2006b; Neumann & Fraser, 2007).
- Indirect dating of the Eastern Creek Volcanics is provided by an age of the Lena Quartzite Member which separates the Cromwell Metabasalt Member from the Pickwick Metabasalt Member. This quartzite yielded a maximum depositional age of 1779±4Ma (Neumann & others, 2006b; Neumann & Fraser, 2007).
- The overlying Bortala Formation within the Myally Subgroup provided an age of 1773Ma (Neumann & others, 2006b; Neumann & Fraser, 2007).
- Above the Calvert Superbasin unconformity, the Fiery Creek Volcanics yield an age of 1709±3Ma (Page & Sweet, 1998).
- By ~1670Ma, the geodynamic setting changed from rifting to passive margin with development of a north-east-facing ramp.
- Detrital zircons have been used to characterise the Gun Unconformity at four locations in the Leichhardt River Domain (Page & others, 2000; Neumann & Fraser, 2007). Detrital zircons in sedimentary units overlying the Gun Unconformity provide maximum depositional ages of 1674±6Ma and 1672±15Ma consistent with age constraints of ~1660Ma provided by tuffs for deposition of the basal Gun Supersequence highstand.

Geophysical characteristics

- The aeromagnetic response in the belt highlights the distribution of the Eastern Creek Volcanics and their subsurface profile, showing the subdivision of eight fault blocks north of Mount Isa. They are characterised by weak to moderate gravity anomalies.
- In the central part of this domain low magnetic anomalies are predominantly associated with the Mount Guide Quartz and various sedimentary units. Moderate magnetic anomalies reflect the Yappo Member.
- Inversion modelling shows the sequence-repeating faults to dip steeply to the south. These faults have been previously interpreted as shallow dipping 'spoon faults' (Dunnet, 1976) or as thrust faults within a duplex (Bell, 1983).
- 3D map input has come from three sources of data: 1) sedimentary basin analysis and sequence stratigraphy; 2) structural analysis allied with potential field modelling; and 3) PIMA-calibrated and ground-truthed remotely sensed imagery. The ultimate aim was an assessment of basin architecture and fault geometries and how these may have served to focus fluid flow at the time of regional alteration and mineralisation.
- Inversion modelling of the aeromagnetic data has provided a constraint on depth to magnetic basement, highlighting a distinct division between the Mount Isa Western Succession and its eastern counterpart (Hensen, 2005).
- The south-western part of the Leichhardt River Domain is characterised by the strong gravity ridge that characterises much of the eastern part of the Mount Isa Block. An extensive gravity low in the south-western part of this domain may indicate the presence of a batholith at depth.

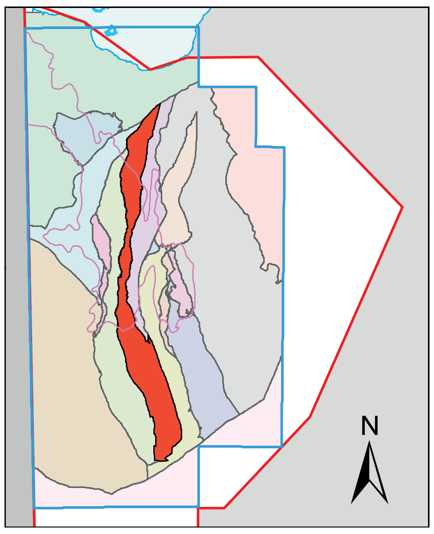
Structure/Deformation history

- Cross faults that partition the belt into blocks, such as the Conglomerate Creek Fault and the Crystal Creek Fault, are folded about N–S axial planes along with the synclines to the south of them. It is possible that the folds had more meridional axial planes initially, but they were reoriented with fault initiation.
- The folds appear to be ramp synclines developed in association with the faults. It has been proposed that the early extensional fault geometry played a significant role in controlling the structural patterns developed during later shortening. Through the integration of detailed surface mapping and forward magnetic modelling, an inverted half-graben was identified beneath the Crystal Creek block, exposing the underlying origin of local structural complexities (O'Dea & Lister, 1995).
- These faults are generally thought to separate the Leichhardt Domain into a series of half-grabens during deposition of the Leichhardt and younger Supersequences, but evidence for this is scant, and is generally applicable to the Paroo Range south of the Conglomerate Creek Fault.
- Two of the cross faults which formed in the Leichhardt Domain show evidence of being active during deposition of the Moondarra Siltstone. These are the Moondarra Fault and the fault along the southern margin of the Bonus 'Basin'. Both show development of wedge-shaped talus conglomerates fanning into the basal Mount Isa Group.
- In addition the existence of a fan conglomerate in the Hero Formation adjacent to the Hero Fault, a time equivalent of Moondarra Siltstone, also records evidence of growth faulting at this time.
- The Mount Gordon Fold/fault zone contains both strike-slip and thrust geometries facilitated by dextral strike-slip faulting. Rotation and associated accommodation problems would therefore produce significant dilation and fracture induced porosity regionally during this event (Hensen, 2005).
- There is a reasonably consistent change in orientation of the axial traces of meridional (mid-Isan) folds from NNW in the south to NNE in the north.

Inter/Intra province relationships

- Compared with the domains to the east and west the Leichhardt River Domain is noteworthy for the division of its northern part into major distinctive north-block-up faults.
- The Leichhardt River Domain is the locus of the thickest development of the Eastern creek Volcanics, with only thinner sequences outside the trough.
- Many of these faults have been regarded as growth faults. Faults such as the Investigator Fault have a thinned sequence on the northern side, but there is no talus conglomerate. The thinned sequence to the north could as well be explained by a sequenced-parallel fault which omits sequence.
- The boundary with the Mount Oxide Domain is marked by a change from tight, north-trending D_2 folds into more open basin and dome structures.
- At the southern end of exposure, the Leichhardt River Domain forms a triangular zone between two basement blocks. The Leichhardt Superbasin forms a series of half grabens with later contractional inversion (a hanging wall anticline cored by Mount Guide Quartzite).
- The Rufus Fault Zone is the western fault in an east-directed thrust system (basement at progressively higher structural level to the west).

Kalkadoon – Leichhardt Domain



Extent/Distribution

- The domain occurs as a long gently arcuate belt, concave to the east, which extends for the full length of the outcropping inlier and covers at least 5000km^2. It is interpreted to continue southwards under Cambrian and Mesozoic cover for approximately 250km almost to the Cork Fault. To the north it appears to project under Cainozoic cover for at least 80km.
- The width of the domain ranges from 30km north of the Mount Remarkable Fault to 65km in the south under Cambrian cover.

Principal geological components

- Kalkadoon Suite granitoids (Kalkadoon Granite, Ewen Granite, One Tree Granite and Wills Creek Granite) and Leichhardt Volcanics form the bulk of the block, with the Kurbayia Metamorphic Complex being a significant component in the southern half of the belt. The Ewen Granite is spatially separated from the Kalkadoon Granite by 10km in the northern part of the domain.
- The Kalkadoon Granite consists of grey biotite (±-rare hornblende) granodiorite and tonalite, pink biotite granite, commonly foliated, porphyritic and xenolithic; minor leucogranite, muscovite granite, microgranite, porphyritic granophyre, porphyritic biotite-muscovite granite, monzonite, diorite and aplite. Undeformed pegmatite, porphyritic hornblende-bearing syenogranite and megacrystic homogenous to rapakivi-textured diorite-granite phases have been identified (Bierlein & others, in press).
- The Leichhardt Volcanics are characteristically grey quartz-feldspar porphyry.
- The Kurbayia Metamorphic Complex consists of dioritic to granitic gneiss (commonly containing many mafic meta-sedimentary inclusions), migmatitic porphyroclastic granitic gneiss, finely porphyritic felsic gneiss and minor pelitic schist.
- The metamorphic rocks are intruded by Kalkadoon Suite granitoids either transgressively or in a transitional *lit-par-lit* fashion, and as such represent the oldest basement protolith remnants within the exposed Mount Isa Inlier.
- The granites and porphyries are intersected by a network of dolerite and gabbroic dykes which trend NW and NNE.
- A feature of the block which has not been alluded to in previous work is the high proportion of metabasalt enclaves and xenoliths. In places these constitute about 15% of the rock volume and in places appear to be transitional into continuous outcrop of Eastern Creek Volcanics or Magna Lynn Metabasalt. If this relationship is correct and given that the apparent constrained age of the Eastern Creek Volcanics is 1790Ma to 1770Ma it suggests the existence of younger granites within the Kalkadoon–Leichhardt Domain.
- An unknown volume of the younger Argylla Formation (~1780Ma) occurs within the domain. The rocks are difficult to distinguish from the Leichhardt Volcanics in the field, but felsic rocks with higher magnetic susceptibility and characteristic higher radiometrics have been assigned to the Argylla Formation.

Age

- Ages of the Kalkadoon Granite range from 1856Ma to 1862Ma (Wyborn & Page, 1983; Magee & others, in preparation).
- The age of the Ewen Granite from Wyborn & Page (1983) is 1840±20Ma, but a more recent age is 1859±3.3Ma (Magee & others, in preparation) from close to the eastern serrated and irregular boundary with Eastern Creek Volcanics.
- For the Leichhardt Metamorphics Wyborn & Page (1983) reported an age of 1852±7Ma, and an age from the recent mapping programme is 1864±3Ma (Magee & others, in preparation).
- A site from within the Kalkadoon Granite in the Prospector Sheet area gave an age of 1775±6Ma (Bierlein & others, in press), indicating that the dated rock is related to the Argylla Formation.

Geophysical characteristics

- A broad magnetic low characterises the block with the exception of local high areas which have been interpreted as Argylla Formation.
- The block is not so well defined on gravity images. They show low to intermediate Bouguer anomalies, particularly south of the limit of outcrop.

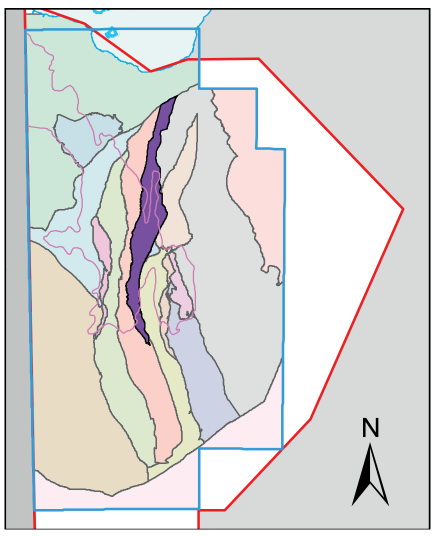
Structure/Deformation History

- The rocks of the domain are variably deformed. They range from weakly deformed granitoids and volcanic rocks through to strongly foliated gneiss and amphibolite.
- The basement units of the Kurbayia Metamorphic Complex and, more rarely, parts of the interfingering Kalkadoon Suite granitoids have a strongly developed gneissic to migmatitic schistosity. This metamorphic layering is attributed to metamorphism and deformation during the 1870–1850Ma Barramundi Orogeny. Re-use and re-orientation of even older fabrics may have taken place during this orogeny, with the meta-sedimentary and some gneissic components of the complex representing pre-1870Ma country rocks intruded by the Kalkadoon Batholith (McDonald & others, 1997).
- The early Barramundi fabrics are moderately to tightly folded about subvertical NE-NNE trending axial planes locally defined by melt veining or new mineral growth. This later trend is best developed in the basement rocks south of the Mount Remarkable Fault where it is defined by NNE-NE trending mafic dykes. In some areas this trend is overprinted by a more north–south trending foliation. These later structures are attributed to the Isan orogeny.
- A dolerite dyke cutting the Leichhardt Metamorphics on the Lake Mary Kathleen spillway returned an age of 763±85Ma. This has been overprinted by a north–south foliation which is superficially similar that related to the Isan Orogeny but must be much younger.

Inter/Intra Province relationships

- Some field evidence suggests that the same rocks mapped as Leichhardt Volcanics are intrusive into the Magna Lynn Metabasalt. This is particularly the case in the Duchess area where a lobe of porphyry interdigitates with a belt of metabasalt to the north.
- Some granite contacts appear to be intrusive rather than unconformable. For the Kalkadoon Granite this is particularly the case south of Lake Julius where it is in contact with the Quilalar Formation. At Black Mountain, the Quilalar and Surprise Creek Formations occur in an inlier which is interpreted as a fault-bounded block (Williams & Blake, 1992). Evidence of granitic alteration of sandstones along the contact suggests that the boundaries may be intrusive.
- The eastern margin of the Ewen Block shows a serrated contact with Eastern Creek Volcanics and Myally Subgroup. This appears to be an intrusive contact rather than an unconformity in spite of the isotopic age data.
- It may be rationalised that there are two distinct ages of the Kalkadoon Granite and Ewen Granite. One may represent an 1850–1860Ma basement phase and there may be granites which are younger than the Surprise Creek Formation. However, isotopic dating has yet to confirm the presence of a younger component.
- The Mary Kathleen Domain lies to the east, the boundary being somewhat arbitrary, but positioned to exclude the main belt of Leichhardt Volcanics and Kalkadoon Granite.

Mary Kathleen Domain



Extent / Distribution

- The Mary Kathleen Domain is an elongate belt about 180km long and about 20km wide along the eastern side of the Kalkadoon Leichhardt Domain. It broadly corresponds to the Mary Kathleen Belt in the North-West Queensland Mineral Province Report (Queensland Department of Mines and Energy & others, 2000).

Principal geological components

- The Mary Kathleen Domain can be divided into two sub-domains by the north-trending Rose Bee Fault. Some interpretations suggest that this fault could be a continuation of the Pilgrim fault, offset by dextral movement on the Fountain Range Fault.
- Basement to the western part of the Mary Kathleen Domain comprises the Leichhardt Volcanics, Kalkadoon Granite, and Argylla Formation.
- In the eastern sub-domain, the oldest rocks are the Boomarra Metamorphics, which consist of a lower unit of felsic granofels that gives ages similar to the Argylla Formation, and an upper unit consisting predominantly of quartzite.
- The Ballara Quartzite unconformably overlies the Argylla Formation in the western sub-domain. It is usually relatively thin (<200m) but south-east of Dobbyn, the recent GSQ mapping shows that it thickens to >1500m. The upper quartzite unit in the Boomarra Metamorphics may be equivalent to this thickened Ballara Quartzite.
- The Ballara Quartzite is overlain by a widespread mixed carbonate-siliciclastic succession (Corella Formation) that has been metamorphosed and altered to calc-silicate rocks, particularly during the Isan Orogeny. The Corella Formation is also mapped overlying the Boomarra Metamorphics in the eastern sub-domain.
- The Ballara Quartzite and Corella Formation are interpreted as correlatives of the Quilalar Formation in the Leichhardt River Domain (Derrick & others, 1980).
- The Corella Formation, Ballara Quartzite and the underlying Argylla Formation are intruded by a series of plutons in a north–south belt named the Wonga Suite (Wyborn & others, 1988). The Wonga Suite has been interpreted as being intruded into an active extensional detachment (Pearson & others, 1992).
- A second suite of bimodal intrusives, the Burstall Suite, is interpreted as being time equivalent to the highly deformed Wonga Suite, but intruded into the upper plate.
- The Deighton Quartzite, White Blow Formation and Knapdale Quartzite unconformably overlie the Corella Formation and have been assigned to the Mount Albert Group.
- This group, as defined, also includes the Coocerina Formation and Lady Clayre Dolomite, which overlie the Knapdale Quartzite. Recent work by GSQ has also shown that a belt of rocks, formerly mapped as Corella Formation, and which includes the host rocks of the Dugald River deposit, is a time equivalent of the Coocerina Formation and Lady Clayre Dolomite, and has been assigned to the Mount Roseby Schist.
- Scattered outcrops of quartzite along the valley of the Leichhardt River north of Kajabbi may be equivalents of the Mount Albert Group.

Age

- The Argylla Formation in the Mary Kathleen Domain has yielded ages of 1777±3Ma, 1778±3Ma, 1782±3Ma, and 1779±3Ma (Neumann & others, 2009a).
- The felsic granofels in the lower part of the Boomarra Metamorphics has yielded SHRIMP ages similar to those in the Argylla Formation — 1774±4Ma and 1775±4Ma (Geoscience Australia: OZCHRON database) and 1776±8Ma (Carson & others, 2008a).
- A tuff in the Ballara Quartzite has been dated at 1755±3Ma (Page, 1988). The maximum depositional age of the Ballara Quartzite is 1767±4Ma (Neumann & others, 2009a). A rhyolitic ignimbrite in the middle of the thickened succession in the Dobbyn area has been dated at 1772±5Ma (Magee & others, in preparation).
- Maximum depositional ages for the Corella Formation are 1770±6Ma and 1776±3Ma (Neumann & others, 2009a). The upper limit for the Corella Formation is constrained by the ages for the Wonga Suite and Burstall Suite (see below).
- Ages for the Wonga Suite have previously been recorded between 1758±8Ma and 1729±13Ma (Pearson & others, 1992). Recent dating suggests two ages of 1778±3Ma (for a granite intruding the Argylla Formation and broadly coeval with it) and an age of 1738±3Ma (maximum depositional ages for the Corella Formation are 1770±6Ma and 1776±3Ma) (Neumann & others, 2009a). This implies that rocks mapped as the Wonga Suite fall into two ages, the younger of which is interpreted as the age of that part of the suite intruding the Corella Formation.
- Ages from the Burstall Suite are 1740±3Ma, 1737±3Ma and 1739±3Ma for the Lunch Creek Gabbro making them coeval with the younger age (1738Ma) for the Wonga Suite.
- The Wonga extension (Pearson & others, 1992) occurred during intrusion of the younger phase of the Wonga Suite (lower plate) and the Burstal Suite (upper plate) and therefore occurred at ~1740Ma.
- The Knapdale Quartzite has a maximum depositional age of 1728±5Ma (Carson & others, 2008a) and is equated with the Prize Supersequence in the Calvert Superbasin (Jackson & others, 2000; Domagala & others, 2000).
- The Deighton Quartzite has been subdivided into five subunits (Wilson & others, 1977). Recent mapping indicates that the Deighton Quartzite is underlain by basalt which is equated with the Fiery Creek Volcanics (Neumann & others, 2009a; Neumann & Fraser, 2007). Although Neumann & others (2009a) suggested that the lower part of the Deighton Quartzite correlates with the Prize Supersequence, the maximum depositional ages of 1748±4Ma and 1751±4Ma for subunits 1 and 3 are not definitive. The upper part of the Deighton Quartzite (subunit 5) has a maximum depositional age of 1715±11Ma determined by Neumann & others (2009a), who equated it with the Isa Superbasin Gun Supersequence.
- The Dugald River Shale (part of the Mount Roseby Schist) has a maximum depositional age of 1686±7Ma (Carson & others, 2008a). This is similar to parts of the Mount Isa Group (Gun Supersequence). The Lady Clayre Dolomite similarly has a maximum depositional age of 1691±9Ma and may also equate with the Mount Isa Group (Gun Supersequence) (Carson & others, in preparation).
- The age of metamorphism in the domain is constrained by ages of ~1570Ma (Hand & Rubatto, 2002), which are inferred to date the peak of metamorphism. A monazite age of 1581±5Ma has been reported as dating the peak of metamorphism in the Rosebud syncline (Rubenach & others, 2008).

Geophysical characteristics

- Strong positive gravity anomalies, which characterise much of the eastern part of the Mount Isa Block, occupy the whole domain with the exception of a large gravity low in the far north, which has a coincident region of low featureless aeromagnetic response. These anomalies have been tentatively attributed to a granitoid of the William Supersuite, in spite of the low magnetic response.
- The central and northern parts of this domain are represented by very strong magnetic anomalies associated with calc-silicates of the Corella Formation.
- Some linear belts with a generally low flat aeromagnetic response within these stronger magnetic anomalies are mapped as Mount Albert Group.
- The Landsborough Graben in the central part of the domain is characterised by an elongate gravity low and by a featureless magnetic response over a section of strong magnetic anomalies associated with the Corella Formation. These responses are interpreted to reflect a thick accumulation of Cambrian and Mesozoic sedimentary rocks in the graben.
- The Wonga Suite in the south is non-magnetic and has lower gravity than the adjacent Corella Formation.

Structure / Deformation history

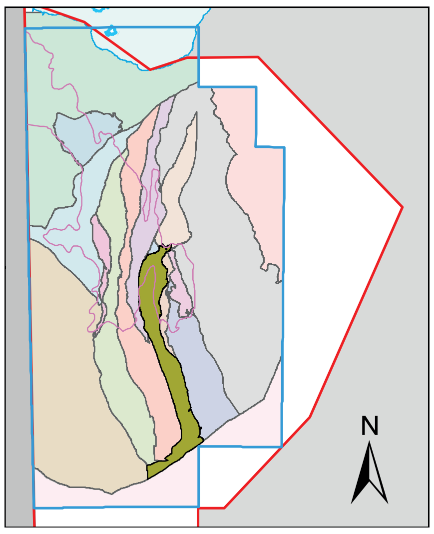
- A major regional extension event — the Wonga Event — is interpreted to be coeval with the intrusion of the Wonga Suite at about 1740Ma (Pearson & others, 1992). This event was accompanied by a metamorphic peak, but Rubenach & others (2008) questioned the regional extent of the metamorphism accompanying the Wonga Event. The domain represents the main one which records the Wonga Extension, although the Double Crossing Metamorphics and Gin Creek Granite within the Marimo– Staveley Domain could have formed during the same event.
- Peak metamorphism occurred at ~1570–1580Ma. This has traditionally been equated with the main east–west compressive phase of the Isan Orogeny (Rubenach & others, 2008).
- Subsequent broadly east–west deformations are associated with younger events in the Isan Orogeny. These have resulted in brittle faulting along major north-east structures such as the Mount Remarkable Fault. The Quilalar Formation may have been continuous with the Corella Formation in the Mary Kathleen Domain prior to translation across one of these younger strike slip faults (Derrick & others, 1980).

Inter/Intra province relationships

- The domain lies along the eastern edge of the Kalkadoon–Leichhardt Domain, the boundary being somewhat arbitrary, but positioned to exclude the main belt of Leichhardt Volcanics and Kalkadoon Granodiorite, although these rocks do occur within the Mary Kathleen Domain underlying the Argylla Formation, south-west of Dobbyn.

- The eastern boundary with the Canobie and Mitakoodi Domains is the Pilgrim and Quamby Fault zones.

Mitakoodi Domain



Extent / Distribution

- The Mitakoodi Domain is up to 50km wide, and extends from just west of Cloncurry south for about 120km to the limit of outcrop. It is interpreted to extend southward under the Georgina and Eromanga Basins to the Diamantina Lineament/Cork Fault zone.

Principal geological components

- The Bulonga Volcanics form the core of the Mitakoodi Domain which was originally mapped as Argylla Formation (Derrick, 1980) due to its lithological similarity. Both units have high magnetic susceptibility, and present as highs in the aeromagnetic images, but zircon dating indicates that the Bulonga Volcanics are ~1760Ma, and are thus 20Ma younger than the Argylla Formation (Geoscience Australia: OZCHRON database, Neumann & others, 2009a). Nevertheless, given that the two units are similar magnetically and lithologically, it is possible that unidentified equivalents of the Argylla Formation are present in the Mitakoodi Domain.
- Overlying the Bulonga Volcanics are the Marraba Volcanics, which consist largely of basalt flows as well as some sedimentary units (Timberoo and Mount Start Members) (Derrick, 1980). These have been equated to the Eastern Creek Volcanics in the Leichhardt River Fault Trough (Queensland Department of Mines and Energy & others, 2000), but the ages of the underlying Bulonga Volcanics and the maximum depositional age of the overlying Mitakoodi Quartzite, indicate that the Marraba Volcanics were erupted rapidly and are clearly younger than the Eastern Creek Volcanics. They thus have no equivalents in the Western Succession.
- Overlying the Marraba Volcanics is a thick quartzose to feldspathic sandstone succession, the Mitakoodi Quartzite. The Mitakoodi Quartzite has a depositional age of ~1755Ma (Geoscience Australia: OZCHRON database, Neumann & Fraser, 2007), based on detrital zircons and the age of minor rhyolitic volcanics within it. The Mitakoodi Quartzite probably partly equates in age to the Ballara Quartzite west of the Pilgrim Fault, although the latter is less feldspathic and could include older rocks (its lower constraint is the underlying 1780Ma Argylla Formation).
- The uppermost unit is the Overhang Jaspilite, which consists of mainly argillaceous sediments and some limestone (locally stromatolitic). Iron-rich jaspilite beds are a relatively minor component. The unit includes the enigmatic siliceous Chumvale Breccia, which is of unknown origin. The unit has not been dated, but based on its stratigraphic position, it may be partly equivalent to the Corella Formation.

Age

- As noted above, rocks in the Mitakoodi Domain were formed over a relatively short time frame (probably 1760–1750Ma — see above).

Geophysical characteristics

- The high magnetic response for the bulk of this domain is thought to be due to high magnetic susceptibility of the extensive Bulonga Volcanics. The Marraba Volcanics may also contribute to this response, although the magnetic susceptibilities are generally lower. The other main unit associated with intense magnetic anomalies within this domain is the Overhang Jaspilite. A ‘V-shaped’ region of low magnetic response correlates with metasedimentary rocks of the Bulonga Volcanics and Malbon Group.
- The generally low gravity response in the northern part of the domain is compatible with the distribution of the felsic Bulonga Volcanics and the batholith of Wimberu Granite. The higher gravity response around the northern margin is probably due to the mafic Marraba Volcanics. Another batholith interpreted under cover, immediately south of the Wimberu Granite, has a low gravity response in the north but higher response in the south suggesting it may not be as extensive here.
- The cause of the high gravity response under Phanerozoic cover in the southern two-thirds of the domain is unclear but may be due to mafic igneous rocks. Lower linear gravity features within this zone may be granite.

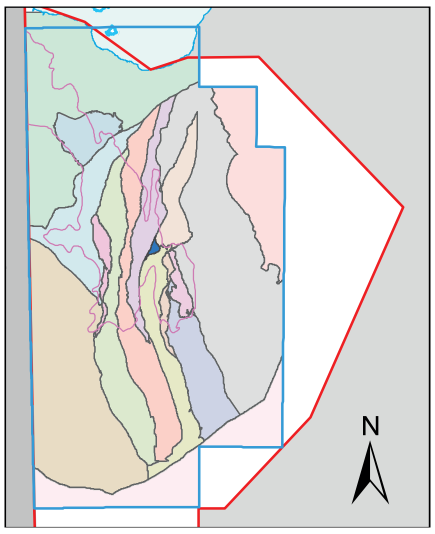
Structure / Deformation history

- The sequence in the Mitakoodi Domain may have been deposited in a graben. The Pilgrim Fault Zone may have been an east-dipping growth fault during deposition of the succession, which is included in the Leichhardt Superbasin (Neumann & others, 2006a).
- The domain is dominated by a large anticlinorium formed during the east–west compressive phase of the Isan Orogeny, and referred to as the Mitakoodi Culmination. From east to west, it consists of the Duck Creek Anticline, Wakefield Syncline and Bulonga Anticline. The folding is largely upright but the Bulonga Anticline is asymmetric with a steeper western limb.
- The metamorphic grade is greenschist facies in the north, increasing southwards to amphibolite facies east of Duchess.

Inter/Intra province relationships

- The eastern boundary of the domain with the Marimo–Staveley Domain is the Overhang Shear. This structure is interpreted (O’Dea & others, 2006) to have formed during the early north–south compressive phase of the Isan Orogeny and to be related to north-westward translation of the Mitakoodi Domain. The fault is thus interpreted as a subhorizontal decollement before folding, with the Mitakoodi Domain in the footwall and the successions in the Marimo–Staveley and Tommy Creek Domains in the hanging wall. In the north, the Overhang Shear is interpreted to be folded around the northern end of the Mitakoodi Domain, although it is also referred to as the Highway Fault.
- The northern boundary is complex. The domain appears to underthrust the Tommy Creek Block, which is of higher metamorphic grade. North of Rocklands prospect, the Overhang Jaspilite is mapped as a folded stratigraphic contact with the Corella Formation, but the contact could be a thrust.
- The western boundary of the Mitakoodi domain is the Pilgrim Fault, which is interpreted as a fundamental structure separating the eastern and western fold belts. This is supported by a change in Nd isotopic ratios of the granites and geophysical modelling (Bierlein & Betts, 2004). The fault separates the Mitakoodi Domain from the Mary Kathleen Domain in the north and from the Kalkadoon Leichhardt Domain in the subsurface farther south.

Tommy Creek Domain



Extent / Distribution

- A triangular area about 20km across in the south, where it adjoins the Mitakoodi Domain and extends north for about 30km. It is bounded on its western side by the Mary Kathleen Domain and by the Canobie Domain to the east.

Principal geological components

- The oldest rocks in the Tommy Creek Domain are in a fault-slice of felsic metavolcanics along the eastern edge of the domain. They were variously assigned to the Tommy Creek Microgranite (Derrick, 1980) or Tommy Creek beds (Hill & others, 1992). Based on SHRIMP zircon ages, Wyborn & others (2001) assigned them to a new unit, the Lalor beds. However, they are now assigned to the Bulonga Volcanics, a unit that occurs mainly in the adjoining Mitakoodi Domain and has identical SHRIMP ages. A small anticlinal core of felsic volcanics within the Corella Formation in the south-west of the domain near Timberu homestead is also assigned to the Bulonga Volcanics.

- Another fault slice containing Mitakoodi Quartzite lies to the north of the Bulonga Volcanics and may be within the fault system defining the eastern margin of the Tommy Creek Domain.
- About half of the Tommy Creek Domain consists of calc-silicate granofels assigned to the Corella Formation.
- The Corella Formation is intruded by microgranite sills assigned to the Tommy Creek Microgranite, which is applied in the sense of Derrick (1980).
- Both the Corella Formation and Tommy Creek Microgranite are overlain unconformably by the Milo beds, a heterogeneous unit which consists of impure marble and calc-silicate rocks, sandstone, graphitic schist and basic to intermediate lavas and volcaniclastic rocks and rhyolite lavas or sills.

Age

- The Bulonga Volcanics in the Tommy Creek Domain have SHRIMP ages of 1762±5Ma and 1758±4Ma (Geoscience Australia: OZCHRON database). These are within error of ages obtained from the Mitakoodi Domain.
- The Tommy Creek Microgranite has SHRIMP ages of 1650±3Ma (Geoscience Australia: OZCHRON database) and 1653±4Ma (Neumann, unpublished data).
- The Milo beds have a range of ages. A sandstone from above the contact with the Tommy Creek Microgranite has a maximum depositional age of 1660±6Ma (Neumann, unpublished data) suggesting that it is partly sourced from the microgranite. However, other SHRIMP ages obtained are 1629±8Ma and 1625±4Ma from rhyolite lavas or sills and 1618±4Ma from a volcaniclastic sandstone (Hill & others, 1992; Geoscience Australia: OZCHRON database). Biotite schist containing relict mafic and felsic volcanic clasts has a unimodal age of 1610±6Ma (Carson & others, in preparation), indicating that the Milo beds represent one of the youngest parts of the succession in the Mount Isa Inlier.

Geophysical characteristics

- Very intense magnetic anomalies characterise the bulk of this domain. Small areas of low magnetic response within this domain reflect the Milo Beds.
- Most of this domain is characterised by strong positive gravity anomalies, although a lower response is evident over some of the Tommy Creek Microgranite.
- The three suites of felsic igneous rocks in the Tommy Creek Domain have contrasting geophysical properties.
  - The Bulonga Volcanics are strongly magnetic, are characterised by intense magnetic anomalies, and have moderate potassium, thorium and uranium radiometric responses.
  - The Tommy Creek Microgranite is also relatively magnetic but is characterised by a relatively high thorium response.
  - In contrast the rhyolitic lavas or sill in the Milo beds are non-magnetic and have a high potassium response.

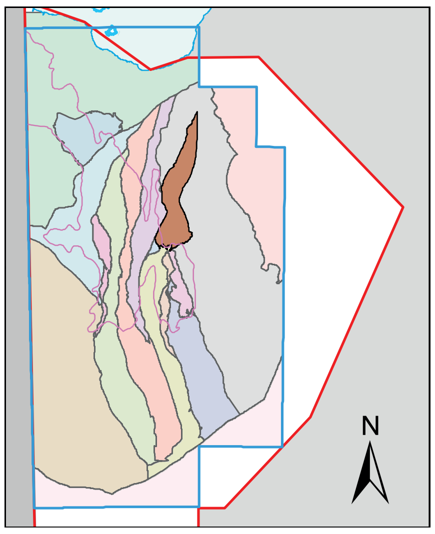
Structure / Deformation history

- The Tommy Creek Domain is bounded to the south and east by thrusts or shear zones that probably formed during the initial Isan Orogeny, but could have been reactivated by later events. The southern margin with the Mitakoodi Domain, which corresponds with the folded Overhang Shear, separates rocks of contrasting metamorphic grade (greenschist in the Mitakoodi Domain and amphibolite facies in the Tommy Creek Domain).
- The southern part of the Tommy Creek Domain is characterised by east-trending recumbent folds that are the earliest in the domain and may have formed in two separate phases (Hill & others, 1992).
- They are refolded by a pervasive deformational event later in the Isan Orogeny that produced upright north–south folds that are the dominant structures in the northern part of the domain.

Inter/Intra province relationships

- The Tommy Creek Domain is entirely fault bounded although the sense of movement on some of these faults is not certain.
  - In the west, it is separated from the Mary Kathleen Domain by the Fountain Range Fault north of where that fault appears to converge with the Pilgrim fault to become the Corella Fault Zone.
  - On the southern margin it is interpreted to be thrust over the Mitakoodi Domain, the thrust being interpreted as part of the Overhang Shear, where it is folded around the Duck Creek Anticline.
  - The eastern margin also may be a thrust, with the Bulonga Volcanics being thrust over the Corella Formation in the Canobie Domain to the east.

Canobie Domain



Extent / Distribution

- The Canobie Domain is mostly concealed, except at its southern end near Cloncurry, and is defined on the basis of its high magnetic response. It is up to 60km wide and extends north from Cloncurry for about 260km where it appears to form a fault-bounded basement high within the Soldiers Cap Domain which flanks it on two sides.

Principal geological components

- At outcrop at its southern end, the Canobie Domain consists of calc-silicate rocks of the Corella Formation. Outcrops of quartzite near Cloncurry have been mapped as Mitakoodi Quartzite, but their exact relationships to the Corella Formation are not known. They partly occur as enclaves and screens within the Levian Granite. Felsic volcanic rocks assigned to the Bulonga Volcanics are also intruded by the Levian Granite.
- The Corella Formation is overlain by scapolitic siltstone tentatively correlated with the Coocerina Formation in the Mary Kathleen Domain. This occurs in a synclinal structure east of Corella Park homestead.
- Felsic to intermediate volcanics assigned to the Mount Fort Constantine Volcanics form several isolated outcrops near the Ernest Henry mine where they host the mineralisation. Based on drillhole information, we have interpreted these rocks to continue northward under cover accounting for much of the highly magnetic rocks in the domain. Based on their isotopic age (see below), they are interpreted to overlie the Corella Formation, but it is possible that some of the magnetic felsic rocks could be older and equivalents of the Argylla Formation.
- Relatively non-magnetic rocks in the northern part of the domain may be Soldiers Cap Group.
- The Levian Granite (Wyborn & others, 2001), is a deformed granite near Cloncurry which is of a similar age to the Mount Fort Constantine Volcanics. It is interpreted as having a similar structural history to the Dipvale Granite in the Mary Kathleen Domain, which is dated at 1752±8Ma (Pollard & McNaughton, 1997).
- The southern end of the domain is intruded by the Naraku Batholith, which consists largely of the Malakoff Granite. Isolated outcrops surrounded by cover rocks east of Ernest Henry have been assigned to the Mount Margaret Granite. These both comprise part of the Williams Supersuite.
- The rocks within the northern concealed part of the domain are intruded by olivine gabbro to norite and granite which have been intersected by drilling. Highly altered felsic rocks, psammite, and pegmatite between the intrusive rocks may be either a shear zone or screen between plutons. A 1550–1500Ma age range (equivalent to the Williams Supersuite) is tentatively suggested.

Age

- The Mount Fort Constantine Volcanics are dated at 1746±9Ma and 1742±6Ma (Page & Sun, 1998) and are therefore likely to overlie or form the upper part of the Corella Formation.
- The Levian Granite has a similar age to the Mount Fort Constantine Volcanics and is 1746±8Ma (Jessie granite of Page & Sun, 1998).
- The Malakoff Granite has been dated at 1505±5Ma, whereas the Mount Margaret Granite is significantly older at 1530±8Ma (Page & Sun, 1998).

Geophysical characteristics

- The Canobie Domain is defined on the basis of a strong magnetic response as much of the domain is under cover. Most of the highly magnetic rocks are interpreted to belong to the Mount Fort Constantine Volcanics (or possibly Argylla Formation), but the presence of granite and gabbro, both of which are highly magnetic, may also explain some of the

response. Magnetic calc-silicate rocks of the Corella Formation as exposed in the southern part of the domain could also be present.
- The magnetic response from the northern part of the domain is dominated by longer frequency anomalies, which contrast with the typically short frequency responses in the south. This variation in the frequency of the response is interpreted as due to downfaulting of the northern part of the domain to deeper levels by the Quamby Fault.
- The gravity response in the domain is mostly high. Areas of low gravity are interpreted as granites, the most pronounced being centred on the Naraku Batholith (Malakoff Granite) in the south near Cloncurry. However, granitoids interpreted in the central part of the domain from magnetic data are associated with moderate gravity anomalies, suggesting that if they are granitoids, they are more mafic and denser than those of the Naraku Batholith.

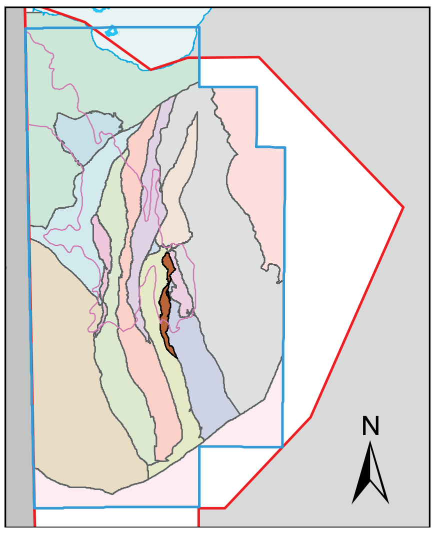
Structure / Deformation history

- The deformation history of the domain is poorly known, because most of the rocks are under cover. In the exposed part of the domain, folds in the Corella Formation and Coocerina Formation trend north-north-west and probably formed during the main D_2 phase of the Isan Orogeny.
- The Levian Granite in the south of the domain has a similar deformational history to the ~1746Ma Dipvale Granite from the Mary Kathleen Domain. The earliest deformation is interpreted as being due to north–south compression (D_1) during the early Isan Orogeny. Later fabrics overprint the earliest fabric and formed during later phases of the Isan Orogeny (Davis & others, 2001).
- The Malakoff Granite is relatively undeformed and probably largely post-dates the Isan Orogeny.

Inter/Intra province relationships

- The Canobie Domain is defined mostly on its magnetic response that contrasts with the Soldiers Cap Domain that lies to the east and also flanks the western side in the northern part of the domain. The contact is assumed to be faulted.
- In its southern part, the domain is faulted against the Tommy Creek Domain and also against the Mary Kathleen Domain along the Quamby Fault.
- The southern margin against the Marimo–Stavely Domain is probably also faulted (thrust?), but the relationships and distribution of rock units are difficult to determine because the area is covered by the floodplain of the Cloncurry River.
- East of Cloncurry, the north-east-trending contact with the Soldiers Cap Domain is also interpreted as a thrust.

Marimo–Staveley Domain



Extent / Distribution

- The Marimo–Stavely Domain forms a narrow north-trending belt less than 15km wide, but extending south for about 200km, from just south-west of Cloncurry to beyond the limit of outcrop of basement outcrop. It lies between the Mitakoodi Domain on the west and the Doherty – Fig Tree Gully Domain and Kuridala–Selwyn Domain to the east.

Principal geological components

- The oldest rocks are the Double Crossing Metamorphics, which occur in the south of the domain, within an antiformal structure that may represent a metamorphic core complex. The metamorphic rocks grade from relatively low-grade chlorite schists into migmatitic gneisses that occur around a core of granitic rocks mapped as Gin Creek Granite. They also include mafic intrusions and probable mafic lavas. Isotopic dating (see below) suggests that they were deposited between ~1755Ma and 1740Ma and may correlate with the Marraba Volcanics in the adjacent Mitakoodi Domain, and that they underwent a metamorphic event at ~1740Ma (see below). Another antiformal structure of Double Crossing Metamorphics with a core of granite (referred to as Houdini Granite) has been interpreted under cover to the south.
- The Double Crossing Metamorphics are flanked by rocks assigned to the Answer Slate and Kuridala Formation, the contacts appearing to be entirely tectonic and possibly a detachment surface (Beardsmore & others, 1988).
- The Staveley Formation consists of fine-grained, locally calcareous sandstone and siltstone.
- In the Marimo area, the Staveley Formation passes gradationally upwards into the Roxmere Quartzite, which consists of very thick-bedded amalgamated quartzose to feldspathic sandstone. Although it generally appears to overlie the Staveley Formation, in places the Roxmere Quartzite may represent a sandy facies within the Staveley Formation.
- The Answer Slate consists predominantly of variably carbonaceous metapelitic rocks. It includes rocks previously mapped as Marimo Slate and Agate Downs Siltstone that pass laterally into the Answer Slate. Isotopic dating (see below) indicates that the Answer Slate is equivalent in age to the Toole Creek Volcanics in the Soldiers Cap Group and Hampden Slate, the upper part of the Kuridala Group. Although there are no definite volcanic rocks, it does contain metadolerite sills.
- All contacts between the Stavely Formation and Answer Slate are interpreted to be faults, marked in many cases by siliceous mylonite zones.

Age

- Maximum depositional ages for the Double Crossing Metamorphics have been determined as 1743±17Ma (Magee & others, in preparation) and 1752±4Ma (Carson & others, in preparation). This suggests that they are probably equivalent in age to the Marraba Volcanics in the adjacent Mitakoodi Domain.
- The Gin Creek Granite and a leucosome in the Double Crossing Metamorphics have given identical ages to each other of ~1740Ma (Page & Sun, 1998; Neumann, unpublished data) indicating that the Double Crossing Metamorphics underwent a metamorphic/deformational event accompanied by granite emplacement within about 10Ma of deposition. The thermal event correlates with the emplacement of the Burstall Granite in the Mary Kathleen Domain.
- Maximum depositional ages for the Staveley Formation cluster around 1740Ma (Neumann, unpublished data; Magee & others, in preparation), suggesting that the sediments were at least partly derived from the Gin Creek Granite or its equivalents and are therefore younger than the Corella Formation with which they have previously been correlated.
- The Roxmere Quartzite has yielded maximum depositional ages of ~1710Ma. Its gradational relationship with the Staveley Formation provides further evidence that the Staveley Formation is part of a younger sequence than the Corella Formation.
- The Answer Slate has maximum depositional ages of ~1655Ma (Carson & others, 2008a; Neumann, unpublished data; Geoscience Australia: OZCHRON database). These include samples of rocks previously assigned to the Marimo Slate. The site of a supposed tuff in the 'Marimo Slate' that gave an age of ~1610Ma (Page & McCready, 1997; Geoscience Australia: OZCHRON database) was re-examined by us and interpreted as a rhyolite dyke in a fault zone.

Geophysical characteristics

- The northern half of the domain is characterised by the low magnetic response associated with the Answer Slate and low to moderate magnetic response Stavely Formation. Linear, more magnetic belts within this part of the domain correspond to metadolerite sills.
- The antiforms of Double Crossing Metamorphics have a strong response that contrasts with that of the relatively weakly magnetic Gin Creek and Houdini Granite in their cores.
- Along the eastern margin in the central part of this domain, intense magnetic anomalies within the Stavely Formation are due to the ironstone belts of the Starra/Selwyn area.
- In the southern portion of this domain, the magnetic response is high, but featureless, suggesting the non-magnetic Answer Slate and Stavely Formation inferred in this area are underlain by deeper magnetic rocks.

- In the northern half of the domain the gravity response is low to moderate, but the southern half of this domain, beneath Phanerozoic cover, is dominated by the strong gravity ridge associated with much of the eastern part of the Mount Isa Block.

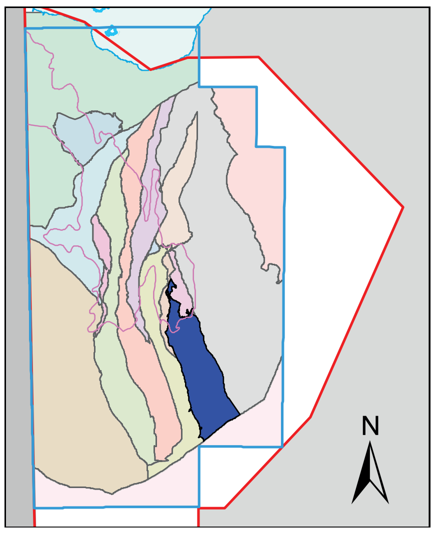
Structure / Deformation history

- The Double Crossing Metamorphics were deformed and metamorphosed from greenschist to upper amphibolite facies at about 1740Ma and are exposed in antiformal structures that may represent a core complex. Contacts with the overlying Staveley Formation and Answer Slate are tectonic and have been interpreted as a detachment (Beardsmore & others, 1988). The metamorphic rocks grade from relatively low-grade chlorite schists into migmatitic gneisses that occur around a core of granitic rocks mapped as Gin Creek Granite. Wyborn & others (2001) note that the Gin Creek Granite is weakly to strongly peraluminous (the only pluton in the Mount Isa Inlier to show this characteristic). This is consistent with it having an identical age to the leucosomes in the migmatites and suggests that it is an S-type granite generated by the thermal event.
- Folding of the Double Crossing Metamorphics and their dominant foliation into the antiforms probably occurred during D_2 in the Isan Orogeny, although overprinting fabrics other than crenulation are difficult to find.
- In places the Staveley Formation is strongly brecciated (although this is more common in the adjacent Doherty – Fig Tree Gully Domain). Coherent outcrops commonly have a characteristic spaced fabric formed by orthogonal arrays of calcite veinlets at a high angle to bedding. The fabric appears to be related to extension and may be an early stage of the brecciation process.
- All contacts between the Stavely Formation and Answer Slate are interpreted to be faults and these are interpreted to have originally been thrusts formed during D_1 of the Isan Orogeny and subsequently relatively tightly folded by D_2 or later events.
- The Staveley Formation and Answer Slate were mainly metamorphosed in the greenschist facies, but the grade increases eastwards and is probably lower amphibolite facies in places.

Inter/Intra province relationships

- The Marimo–Staveley Domain is faulted against the Mitakoodi Domain along the Overhang Shear (or Fault). This structure is interpreted (O'Dea & others, 2006) to have formed during the early north–south compressive phase of the Isan Orogeny and to be related to north-westward translation of the Mitakoodi Domain. The fault is thus interpreted as being originally a subhorizontal decollement, with the Mitakoodi Domain in the footwall and the successions in the Marimo–Staveley Domain in the hanging wall. As with the thrusts within the Marimo–Staveley Domain, the Overhang Shear was steepened to vertical by folding during D_2 and later events.
- In the south, the Marimo–Staveley Domain is faulted against the Kuridala–Selwyn Zone along the Mount Dore Fault.
- The adjacent Doherty – Fig Tree Gully Domain consists predominantly of Staveley Formation, and Roxmere Quartzite intruded by Willams Supersuite Granites. It contains little or no Answer Slate and the metamorphic grade is generally higher. Although this division is somewhat arbitrary, the contact is defined by the Straight Eight Fault and Martin Creek Fault and an unnamed fault west of Roxmere Homestead.

Kuridala Selwyn Domain



Extent / Distribution

- The Kuridala Selwyn Domain lies in the south-east of the province, and has many similarities with the southern Soldiers Cap Domain. It occurs in an area ~350km north–south and about 80km east–west. The southern and eastern parts of the domain are covered by younger sedimentary rocks.

Principal geological components

- The dominant unit in the domain is the Kuridala Group that is subdivided into three formations, the Starcross Formation, New Hope Quartzite and Hampden Slate (top) that can be correlated lithologically with the Llewellyn Formation, Mount Norna Quartzite and Toole Creek Volcanics in the Soldiers Cap Group. Unlike the Toole Creek Volcanics, the Hampden Slate is not known to contain basalt lavas, but does contain numerous metadolerite sills. Like the Soldiers Cap Group, the Kuridala Group is interpreted as a turbidite succession deposited on a continental slope. The two groups are geographically separated by a belt of Staveley Formation and the Squirrel Hills Granite, the largest batholith of the Williams Supersuite. However, in the subsurface, the two Groups are adjacent to each other so that an arbitrary boundary has to be delineated. Future studies might consider dropping the dual nomenclature.
- The Kuridala Group is intruded by granitic and mafic rocks of the Williams Supersuite including the Mount Dore Granite and the Yellow Waterhole Granite. The Squirrel Hills Granite forms the eastern margin of the domain in outcrop. Interpretation of magnetic data suggests that granitic rocks occur under deep cover in the southernmost part of the domain. These may be equivalents of the Williams Supersuite or they may be Palaeozoic.

Age

- Detrital zircons from the Starcross Formation have yielded a maximum depositional age of 1663±21Ma (Carson & others, in preparation). This is somewhat younger than the supposedly coeval Llewellyn Creek Formation, although the age is less precise. The maximum detrital age of the New Hope Quartzite is ~1677Ma (Neumann, unpublished data, Geoscience Australia: OZCHRON database).
- The Mount Dore Granite intrudes the Kuridala Group east of the Selwyn mine. This granite has yielded an age of 1516±10Ma (Pollard & McNaughton, 1997).
- The Yellow Waterhole Granite has yielded ages of 1510±8Ma (Pollard & McNaughton, 1997).

Geophysical characteristics

- The metasedimentary rocks of the Kuridala Group have a relatively low magnetic response, but linear belts of higher response delineate the metadolerite sills within them.
- Rocks with high magnetic response in the southern (undercover) part of the domain are mapped as the Toole Creek Volcanics, part of the upper Soldiers Cap Group.
- Granites in the northern exposed part of the domain (Mount Dore and Yellow Waterhole Granites) also have a higher magnetic response.

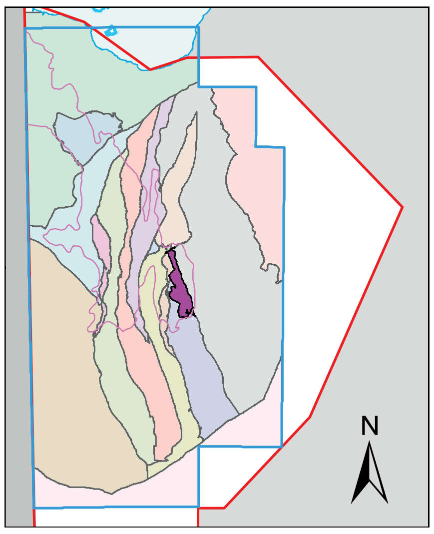
Structure / Deformation history

- The Kuridala Group was tightly folded and metamorphosed during the Isan Orogeny. Tight north-trending folds are delineated by metadolerite sills at Kuridala, and south-east of Selwyn folds are asymmetric with overturned limbs. The grade of metamorphism is probably mainly in the lower amphibolite facies.
- Granitic rocks that are part of the Williams Supersuite were intruded late in the Isan Orogeny.
- The Mount Dore Granite was thrust over the Kuridala Group at the Merlin Mo/Re prospect, probably during a late east–west shortening phase of the Isan Orogeny.

Inter/Intra province relationships

- In the north, the boundary between the Kuridala–Selwyn Domain and the Marimo–Staveley Domain to the west is the Mount Dore Fault.
- The eastern boundary with the Doherty – Fig Tree Gully Domain is arbitrarily taken as the contact of the Squirrel Hills Granite batholith, which separates the Kuridala Group from a belt of high-grade Staveley Formation.
- The southern part of the Kuridala Selwyn Domain is entirely undercover but is probably similar to the southern Soldiers Cap Domain. The boundary between the two domains is arbitrarily defined as the southern extension of the Cloncurry Fault.

Doherty – Fig Tree Gully Domain



Extent / Distribution

- The Doherty – Fig Tree Gully Domain lies in the south-east of the outcropping part of the Mount Isa Province as an elongate belt trending north-north-west for about 125km from the southern limit of exposure to just south of Cloncurry. It is up to 30km wide, narrowing to about 8km in the north.
- In the north, it is flanked by the Marimo–Staveley Domain on the west, but farther south, the Kuridala–Selwyn Domain flanks it on the west and south. The Soldiers Cap Domain lies to the east.

Principal geological components

- The dominant stratigraphic unit is the Staveley Formation, which is generally of higher metamorphic grade (amphibolite facies) in this domain than in the adjacent Marimo–Staveley and Kuridala–Selwyn Domains. The rocks consist generally of calc-silicate granofels and metasandstone and are extensively brecciated and metasomatised. The breccia is matrix-supported and consists of calcareous sandstone or siltstone and calc-silicate rock in a calcareous/ calc-silicate-bearing matrix. The Staveley Formation mostly includes the rocks that were previously mapped as Doherty Formation, which is now regarded as simply a higher grade and generally more metasomatised equivalent of the Staveley Formation.
- As in the Marimo–Staveley Domain, the Staveley Formation is overlain by the Roxmere Quartzite, particularly in the northern part of the domain.
- Some small slivers of Soldiers Cap Group have been mapped along the eastern edge of the domain.
- The southern half of the domain is dominated by numerous plutons containing granitic and mafic rocks of the Williams Supersuite. The largest is the Squirrel Hills Granite, which forms a batholith 60km long and about 25km wide. The Mount Angelay Granite forms a smaller pluton about 25km long and 5km wide. Both are I-type granites and consist of variably porphyritic hornblende-biotite granite. Other small, generally unnamed plutons range from diorite to granite. Small, very widespread intrusions of hornblende gabbro to diorite have been assigned to the Wiggle Waterhole Metagabbro, which may be a mafic end-member of the Williams Supersuite. However, some of these intrusions may be related to the older metadolerite and metagabbro sills that occur throughout the Soldiers Cap and Kuridala Groups.

Age

- Maximum depositional ages for the Staveley Formation in the Marimo–Staveley Domain cluster around 1740–1750Ma (Neumann, unpublished data; Magee & others, in preparation) suggesting that the sediments were at least partly derived from the Gin Creek Granite or its equivalents and are therefore younger than the Corella Formation with which they have previously been correlated. Detrital zircon spectra for the Staveley Formation in the Doherty – Fig Tree Gully Domain are generally similar to those in the Marimo–Staveley Domain, although one sample gave a somewhat older (~1785Ma) age (Neumann, unpublished data; Magee & others, in preparation).
- Metarhyolite was dated by Page & Sun (1998) from the Staveley Formation (or Doherty Formation as it was then known). It gave an age of 1725±3Ma. However, the relationships of this rock to the Staveley Formation (whether extrusive or intrusive) are uncertain. If it is intrusive, it provides a minimum age for the unit.
- The Roxmere Quartzite has yielded maximum depositional ages of ~1710Ma. Its gradational relationship with the Staveley Formation supports the interpretation that the Staveley Formation is part of a younger sequence than the Corella Formation.
- Monzogranite from the Mount Angelay Granite has ages of 1524±4Ma and 1529±4Ma and monzodiorite from the Squirrel Hill Batholith has an age of 1514±5Ma (Pollard & McNaughton, 1997).

Geophysical characteristics

- The more strongly metamorphosed and metasomatised rocks of the Staveley Formation in this domain are more magnetic than their lower grade equivalents and display a strong north-north-west-trending fabric that is consistent with mapped bedding trends. In the northern part of the domain, relatively fewer magnetic areas correspond with areas of lower grade or Roxmere Quartzite.
- The Squirrel Hills Granite and Mount Angelay Granite are characterised by a strong magnetic response similar in intensity to the Staveley Formation but lacking the strong linear fabric. However, the Squirrel Hills batholith does show a weak fabric parallel to its margins, particularly in the west suggesting some zoning. A prominent north-trending zone of de-magnetisation is also evident in the eastern half of the batholith.
- The southern part of this domain is characterised by a gravity low associated with the Squirrel Hills Granite. Moderate gravity anomalies in the central part of this domain reflect the Staveley Formation while a significant gravity low in the far north of the domain suggests a significant granite intrusion may lie at depth below the Staveley Formation.

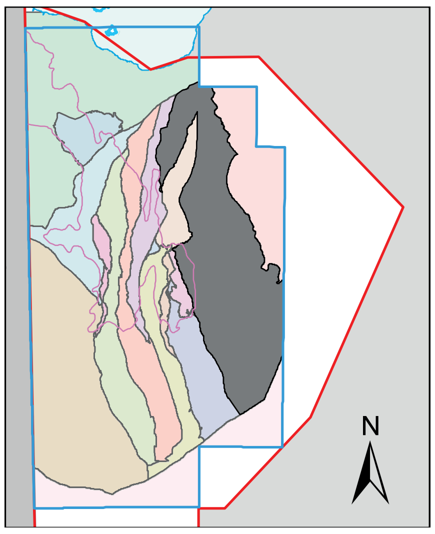
Structure / Deformation history

- As in the Marimo–Staveley and Soldiers Cap Domains, the Staveley Formation is strongly brecciated and appears to be pervasive over large areas with generally subordinate areas of coherent, bedded rocks. The grade of metamorphism is amphibolite facies.
- The brecciated Staveley Formation is generally folded with the coherent Roxmere Quartzite and thus appears to have formed relatively early, at least syn- or pre-D_1.
- The Roxmere Quartzite overlies the Staveley Formation in a series of open upward-facing synforms and downward-facing antiforms. These are interpreted as limbs of folded D_1 nappe structures. Unlike the tightly folded D_1 thrust packages interpreted in the Marimo–Staveley Domain, the refolding of the D_1 nappes in the Doherty – Fig Tree Gully Domain is relatively open.

Inter/Intra province relationships

- In the north, the boundary with the Marimo–Staveley Domain is taken arbitrarily at the easternmost extent of the Answer Slate, although this is partly interpreted as a fault. As noted above, it appears also to correspond with a change from tight to relatively open post-D_1 folding.
- Farther south, the boundary is taken as a series of faults, including the Martin Creek and Straight Eight Faults. There appears to be a marked jump in metamorphic grade across these faults, manifest by the contrast between calcareous sandstone in the Staveley Formation in the Marimo–Staveley Domain and calc-silicate granofels across the faults in the Doherty – Fig Tree Gully Domain.
- The Straight Eight Fault also forms the boundary with the northern part of the Kuridala–Selwyn Domain, where it truncates the tight north-north-east-trending folds that deform the Kuridala Group. Folds in the Doherty – Fig Tree Gully Domain trend predominantly north-north-west as defined by mapped bedding trends and the magnetic fabric.
- Farther south, the boundary with the Kuridala–Selwyn Domain is arbitrarily defined by the contact of the Squirrel Hill Granite.
- The eastern boundary of the domain is the Cloncurry Fault Zone.

Soldiers Cap Domain



Extent / Distribution

- The Soldiers Cap Domain occupies an area ~650km x 200km which is mainly under Phanerozoic cover, except in a narrow area south from Cloncurry. In the north, the Canobie Domain extends into the Soldiers Cap Domain as a fault-bounded basement high.

Principal geological components

- North of Cannington, calc-silicate granofels and breccia, previously assigned to the Doherty Formation and now regarded as a higher grade and metasomatised part of the Staveley Formation, forms a narrow band along the western margin of the domain adjacent to the Cloncurry Fault Zone.
- The Staveley Formation probably underlies the Soldiers Cap Group, but the relationships are not clear and some contacts may be thrusts. Farther north, in the Gilded Rose area south and east of Cloncurry, contacts between the Soldiers Cap Group and large areas of breccia are quite irregular and appear to be intrusive (akin to salt diapirism). Smaller outcrops of breccia, assigned to a separate unit, the Gilded Rose Breccia, form small pipe- and dyke-like bodies and may be diatremes.
- The lower Soldiers Cap Group comprises psammitic and pelitic metasedimentary rocks which are assigned to the Llewellyn Creek Formation and Mount Norna Quartzite in the Snake Creek area south of Cloncurry. The rocks are interpreted as a turbidite succession deposited on a continental slope. They are equivalent to the Kuridala Group in the Kuridala–Selwyn Domain. The metamorphic grade increases southwards and the rocks pass into gneiss and migmatite. In this area, the formations are distinguished on the presence or absence of bluish quartzite that characterises the Mount Norna Quartzite. The units are intruded by mafic sills at least partly related to the overlying Toole Creek Volcanics.
- The upper Soldiers Cap Group comprises the Toole Creek Volcanics. It consists of basalt flows and intervening, largely metapelitic, commonly carbonaceous rocks, intruded by mafic sills.
- A younger succession, herein referred to as the Canobie Sequence, was intersected in the bottom of GSQ Dobbyn 1. The rocks consist of fine-grained, laminated to medium-bedded metasandstone or siltstone, with a schistose foliation. Based on dating of detrital zircon, the succession is clearly younger than the Soldiers Cap Group (see below). The distribution of the Canobie Sequence is unknown, but it could be present over a significant part of the domain. It may correlate with the Langlovale Group that unconformably overlies the Etheridge Group and underlies the 1550Ma Croydon Volcanic Group in the Georgetown Inlier (Withnall & others, 1997).
- The Millungera Basin is a newly discovered succession presumed to be mainly of sedimentary rocks of uncertain age and up to 3km thick, which unconformably overlies the Soldiers Cap Group and is unconformably overlain by the late Jurassic to Cretaceous rocks of the Carpentaria Basin. It is known only from the deep crustal seismic line GA07-IG1 acquired by GA and GSQ in 2007, where it is about 30km wide. Interpretation of magnetic images suggests that it may be at least 100km long from north to south. Two small outcrop areas of reddish sandstone and conglomerate at Mount Fort Bowen and Mount Brown may be part of the Millungera Basin succession, or yet another succession lying stratigraphically between the Soldiers Cap Group and the Millungera Basin.
- The Soldiers Cap Group and Staveley Formation are intruded by granitic and mafic rocks of the Williams Supersuite and Maramungee and Cowie Suites. Interpretation of magnetic data suggests that extensive areas of granitic rocks occur under deep cover in the southernmost part of the domain. These may be equivalents of the Williams Supersuite or they may be Palaeozoic.

Age

- SHRIMP dating of zircons from the Llewellyn Formation and Mount Norna Quartzite in the Snake Creek area indicates maximum depositional ages of ~1685Ma (Neumann & others, 2009c). Trondhjemite in a mafic sill in the Llewellyn Creek Formation was dated at 1678±5Ma (Rubenach & others & others, 2008). These data suggest that the depositional age has to be close to the maximum depositional age and that the sill was intruded soon after.
- High grade metamorphics around the Cannington mine have yielded similar maximum depositional ages of ~1680Ma (Page & Sun, 1998; Giles & Nuttman, 2003) indicating the high grade rocks are part of the same sequence.
- Sandstone in the lower part of the Toole Creek Volcanics have yielded a maximum depositional age of 1658±5Ma (Carson & others, 2008a) suggesting a disconformity between this unit and the underlying part of the Soldiers Cap Group.
- Low grade metasediments from GSQ Dobbyn 1 yielded a maximum depositional age of 1592±5Ma (Carson & others, in preparation), indicating that they represent a younger sequence than the Soldiers Cap Group, the youngest parts of which are interpreted to have depositional ages of ~1650Ma (Neumann & Fraser, 2007). The age suggests that the rocks post-dated the onset of the Isan Orogeny, but the presence of a foliation suggests that they were probably deposited before D_2. The rocks may correlate with the Langlovale Group that unconformably overlies the Etheridge Group and underlies the 1550Ma Croydon Volcanic Group in the Georgetown Inlier (Withnall & others, 1997).
- The Maramungee Granite has yielded an age of 1545±11Ma and the Boorama Tank Gneiss, which may be part of the Cowie Suite (Wyborn & others, 2001) has yielded an age of 1547±5Ma (Page & Sun, 1998). The Saxby Granite, a part of the Williams Supersuite, which also intrudes the Soldiers Cap Group south of Cloncurry has yielded an age of ~1520±8Ma (Rubenach & others, 2008).

Geophysical characteristics

- The metasedimentary intervals in the Soldiers Cap Group have a low magnetic response, but bands of moderate to high magnetic response are associated with mafic bodies (particularly sills). The mafic lavas in the exposed part of the Toole Creek Volcanics commonly only have a moderate response, probably because of magnetite-destruction at the lower metamorphic grades. Farther south where the metamorphic grade is higher, the mafic rocks appear to have a higher response.
- Uniformly moderate to high magnetic regions in the south-eastern deeply covered part of the domain are interpreted as granitoids, although the moderate gravity suggests that they may be relatively mafic and dense.
- Williams Supersuite granitoids are generally variably magnetic and correspond to gravity lows but some unassigned granites are associated with higher gravity, possibly due to the presence of more mafic phases within the plutons.
- The outline of the Millungera Basin is defined mainly from the truncation of magnetic trends within the Toole Creek Volcanics and also by tracing an apparently shallowly dipping moderately magnetic interval that is thought to be in the lower part of the succession. It may represent a red-bed interval or even volcanic rocks. Strong gravity lows within this outline may reflect thicker sediment piles (regional synclines) or non-magnetic granites at depth. Conversely a gravity ridge in the south of the inferred basin outline may reflect a thinner sequence in an anticline or more dense basement.
- On the deep crustal seismic profile, possible granites have been interpreted intruding the Soldiers Cap Group beneath the Millungera Basin.
- Large positively magnetised dykes are evident cutting across the domain. They strike east to east-north-east and can be traced for up to 130km. They post-date the main deformation and could be Neoproterozoic or Palaeozoic.

Structure / Deformation history

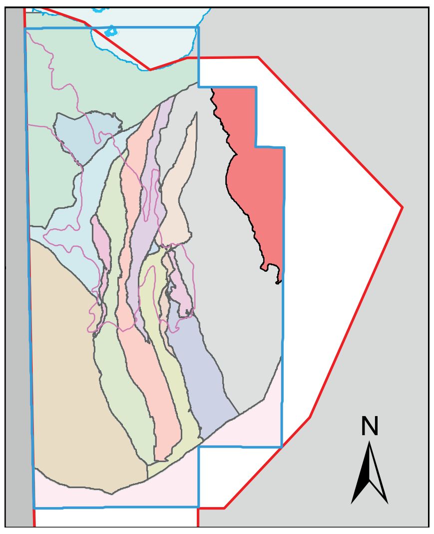
- Rocks of the Soldiers Cap Group have undergone deformation and metamorphism during the Isan Orogeny between ~1600 and 1500Ma. The folding has resulted in complex east-trending and northerly-trending interference fold patterns.
- Three undercover elliptical structures south-east of Cloncurry, defined by magnetic trends that probably reflect mafic rocks in the Toole Creek Volcanics, have been modelled as domes which are partly cored by granite (Edmiston & others, 2008). The most likely explanation for the formation of these structures is folding during E–W shortening with hinge line rotation due to vertical stretching.
- Granitic rocks of the Maramungee Suite and Williams Supersuite were intruded between ~1550 and 1520Ma.
- The age of Canobie sequence is uncertain but the rocks have undergone deformation and low grade metamorphism, presumed to be D_2 or one of the later phases in the Isan Orogeny.
- Thrusts identified in the deep seismic reflection profile along the eastern margin of the Millungera Basin also cut the Middle Devonian granites that lie to the east of the Soldiers Cap Domain. This indicates that Palaeozoic deformation affected at least the eastern part of the Soldiers Cap Domain.

Inter/Intra province relationships

- In the south-west, the domain is bounded by the Cloncurry Fault Zone, which separates it from the Doherty – Fig Tree Gully Domain.
- In the east, the domain is bounded under cover by strongly magnetic granitic rocks that have been dated as Middle Devonian (Carson & others, in preparation).
- The Canobie Domain is faulted against the Soldiers Cap Domain north-east of Cloncurry

and extends into the northern Soldiers Cap Domain as a fault-bounded basement high probably composed largely of intrusive and extrusive igneous rocks and probably some metasedimentary rocks. In this area, the western segment of the Soldiers Cap Domain is faulted against the Mary Kathleen Domain.
- In the north the domain appears to be faulted against the Camooweal–Murphy Domain along an extension of the Fiery Creek Fault, but it probably continues farther north off the coast under the Gulf of Carpentaria.

Claraville Domain



Extent / Distribution

- The Claraville Domain occurs in the north-eastern part of the study area, where it occupies an area ~370km x 100km. It extends east of the study area and is completely under Phanerozoic cover.

Principal geological components

- The Claraville Province is thought to consist largely of granitic rocks and some screens of metamorphic rocks, the latter being either part of the Soldiers Cap Group or extensions of the Etheridge Group that crops out in the Georgetown Inlier to the east (Withnall & others, 1997). The granitic rocks include both Mesoproterozoic granites (Esmeralda Suite — Withnall & others, 1997) and Middle Devonian granitoids (see below).
- Apart from geophysical data, a few drillholes have penetrated basement, the most significant were by Queensland Metals Corporation (Eason & Burban, 1985) near Savannah Downs. These holes intersected porphyritic biotite granodiorite. Some of this core was located in 2009 and has been dated as Middle Devonian (see below). Granite was also intersected in the bottom of petroleum well Gladevale Downs 1.
- Drilling by North Ltd of a prominent magnetic anomaly in the centre of a relatively non-magnetic area intersected magnetite-bearing phyllite (Wightman, 1995).

Age

- Core from the Queensland Metals drilling at Savannah Downs has given a SHRIMP magmatic age of 382±3Ma (Carson & others, in preparation).

Geophysical characteristics

- The Claraville Domain is mostly characterised by a moderate to high magnetic response and a series of oval to elliptical outlines suggesting nested plutons. A series of north to north-north-east and north-west-trending magnetic linears are also evident in places. Some of these are probably demagnetised zones produced by magnetite-destruction along faults. The patterns are more like those in Palaeozoic igneous complexes in the Georgetown and Charters Towers areas to the east than the Proterozoic batholiths in the Mount Isa Block.
- The Queensland Metals Corporation drillholes intersected a large annular magnetic high that rims a prominent magnetic low.
- Non-magnetic rocks cut by a network of linear magnetic bodies (dykes) in the north-east of the domain are probably Mesoproterozoic Esmeralda Suite granites.
- The Claraville Province is mostly represented by relatively low gravity anomalies, increasing slightly to the north, and consistent with a largely granitic terrane.

Structure / Deformation history

- Little is known about the detailed structure of the domain. A series of north to north-north-east and north-west-trending faults are interpreted from the magnetic data.

Inter/Intra province relationships

- The western boundary with the Soldiers Cap Domain trends north-north-west and ranges from an irregular and possibly intrusive contact to smooth and curvilinear. The latter is imaged as a east-dipping thrust in the deep crustal seismic line GA07-IG1 (Korsch & others, 2009).

Proterozoic Geodynamics of the Mount Isa Province

The Proterozoic Mount Isa Inlier of North-West Queensland preserves evidence of ~1900–1500Ma sedimentation and igneous activity. The following summary outlines the discrete changes in sedimentation, stress-field orientations and fault architecture and their interpreted kinematics that have influenced this region as a series of time-slices during the Palaeoproterozoic– Mesoproterozoic. Deposition occurred in the superimposed and unconformity bounded Palaeoproterozoic Leichhardt, Calvert and Isa superbasins (Jackson & others, 2000; Southgate & others, 2000) that were deposited on pre-1800Ma basement rocks. In addition, the region also records poly-phased deformation and a multi-staged metamorphic evolution.

This summary is based on a more detailed report prepared by PGN Geoscience in collaboration with GSQ staff and presented as Appendix 1, along with a time-space plot that details the chronostratigraphy and main tectonic events (Map 2 and Appendix 3). Both the report and time-space plot attempt to reconcile data and interpretations produced by research over the last two decades into a coherent evolution. In particular, they build on the synthesis of the Proterozoic evolution of the Mount Isa region as outlined by Betts & others (2006) by incorporating data and interpretations from the *pmd**CRC I1, I2+3 and I7 projects, recent GSQ mapping and the isotopic dating of Neuman & others (2006, 2009a,b), Carson & others (2008, and in preparation) and Magee & others (in preparation).

Because of the huge volume of other literature that could be quoted against many of the dot points, for clarity of presentation, we have not attempted to reference information and interpretations presented in this chapter. The reader is referred to the key bibliographic references listed in Chapter 1 and the more detailed report in Appendix 1.

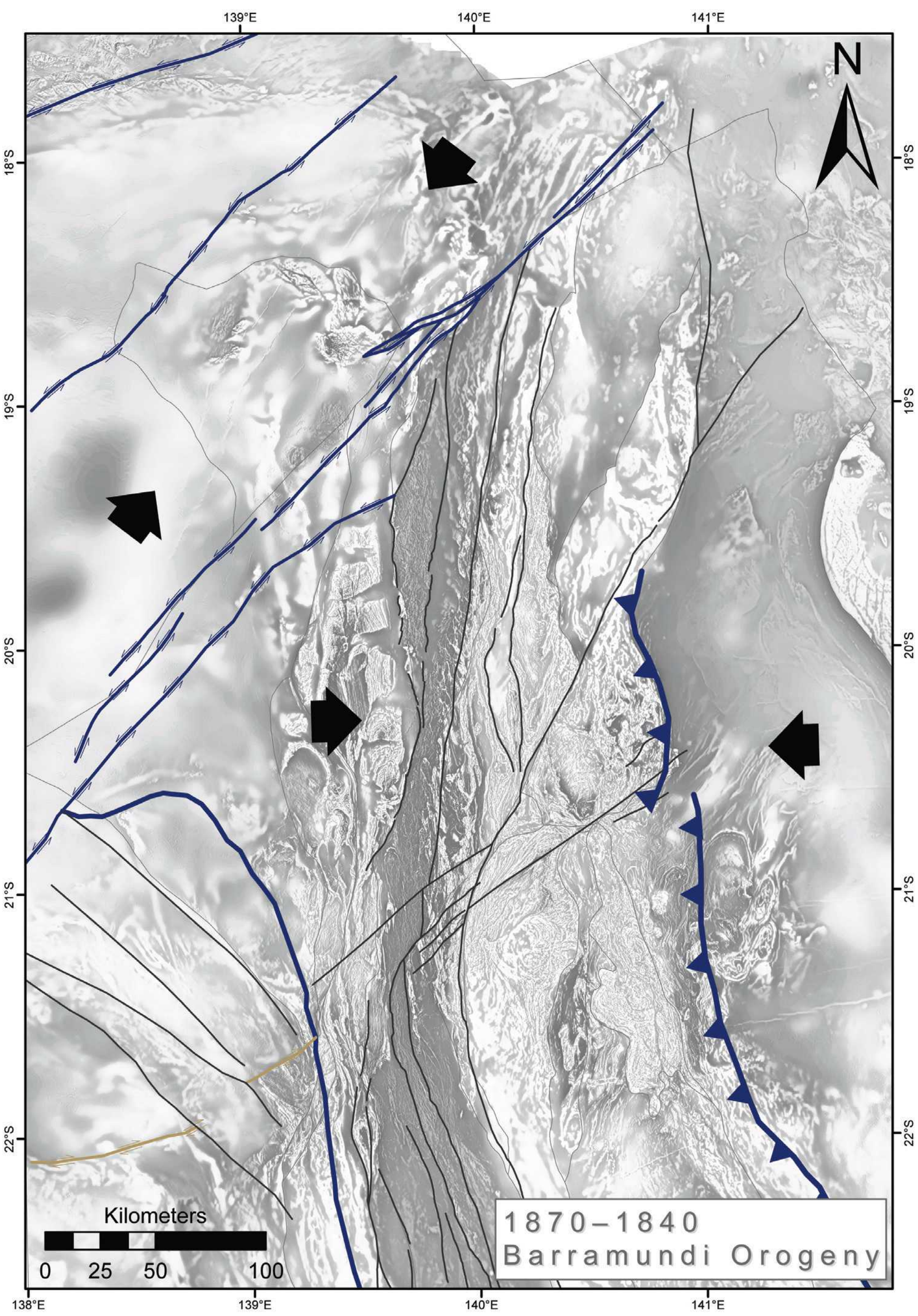


Figure 3.1: Fault architecture associated with E–W to NE–SW shortening during the Barramundi Orogeny

Pre-1870Ma Basement evolution

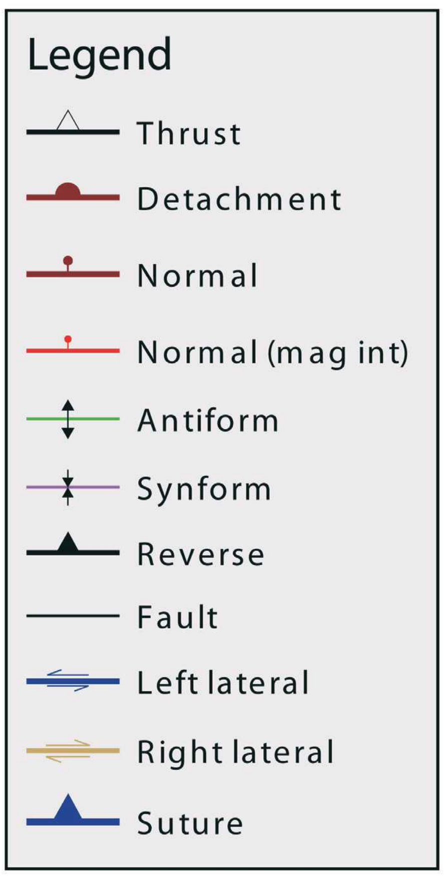
- The earliest known sequences within the exposed Mount Isa Inlier are basement rocks deposited prior to the 1870Ma Barramundi Orogeny. These include sequences now assigned to the Kurbayia Metamorphic Complex, Yaringa Metamorphics and Saint Ronans Metamorphics exposed as remnants within younger basement rocks forming the central spine of the Inlier.
- Deposition within the North Australian Craton (NAC) to the west at this time was controlled by the 1900–1870Ma Barramundi extensional event characterised by a NW-trending normal fault array offset by orthogonal NE-trending transfer structures. A NE-trending structure evident in the gravity data to the north of the Mitakoodi Domain may have also acted as a crustal tear.

1870–1840Ma Barramundi Orogeny

- Mount Isa basement represents a continental ribbon of pre-1870Ma rocks amalgamated to the NAC during rapid continental amalgamation along a major crustal boundary that defines the eastern boundary of the Ardmore–May Downs Domain.
- Kalkadoon Batholith and Leichhardt Volcanics at ~1870–1860Ma — possibly an arc(?) formed during west-dipping subduction along the eastern margin of the Australian continent
- This subduction zone may be represented by a major crustal boundary between the Numil Seismic Terrane (which underlies the Soldiers Cap Domain) and pre-1870Ma Mount Isa basement. This suture is evident in gravity and seismic data.
- Barramundi Orogeny (1870–1850Ma) is characterised by the development of migmatites, an intense bedding-parallel gneissic foliation and N–S-trending upright folds during a regional E–W shortening event.

1840–1800Ma post-Barramundi Orogeny

- Intraplate magmatism represented by the Big Toby Granite, Monaghans Granite and Yeldham Granite, intruded 1800–1820Ma.
- Bimodal Bucket Hole Volcanics were erupted in the Ardmore–May Downs Domain at ~1823Ma.



Legend for Figures 3.1 to 3.11

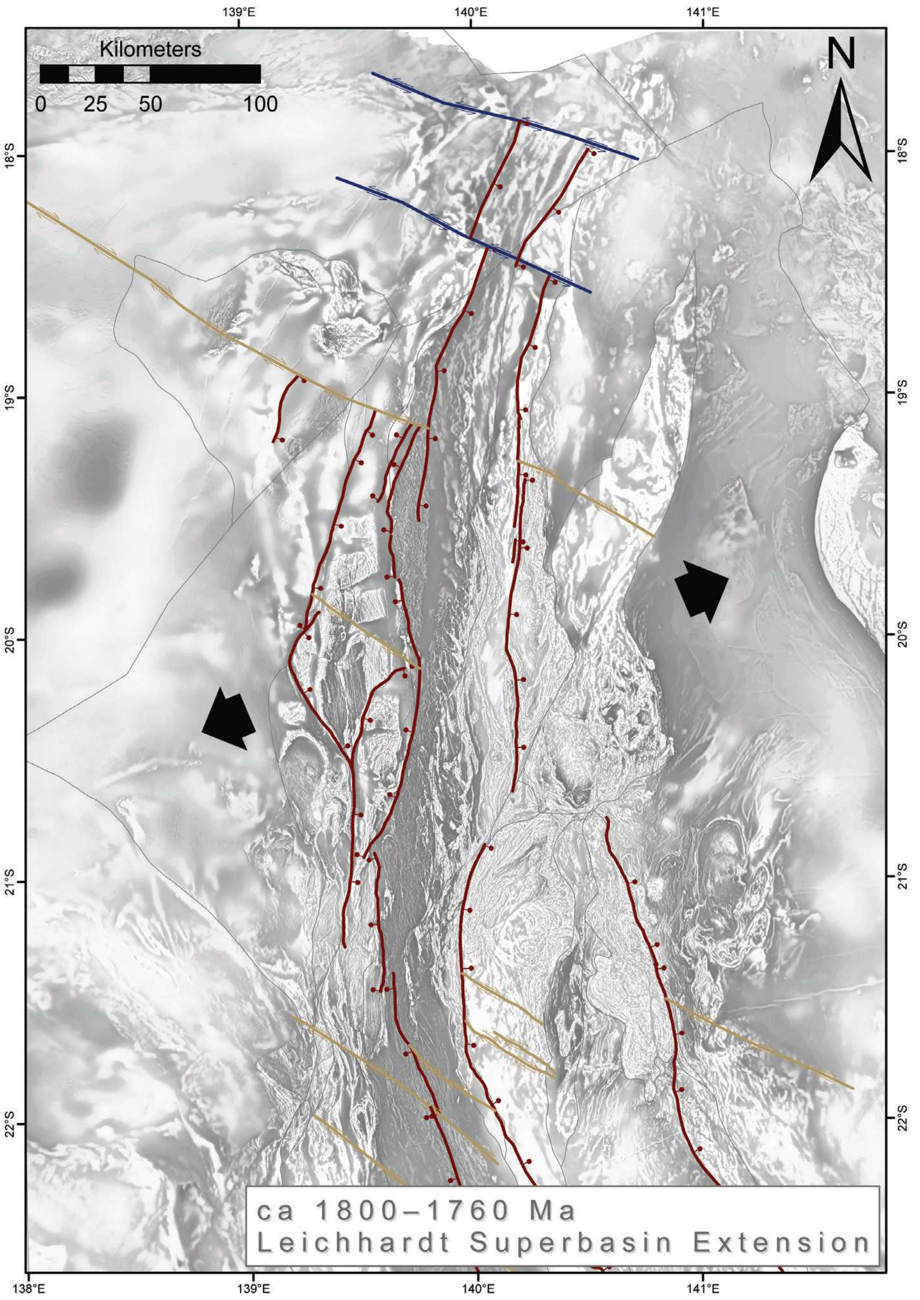


Figure 3.2: Fault architecture of the Mount Isa Inlier between ~1800Ma and 1750Ma. The basin evolution occurred during ENE–WSW extension associated with the development of the Leichhardt Superbasin.

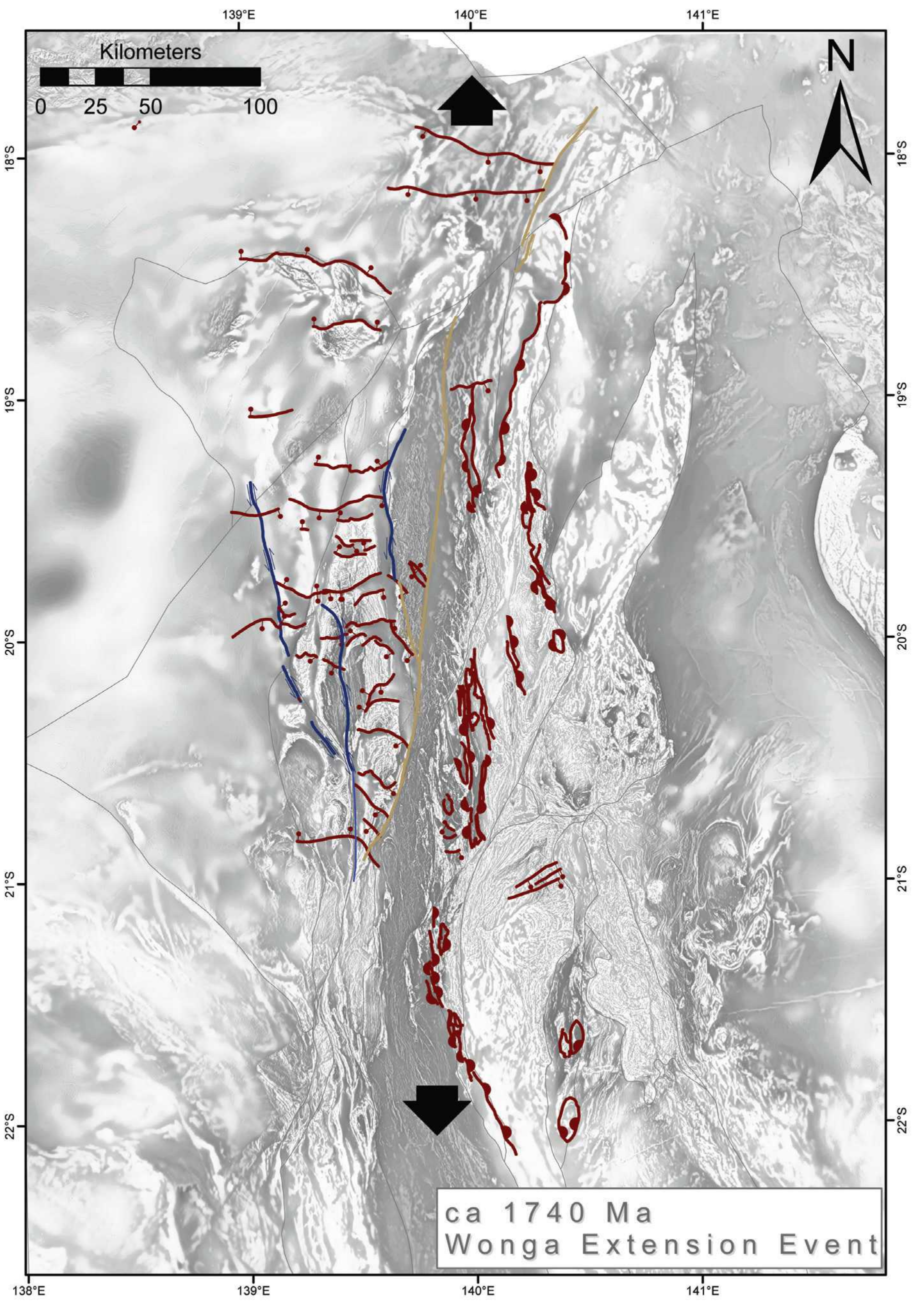


Figure 3.3: North–south directed extension during ~1740Ma Wonga event

1800–1740Ma Leichhardt Superbasin extension

- Episode of major lithospheric extension characterised by fluvial to shallow marine sedimentation in north-south rift axes (pre-1780Ma?) (Leichhardt River Domain)
- Bimodal volcanism in the east — mafic Magna Lynn Metabasalt, felsic Argylla Formation (~1780Ma) (Kalkadoon–Leichhardt and Mary Kathleen Domains)
- Farther east in Mary Kathleen Domain, the Boomarra Metamorphics (~1780Ma) may be partly equivalent to the Argylla Formation
- Voluminous outpouring of continental tholeiitic basalt (Eastern Creek Volcanics) up to 8km thick (close to break-up?) (mainly Leichhardt River Domain)
- Polarity changes across ~E–W to NW-trending transfer faults in the Leichhardt River Domain
- Deposition of the ~1775–1760Ma Myally Subgroup
- Transfer faults reactivated during deposition of the Myally Subgroup
- Younger bimodal volcanism in the Mitakoodi Domain east of the Pilgrim Fault Zone represented by the felsic Bulonga Volcanics (~1760Ma) and basaltic Marraba Volcanics. Deposition of the protoliths of the Double Crossing Metamorphics in the Marimo–Staveley Domain
- Major fault architecture dominated by N–S trending rift bounding faults (possibly including Pilgrim and Cloncurry Fault Zones)
- ~1755Ma syn-rift faults in the Mitakoodi Domain and during deposition of the Ballara Quartzite in the Mary Kathleen Domain represent the end of the Leichhardt Superbasin extension
- Post-rift sag-phase is represented by the carbonate successions of the Corella Formation (east) and upper Quilalar Formation.

1740–1730Ma Wonga extension event

- Major expression is an intensely folded, 1–1.5km thick mid-crustal shear zone with north–south extension along a narrow belt in the Mary Kathleen Domain (Holcombe & others, 1991).
- High temperature amphibolite facies metamorphic conditions
- Emplacement of granitoids into the shear zone and upper plate (Wonga and Burstall Suites) at ~1740Ma. These intrude and constrain the age of the Corella Formation.
- Gneissic domes in the Kuridala–Selwyn Domain consisting of Gin Creek Granite and Double Crossing Metamorphics — probably metamorphic core complexes
- The Levian and Dipvale Granites were emplaced into the Canobie Domain and may be comagmatic with the Mount Fort Constantine Volcanics (~1740Ma).
- Appears to be a lack of sedimentation across the Mount Isa Inlier following the Wonga event and cessation of deposition of the Corella Formation.
- Formation of numerous small Cu deposits in Mary Kathleen Domain
- Formation of Tick Hill gold mineralisation.

1730–1725Ma basin inversion

- Inversion of the Leichhardt Superbasin is recorded in the Mount Oxide, Century and Leichhardt River Domains.
- Inclined north–south folds to the east of the Fiery Creek Domain (Mellish Park Syncline)
- Overturned folding in the southern Leichhardt Domain
- Uplift and erosion along the eastern Leichhardt River Domain — thinning evident across the Mount Gordon Arch.

1720–1700Ma initiation of Calvert Superbasin

- NW–SE extension in the Leichhardt River, Mount Oxide, Century and Camooweal–Murphy Domains
- Characterised by NE-striking normal faults and NW-striking transfer faults
- Possible intrusive-related doming (Fiery Creek Dome cored by Weberra Granite)
- Syn-extension bimodal volcanism (Fiery Creek Volcanics)
- Fluvial to shallow marine environment (Big Supersequence)
- Deposition of Staveley Formation and Roxmere Quartzite (~1710Ma) — Marimo–Staveley and Doherty – Fig Tree Gully Domains.

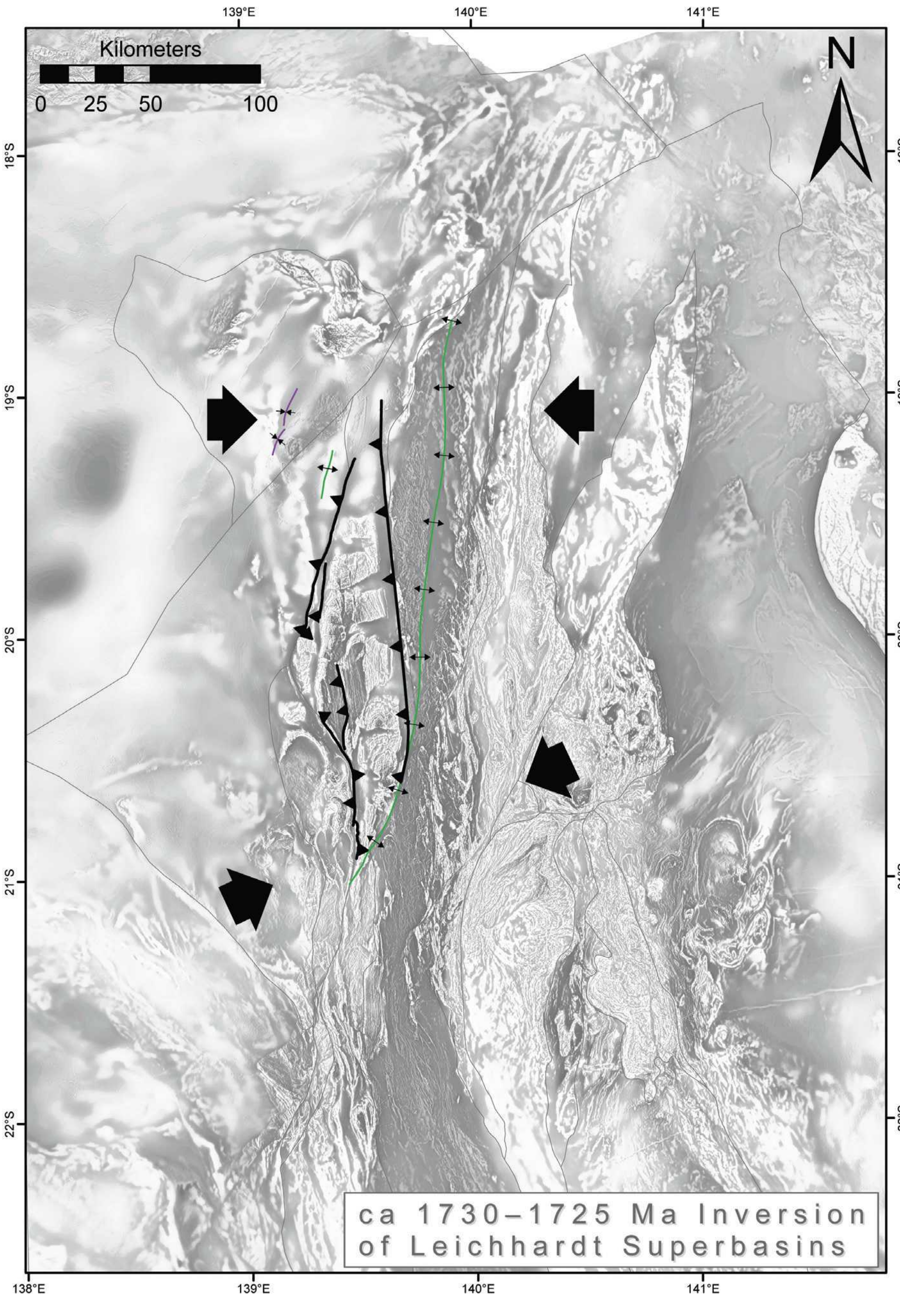


Figure 3.4: E–W to NE–SW-trending shortening during ~1730–1725Ma Leichhardt Superbasin Inversion

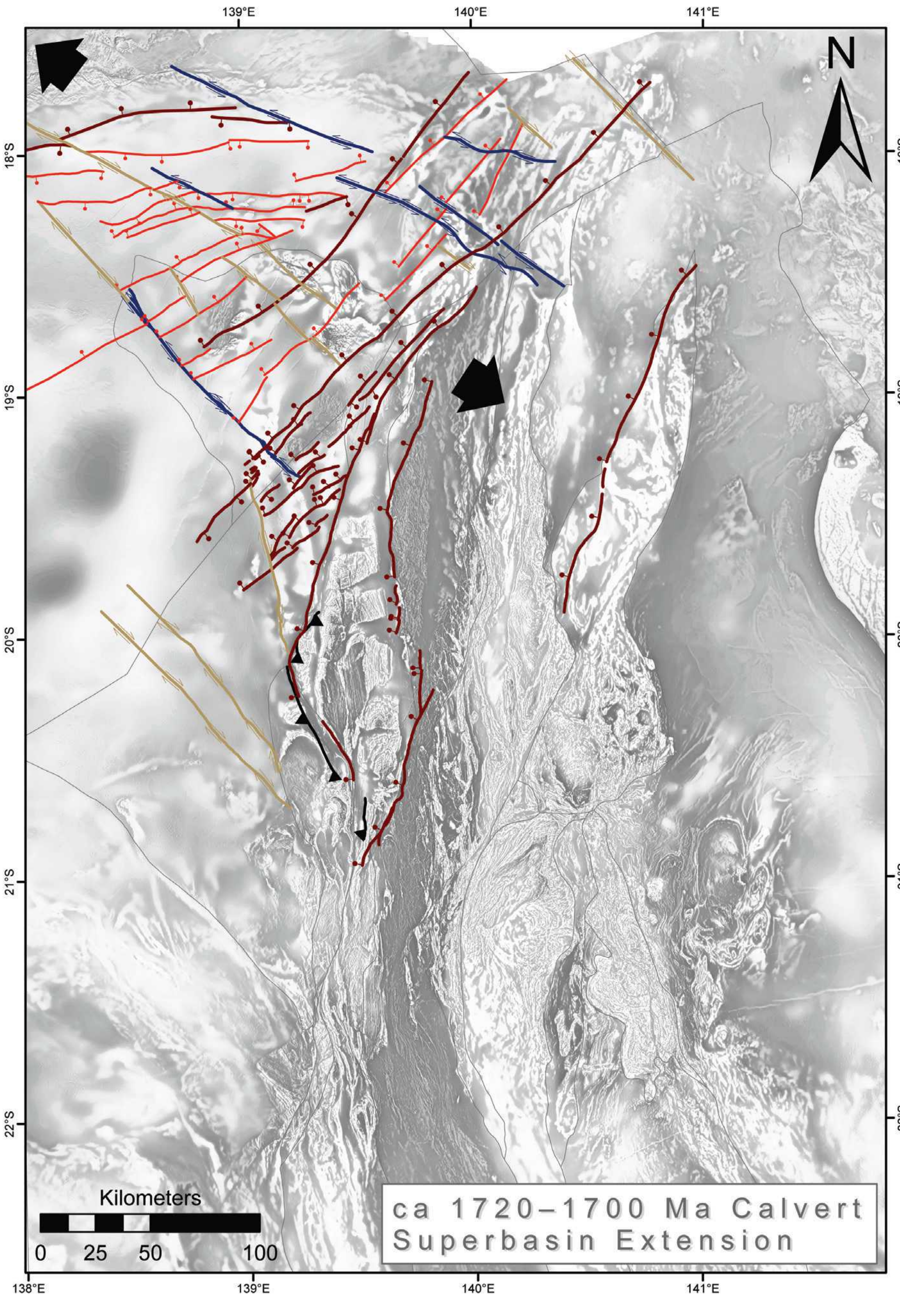


Figure 3.5: NW–SE directed extension during the development of the ~1720–1700Ma Calvert Superbasin

1700–1690Ma Mid-Calvert Superbasin inversion

- Restricted to regions immediately west of the Leichhardt River Domain
- Uplift and erosion of the Bigie Formation and Fiery Creek Volcanics in the northern part of the Sybella Domain, so that Surprise Creek Formation unconformably overlies Eastern Creek Volcanics.

1690–1670Ma Late Calvert Superbasin extension

- Switch to NNE–SSW extension
- Deposition of the Surprise Creek Formation throughout the Kalkadoon, Leichhardt River, Mount Oxide and Century Domains
- In the Myally Sub-basin (Kalkadoon–Leichhardt Domain), NW-trending normal faults control deposition of the Surprise Creek Formation.
- Mid-crustal ductile extensional shear zone (decollement) cored by Sybella Batholith and its high temperature metamorphic aureole (lower plate) in the Sybella Domain — metamorphic core complex
- Stratigraphic excision across major fault zones
- In the Mary Kathleen Domain, the lower part of the Mount Albert Group (Knapdale Quartzite and Deighton Quartzite) was probably deposited during this interval.
- Deposition of the lower part of the Kuridala and Soldiers Cap Groups in the eastern part of the Inlier
- Continuous sedimentation from late Calvert to early Isa Superbasin time likely in the east, but a sedimentary hiatus occurs in the west contemporaneous with the Sybella mid-crustal extension event.
- Cloncurry Fault Zone — major extensional normal fault in likely ENE–WSW extension direction.

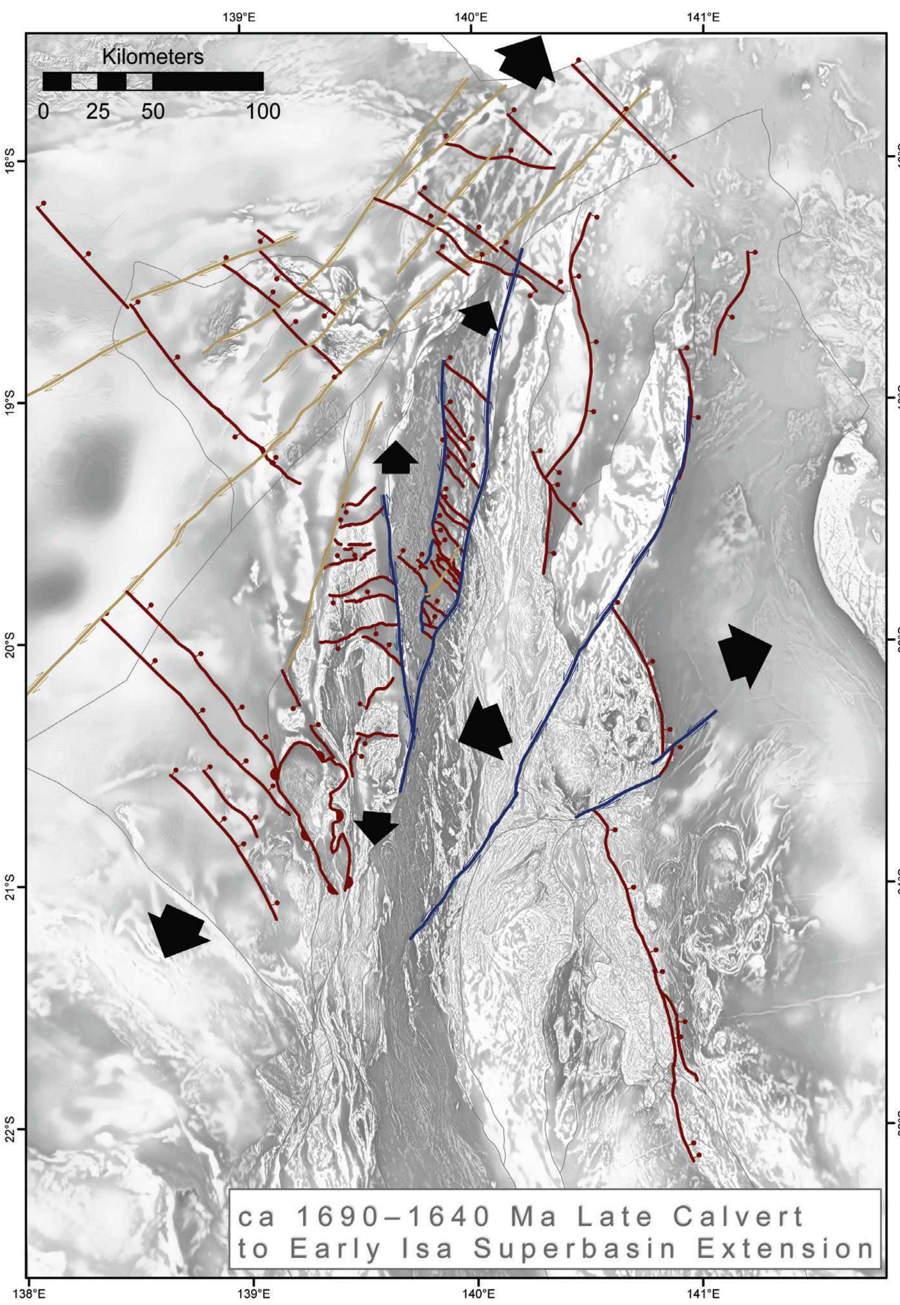


Figure 3.6: Strongly partitioned regions of N–S to ENE–WSW directed extension during Late Calvert Superbasin evolution and the development of the Isa Superbasin

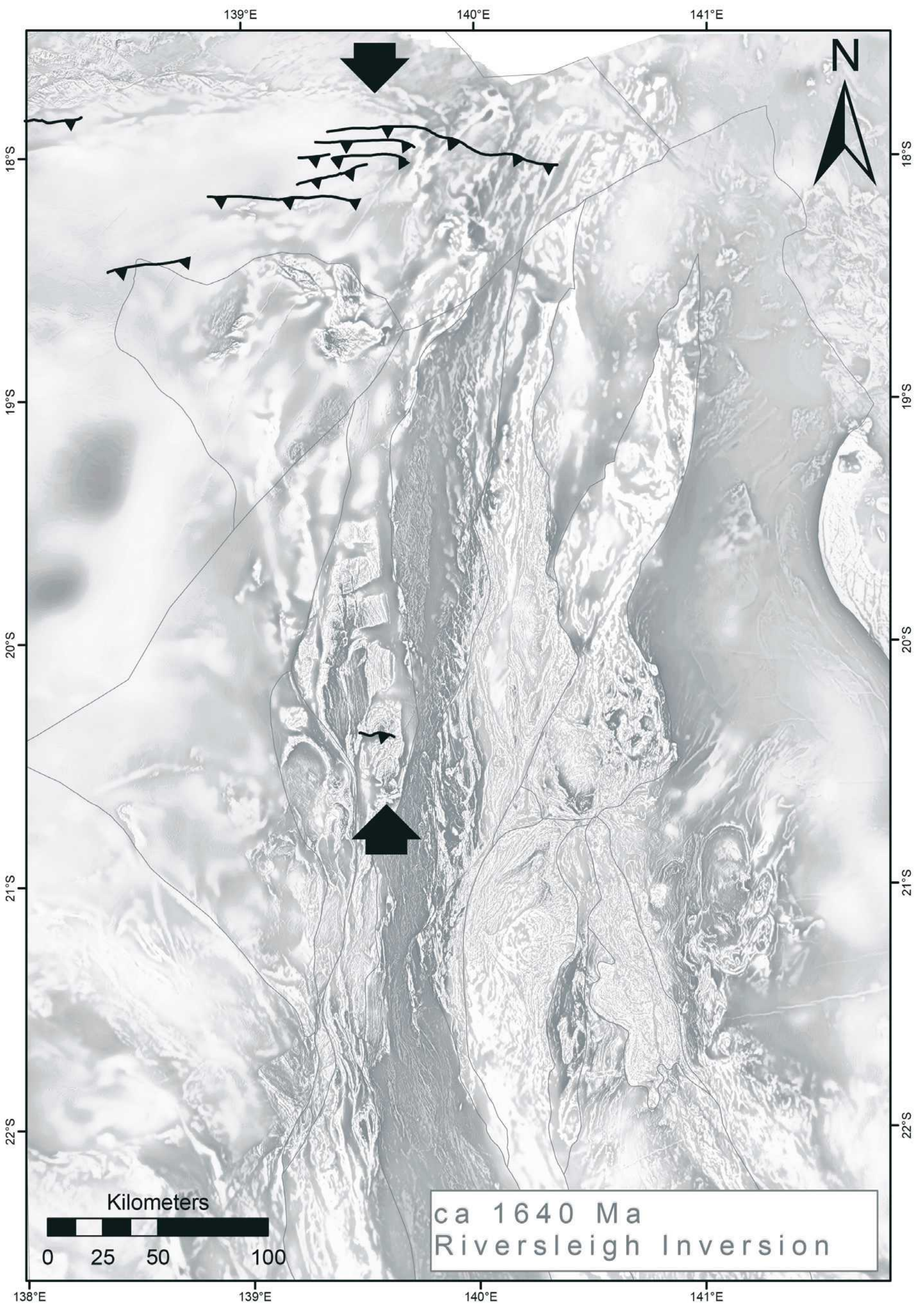


Figure 3.7: East–west trending reverse faults reactivated during the ~1640Ma Riversleigh inversion

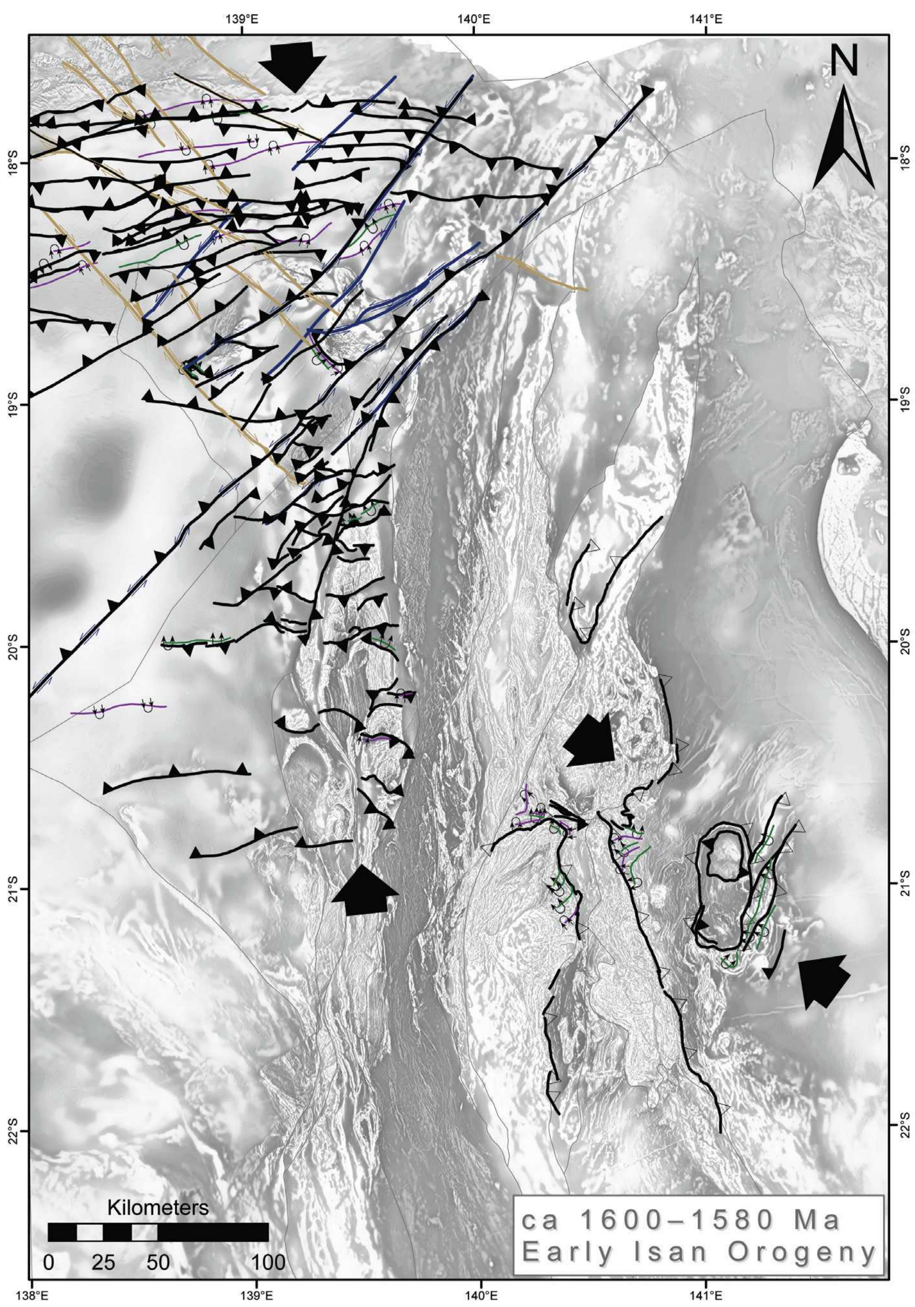


Figure 3.8: Development of north-directed thrusting; east–west fold axes in the west and NE–SW fold axes in the east during the ~1600–1580Ma Early Isan Orogeny

1670–1640Ma initiation of Isa Superbasin

- Initial phase of NNE–SSW extension followed by the onset of sag-phase sedimentation of the Isa Superbasin
- Deposition of the lower Mount Isa Group (Native Bee Siltstone, Urquhart Shale, Spear Siltstone, Kennedy Siltstone, Magazine Shale) in the Leichhardt River Domain
- Deposition of the McNamara Group (Paradise Creek Formation, Esperanza Formation, and Fish River Formation) in the Century, Mount Oxide and Ardmore – May Downs Domains
- Possible continued deposition of the Mount Albert Group in the Mary Kathleen Domain (Lady Clayre Dolomite, Mount Roseby Schist)
- Deposition of the upper Soldiers Cap Group (Mount Norna Quartzite, Toole Creek Volcanics) in the Soldiers Cap Domain
- Deposition of the Answer Slate in the Marimo–Staveley and Kuridala–Selwyn Domains
- Dugald River lead-zinc orebody formed at ~1670–1665Ma (Pb isotope model age)
- Cannington lead-zinc orebody formed at ~1665Ma (Pb isotope model age)
- Mount Isa, George Fisher and Hilton lead-zinc orebodies formed at ~1655–1650Ma (Pb isotope model ages)

1640Ma Riversleigh inversion

- Evidence from seismic reflection data in the northern Camooweal–Murphy Domain
- Reverse reactivation of faults evident in the Riversleigh Formation and draped by younger successions
- Change in sedimentary patterns — excision of tabular stratigraphy beneath the Riversleigh Formation and wedge-shaped stratal geometries above the unconformity
- Transition in the basin evolution — evidenced by a change from carbonates to deeper marine successions
- Coincides with a bend in Australian Apparent Polar Wander Path
- Coincides with lead-zinc mineralisation in the McArthur Basin
- Lady Loretta zinc-lead orebody formed at ~1640Ma (Pb isotope model age)
- ~1640Ma foliation preserved in the core of porphyroblasts in the Soldiers Cap Domain — possibly a mid-crustal expression of this event.

1640–1590Ma Late Isa Superbasin

- The waning stages of Isa Superbasin evolution are represented by the upper McNamara Group, which is restricted mainly to the Century and Camooweal–Murphy Domains, with deposition of deep-water clastics.
- May have been initiated during regional strike-slip and extensional tectonism
- The later part of the deposition of these sediments was during the onset of the Isan Orogeny and may reflect deposition into existing accommodation space due to wrenching.
- Unlikely to represent the remnants of a foreland basin proposed by some authors
- Deposition of siliciclastic sediments, minor carbonates and black shale as well as eruption of bimodal volcanics in the Tommy Creek Domain (~1650–1610Ma)
- Grevillea and Walford Creek zinc-lead orebodies formed at ~1630Ma.

1600–1580Ma Early Isan Orogeny

- Major N–S to NW–SE directed shortening event
- To the west of the Kalkadoon–Leichhardt Domain, strain is controlled by pre-existing extensional fault architecture and involves localised folding and reverse reactivation of normal faults.
- To the east of the Mary Kathleen Domain, strain is thin-skinned with NW-directed lateral translations of nappes comprising rocks equivalent to the Calvert and Isa Superbasin succession (e.g. Marimo Domain, Kuridala–Selwyn Domain).
- Major zones of movement include Overhang Shear Zone and Cloncurry Overthrust.
- Peak metamorphic conditions (upper amphibolite facies)
- Possible drivers for metamorphism include:
  - Inherited elevated geothermal gradients from an episode of crustal extension leading up to the Isan Orogeny
  - Heat derived from voluminous mafic intrusions in the mid-crust
  - Syn-orogenic delamination of the subcontinental lithospheric mantle
  - Emplacement of high heat producing granites in the upper crust followed by burial by thermally insulating sediments (in the case of the Sybella Domain)
- Formation of ironstone-hosted Cu-Au mineralisation at Starra and Osborne.

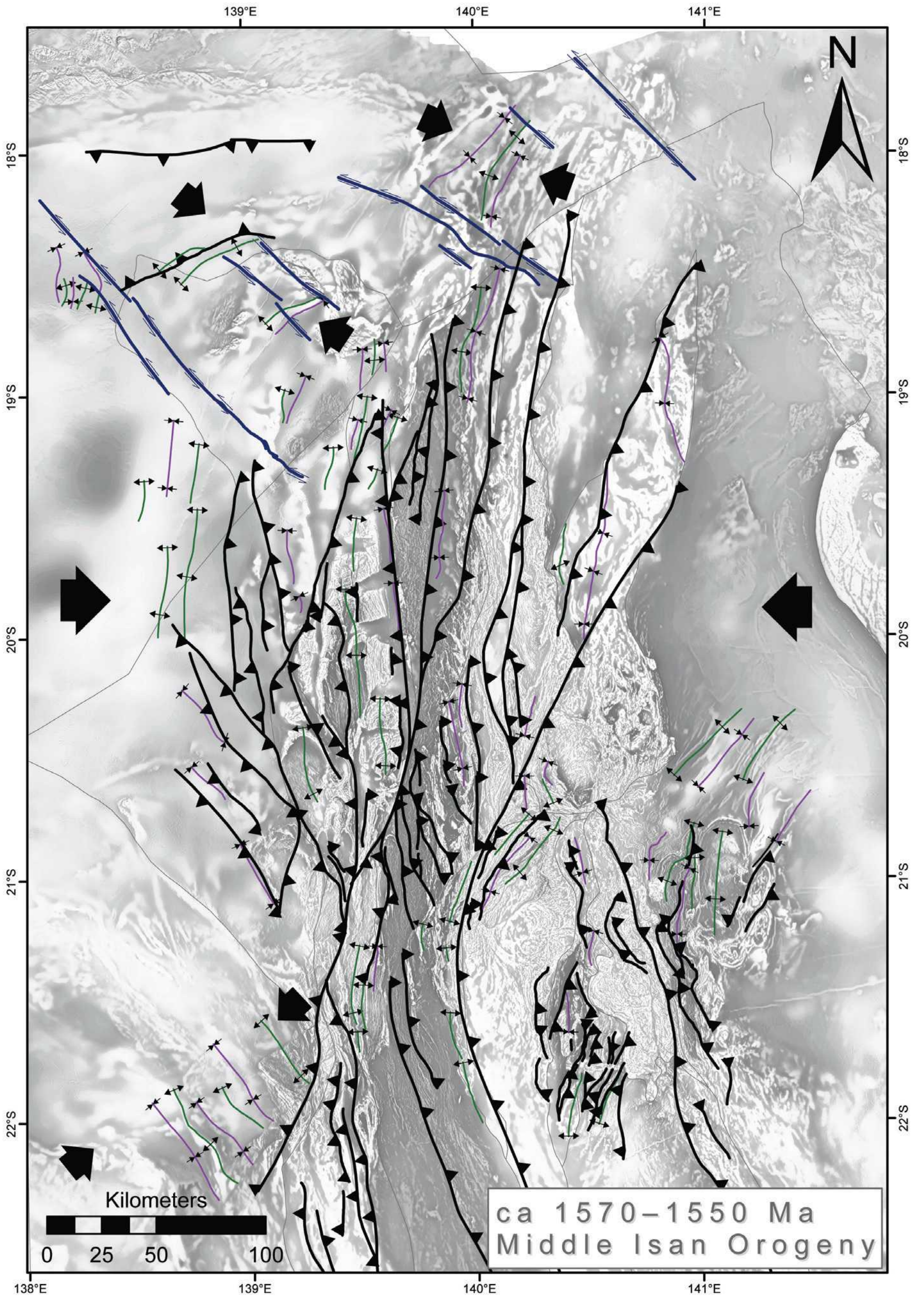


Figure 3.9: Partitioned E–W shortening in the central Mount Isa Inlier and NW–SE shortening in the north-west of the Inlier reactivating pre-Isan structures

1570–1550Ma Middle Isan Orogeny

- Major ~E–W crustal shortening event that defines the structural grain of the Mount Isa Inlier
- Large anticlinal culminations (wavelengths 10km) in the Leichhardt River Domain (Leichhardt Anticline), Mitakoodi Domain (Duck Creek Anticline) and Soldiers Cap Domain (Snake Creek Anticline)
- Development of steeply dipping to vertical axial planar foliations
- Reverse reactivation of major fault systems
- Variations in the apparent shortening direction between different domains are related to local variations in stress and the influence of pre-existing basement and basin fault architecture
- The peak of metamorphism in the Mary Kathleen Domain is linked to steep, north–south structures formed during east–west compression in the Middle Isan Orogeny
- Foliated siliciclastic metasediments intersected by GSQ Dobbyn 1 in the northern Soldiers Cap Domain were deposited post-1590Ma after the onset of the Isan Orogeny.
- Century zinc-lead orebody formed at ~1575Ma (Pb isotope model age).

1550–1540Ma Mid-Isan Orogeny: Wrench Tectonics

- Continued E–W shortening with local variations
- Transition from ductile folding to brittle deformation characterised by wrench tectonics
- Major movement was focussed in the central Kalkadoon–Leichhardt and Mary Kathleen domains
- Largest offsets are along NE-trending dextral faults (up to 30km offset for the Fountain Range Fault)
- Associated with conjugate NW-trending sinistral fault arrays
- Reverse reactivation of Middle Isan Orogeny faults
- Local upright folding and axial planar cleavages
- Valhalla and Andersons uranium mineralisation dated at ~1550–1530Ma.

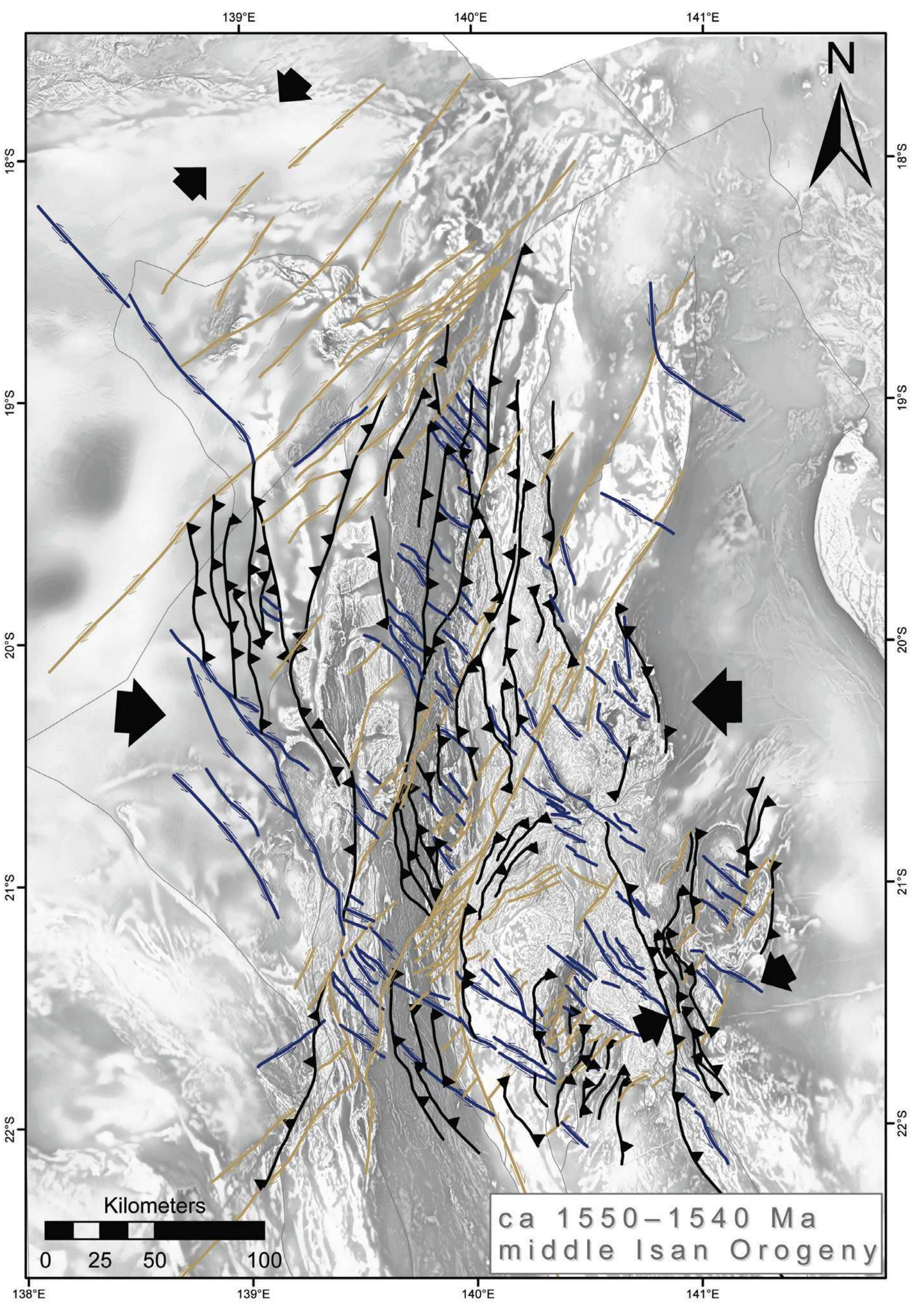


Figure 3.10: Strike-slip dominated fault during ~1550–1540Ma E–W to NW–SE directed shortening

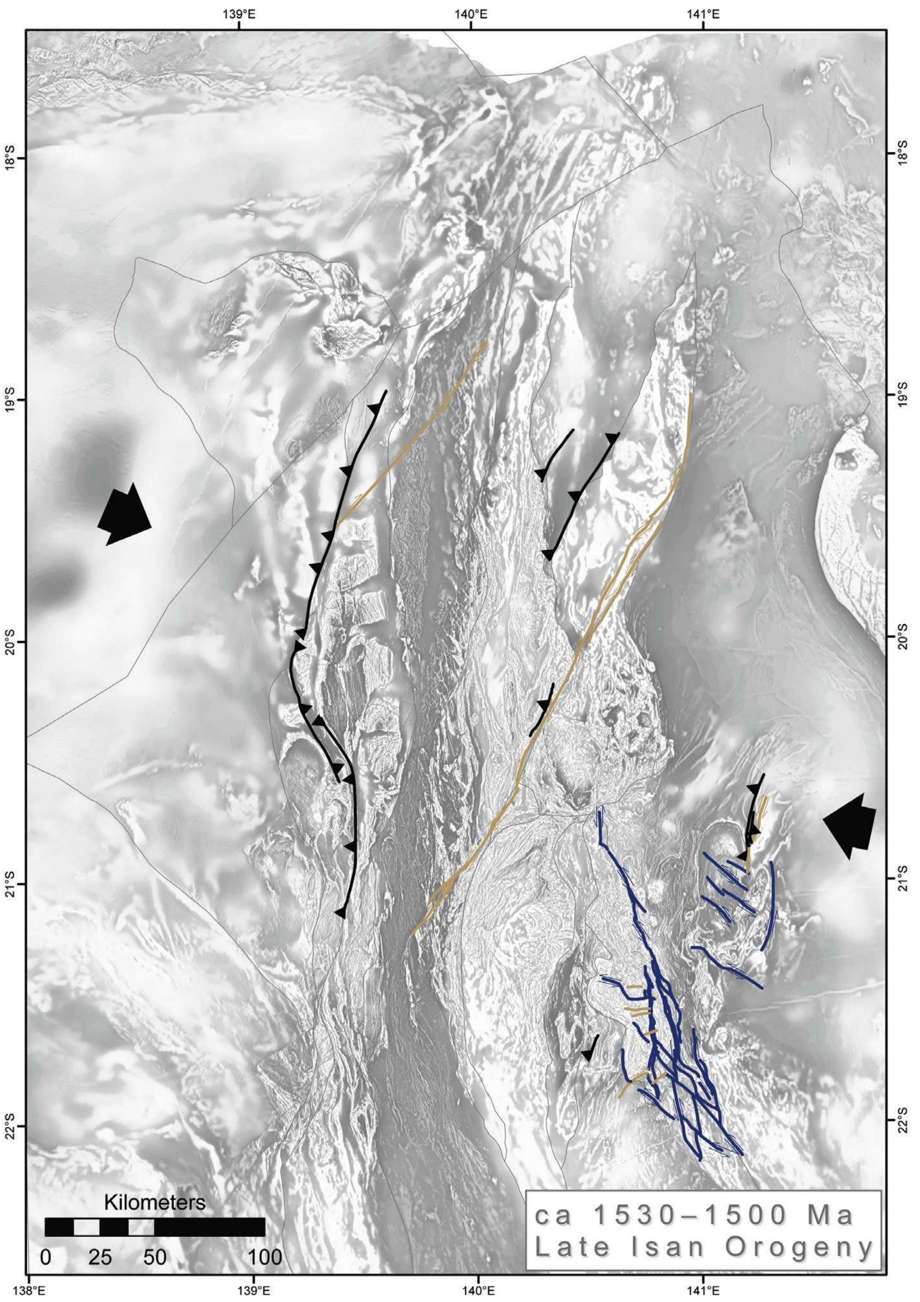


Figure 3.11: Wrench and reverse faulting during the ~1530–1500Ma Late Isan Orogeny

1530–1500Ma Late Isan Orogeny

- ESE–WNW directed shortening
- Brittle reactivation of major fault systems in both the Leichhardt River and Soldiers Cap Domains
- Synchronous with the emplacement of voluminous granitoids of the Williams Supersuite
- Mount Isa copper mineralisation dated at ~1523Ma ($^{40}Ar/^{39}Ar$ biotite dating)
- Formation of breccia- and shear-hosted Cu±Au±iron oxide mineralisation at Mount Elliott, Ernest Henry, E1, Eloise, Mount Dore, etc
- Possible age of skarn lead-zinc mineralisation in east.

Australian Proterozoic Correlations and Geodynamic Synthesis

The absence of exposed post-1850Ma plate boundaries in the Mount Isa Inlier has made the geodynamic context, in which the inlier has evolved, subject to a large amount of speculation and debate. There has been a recent trend away from intraplate tectonic models, which were popular in the 1980s and early 1990s. These models have given way to interpretations that mainly involve plate tectonics processes. Many interpretations of the tectonic context of the inlier have relied on regional correlations with other geological provinces such as the Curnamona Province, Gawler Craton, Georgetown Inlier and the Arunta Block.

This chapter summaries the tectonic context of the Mount Isa Inlier from the perspective of major tectonic events of Proterozoic Australia between ~1870Ma and 1500Ma. It is based on a more detailed review prepared by PGN Geoscience and included with this report as Appendix 2. In that review, the authors correlated the geology and major tectonic events of the Mount Isa Inlier with surrounding geological provinces and used these relationships to constrain a geodynamic model. The evolution of the continent is broken into discrete time-slices that pertain to the evolution of the Mount Isa Inlier. This chapter should be read in conjunction with the Eastern Australia Proterozoic Time-space plot (Map 3 and Appendix 4).

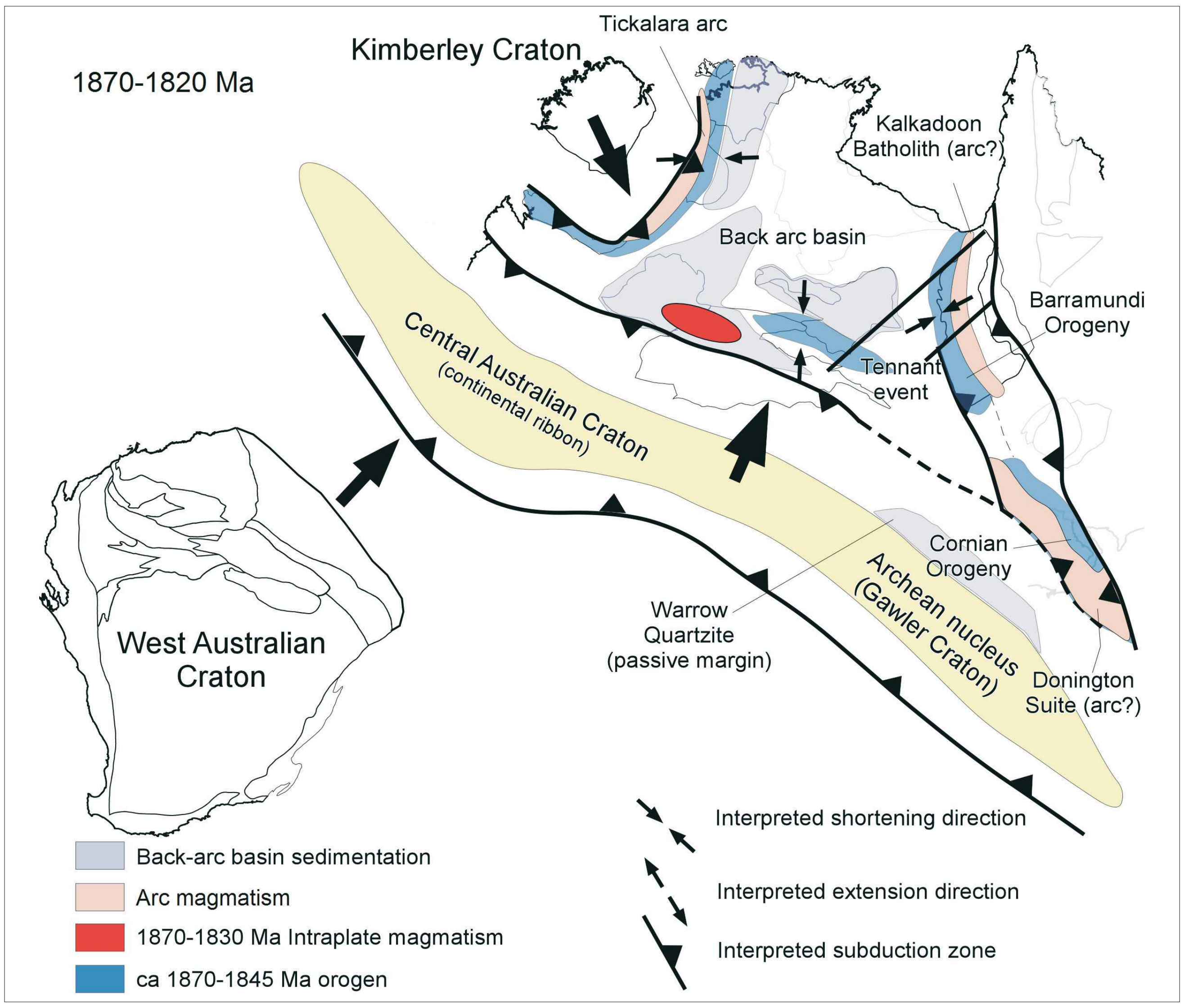


Figure 4.1: Time Slice 1: 1870–1820Ma

Time Slice 1: 1870–1820Ma

Mount Isa

- ~1870–1850Ma Barramundi Orogeny: Orogenic event that is preserved in the central and western Mount Isa Inlier and is characterised by the development of intense gneissic foliation and north trending upright folds. Peak greenschist facies metamorphism in the Ardmore–May Downs Domain and upper amphibolite facies in the Kalkadoon–Leichhardt Domain. Metamorphism of the protoliths of the Kurbayia Migmatite, Yaringa Metamorphics, Plum Mountain Gneiss, Saint Ronans Metamorphics and Sulieman Gneiss
- ~1860–1850Ma: Emplacement of the Kalkadoon and Ewen Batholiths along a prominent north–south trending linear belt in the central part of the inlier and extrusion of the felsic Leichhardt Volcanics within the Kalkadoon–Leichhardt Domain
- ~1850Ma: Metamorphism of the protoliths of the Murphy Metamorphics in the Camooweal–Murphy Domain
- ~1845Ma: Emplacement of the Nicholson Granite Complex and eruption of the Cliffdale Volcanics in the Camooweal–Murphy Domain.

Kimberley – Halls Creek – King Leopold

- ~1870–1865Ma: Deposition of turbidites of the Hooper Complex (Lamboo Complex) onto the Kimberley Craton (Tyler & others, 1999). A separate package of turbidites of the Tikalara Metamorphics was deposited ~1865–1860Ma in an oceanic island arc setting position between the Kimberley Craton and the North Australian Craton (Sheppard & others, 2001).
- ~1870–1860Ma Hooper Orogeny: High temperature – low pressure metamorphic event that was synchronous with the emplacement of the granites of the Paperbark Suite and the Bow River Batholith (Tyler & others, 1999).
- ~1865–1850Ma: Extrusion of the felsic Whitewater Volcanics and emplacement of granites of the Paperback Suite within the Lamboo Complex (Tyler & others, 1999). The Paperbark Suite is interpreted to have been emplaced in an island arc setting or above a south-east dipping subduction zone (Sheppard & others, 2001).
- ~1855–1820Ma Halls Creek Orogen/King Leopold Orogen: These orogens are preserved along the south-eastern and south-western margins of the Kimberley Craton and are characterised by poly-deformation of Paleoproterozoic arc terranes and passive margin sediments (Tyler & others, 1995; Sheppard & others, 1999; Blake & others, 2000).
- ~1850Ma: Emplacement of tonalite and trondhjemite of the Dougall Suite in an island arc setting (Tickalara arc) (Sheppard & others, 1999).

Granites–Tanami terrane

- ~1865Ma: Deposition of the 1865Ma sandstone, siltstone, mudstone, and basaltic magmas of the Stubbins Formation. Magmatism and deposition occurred in a continental back arc setting (Bagas & others, 2010).
- The Stubbins Formation is unconformably overlain by the lower Tanami Group (~1850–1835Ma).
- ~1850Ma: Early deformation phases of the Tanami Orogeny (Bagas & others, 2010)
- ~1845Ma: Emplacement of Inspiration Creek Granite.

Pine Creek

- ~1885–1865Ma: Emplacement of the Nimbuwah Complex
- ~1870–1860Ma: Deposition of siltstone, formation of schist, phyllite and chert and eruption of pitchstone and andesite of the South Alligator Group (Worden & others, 2008)
- ~1870–1860Ma: Emplacement of the Zamu Dolerite
- ~1860Ma: Emplacement of the Jammine Granite and the Wagait Suite granitoids
- ~1860–1850Ma: Finniss River Group, which comprises siltstone, greywacke, sandstone, felsic to mafic volcanic successions
- ~1860–1850Ma Top End Orogeny (Nimbuwah Event): This event is characterised by upright north-north-west trending, close-tight folding overprinted by low amplitude, open east-trending folds formed during regional magmatism (Ahmad & others, 1993; Needham & others, 1988). The final deformation phase produced kinks and drag folding along major faults (Ahmad & others, 1993). High-temperature, low-pressure peak metamorphic conditions varied from greenschist facies to granulite facies (Carson & others, 2008b).

Tennant Creek/Davenport

- ~1880–1860Ma: Deposition of siltstone, shale minor jaspilite, chert and banded ironstone and extrusion of felsic lava and tuff of the Warramunga Formation, Woodenjerrie Beds, and Junalki Formation
- ~1860–1850Ma: Emplacement of the granites and granodiorites of the Tennant Creek Suite, Mumbilla Granite and Cabbage Gum Granite
- ~1850Ma: Tennant Event: Minor deformation event synchronous with granite emplacement.

Arunta Inlier

- ~1880Ma: Emplacement of I-type diorite, tonalite, granodiorite, and granite of the Atnarpa Igneous Complex
- ~1850–1840Ma: Deposition of turbidite successions of the Landers Package above the suture between the northern Arunta lnlier and the Tanami Province.

Gawler Craton

- ~1865Ma: Deposition of the Warrow Quartzite and associated volcanic successions (possibly on a passive margin) (Szpunar & others, 2007)
- ~1865Ma: Deposition/eruption of the rhyolites and calc-silicates of the Bosanquet Formation (Reid & others, 2008)
- ~1850Ma: Emplacement of the voluminous Donington Suite granitoids along a 600km north-trending belt throughout the eastern Gawler Craton (Hand & others, 2007)
- ~1850–1845Ma Cornian Orogeny: Deformation event recorded in the eastern Gawler Craton involving high temperature low pressure metamorphism and clockwise P-T evolution. Deformation and north directed non-coaxial shortening. South-side-down extension synchronous with ~1843Ma microgranites mark the end of the Cornian Orogeny (Reid & others, 2008).

Tectonic interpretations

- The interval ~1870–1830Ma marks a rapid period of continental amalgamation in the North Australian Craton (Betts & others, 2002) coincident with the formation of the supercontinent Columbia (Nuna).
- Continental growth along the eastern margin of the North Australia Craton appears to have involved the docking of a ribbon continent bounded by large sutures on either side. Deformation associated with this accretion is termed the Barramundi Orogeny. The Mount Isa lnlier represents the northern segment of this ribbon and is bounded by a suture on the eastern and western margins. The southern section is possibly preserved in the eastern Gawler Craton to the east of the Kalinjala Shear Zone.
- The Cornian Orogeny also records the collision of the Archaean nucleus of the Gawler Craton onto the margin of the North Australian Craton.
- The Ailleron Province in the northern Arunta and Granites–Tanami terrane accreted along the Willowra Suture (Lineament) and was subsequently draped by the Landers Package (~1840Ma).
- The Central Australian Craton consists of the Arunta lnlier and the central nucleus of the Gawler Craton. Subduction occurred to the south.
- The Donington Suite and the Kalkadoon Batholith may have formed a ~1860–1850Ma belt of granite rocks that extends for greater than 2500km parallel to the sutures zones and therefore it is interpreted that these granites form a continental magmatic arc in this accretionary system.
- The Kimberley Craton collided with the western margin of the North Australian Craton forming the Halls Creek Orogen, which consists of an amalgamation of oceanic arcs and passive margin sedimentary successions.
- The Tennant Event (Tennant Creek/Davenport) records the distal effects of the Ailleron–Tanami collision.
- The interior of the North Australian Craton was subject to turbidite dominated back-arc basin development.

Time Slice 2: 1820–1790Ma

Mount Isa

- ~1820–1800Ma: Emplacement of the Yeldham Granite in the Century Domain
- ~1800Ma: Emplacement of the Little Toby Granite in the Ardmore – May Downs Domain.

Rudall Complex

- ~1820–1795Ma: Yapungku Orogeny (Smithies & Bagas, 1997). Collisional orogenic event associated with the amalgamation of the Central Australian Craton and the West Australian Craton. Orogenesis is characterised by isoclinal folding, stacking of east- and north-east-dipping thrust slices. This event is characterised by medium-pressure peak metamorphism (12kPa, 800°C) and a decompressive clockwise pressure-temperature path (Smithies & Bagas, 1997). Syn- and post-tectonic granites were emplaced ~1790–1765Ma (Bagas, 2004).

Granites–Tanami terrane

- ~1820–1810Ma: Deposition/eruption of rhyolite, ignimbrite and siliclastic sedimentary rocks of the Ware Group (Bagas & others, 2010).

Arunta Inlier

- ~1810–1800Ma: Deposition of the Ongeva Package, which comprises metamorphosed sedimentary and volcanic rocks in the east Arunta Region
- ~1800–1790Ma: Deposition of the Reynolds Range Group, which is dominated by metamorphosed siliciclastic sedimentary successions intercalated with minor carbonates and calc-silicates
- ~1810–1800Ma Stafford Event: Relatively local tectonothermal event (Collins & Shaw, 1995; Claoue-Long & others, 2008a) and emplacement of syn-tectonic granites
- ~1815Ma: Extrusion of the Strzelecki Volcanics (Claoue-Long & others, 2008b).

Pine Creek

- ~1813Ma: Tectonothermal event in the Litchfield Zone identified by the growth of monazite parallel with biotite-defined foliation. Significance and extent is undefined (Carson & others, 2008b).

Tennant Creek/Davenport

- ~1815–1810Ma: Extrusion of the felsic Epenarra Volcanics, Treasure Volcanics and Arabulja Volcanics. Emplacement of dolerite sills (Claoue-Long & others, 2008b). Volcanic packages are part of the Hatches Creek Group

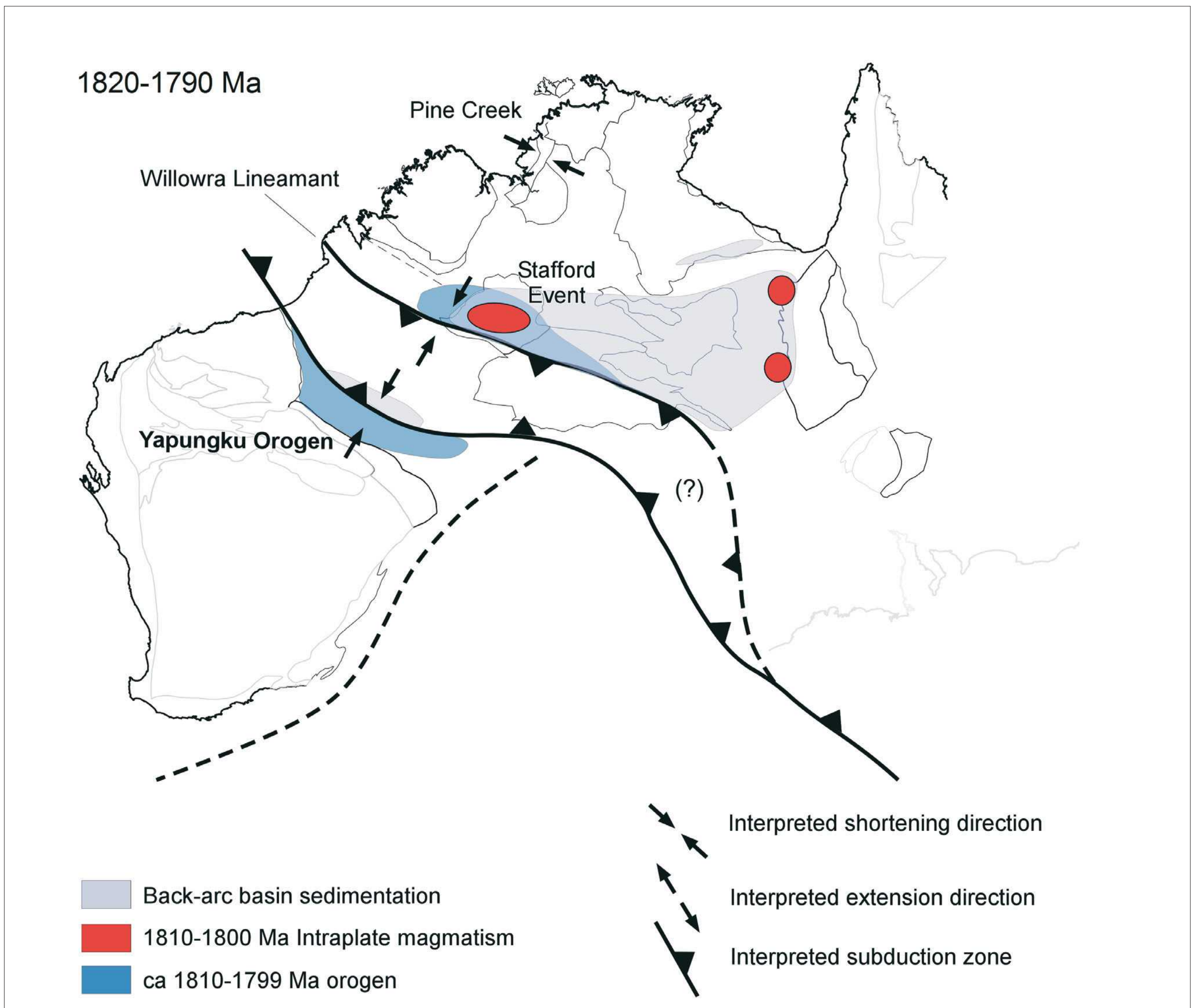


Figure 4.2: Time Slice 2: 1820–1790Ma

and lower Tomkinson Creek Group, which were deposited ~1820–1800Ma.

Gawler Craton

- ~1815Ma: Emplacement of the Tournefort dykes in the southern Gawler Craton (Hoek & Schaefer, 1998)

Tectonic interpretations

- Collision of the Central Australian Craton and Western Australian Craton. Collision between the West Australian Craton and the Central Australian Craton occurred along the Paterson Orogen (Rudall Complex) at ~1795Ma. The central Australian Craton is likely to represent a continental ribbon accreted as part of the overall continental amalgamation event.
- Subduction continued along the southern margin
- Significant granitic plutonism in the Arunta lnlier and Granites–Tanami terrane, and felsic volcanism in the Arunta lnlier and Davenport Province. Sedimentary packages throughout the North Australian Craton were deposited in a continental back-arc setting.
- Tectonism in the eastern and southern parts of the continent was relatively minor.

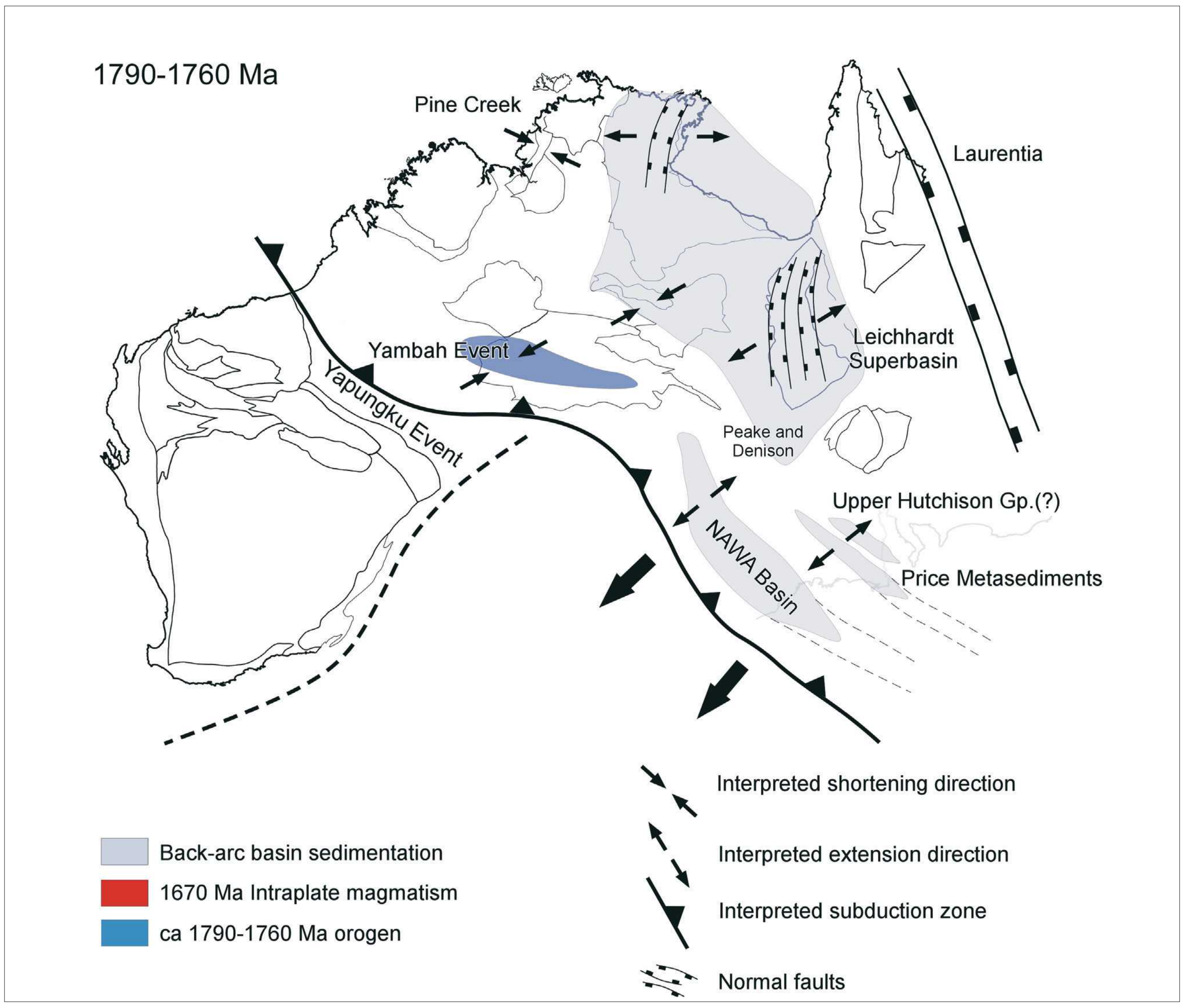


Figure 4.3: Time Slice 3: 1790–1760Ma

Time Slice 3: 1790–1760Ma

Mount Isa

- ~1790Ma: Formation of the protoliths of the Alpha Centauri Metamorphics
- ~1790–1760Ma: Intracontinental extension associated with the development of the Leichhardt Superbasin (Jackson & others, 2000)
- ~1780Ma: Deposition of the marine facies Mount Guide Quartzite and Leander Quartzite 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.
- ~1780–1760Ma: Eruption of the Magna Lynn Basalt followed by voluminous eruption of felsic-dominated volcanic rocks and clastic sedimentation of the Argylla Formation in the eastern part of the Kalkadoon – Leichhardt Domain and throughout the Mary Kathleen Domain. The Bulonga Volcanics were erupted in the Mitakoodi Domain and the Canobie Domain at ~1760Ma. These are overlain by the basaltic Marraba Volcanics.

McArthur Basin

- ~1790–1760Ma: Deposition of the lower Redbank Package, including the eruption of the ~1790Ma basaltic Seigal Volcanics. Basaltic magmatism was followed by deposition of the Sly Creek Sandstone.

Gawler Craton

- ~1790Ma: Extrusion of the Myola Volcanics followed by the deposition of the Broadview Schist in the eastern Gawler Craton
- ~1790–1760Ma: Emplacement of the Wirriecurrie Granite at ~1775Ma and extrusion of the Tidnamurkuna Volcanics and deposition of the protoliths of the Peake Metamorphics in the Peake and Denison lnliers
- ~1770–1760Ma: Deposition of the Price Metasediments in the southern Gawler Craton.

Pine Creek

- ~1780Ma Top End Orogeny: Late stage hydrothermal activity possibly associated with low grade greenschist facies metamorphism (Pietsch & Edgoose, 1988) and movement along shear zones (Rasmussen & others, 2006).

Arunta Inlier

- ~1780–1770Ma Yambah Event: Orogenic event in the Arunta Inlier characterised by poly-deformation, west to south-west vergent thrusting and high temperature – low pressure granulite facies metamorphism (Norman & Clarke, 1990). Late orogenic shortening resulted in north–south and south-east oriented folding (Collins & Williams, 1995).
- ~1780–1770Ma: Emplacement of voluminous syn-tectonic granites and gabbros in the northern and eastern parts of the Arunta lnlier (Collins & others, 1991).

Tennant Creek/Davenport

- ~1780–1770Ma: Crustal shortening that possibly reflects distal effects of the Yambah Event (Claoue-Long & others, 2008b).

Tectonic interpretations

- Subduction and accretion or collision along the southern margin of the Australian continent between ~1780–1770Ma is recorded in the Arunta lnlier and the distal effects are recorded in the plate interior.
- Much of the eastern parts of the continent experienced crustal extension and extensive bimodal volcanism between ~1780–1760Ma. The temporal overlap with accretion in the southern margin of the Australian continent suggests that either (1) roll-back was not the driver for extension in the overriding plate or (2) that the Yambah Event was localised only to central Australia and that the subduction zone to the south of the Arunta lnlier continued to roll back and drive crustal extension in the southern and north-eastern parts of the continent.

Time Slice 4: 1760–1740Ma

Mount Isa

- ~1755–1750Ma: Deposition of clastic sedimentary successions of the lower Quilalar Formation in the Leichhardt River, Mount Oxide and Century Domains. These clastic sedimentary successions correlate with the Mitakoodi Quartzite and Ballara Quartzite.
- ~1755Ma: Extensional normal faulting in the Mitakoodi Domain and the Mary Kathleen Domain associated with deposition of clastic sediments of the Ballara Quartzite and Mitakoodi Quartzite (Williams, 1989; Potma & Betts, 2006).
- ~1750–1740Ma: Deposition of sag-phase carbonate successions of the upper Quilalar Formation (Leichhardt River and Mount Oxide Domains) and the Corella Formation (east of the Kalkadoon – Leichhardt Domain).
- Development of a ~1740Ma mid-crustal extensional detachment in the Mary Kathleen Domain and emplacement of the Burstall and Wonga Suite granites in the Mary Kathleen Domain. Metamorphic conditions reached amphibolite facies (Holcombe & others, 1991)

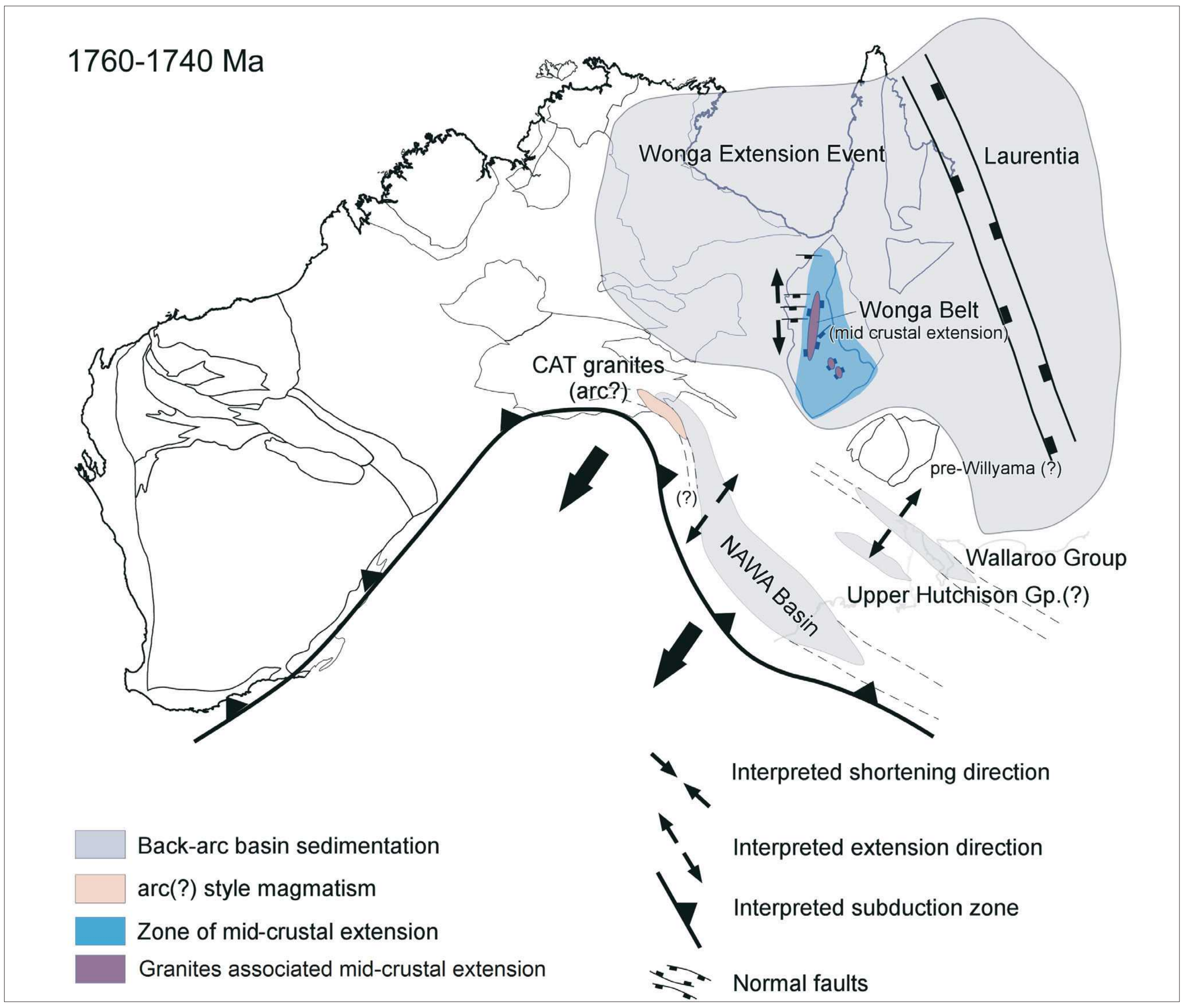


Figure 4.4: Time Slice 4: 1760–1740Ma

- ~1740Ma: Gneissic dome development, granite emplacement and high temperature metamorphism in the Double Crossing – Gin Creek area of the Kuridala – Selwyn Domain
- ~1740Ma: Emplacement of high-level intrusives and extrusives of the Mount Fort Constantine Volcanics in the Canobie Domain.

Gawler Craton

- ~1760–1740Ma: Extensive basin development throughout the Gawler Craton resulting in the deposition of units of the Wallaroo Group, Price Metasediments (?) and the Moondrah Gneiss within the Nawa Basin (Payne & others, 2008).
- ~1750Ma: Emplacement of granites in the eastern (Moonta Porphyry) and northern Gawler Craton
- ~1740Ma: Eruption of the Moonabie Volcanics in the eastern Gawler Craton.

McArthur Basin

- ~1750–1740Ma: Deposition of the lower Redbank Package, including the Rosie Creek Sandstone and the stromatolitic and oolitic dolomite, sandstone, shale, and siltstone of the McDermott Formation.

Pine Creek

- ~1760Ma: Deposition of the Tolmer Group (sandstone, dolomite, siltstone).

Tennant Creek/Davenport

- ~1760–1740Ma: Deposition of the marine sandstone, dolostone, limestone, and siltstone of the upper Tomkinson Creek Group.

Arunta Inlier

- ~1760–1750Ma: Inkamilla Igneous Event (Scrimgeour, 2003; Betts & Giles, 2006). Temporally overlapping magmatic event in which volumetrically low, calc-alkaline-trondhjemitic (CAT) plutons, with strong geochemical affinities with arc magmas (Foden & others, 1988; Zhao & McCulloch, 1995), were emplaced in the southern Arunta lnlier. Temporally overlapping Main Group granites are interpreted to have been derived by partial melting of older island arc-type intrusions or underplated remnants from the Yambah Event (Zhao & McCulloch, 1995).

Tectonic interpretations

- The presence of arc-related magmas in the southern Arunta lnlier suggests that the southern margin of the continent was an active convergent margin between ~1760Ma and 1740Ma. Extensive basin systems developed across large parts of the North Australian Craton and the South Australian Craton at this time, indicating that they formed part of the same contiguous continent by this time. Basins of this age are characterised by basal succession of dominantly clastic sediments that were deposited in an extensional setting, followed by carbonate dominated sedimentation that appears to post-date extension.
- Throughout the history of the North Australian Craton, the development of extensional basins is interpreted to reflect roll-back of a north-dipping subduction zone between the major accretionary events at ~1800–1780Ma, ~1740Ma and ~1690Ma.

Time Slice 5: 1740–1725Ma

Mount Isa

- ~1740–1710Ma: Depositional hiatus in the Leichhardt River Domain
- ~1730–1725Ma: Inversion of of the Leichhardt Superbasin resulting in development of localised folding in the Mount Oxide Domain, and southern Leichhardt River Domain (Derrick & others, 1982; Betts, 1999). This inversion may have caused the development of the Mount Gordon Arch (Derrick, 1982).
- ~1730–1725Ma: Possible depositional hiatus in the eastern parts of the Mount Isa lnlier following the cessation of deposition of the Corella Formation and emplacement of granites at ~1740Ma. However, some of the Staveley Formation may have been deposited during this interval.

Gawler Craton

- ~1740–1725Ma: Kimban Orogeny: Extensive orogenic event preserved across the entire Gawler Craton. It is interpreted to have formed in response to north to north-east dipping subduction outboard of the western Gawler Craton and southern Arunta lnlier. Metamorphic conditions range from greenschist facies to granulite facies (Hand & others, 2007; Dutch & others, 2008). Deformation dominated by sinistral transpressional tectonism along discrete crustal-scale shear zones (e.g. Kalinjala Mylonite). Early deformation involved development of sheath folds overprinted by upright folds.
- ~1740Ma: Extrusion of the bimodal McGregor Volcanics (Daly & others, 1998).

Arunta Inlier

- ~1735–1725Ma: Strangways Event. Orogenic event characterised by poly-deformation and protracted granulite facies metamorphic conditions. Granulite facies metamorphism occurred at ~1735Ma (M1) (Möller & others, 2003; Claoue-Long & others, 2008a). The metamorphic grade decreases to greenschist facies to the north-west (Scrimgeour & Raith, 2001). Synchronous with the metamorphism was emplacement of the Wuluma Granite and Elkendra granites (Lafrance & others, 1995; Page & Sun, 1996). Deformation associated with the Strangways event is characterised by development of kilometre-scale sheath-like folds formed during east-over-west shearing associated with east–west to north-east to south-west crustal shortening (Goscombe, 1991; Collins & Shaw, 1995). The high grade gneissosity formed during this event is deformed by upright folds with a near vertical, north–south trending foliation (Hand & others, 1999).

Tennant Creek/Davenport

- ~1735–1725Ma: Strangways Event. Greenschist facies metamorphism and development of regional north-west trending folds (Claoue-Long & others, 2008b).

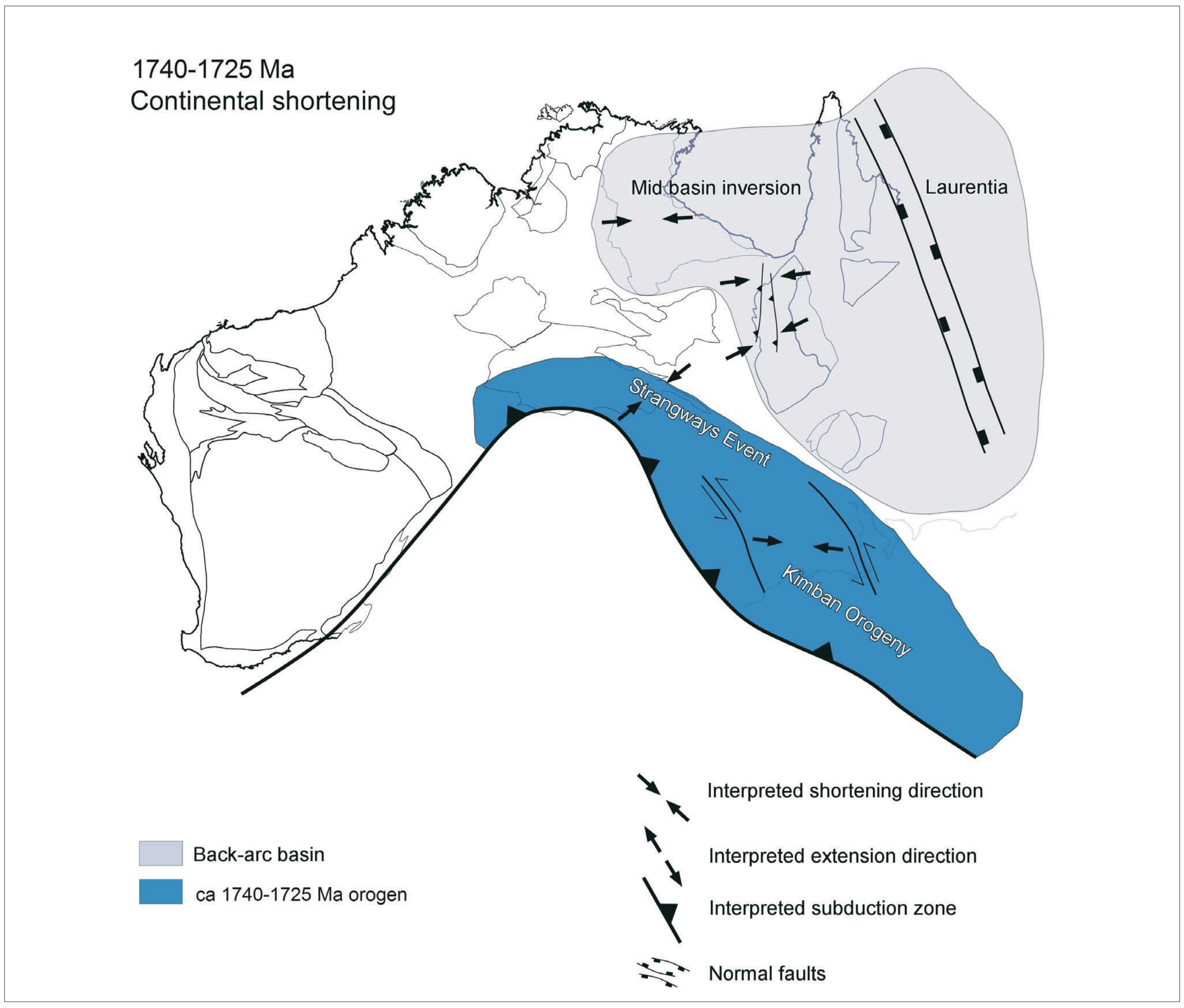


Figure 4.5: Time Slice 5: 1740–1725Ma

McArthur Basin

- ~1740Ma: Mid-basin inversion within the Redbank Package followed by deposition of the arenite of the Wununmantyala Sandstone and lithic and dolomitic sandstone of the Wollogorang Formation.

Tectonic interpretations

- Orogenesis along the southern margin of the Australian continent was driven by north dipping subduction along the southern continental margin. Regional transfer of stresses into the interior of the continent resulted in the inversion of the Leichhardt Superbasin in the Mount Isa lnlier and temporally equivalent successions in the McArthur basins.

Time Slice 6: 1725–1690Ma

Mount Isa

- ~1725Ma: Eruption of the Peters Creek Volcanics in the northern Camooweal–Murphy Domain (Page & Sweet, 1998)
- ~1720–1710Ma: Deposition of fluvial conglomerates and feldspathic sandstone of the Bigie Formation and eruption of bimodal Fiery Creek Volcanics during north-west to south-east directed extension (Calvert Superbasin) (Jackson & others, 2000; Page & Sweet, 1998). Deposition in south-east thickening half grabens in the Mount Oxide, Century and Leichhardt River Domains (Betts & others, 1999)
- ~1710Ma: Emplacement of the Weberra Granite in the Mount Oxide Domain (Betts & others, 1999; Neumann & others, 2009b)
- ~1710Ma: Deposition of the Mount Albert Group in the Kalkadoon–Leichhardt and Mary Kathleen Domains (Foster & Austin, 2008)
- ~1710Ma: Deposition of the Staveley Formation and Roxmere Quartzite in the Marimo–Staveley Domain (Foster & Austin, 2008)
- This era is interpreted to mark the onset of the development of the Calvert Superbasin in the Leichhardt River, Mount Oxide and the Century Domains.

Gawler Craton

- ~1715Ma: Deposition of coarse clastic successions of the Eba and Labyrinth Formations in the central Gawler Craton (Daly & others, 1998)
- ~1725–1690Ma: Waning stages of the Kimban Orogeny associated with upright folding, and the emplacement of syn-tectonic magmas of the Middle Camp Granite (~1725Ma) and Moody Suite (~1715Ma) (Hand & others, 2007; Daly & others, 1998), and the emplacement of the Engenina Granite at ~1690Ma in the northern Gawler Craton (Betts & others, 2003).

Curnamona Province

- ~1720–1690Ma: Deposition of the Curnamona Group and Saltbush Group in the Olary Domain, and the Rantyga Group, Thackaringa Group and the Broken Hill Group in the Broken Hill Domain (lower Willyama Supergroup). These packages are interpreted to have been deposited during intra-continental extension.
- ~1720Ma: Emplacement of the Poodla Hill Granite
- ~1710–1705Ma: Emplacement of the granitoids of the Basso Suite (Olary Domain) and the Alma Gneiss (Broken Hill Domain)
- ~1690–1685Ma: Emplacement of mafic rocks (now amphibolite and mafic gneiss) throughout the Olary and Broken Hill Domains (e.g. Lady Louise Suite).

Georgetown–Coen–Yambo Inliers

- ~1720–1690Ma: Deposition of the protoliths of the Einasleigh Metamorphics and the Bernecker Creek Formation and Daniel Creek Formation (Withnall, 1996; Withnall & others, 1997)
- ~1705–1695Ma: Minor granite emplacement.

McArthur Basin

- ~1720–1690Ma: Deposition of the upper Redbank Package

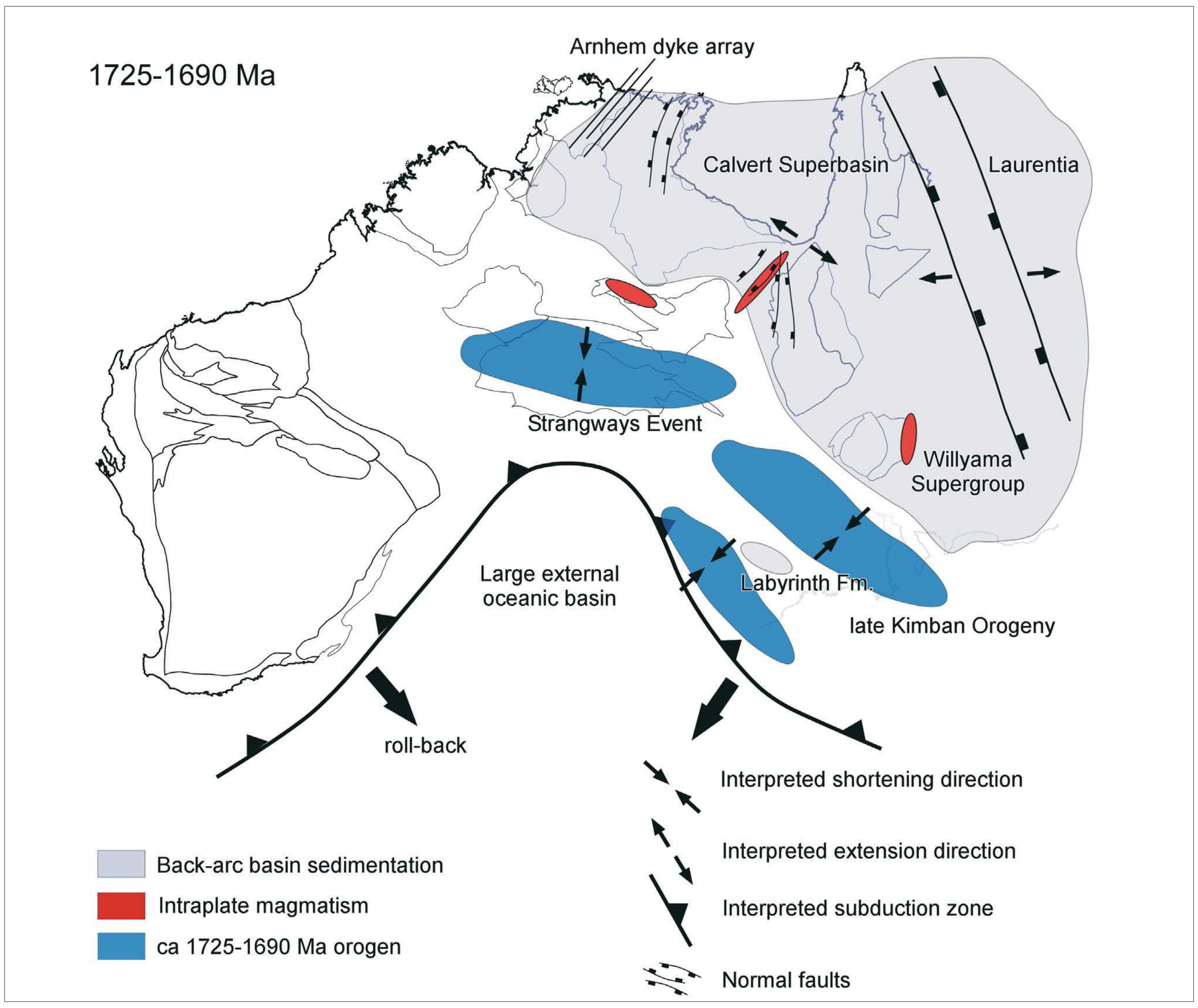


Figure 4.6: Time Slice 6: 1725–1690Ma

- ~1730–1720 Ma: Emplacement of the Settlement Creek Suite and eruption of the Gold Creek Volcanics.

Pine Creek

- ~1725Ma: Emplacement of north-east-trending Arnhem dyke array (Goldberg, 2010).

Arunta Inlier

- ~1730–1690Ma: Continuation of the Strangways Event, characterised by poly-deformation and protracted granulite facies metamorphic conditions. Terminated by syn-extensional mafic dykes at ~1690Ma (Claoue-Long & others, 2008a)
- ~1725Ma: Emplacement of high heat producing syn-tectonic granites.

Tennant Creek/Davenport

- ~1710Ma: Emplacement of Devils Suite granites and lamprophyre (Claoue-Long & others, 2008b).

Tectonic interpretations

- Syn-extensional basin development throughout the North Australia Craton and the Curnamona Province, following the termination of the major phase of Kimban Orogeny (Gawler Craton) and Strangways Event (Arunta lnlier).
- Extensional basins are interpreted to reflect roll-back of 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 (see Giles & others, 2002).

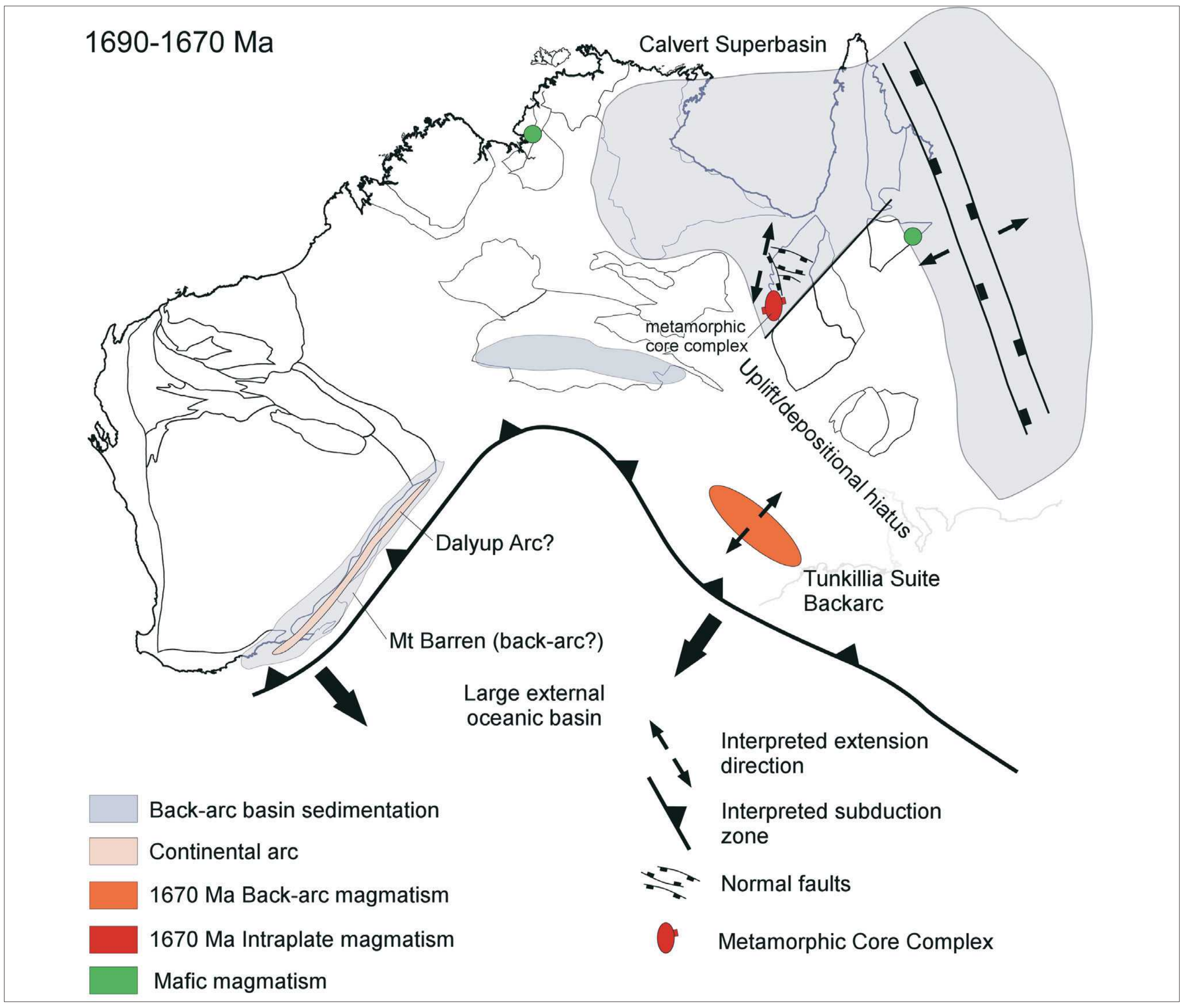


Figure 4.7: Time Slice 7: 1690–1670Ma

Time Slice 7: 1690–1670Ma

Mount Isa

- ~1690–1670Ma: Deposition of Surprise Creek Formation and Torpedo Creek Quartzite (Calvert Superbasin)
- ~1690–1670Ma: Continued deposition of the Mount Albert Group in the Mary Kathleen Domain and commencement of deposition of the lower part of the Soldiers Cap and Kuridala Groups in the Soldiers Cap and Kuridala–Selwyn Domains
- ~1680–1675Ma: Extrusion of the Carters Bore Rhyolite (Sybella Domain)
- ~1675–1670Ma: Emplacement of the Sybella Batholith in the Sybella Domain, interpreted to reflect the development of a metamorphic core complex during north-north-east and south-south-west extension (Gibson & others, 2008).

Gawler Craton

- ~1670Ma: Emplacement of the felsic granitoids of the Tunkillia Suite within a continental back-arc setting in the western and central Gawler Craton (Payne & others, 2010).

Curnamona Province

- ~1690–1685Ma: Deposition of the Broken Hill Group
- ~1680–1670Ma: Depositional hiatus within the Willyama Supergroup.

Georgetown–Coen–Yambo Inliers

- ~1680Ma: Granitoid and dolerite emplacement (Black & others, 1998).

McArthur Basin

- ~1690–1670Ma: Deposition of the shallow marine to fluvial deposits of the upper Parsons Range Group and the Rorruwuy Sandstone.

Pine Creek

- ~1690Ma: Emplacement of the Oenpelli Dolerite.

Arunta Inlier

- ~1680–1670Ma: Eruption/deposition of the Madderns Package (felsic volcanism, and manganiferous and calc-silicates) in the southern Arunta lnlier.

Albany–Fraser Belt

- ~1680–1670Ma: Deposition of the Mount Barren Group (quartzite, sandstone, dolostone, conglomerate, phyllite, pelitic and psammitic schist) in an interpreted continental back-arc setting (Betts & Giles, 2006)
- ~1690–1670Ma: Emplacement of the Dalyup Gneiss along the Yilgarn Craton margin (Nelson & others, 1995). The Dalyup Gneiss comprises felsic and mafic granulites, felsic gneiss, gabbro and metagabbro, amphibolite, microgranite, and pegmatite. Interpreted by Betts & Giles (2006) to reflect plate margin magmatism.

Tectonic interpretations

- This era is interpreted to mark continued development of the Calvert Superbasin and is characterised by fluvial to shallow marine sedimentation in the western parts of the Mount Isa lnlier, metamorphic core complex development in the Sybella Domain and regional depositional hiatus in the eastern parts of the inlier. High Fe tholeiites in Soldiers Cap Group have been interpreted to represent thinned crust (~35km) suggesting extensive thinning of the eastern Australian crust that led to break-up between Australia and Laurentia.
- Uplift (and associated erosion and depositional hiatus) experienced throughout eastern and north-eastern Australia
- Tectonism was driven by roll-back of a north dipping subduction in which back-arc magmatism occurred in the Gawler Craton, and felsic and mafic magmatism and basin development occurred along the eastern margin of the Yilgarn Craton.

Time Slice 8: 1670–1645Ma

Mount Isa

- This interval is interpreted to mark the onset of the Isa Superbasin sag-phase sedimentation.
- ~1660–1650Ma: Deposition of the lower Mount Isa Group (Native Bee Siltstone, Urquhart Shale, Spear Siltstone, Kennedy Siltstone, Magazine Shale) in the Leichhardt River Domain (Isa Superbasin)
- ~1660–1650Ma: Deposition of the McNamara Group (Paradise Creek Formation, Esperanza Formation, and Fish River Formation) in the

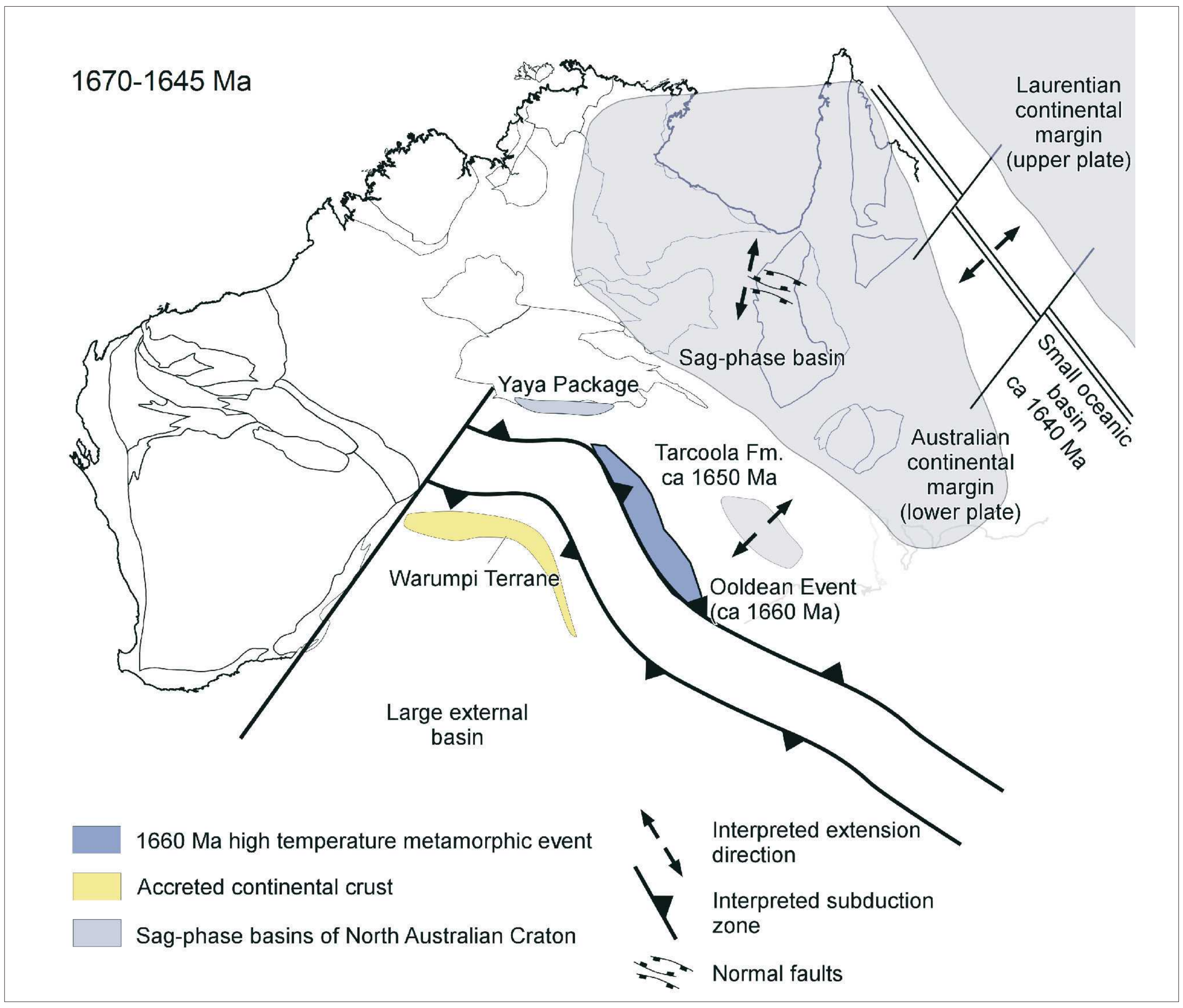


Figure 4.8: Time Slice 8: 1670–1645Ma

Century, Mount Oxide, and Ardmore Domains (Isa Superbasin)
- ~1660–1650Ma: Deposition of the upper Soldiers Cap Group (Mount Norna Quartzite, Toole Creek Volcanics) in the Soldiers Cap Domain (Isa Superbasin)
- ~1655–1650Ma: Deposition of the Answer Slate in the Marimo–Staveley and Kuridala–Selwyn Domains (Isa Superbasin).

Gawler Craton

- ~1660Ma Ooldean Event: High temperature, low pressure (900°C, 10kbars) event recognised from drill core in the western Gawler Craton (Hand & others, 2007)
- ~1650Ma: Deposition of the Tarcoola Formation comprising shale, intercalated with rhyolite to basalt, quartzite, and conglomerate. Deposition in a fluvial to marginal marine environment.

Curnamona Province

- ~1660–1650Ma: Post-rift sedimentation of the Strathearn Group (Olary Domain) and the Paragon Group (Broken Hill Domain) (Conor & Preiss, 2008).

Georgetown–Coen–Yambo Inliers

- ~1670–1660Ma: Emplacement of the Dead Horse Metabasalt (Baker & others, 2010; Withnall & others, 1997) and possibly emplacement of some sills of Cobbold Metadolerite, possibly marking the waning stages of crustal extension
- ~1660–1650Ma: Deposition of the Corbett Formation (mudstone), Lane Creek Formation (mudstone and siltstone) and final emplacement of the Cobbold Metadolerite (Black & others, 1998; Withnall & others, 1997).

McArthur Basin

- ~1660–1650Ma: Deposition of the Masterton Sandstone (lower McArthur Group, Umbolooga Subgroup (dolostone, mudstone, sandstone, evaporite casts, tuffite) and Slippery Creek Siltstone Member (siltstone and mudstone) of the Habgood Group.

Tennant Creek/Davenport

- ~1660–1650Ma: Deposition of Namerinni Group (quartz arenite, sublithic/lithic arenite, dolostone, mudstone, minor conglomerate).

Arunta Inlier/Warumpi Province

- ~1660Ma: Deposition of the Yaya Package (pelite, psammite, and calc-silicate), and minor mafic magmatism.

Tectonic interpretations

- ~1660Ma: This period marks the transition from rift-related sedimentation of the Calvert Superbasin to sag-phase dominated sedimentation of the Isa Superbasin (Southgate & others, 2000; Jackson & others, 2000). 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 plate and underwent continental thermal subsidence. Laurentia occupied the upper plate and underwent regional uplift, deposition hiatus and erosion.
- ~1660–1650Ma: Continued subduction along the southern margin of the Australian continent leading towards the accretion of the Warumpi terrane along 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.

Time Slice 9: 1645–1620Ma

Mount Isa

- ~1650–1630Ma: Deposition of the McNamara Group in the Century and Murphy–Camooweal Domains (Loretta, River, Term Super sequences (Page & others, 2000; Southgate & others, 2000; Scott & others, 1998)
- ~1640Ma: Riversleigh Basin inversion event: Reverse reactivation of east–west to east-north-east faults in the northern Lawn Hill Platform (Century and Mount Oxide Domains)
- Possible development of mid-crustal high temperature metamorphic foliations in the Soldiers Cap Domain (Rubenach & others, 2008).

Curnamona Province

- ~1640Ma: Partial melting of the Willyama Supergroup
- ~1630Ma: High temperature prograde metamorphism evidenced mainly from detrital zircons in modern drainage patterns (Belousova & others, 2006). May be related to slightly younger ~1620–1615Ma monazite growth associated with pre-Olarian Orogeny extension (Forbes & others, 2007).

Georgetown–Coen–Yambo Inliers

- ~1650–1620Ma: Deposition of the upper Etheridge Group.

McArthur Basin

- Deposition of basal successions of the Batten Subgroup, Yarawoi Formation, Conway Siltstone and Vaughton Formation.

Arunta Inlier

- ~1640Ma Leibig Event: Accretion of the Warumpi terrane on the southern margin of the Arunta Inlier at the interpreted southern plate margin of the Australian continent (Scrimgeour & others, 2005)
- ~1640Ma: Emplacement of the Andrew Young Igneous Complex orthopyroxene and olivine norite, gabbronorite, diorite, porphyritic biotite granite, anorthosite and calc-silicate rock
- ~1640Ma: Emplacement of the Mount Webb Granite (heterogeneous granite, hornblende-biotite granite, sodic-calcic altered granite, sericite-altered granite and aplite).

Tectonic interpretations

- Major accretionary event along the southern margin of the Australian Craton resulting in inversion of the interior basins. Continued ocean development between Australia and Laurentia
- ~1640Ma: Major inflection in the Australian Apparent Polar Wander Path (Idnurm, 2000).

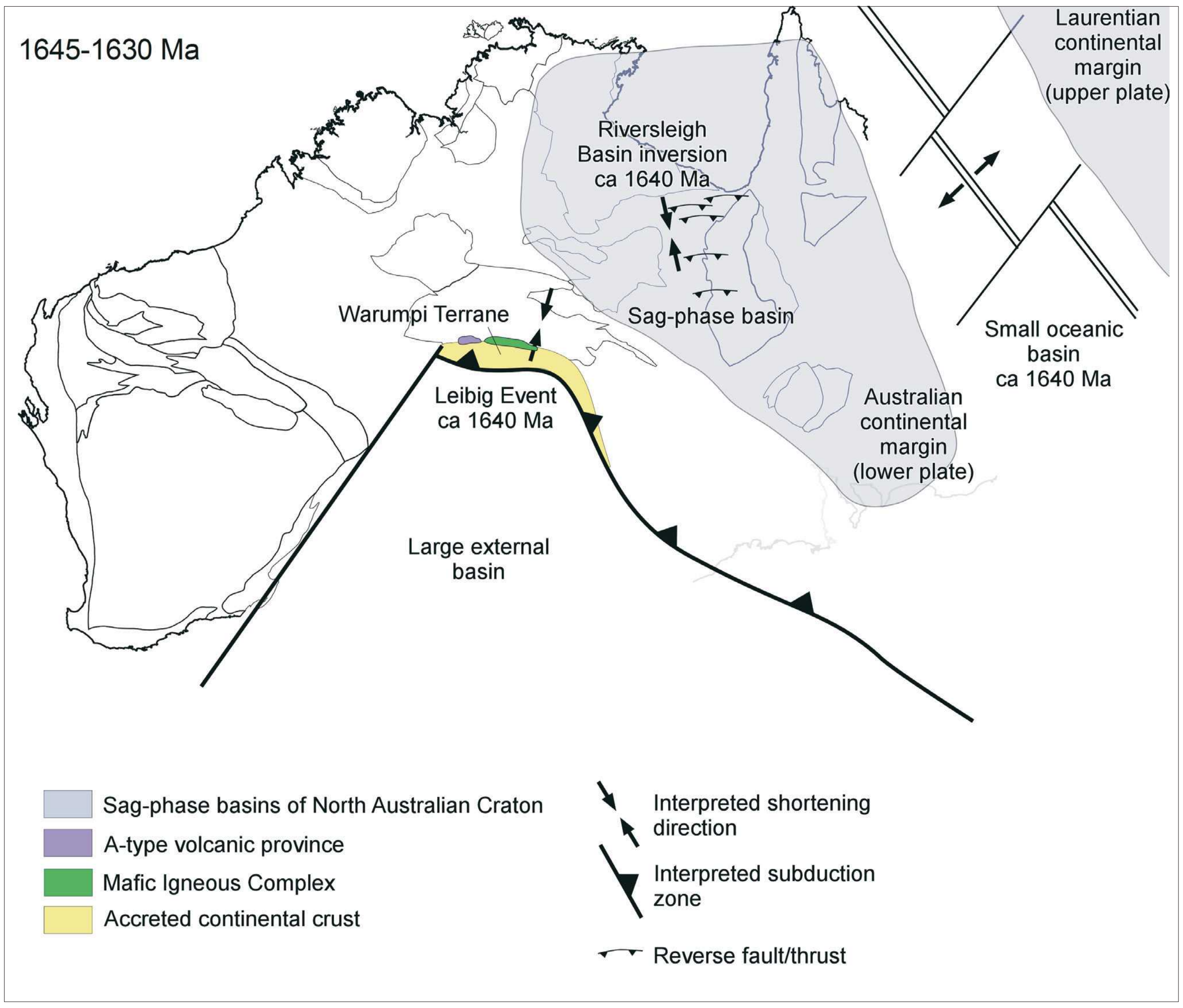


Figure 4.9: Time Slice 9: 1645–1620 Ma

Time Slice 10: 1620–1570Ma

Mount Isa

- ~1620–1595 Ma: Deposition of the upper McNamara Group on the Lawn Hill Platform (Lawn, Wide, and Doom Supersequences — Page & others, 2000; Southgate & others, 2000; Scott & others, 1998)
- ~1610Ma: Deposition of the Milo beds in the Tommy Creek Domain (Carson & others, 2008a)
- ~1600–1570Ma Early Isan Orogeny: This orogenic event is characterised by north–south to north-west–south-east directed crustal shortening. In the Leichhardt River Domain deformation is characterised by inversion of east–west trending normal faults inherited from the pre-Isan basin evolution. In the Mitakoodi and Soldiers Cap Domains, crustal shortening was accommodated by movement along shallow, east dipping decollements (e.g. Overhang Shear Zone) and nappe development in the hanging walls of the decollements (O'Dea & others, 2006).
- ~1580Ma: High temperature – low pressure peak metamorphism. Lower to upper amphibolite in the Soldiers Cap, Mary Kathleen and Sybella Domains. Lower amphibolite to greenschist in the Mitakoodi Domain, Kalkadoon Domain, Leichhardt River and Mount Oxide Domains and sub-greenschist in the Century Domain.

Gawler Craton

- ~1620–1610Ma: Development of the St Peter Suite magmatic arc along the southern margin of the Gawler Craton (Swain & others, 2008)
- ~1610–1590Ma Wartaken Orogeny: Preserved in the central and southern Gawler Craton. Poly-deformation orogenic event involving switches in the regional shortening direction. Much of the deformation was accommodated on major shear zones (Stewart & Betts, 2010).
- ~1595–1575Ma Hiltaba Event: A large felsic-dominated large igneous event in which enormous volumes of A- and I-type magmas were emplaced throughout the Gawler Craton. The voluminous Gawler Range Volcanics (GRV) were erupted in the central and northern Gawler Craton. Magmatism occurred in an extensional tectonic setting following the Wartaken Orogeny. Magmatism associated with the Hiltaba Event is interpreted to be caused by the interaction of a mantle plume with the Gawler Craton lithosphere adjacent to the plate margin (Betts & others, 2009). Iron Oxide Cu-Au mineralisation is thought to be synchronous with this event (Skirrow & others, 2007).
- ~1575–1560Ma Kararan Orogeny: A poly deformation orogenic event that mainly affected the buried northern Gawler Craton. This orogeny is characterised by high temperature metamorphism (Hand & others, 2007) and possibly records the accretion of the Coompana Block to the west of the Gawler Craton (Betts & Giles, 2006).

Curnamona Province

- ~1610–1590Ma Olarian Orogeny: Poly deformation orogenic event that affected the southern margin of the Curnamona Province. Characterised by high temperature metamorphism up to granulite facies. Initial thin-skinned shortening occurred during north-directed crustal translations followed by a switch to north-east–south-west shortening. Late orogenic magmas of the Ninnerie Suite were emplaced in the southern parts of the province at ~1590Ma (Connor & Preiss, 2008; Page & others, 2005a,b).
- ~1590–1580Ma: Voluminous emplacement of undeformed A-type Benagerie Volcanics in the central Curnamona Province. These volcanics are interpreted to form part of a hotspot track along the eastern edge of Proterozoic Australia (Betts & others, 2007).
- ~1600–1590Ma: Deposition of the protolith of the Brindina Schist and the Freeling Heights Conglomerate in the Mount Painter Inlier in the northern Gawler Craton.
- ~1590–1575Ma Painter Orogeny: This event affected the Mount Painter Inlier in the northern Curnamona Province, and is characterised by high temperature metamorphism and polyphase deformation

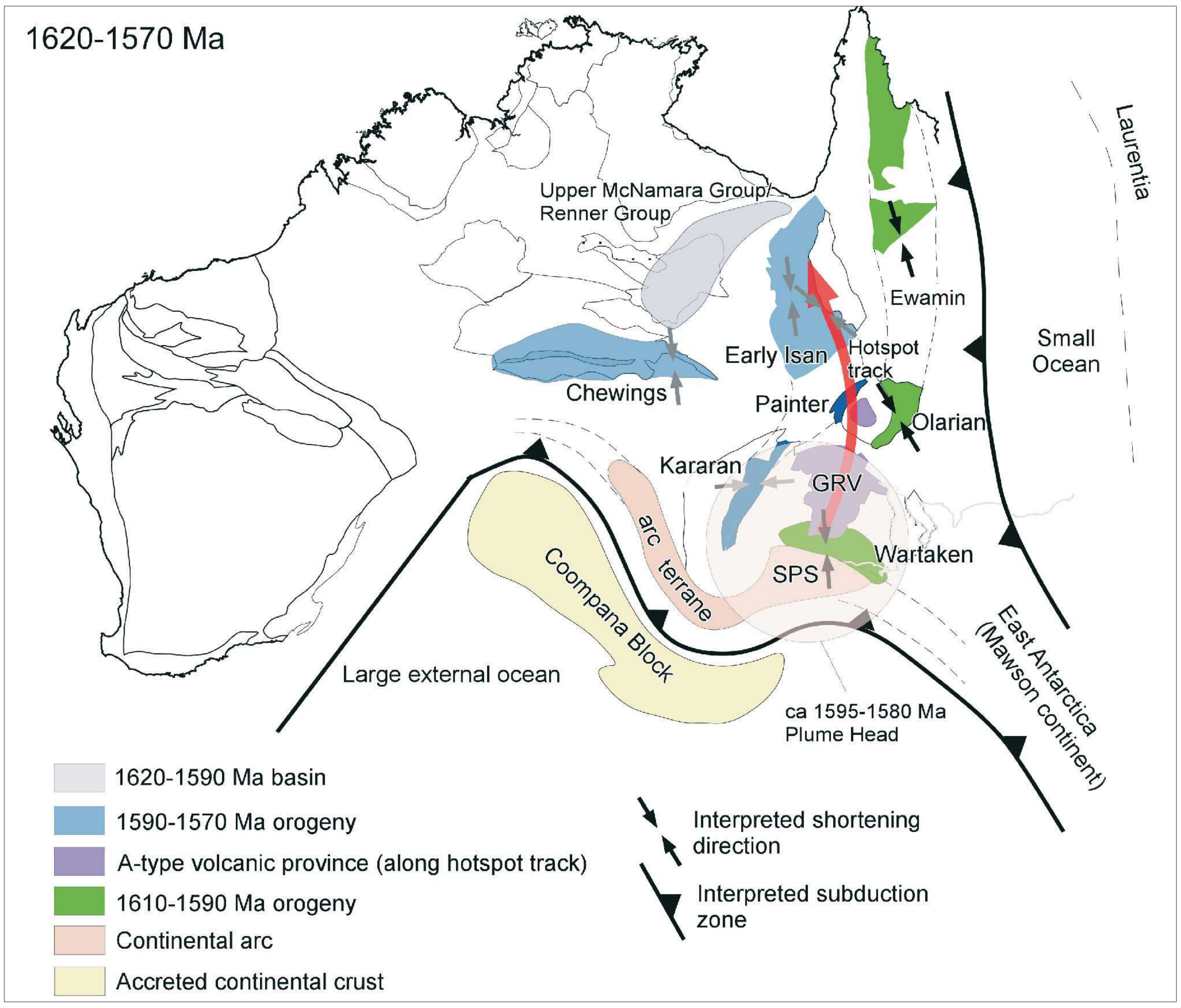


Figure 4.10: Time Slice 10: 1620–1570Ma

involving switches in the regional shortening direction.
- ~1575–1555Ma: Emplacement of A- and I-type granites and extrusion of the Babbage Volcanics throughout the Mount Painter and Mount Babbage inliers in the northern Gawler Craton. These magmas are also interpreted to form part of a hotspot track along the eastern edge of Proterozoic Australia (Betts & others, 2007).

Arunta Inlier

- ~1610–1575Ma Chewings Orogeny: This orogenic event involved north–south shortening and high temperature peak metamorphism at ~1580Ma (Vry & others, 1996).
- ~1605Ma: Syn-tectonic emplacement of the Orminston Granite.

Georgetown–Coen–Yambo Inliers

- ~1600–1580Ma Ewamin Orogeny: This event involved north–south shortening and high temperature peak metamorphism at ~1580Ma (Withnall & others, 1997; Blewett & others, 1998).
- ~1570Ma: Regional uplift and retrogressive metamorphism (Boger & Hansen, 2004; Cihan & others, 2006)
- ~1570–1550Ma: Deposition of the Langlovale Group unconformably on metamorphic basement.

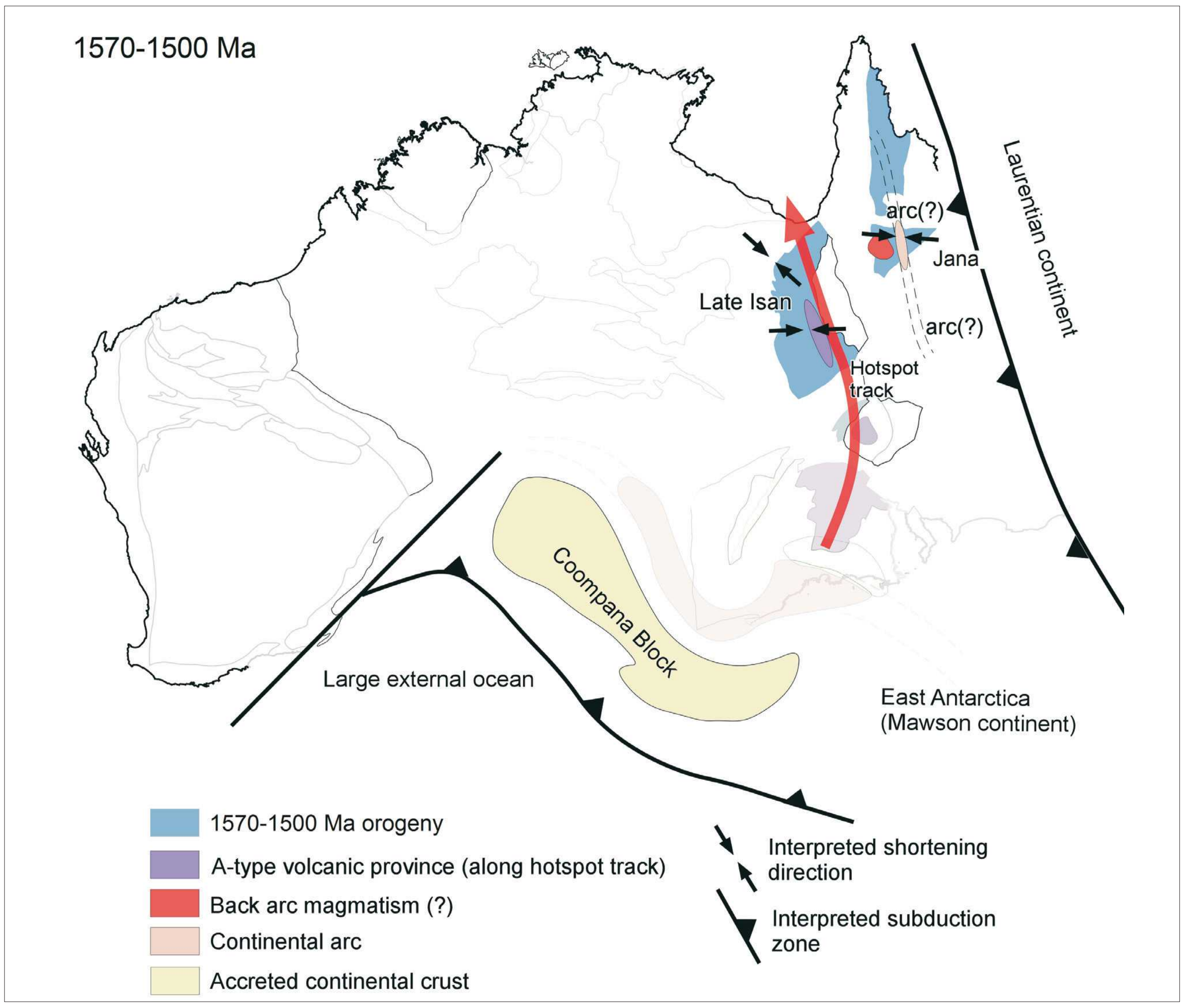


Figure 4.11: Time Slice 11: 1570–1500Ma

Time Slice 11: 1570–1500Ma

Mount Isa

- ~1560–1540Ma Middle Isan Orogeny: East–west crustal shortening involving the development of major north–south oriented fabric
- ~1545–1500Ma Late Isan Orogeny (Wrench tectonics): East–west crustal shortening producing upright folding and movement on north-east-trending dextral faults and north-west-trending sinistral faults. This was followed by a switch to east-south-east and west-north-west regional shortening and reactivation of major fault systems (e.g. Cloncurry Fault: Austin & Blenkinsop, 2010).
- ~1545–1500Ma: Extensive emplacement of A- and I-type granitic batholiths (Williams Supersuite) in a north–south trending belt in the eastern parts of the Mount Isa Inlier. Extensive potassic alteration and Iron Oxide Cu-Au (IOCG) mineralisation is associated with this event (Pollard & others, 1998; Mark & others, 2005).

Gawler

- ~1530Ma: Silsby Granite emplacement in the southern Gawler Craton (Hand & others, 2007).

Curnamona Province

- ~1570–1550Ma Painter Orogeny: Upright folding in the Mount Painter Inlier and possibly in the southern Curnamona Province (Rutherford & others, 2007).

Georgetown–Coen–Yambo

- ~1560–1550Ma Jana Orogeny: East–west to north-west–south-east shortening and low pressure-high temperature metamorphism, associated with main metamorphic zircon growth and emplacement of S-type Forsayth Supersuite (Withnall & others, 1997; Black & others, 1998, 2005)
- ~1550Ma: Eruption of the Croydon Volcanic Group and emplacement of the Esmeralda Supersuite in the west (Withnall & others, 1997)
- ~1550Ma: Emplacement of the volumetrically small, but possibly arc-related Forest Home Suite (Champion, 1991)
- ~1545–1510Ma: Possibly further east–west shortening (Hills 2004; Cihan & others, 2006).

Tectonic interpretations (1620Ma–1500Ma)

- Arc magmatism throughout the southern convergent margin of the Australian continent between ~1620Ma and ~1560Ma (Swain & others, 2008; Wade & others, 2006). Betts & others (2008) interpreted a north-dipping subduction zone and plume interaction at ~1610Ma, resulting in plume-modified orogenesis (Betts & others, 2009) and north–south crustal shortening throughout the eastern parts of the Australian continent between ~1610Ma and ~1570Ma.
- Plume interacted with the 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. The resultant hotspot track formed as Australia migrated southward.
- Collision between Laurentia and Australia caused extensive east–west crustal shortening during the late stages of the Isan Orogeny. Possible arc magmatism in the Georgetown Inlier suggests that the plate margin was located outboard of the eastern margin of the continent.
- Australia continued to migrate over a continental hotspot resulting in the emplacement of the Williams Supersuite in the Mount Isa Inlier. A- and I-type granitoids interpreted by Betts & others (2007) as representing a continuation of the hotspot track associated with Gawler and Curnamona Provinces in the previous interval.

North-West Queensland 3D architecture

The NWQMEP Study 3D model (Figure 5.1) is a conceptual synthesis of the current state of geological knowledge and understanding of the crustal architecture, basin evolution, deformation, fluid flow and mineralising processes of this region.

The model covers an area of over 500 000km^2 and builds on a number of earlier products including the *pmd**CRC I1, I2, I4 and I7 3D models (Murphy & others, 2007). This new model is based on new GSQ geological mapping and seismic and magnetotelluric datasets not available to the *pmd**CRC, and stands as a completely new product with only surfaces from the Lawn Hill and Mount Oxide areas remaining largely unchanged. The new model also expands the coverage of the earlier model by over 70% to include those areas of the Mount Isa Inlier concealed by younger cover sequences. The 3D product also includes a separate coarser-scale regional model showing geophysically modelled regions of the deep crust to provide an appreciation of whole-of-crust processes affecting the project area.

A significant enhancement of the model in covered parts of the terrane is the addition of a surface representing depth to Proterozoic basement (DtB) below the topographic surface. It is anticipated that this surface will be of considerable benefit to explorers for tenement selection, targeting and resource evaluation.

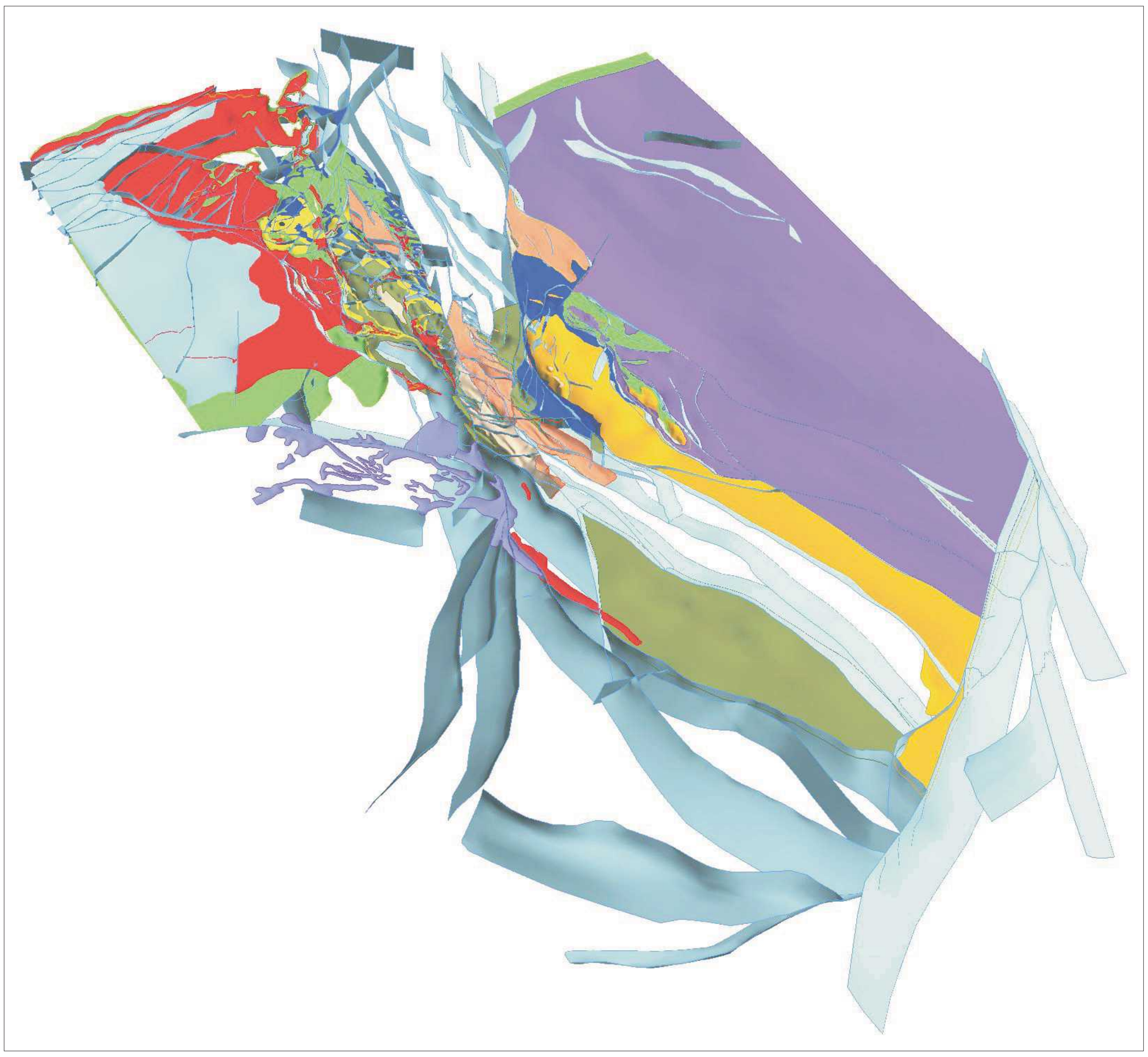


Figure 5.1: Fault network and intrusives — North-West Queensland 3D Model

The objectives of the model are to:

- Represent a comprehensive and internally consistent framework with which to underpin and enhance the understanding of the spatial and temporal distribution of the mineralising systems of North-West Queensland
- Highlight the correlations between potential fluid pathways deep in the crust and the surficial alteration patterns
- Allow an examination of fault interconnectedness and penetration at depth, providing test scenarios for future more detailed numerical modelling studies
- Support evaluations of geodynamic concepts reflected in fault and associated basin development over time
- Provide a detailed depth-to-basement (DtB) surface to assist resource explorers in selection of tenements where prospective bedrock occurs at economic depths.

Methodology

The model has been compiled to encapsulate the GSQ's current understanding of the crustal architecture of the North-West Queensland region.

The basic framework of the model is defined by the fault network, comprising the major faults (those over 10km in strike length) as well as some important smaller faults. Greater strike length faults have been interpreted to demonstrate greater crustal penetration and are modelled as such. Fault orientations are inferred from seismic profiles, potential field data (magnetic and gravity edges or 'worms'), and field orientation data. Where no other reliable data exists, fault geometries are modelled to be consistent with our current conceptual understanding of the structural evolution of the region.

Within each fault-bound compartment throughout the region, a series of litho-stratigraphic surfaces have been constructed based largely on time-correlative groupings. In the western and central part of the region, the lithostratigraphic surfaces are based on the sequence-stratigraphic approach of Southgate & others (2000). In the eastern part of the region, recent SHRIMP dating of detrital zircon populations (Neumann & others, 2009a; Carson & others, 2008a and in preparation; Magee & others, in preparation) and revised GSQ field mapping has enabled further chronostratigraphic correlation across the whole inlier.

As a result, it has now been possible to represent the major stratigraphic superbasin groupings (and their equivalents) as surfaces extending throughout most of the regional 3D model. However, some stratigraphic groupings (representing basin development and volcanism not recognised in the west) have been defined by 3D surfaces unique to the eastern half of the region. The various 3D surfaces represented in the model and their associated stratigraphic groupings are listed in Table 5.1, as well as being displayed in the Mount Isa Time-Space diagram accompanying this report (Appendix 3; Map 2).

Within the outcropping section of the model, the 3D surface elements have been clipped at an elevation equivalent to mean sea level (i.e. zero). Within the covered parts of the model, the 3D surfaces terminate in the upper part of the model against a surface representing depth to Proterozoic basement below mean sea level.

Geological model construction

The surfaces were constructed in GoCAD by interpolation between serial cross-sections built at 10km intervals through strategic parts of the region. The sections were based on the recently revised 1:100 000 scale GSQ surface and solid geology mapping which accompanies this report (Appendix 9a; Map 1).

New geological subdivisions from this mapping were used to define 15 lithostratigraphic surfaces for use in the sections and the final model. Subsurface geometries were inferred from surface observations, seismic reflection traces, potential field data (including magnetic and gravity 'worm' geometries) and, in rare cases, from magnetotelluric profiles (Figure 5.2). The widespread steep surface dips throughout the Inlier are largely not reflected in the seismic profiles at depth, and, as a result, more gently-dipping lithological form surfaces were constructed in the sections linking outcropping horizons. The final 3D model was constructed to incorporate key architectural aspects of each of the seven Deep Seismic transects, summarised in Figures 5.5 to 5.12.

Key geological sections were validated using 2.5D gravity forward modelling. Interpolation between the 10km spaced sections resulted in inevitable simplification of the final geological model with the level of accuracy at the surface

Table 5.1: 3D model stratigraphic groupings

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 South Nicholson Group (base_SNG)	Includes Constance Sandstone and Mullera Formation		
		Base of Tommy Creek Succession (base_Tommy)	Milo beds within the Tommy Creek Domain
Base of Isa Superbasin (base_Isa)	Lower and upper McNamara Group, Mount Isa Group and upper Gun Supersequence		
		Base of Soldiers Cap – Kuridala Successions (base_Solders_Cap)	Soldiers Cap Group, Kuridala Group and Answer Slate
Base of Calvert Superbasin (base_Calvert)	Big and Prize Supersequences (Bigie Formation, Fiery Creek Volcanics and Surprise Creek Formation)	Base of Calvert Superbasin (base_Calvert)	Staveley Formation and Roxmere Quartzite
		Base of Mount Fort Constantine Volcanics (base_Constantine)	Mount Fort Constantine Volcanics
Base of Quilalar/Corella Succession (base_Quilalar)	QuilalarFormation, Corella Formation and equivalents	Base of Quilalar/Corella Succession (base_Quilalar)	Ballara Quartzite, Mitakoodi Quartzite, Overhang Jaspilite and Corella Formation
Base of Myally Subgroup (base_Myally)	Myally Subgroup of the Haslingden Group	Base of Bulonga Volcanics (base_Bulonga)	Bulonga Volcanics, Marraba Volcanics and Double Crossing Metamorphics
Base of Eastern Creek Volcanics (base_ECV)	Eastern Creek Volcanics and lower units of the Haslingden Group		
Base of Leichhardt Superbasin (base_Leichhardt)	Mount Guide Quartzite and equivalents, Bottletree Formation, Magna Lynn Metabasalt and Argylla Formation	Base of Leichhardt Superbasin (base_Leichhardt)	Includes Argylla Formation inferred to exist beneath exposed sequences
Base of Tennant Creek Succession (base_Tennant_Ck)	Includes Bucket Hole Volcanics and Oroopo Metabasalt		
Base of Leichhardt Volcanics and equivalents (base_L_Volcs)	Includes the Leichhardt Volcanics, Candover Metamorphics, and Cliffdale Volcanics; also includes Kamarga Volcanics; this surface also marks the top of pre-Barramundi Orogeny basement rocks (e.g. the Kurbayia Metamorphic Complex, Saint Ronans Metamorphics and Yaringa Metamorphics)	Base of Leichhardt Volcanics equivalents (base_L_Volcs_equiv)	Includes rocks forming basement to Leichhardt Superbasin and younger successions

approximating that of a geological map at 1:1.5M scale.

The fault/lithomodel extends to a depth of approximately 30km, while the accompanying broad-scale crustal model (constructed from five gravity forward-modelled deep crustal sections) extends to a depth of 60km. The crustal scale model was validated by forward modelling using VPmg software.

Depth to basement surface construction

This surface was constructed using stratigraphic and geologic depths extracted from drillhole data contained in the GSQ's company report archive. Over 280 reports were examined and approximately 6000 drillholes were reviewed. Depths to a number of stratigraphic surfaces (such as depth to Proterozoic basement, depth to base of Mesozoic or depth to base of Toolebuc Formation) were recorded. These data, combined with depth information from water bores and stratigraphic drillholes, were used to provide hard constraints for depth-to-magnetic-source geophysical modelling.

ModelVision software was used by the GSQ geophysicists for depth-to-magnetic-source geophysical modelling throughout the project area. Total magnetic intensity (TMI) images (80m grid cell) for each 1:250 000 Sheet were displayed in ModelVision and profiles extracted over magnetic features to be modelled. The International Geomagnetic Reference Field (IGRF) was computed for each sheet area from the airborne survey parameters and activated in the model construction. The regional magnetic field was calculated from the TMI data and displayed on the model profile.

In the initial pass, profiles were produced for multiple transects on each sheet area, with separate transects selected to provide the optimum modelling characteristics for the magnetic anomalies displayed on the image. Individual bodies were modelled along each profile. In each case, modelled bodies on adjoining transects were made inactive so that the model response calculated was not influenced by off-line bodies.

After the initial manual construction of the modelled line profiles, an inversion was run on the profile data and model results compared. Generally the strike of a body was easily defined from the image so was not varied. Inversion model parameters allowed to vary included property (susceptibility), thickness, depth extent, dip and azimuth. The outcome most compatible with the expected geological setting was recorded.

A 3-Second Digital Terrain Model (DTM) was used to extract a ground elevation for the location of each model. Model depths were also corrected for the aircraft flying height and a depth relative to Australian Height Datum (AHD) computed for each point.

Approximately 1300 individual bodies were modelled and susceptibility and depth to the top of the magnetic source recorded. Depths produced were then compared to any drillhole or other depth information available and conflicting results analysed. Models were reinitialised, checked for consistency and a reliability factor was assigned. The lowest ranked model depths that did not agree with otherwise determined depths were discarded where it could be shown that unrealistic geological situations were

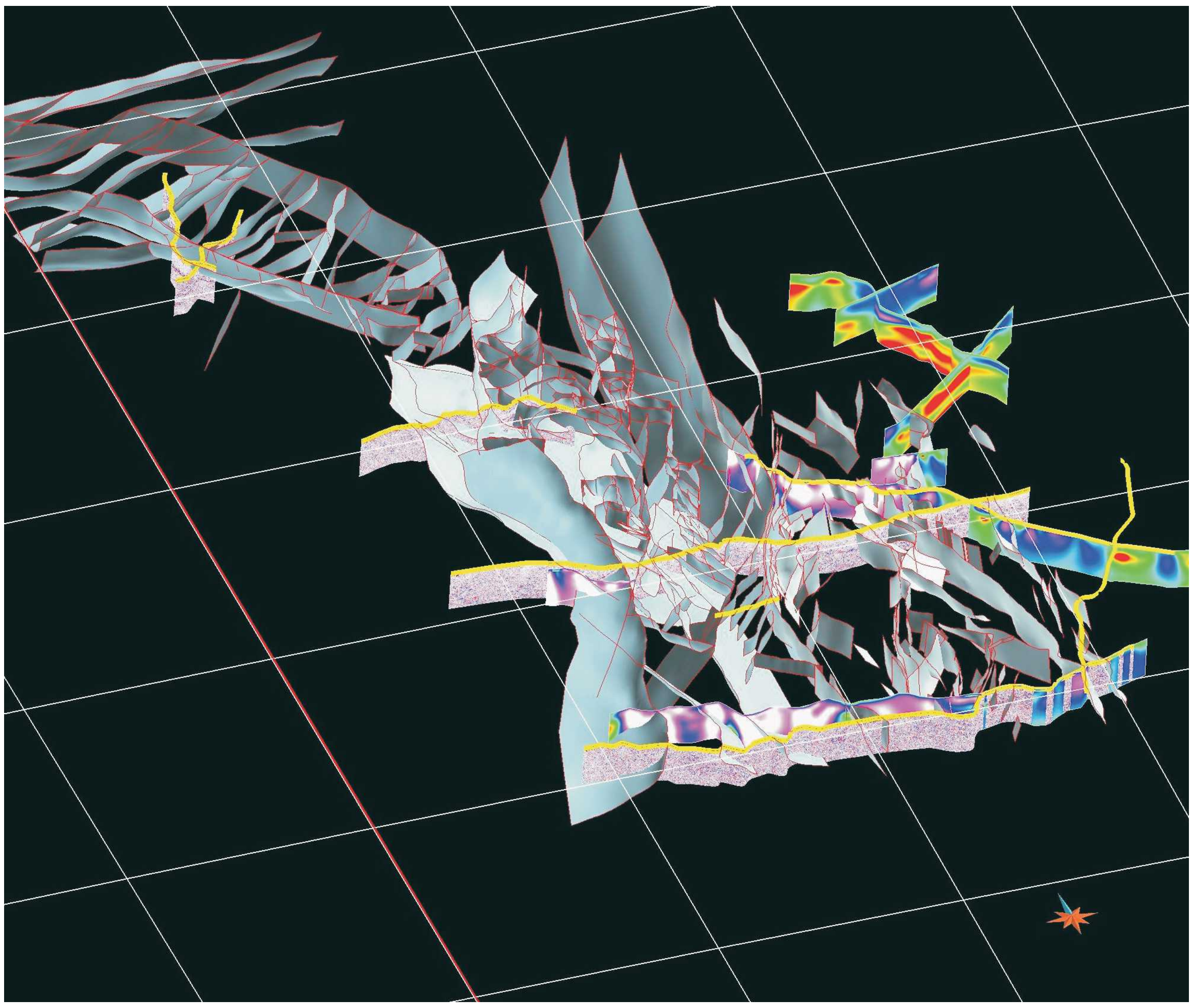


Figure 5.2: Seismic and magnetotelluric profiles act as constraints for surface construction

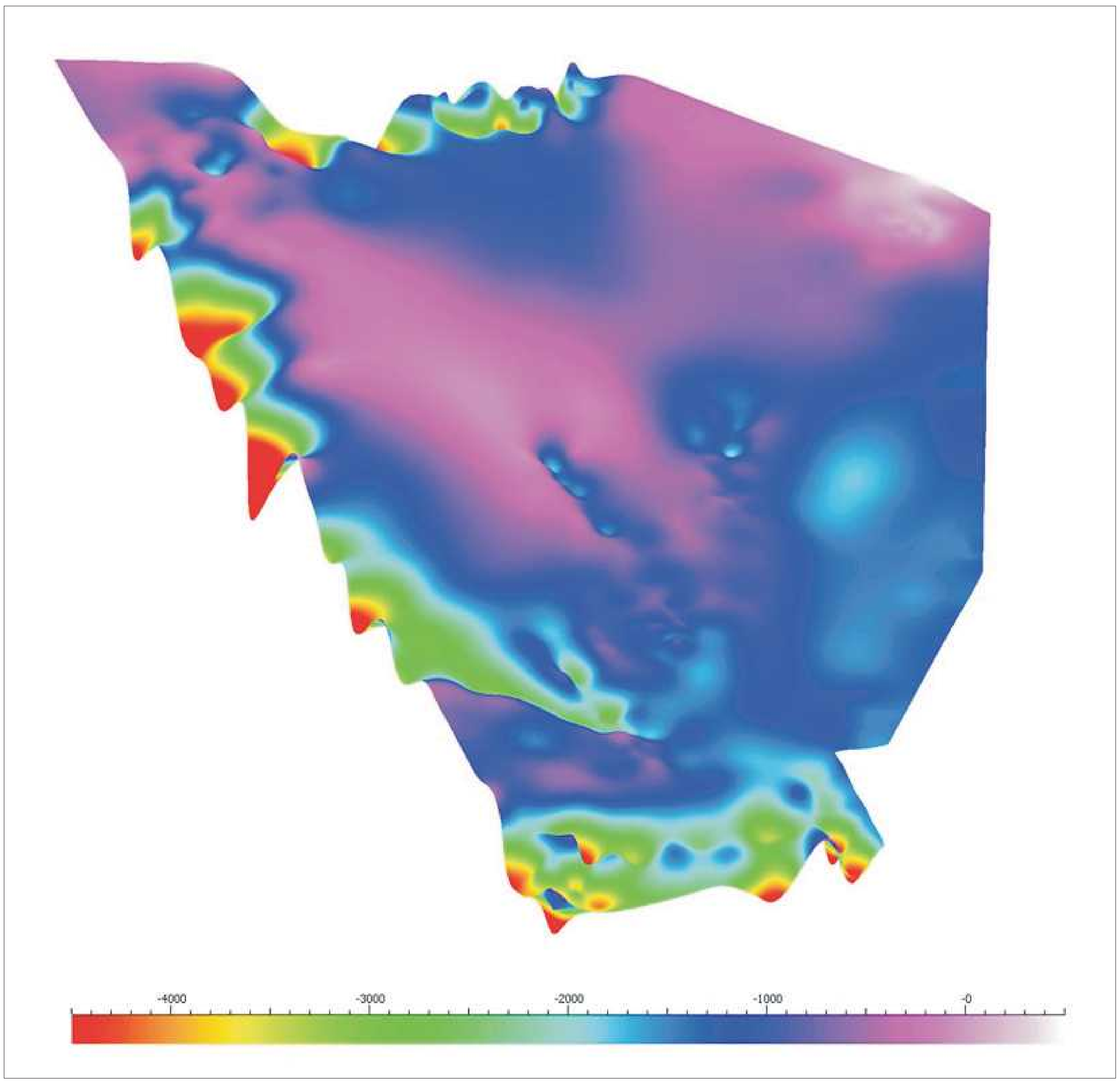


Figure 5.3: Depth to Proterozoic basement surface (x30 vertical exaggeration)

produced. The initial number of model depths was reduced to almost 950 in this manner.

A final grid of acceptable depth solutions was prepared using Geosoft software, and the resulting file imported into GoCAD as a point set for construction of a triangulated surface mesh representing the '***DtB***' horizon (Figure 5.3). It is important to note the distinction between the latter (which represents depth to prospective basement below the DTM) and the '***DtBc***' surface (which represents depth to prospective basement below mean sea level).

Model architecture

The Kalkadoon–Leichhhardt Domain forms a natural divide within the Mount Isa Inlier separating eastern and western sequences which contrast in depositional history, mineralisation style, structure and metamorphic grade. However, a similar geodynamic history has been recognised. Within the 3D model, emphasis has been placed on correlating the structural and lithological units across the whole inlier from west to east where possible.

The upper crustal units represented by the surfaces comprising the 3D model are interpreted to overlie basement rocks that formed during or prior to the Barramundi Orogeny — a widespread event throughout the North Australian Craton. Possible basement remnants are exposed as slivers within the basement high represented by the north-trending Kalkadoon–Leichhardt Domain (e.g. the Kurbayia Metamorphic Complex). The uppermost surface of these old basement rocks is represented in the model as '***base_L_Volcs***' surface. Above this surface are a series of felsic volcanics, volcaniclastics and metamorphics (mainly Leichhardt Volcanics and Candover Metamorphics) which together with Kalkadoon Suite granitoids form a central basement feature separating the eastern and western domains.

The Mount Oxide and Century Domains are characterised by dome and basin features, partly related to granite emplacement. The Mount Gordon Arch within the Leichhardt River Domain has been interpreted as an emergent feature and is modelled with the Myally sediments thinning across it (Gibson & Hitchman, 2005). In the centre and west of the Inlier, the Leichhardt (LSB) and Calvert (CSB) Superbasins represent stacked basins which were broadly controlled by east–west and north–south extension respectively. Correlations between the eastern and western parts of the Inlier are apparent within the later part of the LSB and CSB rift history. The CSB is best represented in the model within the western domains and the Myally Basin, and less so within the eastern domains.

Sediment thickness variations resulting from basin margins, growth faults and magmatic inflation/doming are best represented in the model along the Murphy Tectonic Ridge, and within the Fiery Creek and Kamarga Domes in the west.

The Isa Superbasin (ISB) is interpreted as a widespread sag basin and is best preserved within the western domains, with limited exposure east of the central Kalkadoon–

Leichhardt Domain. Large thickness variations are observed within the ISB with the greatest apparent thicknesses observed within the modelled section of the Century Domain (>4km). Within most of the region the base of the LSB is modelled as relatively shallow with the deepest levels occurring within the central part of the Century Domain (~18km depth), although this shallows greatly within the Kamarga Dome.

A large scale nappe-type structure has been modelled in the Eastern Fold Belt representing the Mitakoodi Culmination, however no other nappe type structures have been recognised.

Significant magmatic belts have been modelled within the region, and are essential to the framework of the Mount Isa Inlier. Intrusives modelled include the Kalkadoon, Toby–Ewan, Wonga, Weberra, Sybella and Williams Suites. These intrusives have been modelled as generally shallow massive flat based bodies.

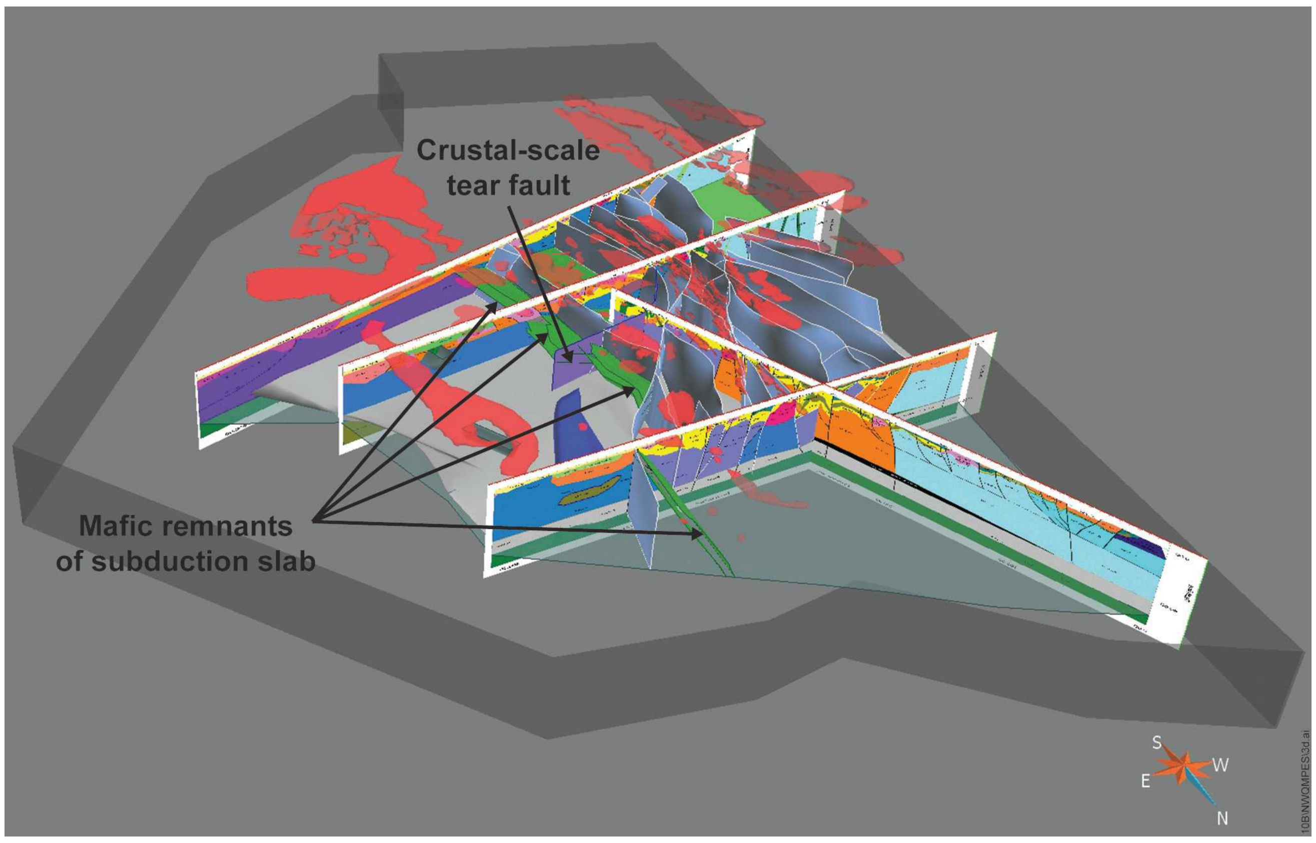


Figure 5.4: Regional 3D model derived from simplified crustal-scale forward modelled sections — proposed mafic slab remnant of ancient west-dipping subduction zone highlighted in green

The fault network is the most critical aspect of the 3D model and represents the framework controlling basin architecture and fluid flow during orogenesis. Relatively steep fault architecture has been interpreted except where seismic data demonstrates otherwise. Most faults demonstrate Isan Orogeny effects but the distinct underlying trends are most likely related to earlier superbasin development and perhaps reactivated structures associated with the Barramundi Orogeny. Predominantly larger strike length faults (>10km) have been modelled. Long strike length structures are typically associated with potential field gradients (worms) and are inferred to be deeper crustal penetrating structures. Domain boundaries are commonly defined by these larger scale structures which probably represent major crustal breaks initiated during earlier Palaeoproterozic orogenesis.

Large shallow east-dipping faults have been constructed along the western margin of the Leichhardt River Domain (Russell Creek/May Downs Fault, 29 Mile Fault and the Riversleigh Fault in the Century Domain) linking into a major detachment at depth. Seismic data has helped constrain the geometries of these faults, in particular within the Century Domain, with the data predominantly demonstrating the listric nature of the larger scale faults, i.e. the Riversleigh and Termite Range faults, which have been modelled as eastward dipping structures within the Century Domain. The Pilgrim Fault has been constructed as a very steep east-dipping feature which shallows to south (largely relying on data from the 06GAM6 GSQ-GA Deep seismic line south of Phosphate Hill) and soles out at a depth of around 25km.

The Cloncurry Fault, one of the most significant structures in the eastern part of the Inlier, has been interpreted as a major normal fault with very significant downthrow to the east during Soldiers Cap Group time. A rapid significant easterly increase in thickness is interpreted under surface cover across the Cloncurry Fault from the Isa–Georgetown GSQ-GA 07GAIG1 Deep Seismic profile. This profile also revealed the existence of a new post-Proterozoic sedimentary basin of unknown age (the Millungera Basin) beneath a Carpentaria Basin cover sequence up to 500m thick.

Unfortunately, both the magnetotelluric surveys conducted by the GSQ in 2009 and existing company drilling failed to give unequivocal 3D definition of the basin extent. As a result, the '***base_Millungera***' surface used in the model has been defined mainly from geophysical gravity and magnetic inversion modelling. The modelled extent of this surface should be treated with caution.

Another key result of the 07GAIG1 seismic survey was the recognition of a significant apparently west-dipping reflectivity contrast between the Mount Isa crust and the crust of the Numil/Abingdon Seismic Province to the east (Chopping & Henson, 2009). This concept, together with the recognition of a possible west-dipping high velocity mafic slab at depth in the 94GAMT1 refraction seismic survey (Goncharov & others, 1998) has been incorporated into the regional crustal scale model accompanying this report (Figure 5.4).

This model has been successfully validated using gravity forward modelling. The suture between these two crustal blocks is interpreted as a possible remnant subduction zone associated with a magmatic arc defined by the north–south trending string of Kalkadoon Suite plutons. The model also highlights steepening of the shallow west-dipping remnant subduction zone towards an east-north-east-trending tear fault recognised in the gravity data and centred on the township of Cloncurry.

Conclusion

It is important to realise that the current 3D model represents one of many geometric solutions that are consistent with currently available geological and geophysical datasets (due to the non-unique nature of potential field modelling techniques). Our knowledge of the subsurface architecture of the Mount Isa Region will continue to evolve as new data is acquired and geophysical inversion technologies improve. While the 3D model will certainly be revised and improved in the future, it still remains a significant benchmark upon which to build greater understanding of this world-class mineral and energy province.

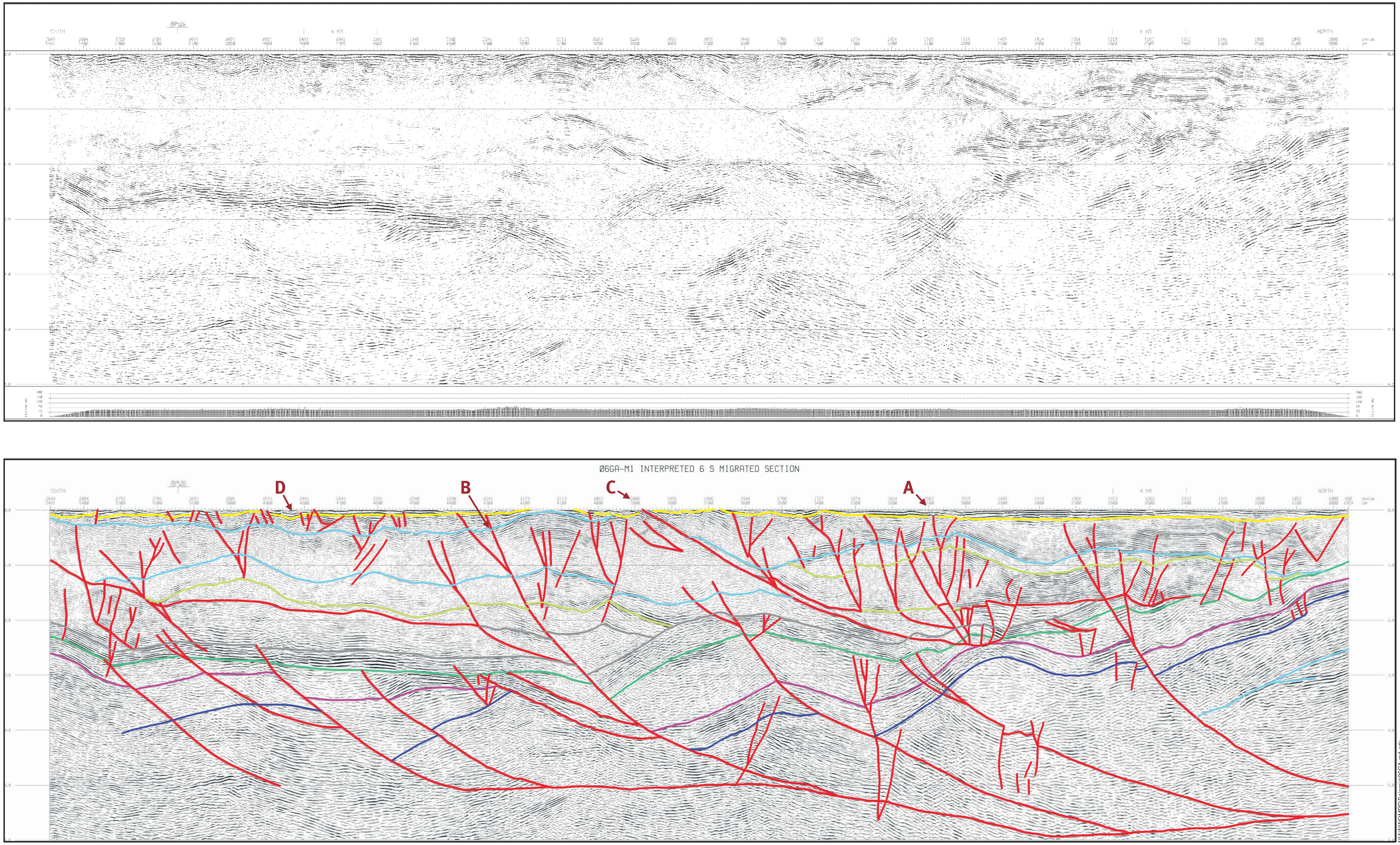


Figure 5.5: Seismic Reflection line 06GA-M1

Seismic Reflection line 06GA-M1

- The top 6 seconds two-way travel time (TWT) (~18km depth) is displayed here. The line was recorded to 20 seconds TWT (~60km depth).
- Line traverses north–south to north-north-east from north to south of the Century mine.
- The Mount Caroline Anticline (A on the diagram above) is clearly cored by thrust faults which formed during contraction which was part of the Isan Orogeny.
- A large growth fault is labelled B on the diagram above, although its actual orientation is unclear from this section.
- The fault labelled C on the diagram above is coincident with the Termite Range Fault. The apparent shallow dip is because the section intersects the fault at a low angle.
- The apparent flat lying bedding (D on the diagram above) is also due to the section line being roughly parallel to the bedding.

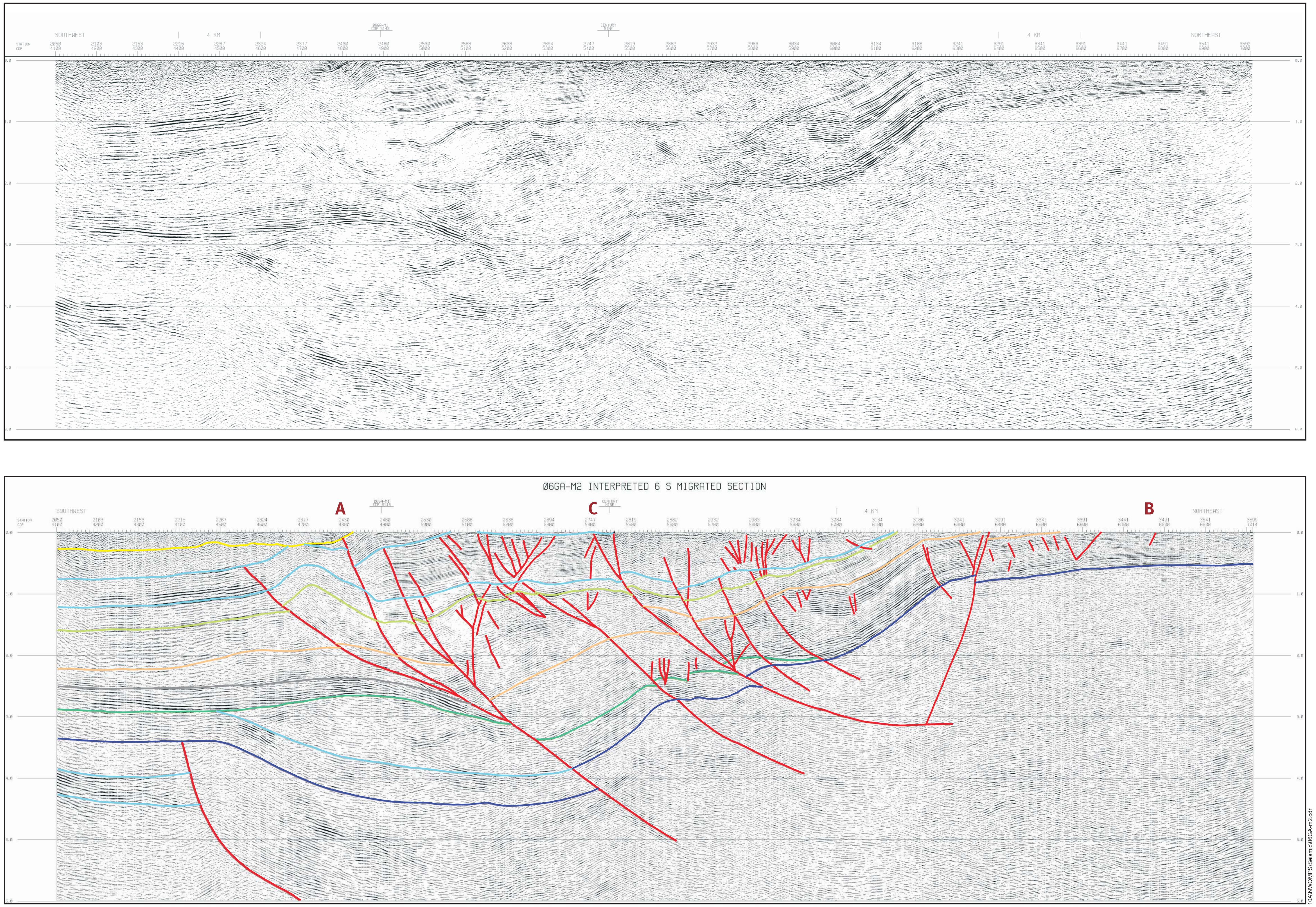


Figure 5.6: Seismic Reflection line 06GA-M2

Seismic Reflection line 06GA-M2

- The top 6 seconds two-way travel time (TWT) (~18km depth) is displayed here. The line was recorded to 20 seconds TWT (~60km depth).
- The major growth fault (A on the section above) is the Riversleigh Structure and comes to near the surface beneath and close to eastern edge of the Georgina Basin.
- The Termite Range Fault (C in the section above) is interpreted as an east-dipping thrust fault rather than a steep west-dipping structure in previous interpretations
- The basement (beneath the purple line) is poorly reflective, but comes close to the surface in the Kamarga Dome (B in the section above).

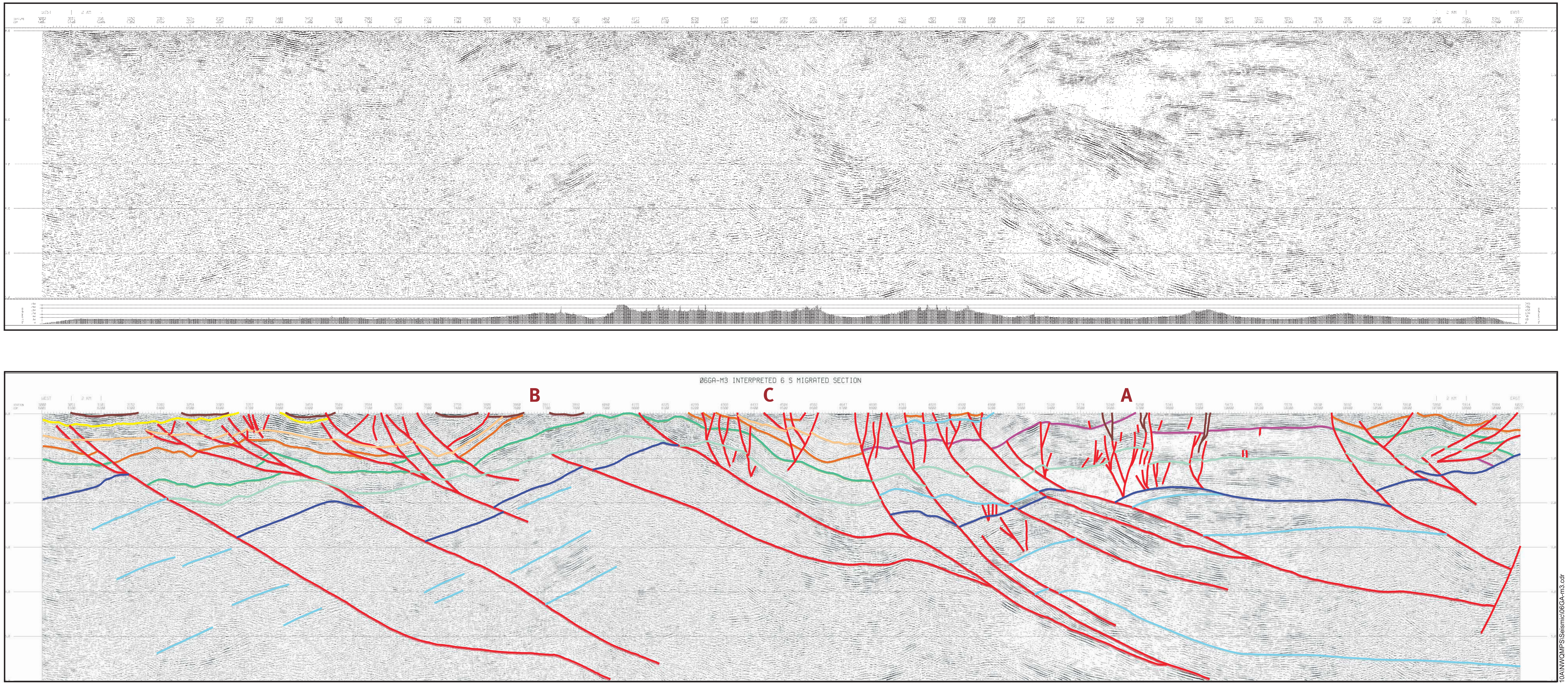


Figure 5.7: Seismic Reflection line 06GA-M3

Seismic Reflection line 06GA-M3

- Thick successions of mafic rocks (prominent reflections) occur within the Leichhardt River Fault Trough (LRFT — A on Figure 5.7).
- Thinner successions occur to the west on the flank of the LRFT (B on Figure 5.7).
- Normal faults which define the western margin of the LRFT extend to near the surface near the Mount Gordon Fault Zone (C on Figure 5.7).
- The Mount Gordon Fault Zone is interpreted as a strike-slip fault superimposed on the earlier normal faulting described above.
- The normal faults have been inverted, probably during the Isan Orogeny.
- Mineralisation at the Mount Gordon and Mount Kelly mines occur in second order faults which intersect the inverted normal faults.

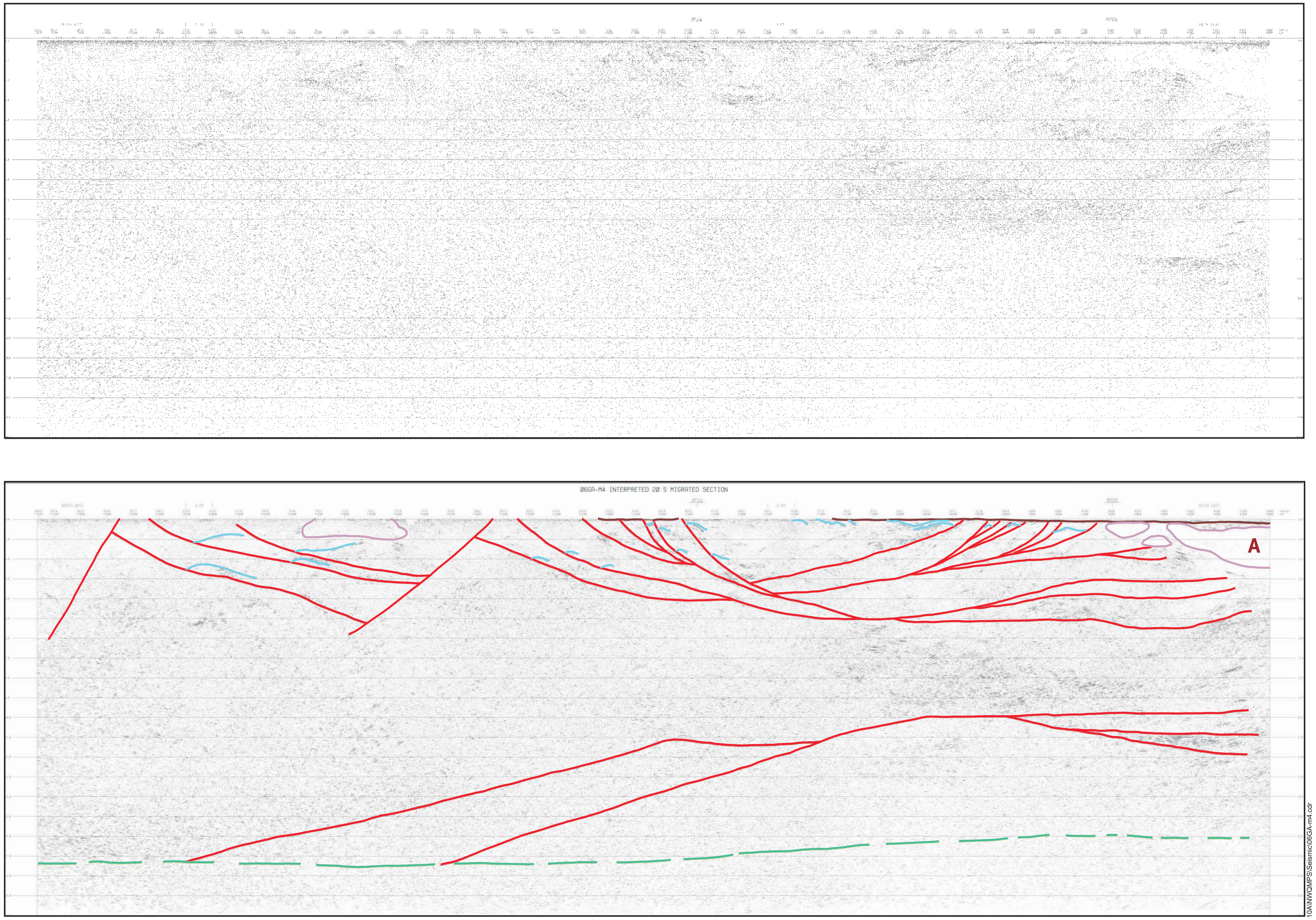


Figure 5.8: Seismic reflection line 06GA-M4

Seismic reflection line 06GA-M4

- Line 4 is displayed to 20 seconds TWT (~60km depth).
- Reflections are poorly represented in this section, particularly in the western half.
- In the eastern part of the section, reflections indicate thin skinned tectonics in the mid- to upper crust in the Eastern Fold Belt.
- The Moho is poorly defined and the lower crust is weakly reflective.
- Bland zones in the upper crust (A on Figure 5.8) are interpreted as granites of the Williams Supersuite.

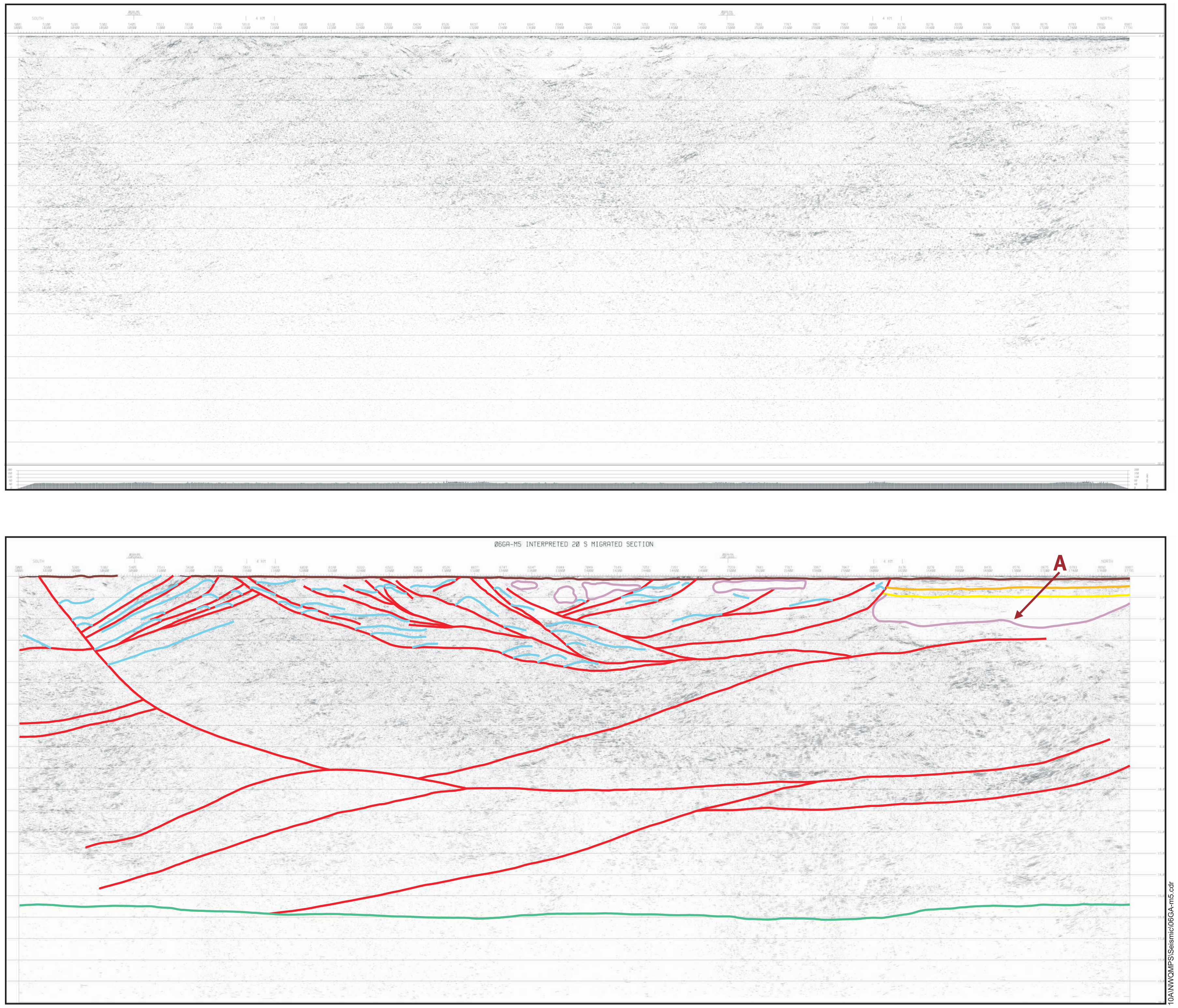


Figure 5.9: Seismic reflection line 06GA-M5

Seismic reflection line 06GA-M5

- Line 5 displayed down to a depth of 20 seconds TWT (~60km)
- At the north-eastern end of the line (A on Figure 5.9) the non reflective zones are interpreted as granite and appear to be overlain by a previously unknown sedimentary succession (possibly the Millungera Basin that is imaged in 07GA-IG1) and this is in turn overlain by the Jurassic–Cretaceous Carpentaria Basin succession.
- The eastern fold belt succession in this line is underlain by a mid-crustal detachment.
- Mid- to lower crustal rocks have poorly developed reflectivity and consequently the Moho is indistinct.

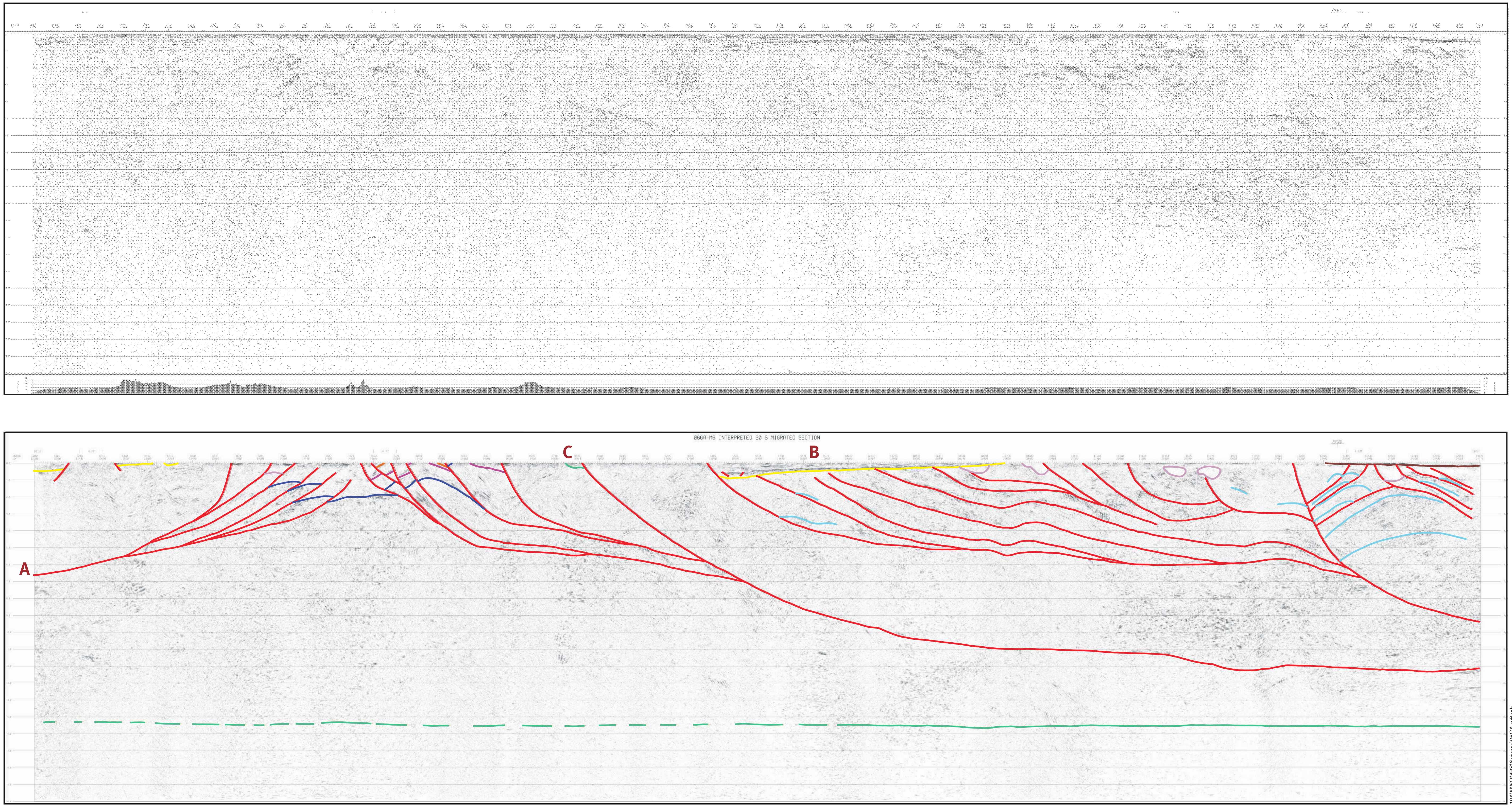


Figure 5.10: Seismic reflection line 06GA-M6

Seismic reflection line 06GA-M6

- Line 6 transects the whole of the Mount Isa Province, imaging both the Eastern and Western Fold Belts. It is displayed down to 20 seconds TWT (~60km depth).
- West-dipping reflections at the western end of the line (A on Figure 5.10), are interpreted to occur within the Arunta Province or Tennant Creek Block rocks which lie to the west of the Mount Isa Inlier.
- Almost flat reflections in the middle part of the line (B on Figure 5.10), are produced by sedimentary rocks of the Georgina Basin, within a half graben that is part of the Burke River Structural Belt.
- Near the western end of the Georgina Basin sequence, the Pilgrim Fault, which is poorly imaged on Figure 5.10, is commonly regarded as the boundary between the Eastern and Western Fold Belts.
- Thrust faults in the Western Fold Belt (C on Figure 5.10) extend to depths of ~12s TWT (~36km depth), while thrusts in the eastern Fold Belt sole into a detachment at ~6s TWT (~18km depth). This could explain the presence at the surface in the Kalkadoon Leichhardt Belt (west of Pilgrim Fault) of older basement rocks which do not crop out in the Eastern Fold Belt.

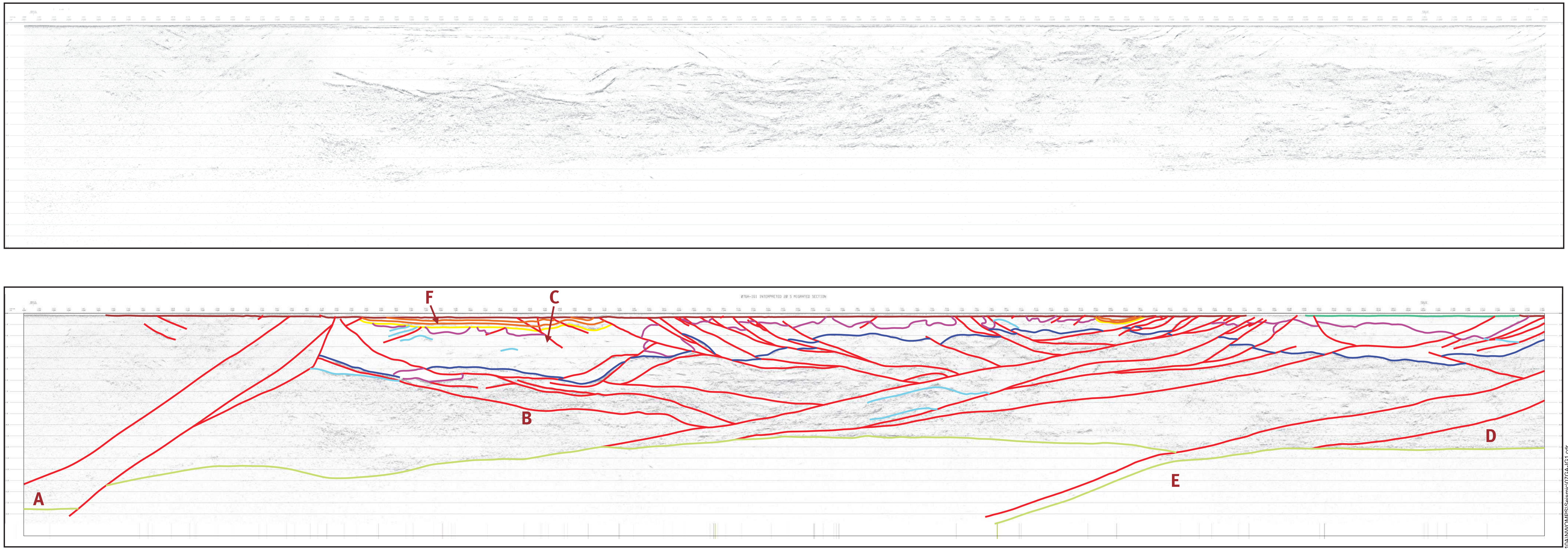
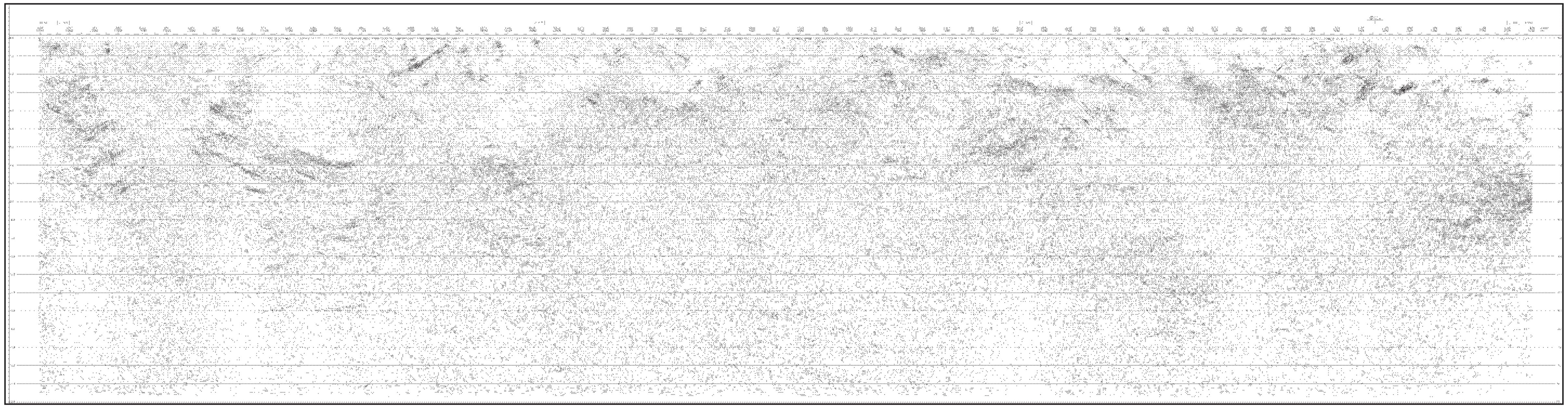


Figure 5.11: Seismic reflection line 07GA-IG1

Seismic reflection line 07GA-IG1

- This section traversed from north of Cloncurry to east of Croydon, and is displayed down to 20 seconds TWT (~60km depth).
- The section traverses between the Mount Isa and Georgetown Inliers. The Numil, Kowanyama, and Abingdon Seismic Provinces are identified at depth between the two inliers. The geological setting of these Seismic Provinces is not known as they are only known from these deep seismic profiles.
- The boundary between the Mount Isa and Numil Seismic Province corresponds to a change in the depth of the Moho (A on Figure 5.11). The change in the Moho occurs at an enigmatic west-dipping feature which has been interpreted as a major crustal suture and possibly a subduction zone related to an interpreted volcanic arc in the Kalkadoon–Leichhardt Domain at ~1860Ma.
- This zone also corresponds to a change from a lower crust with strongly developed multiple reflections to the east and a homogenous lower crust without strong reflections to the west.
- The reflective lower crust (B on Figure 5.11) to the east cannot be tracked to the surface and so its age or character is unknown. It was named the Numil Seismic Terrain by Korsch & others (2009).
- The less reflective seismic province in the upper part of the section (C on Figure 5.11) east of the suture is the Kowanyama Seismic Province. The contact between the Kowanyama and Numil Seismic Provinces is interpreted to be a shallow thrust.
- The eastern end of the section below ~ 5s TWT (~15km) is the Abingdon Seismic Province. These rocks are thrust beneath the Numil Seismic Province along a structure interpreted as a fossil subduction zone (E on Figure 5.11) (Korsch & others (2009).
- The Millungera Basin is a newly discovered sedimentary basin beneath the Jurassic–Cretaceous Eromanga and Carpentaria Basins and above the Kowanyama Seismic Province (F in Figure 5.11).



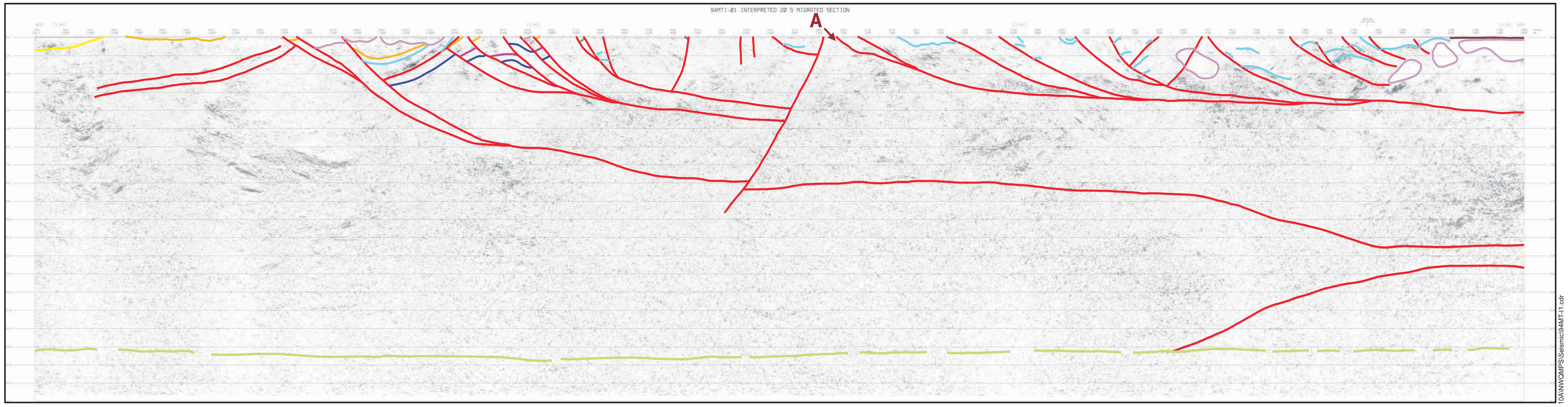


Figure 5.12: Seismic reflection line 94MTI-01

Seismic reflection line 94MTI-01

- This line was shot in 1994 but was reprocessed at Geoscience Australia in 2008.
- The data are displayed down to 20 seconds TWT (~6km depth).
- The eastern end of the line shows a series of listric faults soling out in a detachment at about 4 seconds TWT (~12km depth). These faults are interpreted as thrusts related to shortening during the middle Isan Orogeny.
- The western half of the line does not display the detachment interpreted in the east. The pre-Leichhardt Superbasin basement rocks, known from the Western Fold Belt, are not exposed in the Eastern Fold Belt and this may be because the detachment separates deeper crustal pre-Leichhardt Superbasin rocks from shallower crustal rocks.
- The Pilgrim Fault, which is interpreted as a major crustal suture between the Western and Eastern Fold Belts, is coincident with an east-dipping listric thrust fault. However this zone has a complex history, and the Pilgrim Fault may have a steep dip and therefore may not be imaged on the section.
- At the western end of the line, rocks with west dipping reflections are interpreted as being part of the Arunta and Tennant Creek Blocks (compare with line 06GA-M6, Figure 5.10).

North-West Queensland mineral systems analysis

Classifications of mineral deposits have traditionally followed two alternative approaches, focusing either on descriptive features of the mineralisation such as host rock type and orebody 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; *pmd**CRC I7 Project Team, 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 NWQMEP 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 part of the province (Table 6.1), structurally-controlled epigenetic Cu±Au deposits in the west (Table 6.2), Ag-Pb-Zn in high-grade metamorphic terrains in the east (Table 6.3), stratabound sediment-hosted Zn-Pb-Ag in the west (Table 6.4) and phosphate (Table 6.5). A key output of the models is sets of measurable targeting criteria that can be used in quantitative assessments of mineral potential.

Table 6.1: Mineralising system for structurally-controlled, epigenetic Cu±Au±iron oxide (east of the Kalkadoon – Leichhardt Domain) — ingredients, processes and mappable features (modified from Skirrow & others, 2009 and Huston, 2010)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q1	Passive margin, distal back arc basin or intracontinental extension pre-mineralisation events	Sedimentary-volcanic rocks in subaerial to shallow water basin settings provide sources of metals and salinity, and maintain fluid redox at intermediate to high levels.	Unknown	• Passive margin, distal back arc or intracontinental extensional basins • (Meta)evaporate sequences	Importance of pre-Cu-Au setting? Can other settings provide similar sources and buffering	Continental to terrane
Q1	Pre- to syn-Cu-Au orogenesis on margin of craton; terrane accretion	Pre-Cu-Au orogenesis and/or terrane accretion provides crustal-scale fluid pathways	Desirable	• Metamorphic belts • Crustal-scale faults/shears	Tectonic setting of orogenesis not well understood	Continental to terrane
Q1, Q4	Major (mantle-driven?) thermal anomaly at Cu-Au time; low pressure-high temperature metamorphism	High geothermal gradients; formation of A-type and I-type melts; mantle melts are source of some metals; low pressure-high temperature indicative of high geothermal gradients regionally, needed to maintain high temperatures of fluids in near-surface; drives convection of brines deep into basement	Essential	• A-type crustal melts emplaced at shallow levels • Alkaline mafic magmatism, indicating melting of metasomatised lithospheric mantle • Region may also have high-temperature I-type crustal melts and comagmatic volcanics • Low pressure – high temperature metamorphic assemblages in syn-Cu-Au orogens but not necessarily in shallow-crustal Cu-Au districts	Tectonic setting of orogenesis and A-type magmatism not well understood; Are thermal anomalies mantle-derived or radiogenic in origin? Not clear if convection was necessary, or if single-pass systems.	Continental to district (camp)
Q1	Presence of shallow A-type granitoids immediately pre- to syn-Cu-Au	Exposure of Cu-Au-rich sources to shallow oxidised fluids	Essential to desirable	• Surface and subsurface distribution of intrusions	Relative importance of various potential fluid sources in ore formation	Terrane to district (camp)

Table 6.1 (continued)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q2, Q4	Crust-penetrating shear/fault zones separating crustal blocks or orogens; district-scale fault networks reactivated during Cu-Au mineralisation	Magma & fluid pathways from mantle and lower crust to near-surface; permeability control on flow of deep-sourced and possibly meteoric fluids. Major systems may preferentially occur in hanging wall of boundary zones between crustal blocks, above zones of partial crustal melting and mafic underplating.	Highly desirable	• PTt variations across crustal block boundaries • Geophysical responses of deep crustal fault/shear zones – gravity and magnetic worms • Cu-Au-related alteration along faults • Ages of fault movement • Alignment of mineral deposits. • Major crustal boundary zones, with greatest potential in hanging wall above steps in Moho or above highly reflective seismic zones in mid-lower crust. • Network of syn-orogenic major faults/shear zones, reactivated during high temperature magmatic events. • The intersections of second-order cross structures with crustal-scale terrane boundaries are favoured locations for Cu-Au-iron oxide systems.	Extensional or compressional or strike-slip?	Terrane to district (camp)
Q2	Close association of deposits with gradients of major gravity ridges	Gradients represent crustal block boundaries (major fluid pathways)	Desirable	• Gravity data (upward continued) worms	Nature of these boundaries	Terrane
Q2	Brecciation at high crustal level	High permeability fluid pathways	Essential to desirable	• Breccias of hydrothermal, and/or tectonic and/or phreato-magmatic origins • Pre-existing basinal structures and second-order cross structures (for example, conjugate fault sets) that localise dilational deformation, brecciation (at high crustal levels) and fluid flow.		District (camp) to deposit
Q2, Q4	Regional flow of high temperature brines	Large Cu-Au deposits require very large volumes of fluid	Essential	• Mapping of regional magnetite-bearing albite or K-feldspar alteration zones • Inversion modelling of gravity and magnetic data to map magnetite- and hematite-bearing hydrothermal alteration.		District (camp) to deposit
Q3, Q4	Moderate to high temperature (300–550°C) Fe-rich (hyper)saline brine, magnetite- (to ?hematite-) stable	Carries Fe (±S, Cu) to form Fe^{2+}-bearing oxides, silicates, carbonate and sulphides	Essential	• Presence of fossils; moderate to high temperature brines trapped in hydrothermal minerals	Is magnetite-stable brine necessary, or is the high temperature brine only hematite-stable in some systems? Magmatic versus nonmagmatic contributions? Role of alkaline mafic sources of U, REE, Cu, Au?	District (camp) to deposit
Q3, Q4	Diverse fluid sources, including sedimentary formation waters in basins, magmatic, metamorphic (basinal and basement units), meteoric and possibly mantle-derived.	Combinations of fluids in different proportions across gradients in salinity, temperature and pressure are important controls on ore deposition.	Essential to desirable	• Evidence of fluid mixing in isotopic and fluid inclusion data. • Fluid flow is enhanced by juxtaposition of earlier rift basins with high temperature melt provinces.	What are the relative contributions of metals and sulphur from the various fluid sources through time? What are the relationships between fluid sources and deposition of Cu, Cu-Au, U and Mo-Re?	Terrane (basin) to district (camp)
Q3	Evaporite or ex-evaporite bearing sequences in basement and/or cover	Sources of Cl^- for complexing of Fe, Cu; source of CO_3^- and SO_4^{2-} for complexing of U; buffered redox state of fluids to moderate to oxidised levels	Unknown	• Presence, extent and distribution of evaporite or ex-evaporite minerals (for example, scapolite) and related rocks • Fluid inclusion evidence (for example, Br/Cl) suggestive of interaction of fluids with evaporites	Source of salts in either high or low to moderate temperature brines poorly constrained; however, a non-magmatic contribution is present	Terrane (basin) to district (camp)
Q4	Repeated fault movement during major orogenic events	Reactivation of fault networks leads to formation of dilatant zones, fluid pumping and remobilisation and concentration of previously deposited mineralisation.	Essential to Desirable	• Fault networks with history of repeated reactivation and movement during major orogenic events. • Mapping of alteration indicating multiple fluid pulses. • Inflections in apparent polar wander path indicating periods of significant deformation and tectonic readjustment.	Kinematic history of fault networks not well constrained.	District (camp) to deposit

Table 6.1 (continued)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q5	Reductant: ◦ Fe^{2+} oxides, silicates, carbonates ◦ and/or sulphides ◦ and/or reduced C	Fe^{2+}-bearing oxides, silicates, carbonate and sulphides may act as reductants for Cu-Au-bearing fluids	Essential to desirable	• Presence of Fe^{2+}-bearing oxides, silicates, sulphides, carbonates • Presence of alkali feldspars (albite in deeper zones, K-feldspar in shallower zones)		District (camp) to deposit
Q5	Late stage oxidation of earlier alteration assemblages	Indicates influx of oxidised fluids, possibly carrying Cu-Au; deposition by fluid-rock reaction	Desirable	• Late stage overprint of hematitic alteration and Cu-Au mineralisation associated with chlorite, sericite, carbonate. • Hematite-rich zones may be lateral to, or above, magnetite-bearing zones.		District (camp) to deposit
Q5	Fluid mixing	Cu-Au via mixing with reduced fluid; can produce high grades. Sulphides were deposited through combinations of fluid cooling, wall rock reactions and phase separation.	Desirable	• Evidence for two or more fluids (for example, barite, fluid inclusion evidence, isotopic evidence). • Steep fluid pathways, such as along major faults, connecting different fluid reservoirs.	Role of mixing versus two-stage fluid-rock reaction unresolved; can either produce ore-grade Cu-Au?	Deposit
Q5	Dilatant zones	Dilatant zones allow metal deposition via fluid mixing, cooling and de-pressurising.	Desirable	• Potential dilatant zones represented by breccia zones, fault bends and jogs, fault intersections, competency contrasts.	Kinematic history of fault networks not well constrained.	District (camp) to deposit
Q5	Replacement	Many significant deposits include replacement of suitable host rocks as a significant component of mineralisation.	Desirable but not essential	• Mapping of potentially chemically replaceable units such as ironstones	Are the ironstones syngenetic or metasomatic in origin?	District (camp) to deposit
Q5	Presence of mafic rocks	Many deposits are adjacent to or hosted in part by mafic rocks. Fluids from, or passing through, mafic rocks deposited metals by mixing or wall rock interaction in the vicinity of the mafic rocks.	Desirable	• Mapping of mafic rocks by geophysical methods.	Are the mafic rocks significant because they are potential metal sources or because of competency contrasts? Are the mafic rocks intruding older structures that were reactivated during mineralisation?	District (camp) to deposit
Q6	Deep weathering and supergene enrichment	Deep weathering in some areas has resulted in substantial, easily mined, supergene copper resources, despite the relatively low sulphide content of many deposits.	Desirable	• Cu-stained gossans and shear zones. Gossans may be preserved below cover. • A number of elements including Cu and Au may be dispersed upwards and laterally into Mesozoic cover rocks during the weathering and hydrological cycle as part of a reduction/oxidation (REDOX) process. • Dispersion patterns or halos within the Mesozoic cover may extend the full strike length of deposits and be wider than the mineralised zones.	Are there any correlations between grade/tonnage of sulphide mineralisation and grade/tonnage of resulting supergene deposits?	Deposit

Q1: What is the geodynamic and P-T-t history of the system?
Q2: What is the architecture of the system?
Q3: What are the fluid characteristics and the sources (reservoirs) of water, metals, ligands and sulphur?
Q4: What are the fluid flow drivers and pathways?
Q5: What are the transport and depositional processes for metals, ligands and sulphur?
Q6: How and where do later geological processes allow preservation of deposits?

Table 6.2: Mineralising system for structurally-controlled epigenetic Cu±Au deposits (west of the Kalkadoon – Leichhardt Domain) — ingredients, processes and mappable features

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q1	Intracontinental extension pre-mineralisation events	Hosted by rift sediments. Sedimentary-volcanic rocks in subaerial to shallow water basin settings provide sources of metals and salinity. Fault architecture provides pathways for fluid movement during later compressional events.	Essential	• Intracontinental extensional basins • (Meta)evaporate sequences • Fault networks		Continental to terrane
Q1	Compressional orogenesis	Compressional orogenesis and deformation, with shortening and crustal thickening, drives fluid movement and formation of dilational traps. Mineralisation is associated with peak to retrograde metamorphism.	Essential	• Crustal-scale faults/shears active during compression	Tectonic setting of orogenesis not well understood	Continental to terrane
Q2, Q4	Crust-penetrating shear/fault zones separating crustal blocks or orogens; district-scale fault networks reactivated during Cu mineralisation	Magma & fluid pathways from mantle and lower crust to near-surface; permeability control on flow of deep-sourced and possibly meteoric fluids. This synmetamorphic fault-related fluid circulation system connects fluid sources, oxidised rocks and host metasediments. Major systems may preferentially occur in hanging wall of boundary zones between crustal blocks. Alteration patterns in some deposits suggest emanation of fluids from footwall adjacent to major faults.	Highly desirable	• PTt variations across crustal block boundaries • Geophysical responses of deep crustal fault/shear zones — gravity and magnetic worms • Cu-related alteration along faults • Ages of fault movement • Alignment of mineral deposits. • Major crustal boundary zones, with greatest potential in hanging wall • Network of pre- to synorogenic major faults/shear zones, reactivated during compressive events.		Terrane to district (camp)
Q2	Rift-hosted sedimentary sequences	Deposits hosted by strongly reducing and reactive, low-grade metamorphosed pyritic, carbonaceous (and preferably dolomitic) metasedimentary successions with mechanical contrasts within the sequence. These rock packages are localised in sub-basins confined to accommodation zones resulting from episodic reactivation of fault systems that accompany sedimentation and also host stratabound Ag-Pb-Zn mineralisation.	Essential	• Rift sequences mapped from surface geology, sequence stratigraphy and geophysics.	Role of precursor pyrite or other sulphide mineralisation.	Terrane to district (camp)
Q2, Q3	Presence of mafic volcanic rocks in footwall of faults	Many deposits are adjacent to mafic volcanic rocks of the Eastern Creek Volcanics. Metabasalts are a potential Cu source.	Desirable	• Mapping of altered and demagnetised mafic volcanics by geophysical methods • Surface and subsurface distribution of mafic volcanics in relation to faults and potential host rock packages.	Is the Cu in the metabasalts of the Eastern Creek Volcanics pre- or syn-mineralisation?	District (camp) to deposit
Q2, Q4	Regional flow of high temperature brines	Large Cu deposits require very large volumes of fluid	Essential	• Inversion modelling of gravity and magnetic data to map hydrothermal alteration. • District-scale envelope of systematic ^{18}O and ^{13}C depletion in carbonates may correlate with mineralising faults.	Source of fluid(s)	District (camp) to deposit
Q3, Q4	Saline, H_2S-poor, high SO_4^{2-}/H_2S fluids at 200–400°C	Saline, H_2S-poor, relatively oxidised fluids (SO_4 total $\geq H_2S$), are required for the mobilisation and transport of copper, sulphur and other ore-forming components. Fluid pathways involve evaporite environments and oxidised rock masses.	Essential	• Presence of fossil moderate to high temperature brines trapped in hydrothermal minerals	Source of fluid(s)	District (camp) to deposit
Q3, Q4	Diverse fluid sources, including sedimentary formation waters in basins, magmatic, metamorphic (basinal and basement units), meteoric and possibly mantle-derived.	The origins of fluids potentially associated with mineralisation are diverse and include sedimentary formation waters in basins, magmatic, metamorphic (basinal and basement units), meteoric and possibly mantle sources. Combinations of fluids in different proportions across gradients in salinity, temperature and pressure are important controls on ore deposition.	Essential to desirable	• Evidence of fluid mixing in isotopic and fluid inclusion data. • Evidence of potential source rocks (rift-related volcanics) and diagenetic aquifers in lower parts of the stratigraphic pile, comprising thick proximal clastic sequences with potential to be buried to 5–10km depth at time of mineralisation.	What are the relative contributions of metals and sulphur from the various fluid sources through time?	Terrane (basin) to district (camp)

Table 6.2 (continued)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q3	Evaporite or ex-evaporite bearing sequences in basement and/or cover	Fluid pathways may involve evaporite environments and oxidised rock masses. Sources of Cl^- for complexing of Fe, Cu; source of CO_3^- and SO_4^{2-}; buffered redox state of fluids to moderate to oxidised levels	Unknown	• Presence, extent and distribution of evaporite or ex-evaporite minerals (for example, scapolite) and related rocks • Fluid inclusion evidence (for example, Br/Cl) suggestive of interaction of fluids with evaporites	Source of salts in either high- or low to moderate temperature brines poorly constrained. Host rocks may have provided all or part of sulphur component of Cu ores.	Terrane (basin) to district (camp)
Q4	Repeated fault movement during major orogenic events	Reactivation of fault networks leads to formation of dilatant zones, fluid pumping and remobilisation and concentration of previously deposited mineralisation. Deposits generally lie along fracture zones that are closely related to faults that splay off the major faults.	Essential to desirable	• Fault networks with history of repeated reactivation and movement during major orogenic events. • Mapping of alteration indicating multiple fluid pulses. • Inflections in apparent polar wander path indicating periods of significant deformation and tectonic readjustment.	Kinematic history of fault networks not well constrained.	District (camp) to deposit
Q4, Q5	Hydrothermal alteration	Copper grades correlate with intensity of silicification in silica and silica-dolomite alteration zones. Hydrothermal phengite has been identified in a variety of forms (at basal contacts, along mineralised faults and as a halo surrounding quartz veins) along the Mount Isa Fault and in broad but significant halos surrounding the Hilton, George Fisher and Mount Isa Ag-Pb-Zn and Cu deposits.	Desirable	• Alteration mapping • Hyperspectral mineral maps		District (camp) to deposit
Q5	Fluid mixing	Wide ranges in salinity and homogenisation temperatures for fluid inclusions and evidence for multiple fluid sources, as suggested by halogen ratios, indicate fluid mixing as an important process in genesis. Most of the ore deposits and regional alteration have mixed geochemical signals indicating the involvement of at least two of the fluid end-members. Cu deposition may be due to mixing of an oxidised brine (that possibly circulated within metabasalts) with a reduced sulphur-rich fluid from overlying metasediments or a younger basin.	Essential to desirable	• Evidence for two or more fluids (for example, fluid inclusion evidence, isotopic evidence). • Steep fluid pathways, such as along major faults, connecting different fluid reservoirs.	Role of mixing versus two-stage fluid-rock reaction unresolved; can either produce ore-grade Cu?	Deposit
Q5	Dilatant zones	Dilatant zones allow metal deposition via fluid mixing, cooling and de-pressurising. Fault networks comprising the major faults, splays, subsidiary faults and cross faults provide a district-scale control by providing sites of dilation, brecciation and fluid pathways during compressive events and interacting with reactive rocks such as laminated siltstones and carbonaceous shales and feldspathic sandstones.	Essential	• Potential dilatant zones represented by breccia zones, fault-fold systems, reactivated segments of earlier fault systems, fault bends and jogs, fault intersections, competency contrasts. • Zones of higher strain relative to surrounds.	Kinematic history of fault networks not well constrained.	District (camp) to deposit
Q5	Chemical traps/ replacement	Many significant deposits include replacement of suitable host rocks as a significant component of mineralisation. Chemical traps include large bodies of dolomite, and pyrite or some other sulphur source.	Desirable but not essential	• Mapping of potentially chemically replaceable and sulphur-rich units. • The ferroan dolomites associated with the Mount Isa mineralisation make a potentially useful exploration tool.	To what extent are the trap rocks a sulphur source?	District (camp) to deposit

Table 6.2 (continued)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q6	Deep weathering and supergene enrichment	Deep weathering in some areas has resulted in substantial, easily mined, supergene copper resources, despite the relatively low sulphide content of many deposits.	Desirable	• Cu-stained gossans and shear zones. Gossans may be preserved below cover. • Distribution of Cu±Au in rock chips, soils and stream sediments. • A number of elements including Cu and Au may be dispersed upwards and laterally into Mesozoic cover rocks during the weathering and hydrological cycle as part of a reduction/oxidation (REDOX) process. • Dispersion patterns or halos within the Mesozoic cover may extend the full strike length of deposits and be wider than the mineralised zones.	Are there any correlations between grade/tonnage of sulphide mineralisation and grade/tonnage of resulting supergene deposits?	Deposit

Q1: What is the geodynamic and P-T-t history of the system?
Q2: What is the architecture of the system?
Q3: What are the fluid characteristics and the sources (reservoirs) of water, metals, ligands and sulphur?
Q4: What are the fluid flow drivers and pathways?
Q5: What are the transport and depositional processes for metals, ligands and sulphur?
Q6: How and where do later geological processes allow preservation of deposits?

Table 6.3: Mineralising system for Ag-Pb-Zn in high-grade metamorphic terranes (east of the Kalkadoon – Leichhardt Domain) —— ingredients, processes and mappable features

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q1	Intracontinental or continental margin rifted setting of relatively thin crust dominated by folding and ductile shearing rather than block faulting. Rifting is accompanied by mafic and felsic volcanism, active extensional tectonics, high geothermal gradients and abundant hydrothermal activity in shallow to deep submarine settings.	Sedimentary-volcanic rocks provide sources of metals and salinity. High geothermal gradients and hydrothermal activity are conducive to formation of submarine exhalites and synsedimentary/ syndiagenetic mineralisation. Pb isotope studies support a model where mineralisation formed in feldspathic clastic rocks deposited in a deep water turbiditic basin in the east that developed during incision and granite emplacement in the west.	Essential	Zones of extensional rifted tectonics along the Eastern margin of Proterozoic Australia. This setting is represented by multiply deformed high-grade metamorphic belts of the Soldiers Cap rift event (1690–1670Ma) in the Eastern Fold Belt Province of the Mount Isa Orogen.	Relative importance of various potential fluid sources in ore formation. Is synsedimentary/ syndiagenetic mineralisation the sole source of the metals? Are these deposits sedimentary exhalatives or volcanogenic massive sulphides?	Continental to terrane
Q1	Multiply deformed high-grade (amphibolite-granulite facies) metamorphic belts	Economic grades due to modification, metal remobilisation and zoning during metamorphism and deformation.	Essential	Distribution of amphibolite-granulite facies metamorphism.	Can these deposits form at lower metamorphic grades?	Terrane to district (camp)
Q1, Q3	Late-stage metasomatic activity due to intrusions	Many deposits show evidence of late-stage metasomatic modification and/or mineralisation. Some deposits are considered to have their genesis as Zn skarns. Epigenetic mineralisation may have occurred during waning orogeny in D_3 and D_4 events.	Highly desirable	Surface and subsurface distribution of Williams–Naraku age intrusions. Evidence of metasomatic activity along major faults.	Relative importance of various potential fluid sources in ore formation. To what extent are additional metals introduced during metasomatism?	Terrane to district (camp)
Q2	Deposits are sited in small sub-basins that are probably fault-bounded entities within larger basins.	Sub-basins provide conditions for formation and preservation of mineralisation. Marine sediments and associated bimodal volcanics reflect active extensional tectonics. These basins underlie or are adjacent to shelf, lacustrine (evaporative) and terrestrial environments.	Highly desirable	Distribution of sub-basins from surface mapping and geophysics under cover	How can we recognise these sub-basins following extensive metamorphism, deformation and metasomatism?	District (camp) to deposit

Table 6.3 (continued)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q2, Q4, Q5	Association with crust-penetrating regional faults.	Transcrustal extensional or transtensional faults developed during early organic events permitted large-scale cross-stratal fluid migration (and advective heat transfer) during basin growth and deformation. Fault-related fluid circulation systems were active during rift sedimentation and igneous intrusion into the rift succession; permeability control on flow of deep-sourced and possibly basinal fluids; internal heterogeneity promotes ore trapping by focussing fluid along competency boundaries and through chemically replaceable in-fault slivers.	Highly desirable	Regional structural settings include: • north-north-west- trending rift sidewall faults or transfer zones; and • at intersections with east-west-trending rift normal faults and/or reactivated north-west-trending basement structures Geophysical responses of deep crustal fault/shear zones — gravity and magnetic worms; alteration along faults; ages of fault movement.		Terrane to district (camp)
Q3	Metals sourced from a combined mafic-felsic igneous source derived from mantle; possible inputs from feldspar-bearing rocks such as crustal granites, dacitic-rhyolitic volcanics and pyroclastics, and clastic sedimentary units.	Pb isotopes indicate that the source of Pb is not upper crustal; a mantle or mafic volcanic/intrusive rock source is implicated. Significant syngenetic or diagenetic base metals contributed via exsolution of a CO_2-H_2O-S fluid late during fractional crystallisation of mafic rocks in the 1700–1620Ma period.	Essential to highly desirable	Distribution of mafic igneous activity. Mapped distribution of the top of the rift succession, corresponding to the last manifestations of rift-related bimodal igneous activity (immediately prior to the commencement of the sag phase).	What are the relative contributions of metals and sulphur from the various sources through time?	Terrane to district (camp)
Q3	Reduced (H_2S stable), moderate temperature (150–250°C), slightly acidic, high salinity fluids	A hot reduced metalliferous brine entering a relatively oxidised marine basin will deposit Pb-Zn mineralisation within a pyrite-poor but Fe-silicate or Fe-oxide-rich sedimentary environment.	Essential to highly desirable	Redox fronts	Nature of fluids not well constrained	Terrane to district (camp)
Q3	Evaporite or ex-evaporite bearing sequences underlying or adjacent to rift sediments.	Circulation of basinal brines may have been important, potentially in stripping and redistributing metals originally sourced from mafic rocks. The chemical character and metal ratios of the deposits may partly reflect an evaporite fluid source and fluid path history through the relatively oxidised rift succession.	Highly desirable	Presence, extent and distribution of evaporite or ex-evaporite minerals (for example, scapolite) and related rocks; fluid inclusion evidence (for example, Br/Cl) suggestive of interaction of fluids with evaporites	Are evaporites essential? What are the relative contributions of metals and sulphur from the various sources through time?	Terrane to district (camp)
Q3	Remobilisation of metals and modification and zoning of deposits by metamorphic and metasomatic events	PIXE analyses indicate that fluid inclusions from Cannington were entrapped during a high temperature metasomatic event and contain very high Pb, high Zn, low Cu and are rich in Mn. Pb isotopes indicate lead contributions from regional source rocks during an event at least 80my younger than the stratabound mineralisation; probably associated with amphibolite facies metamorphism of the Isan Orogeny.	Highly desirable	Isotopic and textural evidence from deposits. Host rocks show a long and complex history of prograde and retrograde metamorphism with metasomatic overprints and ductile/brittle deformation.	What are the relative contributions of metals and sulphur from the various sources through time? To what extent are additional metals introduced during metamorphism and metasomatism?	Terrane to district (camp)
Q4	Subvolcanic (rift-stage) intrusions may play a significant role in driving fluid circulation systems involved in forming early stratabound mineralisation.	The most effective heat sources to drive large circulation systems are gently dipping sills.	Highly desirable	Distribution of mafic igneous activity. Mapped distribution of the top of the rift succession, corresponding to the last manifestations of rift-related bimodal igneous activity (immediately prior to the commencement of the sag phase).		Terrane to district (camp)

Table 6.3 (continued)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q5, Q4	The lithological constitution, stratigraphic evolution and architecture of the host successions are consistent with their evolution in a rift zone, followed by sag (thermal subsidence) phase sedimentation.	Mineralisation is localised at the top of the rift succession, corresponding to the last manifestations of rift-related bimodal igneous activity, immediately prior to the commencement of sag phase sedimentation. This setting allows some direct access to mantle and crustal hydrothermal brines rich in Cu, Pb, Zn, Ag and Ba.	Essential to highly desirable	In the Eastern Fold Belt, the host lithostratigraphic setting is in the top of the rift stratigraphy (magnetically subdued, psammite-dominated metasedimentary succession of the Mount Norna Quartzite and Gandry Dam Gneiss of the Soldiers Cap Group) and stratigraphically below more mature siliciclastic sag phase sediments (Toole Creek Volcanics).	Are there any other prospective settings?	Terrane to deposit
Q5	Stratabound ore lenses affected by folding	Deposits generally exhibit repetition of ore lenses and host sequences, reflecting broad scale folding. Structural thickening in fold hinges is often critical to make economic ore thicknesses.	Essential to highly desirable	Style and distribution of folding events from mapping and geophysical interpretation.	Which events have been most significant in structural thickening of deposits?	Terrane to deposit
Q5	Stratabound mineralisation due to introduction of reduced ore fluids into an oxidised environment	The host sequence is oxidised (high Fe^{3+}/Fe^{2+}) whereas the ore assemblage is reduced. Metal deposition is due to fluid oxidation, neutralisation and possibly cooling.	Essential to highly desirable	The host environment is a mixed oxidised/reduced sedimentary package of argillites, clastics, carbonates and banded iron formation. Orebodies tend to be located at the transition from coarse quartzo-feldspathic to finer pelitic sedimentary facies.		Terrane to deposit
Q5	Stratabound mineralisation due to introduction of reduced ore fluids into an oxidised environment	Most deposits are associated with stratabound, complex Fe-Mn-Ca-silicate ironstones, some of which can be observed passing laterally into carbonate units or developing by magnetite replacement of non-ironstone units. These represent compositionally layered pelitic and psammopelitic metasediments.	Essential to highly desirable	The 'unremarkable' nature of the host quartzo-feldspathic gneisses with minor amphibolites does not represent a particularly useful lithostratigraphic marker package. Potentially useful marker units are likely to include laterally extensive, siliceous and Ca-Mn-Fe-F-rich metasediments that form chemical sedimentary packages with oxide, silicate, carbonate and sulphide facies, including quartz-gahnite units and thin banded iron formations. These chemical metasedimentary packages are generally variably magnetically active and may be distinguishable from generally non-magnetic sequences surrounding them.	Relative importance of various potential fluid sources in ore formation. Is syn-sedimentary/ syn-diagenetic mineralisation the sole source of the metals? Are these deposits sedimentary exhalatives or volcanogenic massive sulphides?	District (camp) to deposit
Q5	Presence of mafic rocks	Many deposits are adjacent to or hosted in part by mafic rocks. Host sequences include high-iron MORB-like tholeiites that are generated by large degrees of mantle melting and emplaced into intraplate, extensional environments.	Desirable	Mapping of mafic rocks by geophysical methods.	Role of mafic rocks as metal and heat sources.	District (camp) to deposit
Q5	Metamorphic and metasomatic remobilisation of metals and modification of pre-existing mineralisation.	Economic grades due to modification, metal remobilisation and zoning during metamorphism, deformation and metasomatism. Skarn and/or transgressive mineralisation has been noted in several deposits.	Essential to highly desirable	Distribution of amphibolite-granulite facies metamorphism and metasomatic alteration. Large-scale stratabound alteration halos represent a significant semi-regional exploration target. The occurrence of fine-grained garnet-K-feldspar, increased relative abundance of sillimanite and lack of migmatitic sweats makes the alteration package visually distinct from the regional host lithologies.	Are these deposits modified syn-sedimentary/ syn-diagenetic deposits or are they skarns? Are both processes important?	Terrane to deposit

Table 6.3 (continued)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q6	Weathering and supergene enrichment	Weathering in outcrop leads to development of gossans that may be indicative of substantial sulphide systems at depth.	Not important	Gossanous quartz-garnet-gahnite lode outcrops with abundant Mn and Fe oxides and some Cu carbonates and oxides at surface, with secondary Ag enrichment at depth. Many of the phases associated with mineralisation and alteration (for example, garnet, gahnite) are resistate and would concentrate in natural drainages and lags. Anomalous Pb, Zn, Ag, Mn and Ba in RAB, rock chip, soil and stream sediment samples appear to be the most direct geochemical and mineralogical signals of potential targets.		Deposit
Q6	Burial by subsequent erosion and sedimentation.	Prospective targets under recent and Mesozoic cover rocks. Known deposits under up to 100m of cover. The high-grade, high net-worth ore of deposits such as Cannington justifies underground development under substantial cover depths.	Not important	Mesozoic cover rocks provide a geochemical (and geophysical) blanket. Gossans may or may not be preserved under cover. A number of elements including Ag, Pb, Cu and Mn may be dispersed upwards and laterally into Mesozoic cover rocks during the weathering and hydrological cycle as part of a reduction/oxidation (REDOX) process. Anomalous Pb, Zn, Ag, Mn and Ba in basement RAB samples may delineate geochemical targets.	What are the best criteria for targeting under cover?	District (camp) to deposit

Q1: What is the geodynamic and P-T-t history of the system?
Q2: What is the architecture of the system?
Q3: What are the fluid characteristics and the sources (reservoirs) of water, metals, ligands and sulphur?
Q4: What are the fluid flow drivers and pathways?
Q5: What are the transport and depositional processes for metals, ligands and sulphur?
Q6: How and where do later geological processes allow preservation of deposits?

Table 6.4: Mineralising system for stratabound sediment-hosted Zn-Pb-Ag (west of the Kalkadoon – Leichhardt Domain) — ingredients, processes and mappable features

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q1, Q3	Intracratonic rift or distal back arc to passive margin environment with abundant mafic and felsic volcanic rocks and a thick sediment pile. Rifting is accompanied by active extensional tectonics, high geothermal gradients and abundant hydrothermal activity in shallow to deep submarine settings.	• Sedimentary-volcanic rocks provide sources of metals and salinity. • High geothermal gradients and hydrothermal activity are conducive to formation of submarine exhalites and synsedimentary to syndiagenetic mineralisation.	Essential	Zones of extensional rifted tectonics observable from geological maps and regional geophysical signatures, particularly the magnetic expression of rift-related mafic sequences.	Tectonic setting and history of Mount Isa Inlier is still contentious	Continental to terrane (basin)
Q1, Q4	A history of repeated extension and inversion pre-to syn-mineralisation events	• There is a strong basement control on basin architecture and the orientation of faults active at the time of basin formation. • Extension and growth faulting are potential divers of fluids by underpressure, dilation and downward convective flow. • Inversion, compressional folding and faulting are potential drivers of fluids by upward expulsion from breached reservoirs.	Essential	Regional potential field data can be used to define basement structures, basin margins, the nature and thickness of basin fill (depocentres) and other (?synsedimentary) structures.	Tectonic setting and history of Mount Isa Inlier is still contentious	Continental to terrane (basin)

Table 6.4 (continued)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q2	Crustal-scale, syn-sedimentation fault systems and related fault-bounded foundering sedimentation compartments/sub-basins exhibiting block tilting, anomalous sedimentation thickness distributions and systematic facies variations towards structures	• Sub-basins provide conditions for formation and preservation. • Marine sediments and associated volcanics reflect active extensional tectonics.	Essential to highly desirable	• The interpretation of geophysical data (magnetics, gravity and EM), combined with geological mapping, can be used to define the fault systems that form key parts of plumbing systems and compartmentalise lithofacies distributions. • Reflection seismic studies can contribute significantly to fault and stratigraphic mapping. • Sub-basins are characterised by: ◦ marked thickening of stratigraphy over a limited interval, reflecting sub-basin foundering/rapid subsidence; ◦ uncommon lithofacies, particularly thick accumulations of carbonaceous shale/siltstone accompanied by coarser clastics in one or more coarsening upwards cycles; ◦ synchronous local uplift and erosion producing coarser grained facies (arenites and rudites) and local unconformities.	Are other settings prospective?	Terrane (basin)
Q2	Rift-hosted sedimentary sequences that are often the latest sag phase of a series of rift-sag phases.	• Hosted by sag phase sedimentary successions of Cover Sequence 3 that are commonly evaporitic and enriched in carbonaceous matter and/or pyritic sediments. • Depositional environment varies from deep, euxinic, starved marine to shallow-water restricted shelf. • Mineralisation is not confined to a particular stratigraphic level or single basin phase.	Essential	• Evidence of shallow-water and deeper water carbonaceous and argillaceous host rocks (carbonate and siliceous clastic rift-fill packages containing organic-rich lutites interbedded with coarser clastics) in upper levels of youngest (pre-orogenic) Isa Superbasin. • Host rocks are characteristically anoxic and located at or near maximum flooding surfaces. • Abundant stratabound fine-grained (diagenetic) pyrite in prospective host rocks	Role of precursor pyrite or other sulphide mineralisation	Terrane (basin) to district (camp)
Q2, Q4, Q5	Association with crust-penetrating regional faults that were active/reactivated episodically during one or more sedimentation and mineralising events	• Transcrustal extensional or transtensional faults developed during early orogenic events permitted large-scale cross-stratal fluid migration (and advective heat transfer) during basin growth and deformation. • Fault-related fluid circulation systems were active during rift sedimentation and provided permeability control on flow of deep-sourced and probably basinal fluids.	Essential to highly desirable	• Linear, strike extensive faults that tap deep into the crust can be quantitatively assessed using fault strike length data from mapping and interpreted potential field data (especially gravity and magnetic worms). • Alteration along faults indicating multiple fluid pulses. • Ages of fault movement. • Intersections of strike extensive faults with north-west-, east-west- and north-east-trending basement fault systems (reactivated earlier rift structures) • Inflections in apparent magnetic polar wander path indicating periods of significant tectonic readjustment.	Kinematic history of fault networks is not well constrained. Are normal faults (syn-sedimentary to syn-diagenetic models) or reverse faults (syn-tectonic models) the most important fluid conduits?	Terrane (basin) to district (camp)

Table 6.4 (continued)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q3	Potential source rocks (rift-related volcanics and sediments) and diagenetic aquifers in lower parts of stratigraphic pile, comprising thick proximal clastic sequences with potential to be buried to 5–10km depth at times of mineralisation, for example, Leichhardt Superbasin sediments and volcanics.	• Pb isotope studies indicate that Pb has a strong crustal isotopic signature and was sourced mostly from underlying basins and continental crust. • Metals sourced from substrates to the sag phase basins that comprise mainly older rift materials, including felsic and basic igneous rocks, siliciclastic and less mature sediments, plus some carbonates and evaporites • A primitive Os signal at Century points to a reduced mantle reservoir component and the capacity to tap this reservoir may be a key part of the process of forming most of the larger deposits within the Isan mineral system.	Highly desirable	• Evidence from mapping and potential field data for older rift sequences (Leichhardt and Calvert Superbasins) in deep footwall of crustal penetrating faults. • High resolution aeromagnetic data can be interpreted to map the extensional architecture beneath younger post-rift and post-Isan successions.	Relative importance of basinal and mantle-derived metal sources.	Terrane (basin) to district (camp)
Q3	Evaporite or ex-evaporite bearing rocks in older basin sequences and/or cover.	• The sources of Cl, S and metals are poorly-constrained. A possible source of Cl is in evaporitic rocks that may also have provided S through dissolution of anhydrite or as H_2S gas through thermochemical sulphate reduction. Sulphur may also have been derived from seawater or from a more deep-seated (mantle) source. • A possible source of bittern brines is perched basins that may have existed at the time of the Isan Orogeny and subsequently been eroded.	Highly desirable	Evidence of saline brines, evaporites or remnants thereof in deeper parts of sediment pile. Presence, extent and distribution of ex-evaporite minerals (for example, scapolite) and related rocks. Fluid inclusion evidence (for example, Br/Cl) suggestive of interaction of fluids with evaporites.	Are evaporites essential? Source of salts in brines is poorly constrained. What are the relative contributions of metals, sulphur and brines from the various potential sources through time?	Terrane (basin) to district (camp)
Q3	Cool, relatively oxidised, near neutral, saline basinal brines are favoured for transporting base metals (and possibly sulphur as sulphate) to mineralisation sites	• The ore component transporting fluids are inferred to have been: ◦ initially at temperatures of 100° to 150°C, resulting from circulation deep into the sedimentary pile and basement followed by rapid ascent in fault systems to ore depositional environments ◦ highly saline (reflecting evaporitic sources) and consequently relatively acid (particularly if the fluids were clay-carbonate buffered during circulation), and hence sulphate-bearing, H_2S-poor and metal enriched (that is, metals >H_2S and SO_4^{2-}>>H_2S); ◦ Ba- and Cu-poor, but with relatively high Zn/Pb ratios, features that are reflected in the chemistry of the mineralised zones.	Essential to highly desirable	• Mapped extent of potential fluid reservoirs, particularly subsurface. • Presence of fossil brines trapped in hydrothermal minerals. • The pre-existing Leichhardt and Calvert Superbasins provided permeable aquifers and fluid reservoirs for many of the metals that are hosted by the Isan Superbasin or deposited during the Isan Orogeny. Where basins are thickly developed, as in the Leichhardt River Fault Trough, heterolithic proximal facies sediments are identified as diagenetic aquifers for storage of sedimentary formation waters. • Possible reservoirs in the Isa Superbasin are salty fluids from the McNamara Group, particularly the Lady Loretta and Paradise Creek Formations.	Could hot reduced fluids have produced some deposits? Are these deposits syngenetic, diagenetic or syntectonic, or a combination of these?	Terrane (basin) to district (camp)
Q3, Q4	Regional flow of metal-bearing brines	Large deposits require very large volumes of fluids	Essential	Alteration mapping using remotely sensed and geophysical data to identify zones of fluid movement along faults and within sediments.	Source of fluids	Terrane (basin) to deposit

Table 6.4 (continued)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q5	Fluid infiltration zones in organic-rich and/or carbonate-rich sedimentary packages in hanging wall positions fed by discordant fault systems. Chemical traps/replacement.	• The main processes contributing to Zn-Pb-Ag mineral deposition in infiltration zones were: ∘ fluid cooling; ∘ host rock carbonate dissolution (stylolites) and acid neutralisation; and ∘ thermochemical sulphate reduction due to mixing with reduced fluids and/or interaction of Zn-Pb-Ag-transporting fluids with organic matter and/or migrated but locally sourced hydrocarbons. • Chemical traps include dolomite and other carbonates and reduced packages such as carbonaceous shales, pyritic shales, and kerogen/hydrocarbon- rich sediments.	Essential to highly desirable	• Mapping of suitable host rock packages, including C- and S-rich and potentially chemically replaceable units. • Mapping of carbonate alteration halos, which may be zoned from Fe-rich near-ore, through Mn- and Fe-rich to Mg-rich away from ore. • Discordant faults. • Evidence of fluid reaction with host rocks, for example, stylolites.	To what extent are the trap rocks a sulphur source?	District (camp) to deposit
Q5	Hydrothermal alteration	Movement and interaction of mineralising fluids should leave distinctive signatures along fluid pathways and within host sequences.	Desirable to not essential	• Ferroan carbonate alteration envelope and stylo-laminated lutites; pyrite. • Broad but significant halos of hydrothermal phengite alteration surround some Zn-Pb-Ag deposits, and have also been detected along mineralised faults. Phengite Mineral Index maps from ASTER and HYMAP data can be used to delineate these zones. • Alunite corresponds closely to Zn-Pb-Ag gossans and represents supergene alteration of sulphides. • Illite crystallinity halo at Century.	Because alteration is generally subtle, distinctive alteration signatures are not readily apparent. Characterisation of drill core using HyLogger™ may provide new insights.	District (camp) to deposit
Q5	Iron, zinc and lead sulphides in stratabound zones through 50–700m of stratigraphy	Mineralisation generally comprises stratiform sulphide laminae (± discordant veins and breccias) in stratabound, concordant to weakly discordant, stacked tabular to lenticular zones.	Essential to highly desirable	• Prospective carbonaceous (and pyritic) lithological packages are conductive, limiting the direct imaging of base metal sulphide conductors. ∘ Induced polarisation is probably the most effective technique for unmetamorphosed sediment-hosted zinc deposits. ∘ Electomagnetics is usually the most appropriate method for deposits that have been strongly metamorphosed. • Detailed gravity surveys can reveal the presence of high-grade Zn-Pb mineralisation at depths of up to several hundred metres • Broader stratabound envelopes of secondary ferroan carbonate	Are stratiform sulphide textures sedimentary or epigenetic/replacement? Is precursor syngenetic sulphide mineralisation essential for later syndiagenetic or syntectonic mineralisation?	District (camp) to deposit
Q5	Metamorphic and metasomatic remobilisation of metals and the modification of pre-existing mineralisation.	Intense folding during the Isan Orogeny may lead to structural thickening of banded ore and grade enhancement due to remobilisation during deformation and formation of high-grade breccia ore.	Highly desirable but not essential	Style and distribution of folding events from mapping and geophysical interpretation.	• Are these deposits metamorphosed syngenetic mineralisation or have the metals been deposited during deformation? • To what extent are additional metals introduced during metamorphism and metasomatism? • Which events have been most significant in structural thickening and grade enhancement?	District (camp) to deposit

Table 6.4 (continued)

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q6	Weathering and supergene alteration	Weathering in outcrop leads to development of gossans that may be indicative of substantial sulphide systems at depth.	Not essential	• Gossans anomalous in Pb, Ag, As, Tl, Fe, Ba and S but low in Zn. • Some deposits have distinctive vegetation anomalies. • Alunite corresponds closely to Zn-Pb-Ag gossans and represents supergene alteration of sulphides. • Anomalous base metals in stream sediment, rock chip and soil samples. • Weathering of the shales overlying mineralised and unmineralised areas produces kaolinite, dickite and muscovite, with less feldspar breakdown above the unmineralised areas • Enriched Zn, Pb, Cu, Ag, Tl, Hg and Mn in lithochemical halos can provide vectors to hidden mineralisation	Are there any correlations between grade/tonnage of sulphide mineralisation and grade/tonnage of resulting oxide and supergene deposits?	Deposit
Q6	Burial by subsequent erosion and sedimentation	• Prospective targets may occur under Palaeozoic, Mesozoic and Cainozoic cover. • Large high-grade deposits justify underground development under substantial depths of cover.	Not important	• Cover rocks may provide a geochemical and geophysical blanket. • Gossans may or may not be preserved under cover. • A number of elements, including Ag, Pb, Mn and Fe may be dispersed upwards and laterally into cover rocks during the weathering and hydrological cycle. • Anomalous Pb, Ag, Zn, As, Tl, Fe, Mn, Ba and S in basement RAB samples may delineate geochemical targets • Geophysical datasets should still be useful in at least identifying prospective host sequences.	What are the best criteria for targeting under cover?	District (camp) to deposit

Q1: What is the geodynamic and P-T-t history of the system?
Q2: What is the architecture of the system?
Q3: What are the fluid characteristics and the sources (reservoirs) of water, metals, ligands and sulphur?
Q4: What are the fluid flow drivers and pathways?
Q5: What are the transport and depositional processes for metals, ligands and sulphur?
Q6: How and where do later geological processes allow preservation of deposits?

Table 6.5: Mineralising system for phosphate in the Georgina Basin — ingredients, processes and mappable features

Question	Ingredient / process	Reason	Importance	Mappable/measurable characteristics	Outstanding questions	Scale
Q1,2	Intracontinental or shallow continental margin (sag phase). A low palaeolatitude is required.	Phosphate deposits require predominantly carbonate sedimentation	Essential	General criteria for phosphate deposition: • A broad shallow downwarp adjacent to a seaway • High productivity in the vicinity • Minimal terrigenous sedimentation in a shallow marine environment • A major transgression • A trap such as a bay or carbonate bank.		Continental to terrane
Q5	Phosphate facies controlled by relative sea level, palaeography and palaeotectonics. A broad shallow downwarp adjacent to a seaway is required.	Many deposits related to marine transgression on an irregular palaeotopography. A trap such as a bank of bay is required.	Essential	In each of these sequences, the 'retrogradational parasequence sets of the transgressive sytems tract' comprise a repeating suite of phosphorite, phosphatic limestone and organic rich shales.		Terrane to district (camp)

Q1: What is the geodynamic and P-T-t history of the system?
Q2: What is the architecture of the system?
Q3: What are the fluid characteristics and the sources (reservoirs) of water, metals, ligands and sulphur?
Q4: What are the fluid flow drivers and pathways?
Q5: What are the transport and depositional processes for metals, ligands and sulphur?
Q6: How and where do later geological processes allow preservation of deposits?

Global Significance of the North-West Queensland Mineral and Energy Province

Mineral endowment

Zinc

The NWQMEP can be regarded as the premier zinc region in the world based on the following:

Number and Tenor of World Class Zinc Deposits

World class zinc deposits are defined by Singer (1995) as those in the upper 10% in terms of zinc metal content, containing a minimum of 1.7Mt zinc. Of the 57 deposits outside the CIS countries and China that meet this criterion (Table 7.1), by far the largest concentration (six) occurs within the NWQMEP , namely, George Fisher, Century, Mount Isa, Dugald River, Cannington and Lady Loretta. Of these deposits, four are ranked among the top nineteen in the world in terms of contained zinc in economic reserves, namely, George Fisher (2nd), Mount Isa (6th), Century (8th), and Dugald River (19th).

Total Zinc Endowment

The NWQMEP is the largest known repository of economically mineable zinc in the world. An indication of its global supremacy can be gauged from Table 7.2 and Figure 7.1, which compare the total contained zinc in economic reserves of the six largest deposits in the NWQMEP (George Fisher, Century, Mount Isa, Dugald River, Cannington and Lady Loretta) with various combinations of total zinc endowment for the largest zinc provinces world wide. The pre-eminence of the NWQMEP is illustrated by the fact that the total zinc content of these six deposits alone is:

- 5.5 times higher than the total contained zinc in the numerous deposits of the Tri-State District, which has the largest zinc content of all the North American Mississippi Valley districts.
- 4.3 times higher than the total zinc content of the 19 largest known carbonate-hosted zinc deposits in the Irish Central Plain.
- 3.5 times higher than the total of the Abitibi Subprovince (Noranda, Matagami, Chibougamau areas, etc) of Quebec/Ontario in Canada, which has the largest zinc content of all the volcanogenic massive sulphide districts in the world.
- 2.5 times higher than the total zinc content of the 11 largest sediment-hosted deposits of the Selwyn Basin in Yukon/British Columbia, Canada.
- 1.6 times higher than the total of 85 deposits in the Iberian Pyrite Belt, which is regarded as the largest concentration of massive sulphide mineralisation in the world.

Lead

Of the 31 deposits outside the CIS countries and China (Table 7.3) that meet the Singer (1995) definition of world class lead deposits (>1Mt Pb), four are in the NWQMEP. These four rank among the 18 largest lead deposits in the world

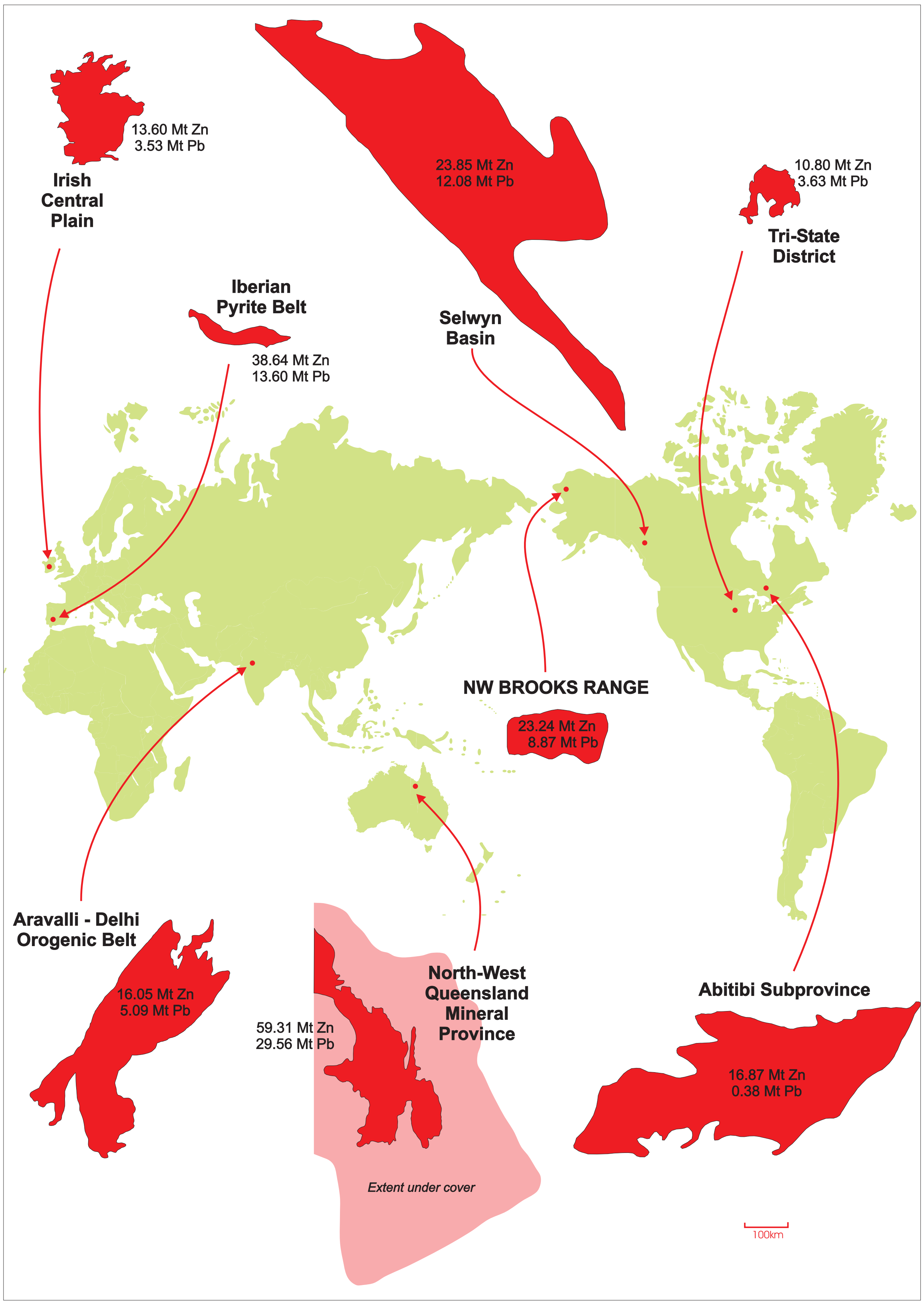


Figure 7.1: Comparison of size and Zn-Pb content of the world's major zinc-lead provinces

— George Fisher (2nd), Mount Isa (3rd), Cannington (7th) and Century (15th).

Silver

The bulk of the world's silver production has come from high-grade vein deposits in Bolivia, Mexico and Peru, from high temperature carbonate-hosted lead-zinc deposits in Mexico and Peru, and as a by-product of lead-zinc mining. In the latter category, the four largest known deposits (production + current reserves) are Broken Hill (1016Moz silver) in New South Wales, followed by three deposits in the NWQMEP — Cannington (870Moz), Mount Isa (643Moz) and George Fisher (632Moz). An indication of the significance of these deposits in a world context can be gauged from Table 7.4, which lists the estimated silver content (production + reserves) of the world's largest silver districts/deposits.

Copper

In terms of total copper mineral endowment, the NWQMEP is not in the same league as the major porphyry and sediment-hosted copper belts of the world. Nevertheless, the two largest deposits in the region, Mount Isa (255Mt at 3.3% Cu) and Ernest Henry (127Mt at 1.1% Cu and 0.55g/t Au) represent attractive exploration targets by world standards by virtue of their high in-ground value per tonne. The Mount Isa deposit, best known as a world class zinc body, is also of world class stature in copper according to the Singer (1995) definition that world class deposits contain >2Mt copper.

Mineral Production

Zinc

The NWQMEP is a leading source of the world's zinc. Total mine production in the year to end June 2009 (Table 7.5) amounted to some 726 200t Zn. With an output of 360 569 Zn in the period of production from end June 2008 to end June 2009, the Century mine was the region's largest producer in the 2008/2009 year. At its current production rate of some 360 000tpa Zn, Century is the second largest individual zinc producer in the world behind Red Dog in Alaska (~ 515 000tpa Zn). At the district-scale, the NWQMEP became the foremost world zinc producer in 2002 when both Century and the George Fisher mine (~170 000tpa Zn) were in full production. At that time, the NWQMEP yielded around 10.9% of the western world zinc output.

Lead

The NWQMEP contains the two largest lead producers in the world — Cannington (~233800tpa) and Mount Isa/George Fisher (~189177tpa).

Silver

In terms of annual production Cannington (~37.3Moz per annum) is currently the world's second largest silver producing mine, behind Fresnillo in Mexico (~38Moz/yr), Mount Isa/George Fisher (~11.8Moz per annum) is currently ranked third among individual mine silver producers.

Copper

With an output of 302 000t in the 2008/2009 year, the NWQMEP provided almost half of Australia's total mine production of copper. In a world context, the NWQMEP output is small compared with the top producers — Chile (4.19Mt in calendar 2003) and USA in 2007 (1.19Mt) — but is nevertheless significant when compared with the likes of Peru (839 223t in 2003), Zambia (664 000t in 2009) and Mexico (300 329t in 2003), three major copper-producing countries.

Discovery Record

Table 7.6 lists significant zinc and copper discoveries world wide (outside the CIS countries and China) over the past 30 years. In that period, the NWQMEP can claim to have the best greenfields zinc discovery rate of any mineralised province in the world in terms of the number and size of the discoveries (Century, Cannington, Walford Creek, Grevillea). Century is the second largest zinc discovery of the past three decades behind Red Dog and, although Cannington is primarily a lead-silver deposit, its zinc content is such that it is fifth largest in the ranking of zinc discoveries since 1980 (Table 7.7).

In terms of total greenfields zinc metal discovered since 1980, the NWQMEP is the second ranked region in the world behind the Brooks Range of Alaska, where the various components of the Red Dog deposit now amount to 26.7Mt and the Anarraaq discovery in 1999 added a further 18.0Mt. In addition to the new discoveries, there have also been significant additions to the total zinc resource endowment of the NWQMEP over the past decades through further drilling of the Dugald River, Lady Loretta and George Fisher deposits, all of which were discovered prior to 1980.

Regarding copper, there have been no discoveries in the NWQMEP to match the size of those in the porphyry belts of Chile and Indonesia, but the region nevertheless boasts a good discovery record for medium-sized copper-gold deposits. Since 1980, three such deposits have been found and put into production — Selwyn (37.14Mt at 1.13% Cu and 1.52g/t Au), Eloise (9.91Mt at 3.1% Cu and 0.6g/t Au) and Ernest Henry (219Mt at 1.1% Cu and 0.51g/t Au).

As for gold, there are no known major deposits of world class stature in the region, but the 1989 discovery of the small, high-grade Tick Hill deposit proved to be a lucrative find for Mount Isa Mines Ltd. In the 1992 to 1995 period, the deposit yielded a total of 511 000oz Au from 706 000t of ore for an average grade of 22.5g/t Au.

Table 7.1: Ranking of world class zinc deposits by zinc content

DEPOSIT	LOCATION	STATUS	Mt n
BROKEN HILL	New South Wales, Australia	o.m.	37.49
GEORGE FISHER	North-West Queensland	o.m.	24.62
RED DOG	Alaska, USA	o.m.	18.7
McARTHUR RIVER	Northern Territory, Australia	o.m.	14.62
ANTIMINA	Peru	o.m.	14.08
CENTURY	North-West Queensland	o.m.	12.71
BRUNSWICK No. 12	New Brunswick, Canada	o.m.	11.81
GAMSBERG	South Africa	a.p.	10.65
MOUNT ISA	North-West Queensland	o.m.	10.5
RAMPURA AGUCHA	India	o.m.	8.66
SULLIVAN	British Columbia, Canada	f.m.	8.5
KIDD CREEK	Ontario, Canada	o.m.	8.40
CERRO de PASCO	Peru	o.m.	7.36
NAVAN	Republic of Ireland	o.m.	6.79
ANGOURAN	Iran	o.m.	6.73
HOWARDS PASS	Yukon, Canada	a.p.	6.24
KIPUSHI	Democratic Republic of the Congo	o.m.	6.16
DUGALD RIVER	North-West Queensland	a.p.	6.05
MEHDIABAD	Iran	a.p.	5.55
REOCIN	Spain	o.m.	5.39
SAN GREGORIO	Peru	a.p.	5.13
ZINKGRUVAN	Sweden	o.m.	4.99
RAMMELSBERG	Germany	f.m.	4.46
FRANKLIN	New Jersey, USA	f.m.	4.08
CIRQUE	British Columbia, Canada	a.p.	4.06
ROSEBERY	Tasmania, Australia	o.m.	4.04
MEGGEN	Germany	f.m.	3.85
ELURA	New South Wales, Australia	o.m.	3.80
NEVES CORVO	Portugal	o.m.	3.70

DEPOSIT	LOCATION	STATUS	Mt n
SANTA EULALIA	Mexico	f.m.	3.65
SANTA BARBARA	Mexico	o.m.	3.44
CANNINGTON	North-West Queensland	o.m.	3.44
NICOLET	Wisconsin, USA	a.p.	3.40
FARO	Yukon, Canada	f.m.	3.28
POLARIS	Nanavut, Canada	f.m	3.24
SAN VICENTE	Peru	o.m.	3.12
KABWE	Zambia	f.m.	3.10
BALMAT	New York, USA	f.m.	3.07
LISHEEN	Republic of Ireland	o.m.	2.93
FLIN FLON	Manitoba, Canada	o.m.	2.58
ANARRAAQ	Alaska, USA	a.p.	2.58
LADY LORETTA	North-West Queensland	a.p.	2.38
BUCHANS	Newfoundland, Canada	f.m.	2.35
HELLYER	Tasmania, Australia	f.m.	2.29
MASA	Brazil	o.m.	2.29
FEITAS /MOINHO	Portugal	o.m.	2.15
HEATH STEELE	New Brunswick, Canada	f.m.	2.13
FALUN	Sweden	f.m.	2.10
ARCTIC	Alaska, USA	a.p.	2.00
VAZANTE	Brazil	o.m.	1.99
SKORPION	Namibia	o.m.	1.97
LIK-SU	Alaska, USA	a.p.	1.96
IZOK LAKE	North West Territories, Canada	a.p.	1.89
IRANKUH	Iran	o.m.	1.86
EL AGUILAR	Argentina	o.m.	1.86
SCUDDLES	Western Australia, Australia	f.m.	1.80
TAXCO	Mexico	f.m.	1.70
WOODLAWN	New South Wales, Australia	f.m.	1.49

- Compiled from numerous sources o.m. operating mine; f.m. former mine; a.p. advanced project
- Deposits in the CIS countries and China are not included
- The zinc contents listed are based on published resource and reserve estimates of a variety of categories, comprising Indicated and Measured Resources, Probable and Proved Reserves and Previous Production. Where known, Inferred Resources have not been included.

Table 7.2: Comparison of overall lead and zinc contents in major mineralised provinces world wide

PROVINCE	Composition of total	Mt Pb	Mt Zn	Source of Data
NWQMEP Australia	The six largest known deposits	29.56	59.31	See table
BROOKS RANGE Alaska	Red Dog, Anarraaq and Lik-Su	8.87	23.24	QDME & others (2000)
SELWYN BASIN Canada	The eleven largest known deposits	12.08	23.85	QDME & others (2000)
ABITIBI Canada	All known economic resources in the district	0.38	16.87	Barrie & others (1993)
TRI-STATE DISTRICT USA	All known economic resources in the district	3.63	10.80	Kyle (1994)
ARAVALLI-DELHI BELT North-west India	The ten largest known deposits	5.09	16.05	Deb & others (1989)
IBERIAN PYRITE BELT Spain and Portugal	85 deposits, the majority of which are subeconomic	13.60	38.64	Leistel & others (1998)
IRISH CENTRAL PLAIN Republic of Ireland	19 deposits, 14 of which are subeconomic	3.53	13.60	Johnston (1999)

Table 7.3: Ranking of world class lead deposits by lead content

DEPOSIT	Location	Status	Mt Pb
BROKEN HILL	New South Wales, Australia	o.m.	27.07
GEORGE FISHER	NWQMEP, Australia	o.m.	12.54
MOUNT ISA	NWQMEP, Australia	o.m.	9.00
SULLIVAN	British Columbia, Canada	f.m.	8.50
McARTHUR RIVER	Northern Territory, Australia	o.m.	7.68
RED DOG	Alaska, USA	o.m.	7.60
CANNINGTON	NWQMEP, Australia	o.m.	5.08
BRUNSWICK No. 12	New Brunswick, Canada	o.m.	4.82
SANTA EULALIA	Mexico	o.m.	4.40
HOWARDS PASS	Yukon, Canada	a.p.	2.87
TSUMEB	Namibia	f.m.	2.80
CERRO de PASCO	Peru	o.m.	2.80
ELURA	New South Wales, Australia	o.m.	2.39
FARO	British Columbia, Canada	f.m.	1.96
CENTURY	NWQMEP, Australia	o.m.	1.89
SANTA BARBARA	Mexico	o.m.	1.81
MEHDIABAD	Iran	a.p.	1.79
EL AGUILAR	Argentina	o.m.	1.65
RAMMELSBERG	Germany	f.m.	1.62
ZINKGRUVAN	Sweden	o.m.	1.54
SAN GREGORIO	Peru	a.p.	1.53
NAVAN	Republic of Ireland	o.m.	1.31
HELLYER	Tasmania, Australia	f.m.	1.22
ROSEBERY	Tasmania, Australia	o.m.	1.22
BUCHANS	Newfoundland, Canada	f.m.	1.22
RAMPURA AGUCHA	India	o.m.	1.21
JASON	Yukon, Canada	a.p.	1.00
ANGOURAN	Iran	o.m.	0.84
KABWE	Zambia	f.m.	0.80
REOCIN	Spain	f.m.	0.62
PRAIRIE CREEK	North West Territories, Canada	a.p.	0.58

- o.m. operating mine; f.m. former mine; a.p. advanced project.
- Compiled from numerous sources.
- Deposits in the CIS countries and China are not included.
- The lead contents listed are based on published resource and reserve estimates of a variety of categories, comprising Indicated and Measured Resources, Probable and Proved Reserves and Previous Production. Where known, Inferred Resources have not been included.

Table 7.4: The world's largest silver districts/deposits

District/Deposit	Location	Production + Reserves Moz Ag
CERRO RICO DE POTOSI	Bolivia	~2000
PACHUCA DISTRICT	Mexico	1400
GUANAJUATO DISTRICT	Mexico	1050
BROKEN HILL	New South Wales, Australia	1016
CANNINGTON	NWQMEP, Australia	673
MOUNT ISA	NWQMEP, Australia	643
PASCUA/LAMA	Chile/Argentina	635
GEORGE FISHER	NWQMEP, Australia	632
SANTA EULALIA	Mexico	511
SAN CRISTOBAL	Bolivia	450
RED DOG	Alaska	457
FRESNILLO	Mexico	450

Table 7.5: NWQMEP, year 2008–2009 or final year

DEPOSIT Owner(s) Start of Production	Ore mined (tonnes)	Ore treated						Metal content of product				
		Tonnes	% Cu	% Pb	% Zn	g/t Au	g/t Ag	Copper	Lead	Zinc	Silver	Gold
CANNINGTON BHP Ltd 1997									233800t in Pb concentrates	61000t in Zn concentrates	28.63Moz in Pb concentrates	
CENTURY MMG Ltd 1999									16277in concentrates	360569t in Zn concentrates	0.779Moz in Pb concentrates	
ELOISE FMR Investments Pty Ltd 1996								37481 in Cu concentrates			9 9673oz in Cu concentrates	1703oz in Cu concentrates
ERNEST HENRY Xstrata Plc 1997		802446						35562 in concentrates			35352t in Cu concentrates	45227oz in Cu Concentrates
GEORGE FISHER (North and South) Xstrata Plc 1987		2320000		3.7	7.7		79		118400t in Pb concentrates	246400t in Zn concentrates	7222857oz in concentrates	
MOUNT ISA Xstrata Plc Pb-Ag 1931 Zn 1935 Cu 1939		6083222 copper ore 3437271 lead-zinc ore	3.9	3.6	4.3			215461t anode copper	75475t crude lead	147534t in Zn concentrates	4.7Moz in crude lead	
OSBORNE Barrick Gold Corp. 1994		2056000						41500t in Cu concentrates				43000oz in Cu concentrates
							TOTAL	301986t	369215t	7262375t	46Moz	212179oz

Source of data: Company Quarterly and Annual Reports, plus Department of Employment, Economic Development and Innovation statistics

Table 7.6: Base metal discoveries 1980 to 2010

Year discovered/deposits		Ore (Mt)	% Cu	% Pb	% Zn	g/t Ag	g/t Au
1980							
MIDWAY	(Silvertip) British Columbia, Canada	2.57		6.47	8.8	325	0.63
RAMPURA AGUCHA	India	63.7		1.9	13.6	45	
SELWYN	Queensland, Australia	37.14	1.13				1.52
RED DOG	Alaska, USA	173		4.4	15.5	82	
1981							
HARPER CREEK	British Columbia	569	0.32				
NIFTY	Western Australia, Australia	83.9	1.80				
ANSIL	Quebec, Canada	1.6	7.2		0.9	26	1.6
ZALDIVAR	Chile	421	0.67				
EL TESORO	Chile	505	0.81				
ESCONDIDA	Chile	2118.0	1.31				
BISMARK	Mexico	8.5	0.39	0.6	8.4	55	
LEPANTO	F.S.E. Philippines	777	0.67			1.03	
BOU GRINE	Tunisia	5		2.6	11.7		
ADMIRAL BAY	Western Australia, Australia	72		2.9	3	1	18
1982							
PERKOA	Burkina Faso	5.6		18.2			
ISCAYCRUZ	Peru	10		2.1	7.3	17.7	
WINSTON LAKE	Ontario, Canada	3.0	1.0		15.6	31	1.0
1983							
HELLYER	Tasmania, Australia	16.5	0.3	8.2	13.9	167	2.5
1984							
CADJEBUT	Western Australia, Australia	8.0	5.0	9.0			
HAJAR	Morocco	30	0.43	2.4	8.3	60	
1985							
AGUAS TENIDAS	EAST Spain	12.7	1.7	1.9	6.2	60	
SHEEP CREEK	U.S.A.	8.5	3.2				
ISLE DIEU	Quebec, Canada	3.1	1.01		17.9	76.6	0.46
NORITA EAST	Quebec, Canada	1.08	0.8		10.2	41.4	0.74
1986							
12 MILE BORE	Western Australia, Australia	2.4		2.7	10.1	38	
GALMOY	Republic of Ireland	8.4		1.8	13.2		
VALVERDE	Spain	11.9	0.57	1.3	4.2		
1987							
LA CANDELARIA	Chile	366	1.29				0.3
DUDDAR	Pakistan	14.3		3.2	8.6		
DUCK POND	Newfoundland, Canada	4.1	3.3	1.12	5.7	59	0.9
1988							
ESKAY CREEK	British Columbia, Canada	1.5		1.77	5.6	3597	75
GRASBERG	Indonesia	3100	1.13			1.0	
ELOISE	Queensland, Australia	9.9	3.1		16	0.6	
1989							
AYNAK	Afganistan	240	2.3				
KANGAROO CAVES	Western Australia	6.3	0.50		3.34		
LOUVICOURT	Quebec, Canada	24	3.9		2.0	31	1
GREVET	Quebec, Canada	6.05	0.72	0.15	10.41	51.04	0.09
CHIMBORAZO	Chile	236	0.6				
OSBORNE	Queensland, Australia	31.2	2.04			0.78	
DIDIPIO	Philippines	63.3	0.44			1.01	
SOTIEL/MIGOLLAS	Spain	57.6	0.88	1.12	2.23		
SANDIEGO	Western Australia	3.95	1.5	0.3	3.8	17.0	0.33
1990							
PROSPERITY	British Columbia	1,010	0.24				0.41
BATU HIJAU	Indonesia	1887	0.42			0.29	
ALEJANDRO HALES	Chile	500	1.5				
SAN ANTONIO	Dominican Republic	No resource reported to date					
LISHEEN	Ireland	22.5	2.19	15.02	26		
CENTURY	Queensland, Australia	91.9		1.5	11.6	36.4	
CANNINGTON	Queensland, Australia	43.8		11.6	4.4	538	
WALFORD CREEK	Queensland, Australia	6.5	0.6	1	6	2.1	25

Table 7.6 (continued)

Year discovered/deposits		Ore (Mt)	% Cu	% Pb	% Zn	g/t Ag	g/t Au
MOUNT ROSEBY	Queensland, Australia	62.5	0.75				
CERATEPPE	Turkey	1.6	8.8		1.1	33	1.4
LYNNE	U.S.A	6.1	0.64	1.65	8.7	84	0.8
1991							
DON MARIO	(Upper Zone)Bolivia	1.17	1.5			10.24	
UJINA	Chile	1266	0.78				
BATU HIJAU	Indonesia	1445	0.43			0.3	
ERNEST HENRY	Queensland, Australia	219	1.1				0.51
MILPILLAS	Mexico	230	0.85				
1992							
SALOBO	Brazil	784	0.96				0.6
KEMESS SOUTH	British Columbia	195	0.14			0.27	
DAMIANA	Chile	300	0.3				
TAMPAKAN	Philippines	2400	0.6			0.20	
RIDGEWAY	New South Wales, Australia	44.0	0.82			2.6	
NORTHPARKES	New South Wales, Australia	162.8	0.94			0.38	
1993							
KUDZ ZE KAYAH	Yukon, Canada	11.3	0.9	1.5	5.9	133	1.3
PRAIRIE CREEK NWT,	Canada	5.84	0.33	9.9	10.7	161	
CITRONEN FJORD	Greenland	20		1.0	7.0		
PUTHEP	Thailand	183	0.5			0.13	
BELLALLARD	Quebec Canada	0.98	1.1		11.8		
1994							
SLAB	Yukon	20.0	0.35			0.17	
VOISEY'S BAY	Labrador	31.7	1.69				
AREX	Brazil	9.4	0.3	1.3	2.5	35	0.3
LOMAS BAYAS	Chile	239.2	0.36				
GREVILLEA	Queensland, Australia	No resource reported to date					
SAN GREGORIO	Peru	69		2.19	7.33	14	
RELINCHO	Chile	397	0.43			0.3	
LAS CRUCES	Spain	16	6.0				
RIO BLANCO	Peru	1,257	0.57				
1995							
KUDZ DE KAYAH	Yukon	11.3	1.33	1.5	5.9	133	1.3
MYRA FALLS	British Columbia	14.1	1.1		6.4	46	1.3
DUDDAR	Pakistan	14.5		3.4	9.9		
PALLAS GREEN	Ireland	24.1		1.35	7.85		
WOLVERINE	Yukon, Canada	4.5	1.16	1.6	12.14	354.8	1.7
FRANCISCO I MADERO	Mexico	34.9		1.1	5.2	31	
ALEMAO	Brazil	165	1.5			0.9	
WHIM CREEK	Western Australia, Australia	1.03	1.36	0.19	2.12	9.02	0.7
LARA	Peru	18.6	0.53				
ANTAMINA	Peru	840	1.06		2.03		
1996							
ICE	Yukon	4.5	1.48				
MARG	Yukon	6.1	1.76	2.46	4.6	62.7	0.98
LOMA HIERRO	Cuba	0.28			581		
GALORE CREEK	Yukon	786	0.5				0.3
REKO DIQ	Pakistan	730	0.6				0.4
TRITTON	New South Wales, Australia	17.6	2.3				
SAN CRISTOBAL	Bolivia	231		0.58	1.54	68	
VALLEY	Brazil	11.6		2.25	6.29	65	0.25
FYRE LAKE	Yukon, Canada	3.57	1.6			0.61	
LUMWANA	Zambia	355.6	0.75			0.14	
SPENCE	Chile	313	1.1				
GABY	Chile	580	1.41				
ACCHA	Peru	9		9.0			
1997							
KONA	Yukon	6.42	1.2			0.5	
SOSSEGO	Brazil	245	1.0			0.28	
SAN NICOLAS	Mexico	65	1.32		2.04	32.1	0.53

Table 7.6 (continued)

Year discovered/deposits		Ore (Mt)	% Cu	% Pb	% Zn	g/t Ag	g/t Au
BONGARA	Peru	No resource reported to date					
DIMAKAWAL	Philippines	No resource reported to date					
SEPON (Khanong)	Laos	14.8	5.11				
SEPON (Khanong)	Laos	28.7					0.21
1998							
WOLF	Yukon	4.1		1.8	6.2	84	
DAIRI(Sopokomil)	Indonesia	6.32		9.9	16.0		
STORLIDEN	Sweden	1.8	3.5		10.3	24	0.28
KANSANSHI	Zambia	444	1.25			0.19	
1999							
LOS CHANCAS	Peru	355	0.62			0.04	
ANARRAAQ	Alaska, USA	12		5	18	90	
2003							
OYU TOLGOI	Mongolia	1149	2 1		30	0.47	
2004							
KUTCHO	British Columbia	10.9	2.01		2.8	29.8	0.36
LOS AZULES	Argentina	92	0.55				
2005							
AYNAK	Afghanistan	No resource reported to date					
E1 CAMP	Queensland, Australia	19.6	0.85			0.25	
2006							
TENKE FUNGURUME	Democratic Republic of Congo	135	3.1				
BRACEMAC-MCLEOD	Quebec	3.6	1.6		11.52	31.6	0.49
2007							
TOBERMALUG	Ireland	11.3		1.9	10.2		
JACKSON/CHLOE	Queensland Australia	3.3		2.0	4.6	52	
ROCKLANDS	Queensland, Australia	78	0.53			0.81	
2008							
AUSTIN	Western Australia	1.5		1.0	1.3	3.5	0.24
BENTLEY	Western Australia	2.	1.8	0.6	9.8	121	0.6
2009							
DEGRUSSA	Western Australia	10.7		5.6	15.0	1.9	
MONAKOFF	Queensland, Australia	4.0	1.3			0.42	

The year of discovery is defined as the date of the first drill intersection of economic tenor mineralisation

Table 7.7: The largest zinc discoveries since 1980

Ranking	Deposit	Total Contained Zinc (Mt)
1	Red Dog: Alaska, USA	18.70
2	Century: NWQMEP, Australia	12.71
3	Rampura Agucha: India	8.66
4	San Gregorio: Peru	5.13
5	Cannington: NWQMEP, Australia	3.44
6	Lisheen: Republic of Ireland	2.93
7	Hellyer: Tasmania, Australia	2.29
8	Skorpion: Namibia	1.97

Geochemistry of North-West Queensland

The NWQMEP has been the focus of base metals, precious and strategic minerals, oil, gas and oil-shale explorations since the mid-1800s. Since the introduction of regulated exploration in Queensland in the 1950s, over 4100 exploration permits have been granted for minerals, petroleum and gas search. Mineral explorers have conducted extensive geochemical programs over the outcropping parts of the Mount Isa and Georgetown Inliers in contrast to the limited geochemical work in the areas under the Phanerozoic cover that fringe these well-explored terrains. As part of Queensland's reporting requirements in accordance with the *Mineral Resource Act 1989*, companies undertaking mineral exploration are required to submit annual and six monthly exploration reports to the GSQ. Data from the open-file company exploration reports have been compiled by Terra Search Pty Ltd and by the GSQ to form the Queensland Exploration Geochemical and Drillhole Database (QEGD).

The Exploration Geochemical and Drillhole Data

The QEGD data for the NWQMEP comprises 1 374 000 well-attributed data points, which are made up of surface and drillhole samples. The data distribution shows a good spatial coverage with high data density in or surrounding the known Proterozoic outcrops (Plate 20). This NWQMEP database is included as a DVD appendum in this report and is supplied with a read-only Explorer 3 data management system as well as in ASCII format. The data is highly heterogeneous with 2043 data variables from the combination of 4 data categories, 26 major sample types, 851 preparation methods, 140 laboratories and 1184 analysis types. The four data categories are the stream sediments (16.9% of all sample types), rock chips (7.9%), soils (30.0%) and drillhole (45.2%). Within each data category are numerous data types:

- Stream sediment samples: There are thirteen stream sediment sample types that include bulk alluvial sample, bulk cyanide leach sample, bulk unsieved sediment, coarse fraction sediment, bulk samples for heavy minerals (diamond), ferruginous gravel, gravel, lag, magnetic fraction, orientation sample, pan concentrate or heavy mineral concentrate, sieved samples and suspended silt samples.
- Soil samples: The eleven soil sample types are orientation sample, bulk cyanide leach sample, lag, termite mound sample, sieved sample, bulk unsieved sample, auger sample, regolith sample, partial digest sample (mobile ion and pyrophosphate) and magnetic fraction.
- Rock chip sample includes trench, channel and whole-rock samples
- Drillhole data are recorded in five relational data tables and these component tables are designed so that they can be imported into most drillhole plotting packages.
    - Hole-collar file records drillhole location, and may include information such as drill-rig type, depth of transported cover, water table, logger, dates, data source report and tenement.
    - Sample table holds the assay data.
    - Survey table records all downhole survey information.
    - Hole-text file records text details such as results and comments, including material left downhole.
    - Downhole geology stores all lithological, textural and geological descriptive information in coded form, including regolith profile and regime.

Most geochemical samples were analysed for multi-elements, although the suite of elements analysed for a particular sample batch depended on the exploration targets and concepts at the time. The assays can contain up to 30 separate elements, and the more commonly assayed elements with regional distributions are Cu, Zn, Pb, Ag, Au, As, Ni, Mo, Mn, Fe and Co. The early exploration philosophy (pre-1990) sought out large ore-grade targets and the associated chemistry had relatively low precision with detection limits often above the background levels. Modern exploration relies on high precision data and uses sophisticated analytical techniques such as mass-spectrometry and neutron activation methods and these data are applicable in deposit prediction, targeting and modelling.

Using exploration geochemical data in NWQMEP exploration

The QEGD is an integrated regional database of different data types and methodologies across exploration lease boundaries, and is independent of exploration concepts to allow a 'big picture' overview of the NWQMEP. The number of data points, the vast spatial distribution of different data types and the range of elements assayed make the database a powerful exploration tool to:

- Identify regions of data-gap in intensely explored areas that could offer further exploration opportunities
- Establish a mineral potentiality map of the region by defining the background concentration and the anomalous threshold concentration of various elements using statistical means
- Identify geochemical anomalies using multi-data types and multi-elements appraisal.

The data heterogeneity limits the ability to directly use, compare or plot a single geochemical variable from different geochemical batches or sample types. In this report, the GSQ applied a statistical approach to analyse the entire NWQMEP geochemistry as a single population that is capable of overcoming the issues of sample and analytical heterogeneity. Only surface samples were processed to showcase the mineral potentiality of the province. To efficiently process the data, the database was subset into 11 groups based on data types, size fractions and analytical methods using methods of Tang (2004), prior to statistical appraisal. Although up to 30 elements per sample could be assayed, only the eight most commonly assayed elements (Cu, Zn, Pb, Ag, Au, As, Ni and Mo) were evaluated. Assays with values below the detection limit were arbitrarily assigned at half the analytical detection limits for the mathematical computation. For each subset, statistical analysis determined the range, mean, median, standard deviations, mode and percentiles at 75, 90, 95 and 99 and the 'mean plus 2 standard deviation values' for each of the 8 elements (Table 8.1). Geosoft Target and IoGAS programs were used for the statistical computation and data variations were visually checked using probability plots (Q-Q plots) generated by Geosoft Target.

The primary aim of the statistical appraisal is to establish the baseline concentrations and the anomalous concentration thresholds of various elements for different sample types. The threshold values between background and anomalous populations vary significantly between sample subsets, and such variations highlight intrinsic differences relating to different data types, background levels and/or analytical processes. In a normal population distribution, 95.46% of the data will lie within two standard deviations from the mean (Rollinson, 1993). However, in the presence of an anomalous/ enriched population such as in the vicinity of mineralised systems, the geochemical deviation from the mean will be greater. The 'mean plus 2 standard deviation values' will be greater than the values at the 95 percentile of a normal distribution curve. The presence of anomalous population(s) for each subset was carefully checked against corresponding Q-Q plots to ensure that graphic display supported their presence. Graphically, the 99 percentile in most graphs represented the highly enriched fraction of the population, and therefore is arbitrarily regarded as the anomalous threshold in this modelling. The lack of variations in subsets such as SEDLAG, SOILLAG, SOILPD or SEDPC was confirmed graphically and their 'mean plus 2 standard deviation values' which were less than the 99 percentile were not regarded as the anomalous concentration thresholds.

The eight most commonly assayed elements (Cu, Zn, Pb, Ag, Au, As, Ni and Mo) were processed using the above methodology and their statistical summary (tabulated in Table 8.1) can be adopted for future NWQMEP data modelling. Regional geochemical anomaly plots of 5 major elements (Au, Ag, Cu, Pb and Zn) and two combinations of elements (Cu-Au and Pb-Zn) are included as layers within the GIS package that accompanies the report. These anomalous plots (Figure 8.1) highlight areas of high mineral potentiality for the various elements within the NWQMEP that justify future exploration.

Gold anomalies

Au anomalies in the NWQMEP occur almost exclusively in the Eastern Fold Belt of the Mount Isa Inlier and in the Georgetown Inlier. There are few anomalous locations within the Kalkadoon–Ewen Province, in the South Nicholson Basin, or within the Eromanga Basin. In the Eastern Fold Belt, most anomalies occur within the Palaeoproterozoic Soldiers Cap Group and the Proterozoic Mary Kathleen Group, particularly within a 50km radius south of Cloncurry. Clusters of anomaly also occur within the Palaeoproterozoic Tewinga Group to the north-east of Duchess and in the Proterozoic

Malbon Group to the south-west of Cloncurry. Anomalies around the Blackard, Dugald River, Selwyn and Mount Dore deposits may be related to the local Cu-Au mineralisation in the areas.

In the Eromanga Basin, a cluster of Au anomalies was verified from soil samples approximately 120km north-west of Bedourie. These anomalies are not associated to known workings and deserve further geologic investigation.

Silver anomalies

Ag anomalies are widespread within the Eastern and Western Fold Belts of the Mount Isa Inlier and in the Georgetown Inlier. Two outlier Ag anomalies outside the Proterozoic terranes, are within the Carpentaria Basin (38km north-north-west of Gregory Downs) and in the Georgina Basin (126km west of Boulia). Anomalies in the Eastern Fold Belt occur within the Soldiers Cap Group and the Proterozoic Mary Kathleen and Malbon Groups, with tight clusters around Selwyn, 18km west to south-west of Quamby and south-east of Cloncurry. In the Western Fold Belt, most silver anomalies occur within the Gunpowder Creek Formation and in and surrounding the Palaeoproterozoic Mount Isa Group. The anomalies around the Mount Isa Township are closely associated with the Mount Isa and George Fisher Mines. Scattered anomalies occur around the Century and Lady Loretta mines and could represent extension of Ag-Pb-Zn mineralisation mined from respective deposits.

Copper anomalies

Cu anomalies in the NWQMEP are limited to, and immediately adjacent to, the Proterozoic Mount Isa and the Georgetown Inliers. In the Eastern Fold Belt and Kalkadoon–Ewen Province, Cu anomaly occurs in all Proterozoic stratigraphic units, but the Mary Kathleen, Soldiers Cap, Malbon and Tewinga Groups host the majority of all interpreted anomalies. The anomalous patterns mimic the north-north-east, north–south and the north-west tectonic fabrics and major anomalies are found around present and past workings including the major deposits such as Mount Dore, Mount Elliott, Fountain Range, Las Minerale, Dugald River and Blackard. Cu anomalies in the Western Fold belt have a more restricted and patchy distribution with major anomalous clusters occurring around major mines such as Esperanza, Mammoth, Gunpowder and the Mount Isa mines, as well as other smaller workings. Numerous anomalies not associated with known deposits were identified from the QEGD and these include areas east of Mount Oxide, 10km west and north-west of Century mine and a cluster of soil anomalies 36km north of Gregory Downs.

Lead anomalies

Lead anomalies are widespread and occur in the Proterozoic Mount Isa and Georgetown Inliers, the Palaeozoic Georgina Basin and a spot anomaly in the Eromanga Basin. In the Eastern Fold Belt, anomalies are confined to the Mary Kathleen and the Soldiers Cap Groups, and most coincide with old mine workings and/or mineral occurrences in the region. Two subparallel, north–south trending Pb anomalies were interpreted to the west of Selwyn. The Selwyn anomalies and a few clusters of anomalies south of Cloncurry are not associated with known mine workings and were interpreted from rock chip, stream sediment and soil information.

In the Western Fold Belt, numerous clusters of Pb anomalies were identified near Mount Isa, north of Lady Loretta mine, north of George Fisher mine and around the Century and Mount oxide mines. Many of these anomalies are associated with old mine workings but the anomaly north of Lady Loretta is inferred from soil and stream sediment data.

Clusters of Pb anomalies were identified in the Georgina Basin from a combination of rock chip, stream sediments and soil data. The anomalous area is located about 50–70km north-east of Camooweal and occurs within the Cambrian Age Creek Formation, Camooweal Limestone, Thorntonia Limestone and Currant Bush Limestone. An old Pb prospect (Totts Creek prospect) occurs near these anomalies and its presence supports the likelihood of further Pb discoveries.

Zinc anomalies

The regional Zn anomaly pattern is similar to the Pb pattern suggesting that the two elements are co-genetic or formed under similar environment (Betts & others, 2003a). Zinc anomalies occur primarily within the Proterozoic Mount Isa and Georgetown Inliers, and a few anomalous clusters occur within the Palaeozoic Georgina Basin and the Eromanga Basin. In the Eastern Fold Belt, the Zn anomalies occur in the Mary Kathleen and the Soldiers Cap Groups, and spot anomalies occur within the Wimberu, Wonga and Williams Granites, and within the overlying Cainozoic sediments around Cannington mine. A prominent Zn anomalous cluster 18km south-west of Cloncurry warrants further investigation. In the Western Fold Belt, Zn anomalies occur in all stratigraphic units, particularly in proximity to old workings and major mines such as Mount Isa, George Fisher, Century and Lady Loretta. A few large anomalous clusters were identified 28km south-east of the Century mine, 18km north of Mount Oxide mine and 50km south of Gregory Downs.

Within the Georgina Basin, two Zn anomalies were identified. The Zn (and Pb) anomaly 75km north-east of Camooweal was established from a combination of rock chip, stream sediments and soil data, and occurs within the Age Creek Formation, Camooweal Limestone, Thorntonia Limestone and Currant Bush Limestone. A second anomaly cluster occurs 40km south of The Monument based on stream sediment and rock chip samples. In the Eromanga Basin, an anomalous area was interpreted from soil samples (partial digestion method) at a locality 117km north-west of Bedourie.

Zn anomalies in the Georgetown Inlier occur only within Proterozoic units. The majority of anomalies are associated with old mine workings.

Copper-Gold anomalies

Another way of modelling geochemical information is to use a combination of geochemical elements based on known mineralisation model. The Cu-Au association is a common mineralisation model in the Mount Isa region from the iron oxide Au-Cu (IOGC) style deposits (Geordie & others, 2005; Baker & others, 2001). Applying the combined anomalies of both Cu and Au, potential IOGC style mineralisation is identified almost exclusively in the Eastern Fold Belt and the Kalkadoon–Ewen Province of the Mount Isa Inlier. The majority of these anomalies are confined to the Soldiers Cap, Mary Kathleen and Malbon Groups, and only a few outlier anomalies occur within the Williams Granite and Tewinga Group. Most of these anomalies are found away from the major mines and the anomalous pattern follows a north–south trend. There are few anomalous localities west of Century Mine, south of Mount Isa.

Lead-Zinc anomalies

The lead-zinc association is a common mineralisation style for the Century and Cannington mines in the Western Fold Belt (Waltho & Andrews, 1993) and Mount Isa and George Fisher deposits in the Eastern Fold Belt (Chapman, 2004; Betts & others, 2003a). In the NWQMEP, most Pb-Zn anomalies occur within the Western Fold Belt around major mines such as the Mount Isa, Century and Lady Loretta, and are also associated with small previous mineral workings in the area. In the Eastern Fold Belt, Pb-Zn anomalies occur around the Dugald River and Selwyn deposits but spot anomalies occur the Soldiers Cap and Mary Kathleen Groups.

A Pb-Zn anomaly in the Georgina Basin was identified approximately 70km north-east of Camooweal, and occurs within the Age Creek Formation, Camooweal Limestone, Thorntonia Limestone and Currant Bush Limestone.

Conclusions

The foregoing statistical analysis of archival data demonstrates that the QEGD is a useful exploration tool for the identification of mineralisation in the NWQMEP. Data processing on this regional scale utilised broad subdivisions or data subsets, which can be refined when working at local scales. The integration of archival geochemical data into modern exploration programs is a cost effective geochemical exploration technique, whereby the QEGD is capable of telescoping into anomalous areas worthy of follow-up work. The spatial distribution of data can identify areas of data-gap or poorer quality data that can potentially be re-explored. Infilling the information gap with high precision and multi-element geochemistry (mass spectrometry method for trace element chemistry) will likely yield favourable results. High precision trace element geochemistry will better define the geochemical background and detect traces of mineralisation under the Mesozoic cover and in greenfield exploration.

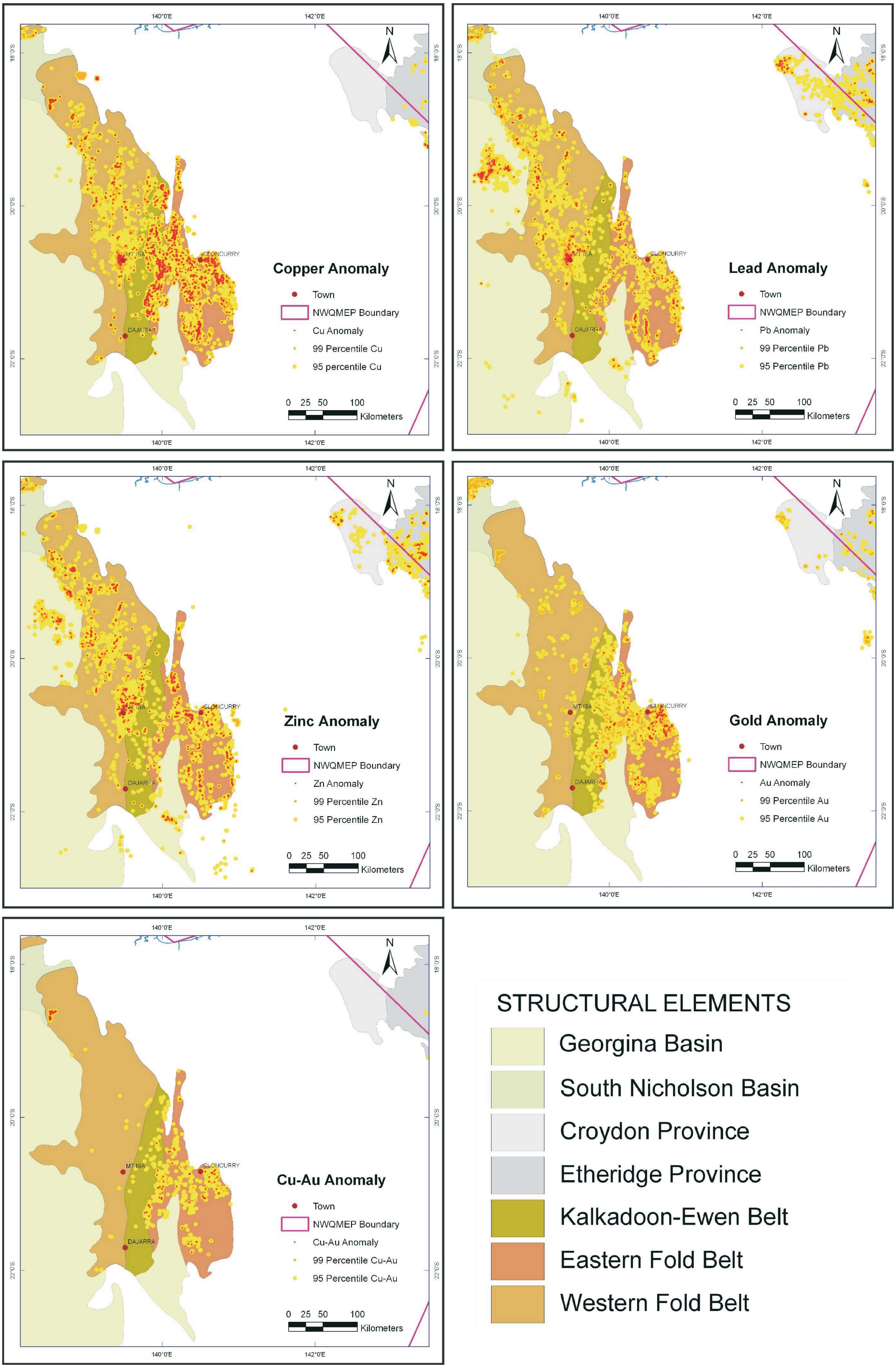


Figure 8.1: Interpreted regional stream sediment, soil and rock chips geochemical anomalies based on statistical appraisal of data from the Queensland Exploration Geochemical and Drill hole database.

Table 8.1: Combined statistical analysis

Element	Sample Type	N	Minimum	Maximum	Mean	Standard Deviation	Variance	Mode	Median	75 percentile	90 percentile	95 percentile	99 percentile	Mean + 2SD
Ag	ROCK CHIP	57032	0	1400	1.20	14.55	211.77	0	0	0	1	2	15	30.3
Ag	SED80M	49108	0	1470	0.31	7.02	49.29	0	0	0.5	0.9207	1	2	14.4
Ag	SED80P	5303	0	5288	2.47	101.53	10308.20	0.5	0.5	0.5	0.5	0.9	1.2	205.5
Ag	SEDBCL	10331	0	10320	4.98	127.16	16170.40	0	1.1	2.98	6.9	10	23.8	259.3
Ag	SEDLAG	1334	0.1	6	0.40	0.34	0.11	0.5	0.5	0.5	0.5	0.6	1	1.1
Ag	SEDPC	676	0.1	71	1.65	4.55	20.73	0.5	1	1.9	2.5	2.5	20	10.8
Ag	SOIL80M	104470	0	2000	0.26	6.55	42.88	0	0	0	0	1	2	13.4
Ag	SOIL80P	40898	0	96	0.16	1.38	1.91	0	0	0.5	0.5	0.9	1.8	2.9
Ag	SOILBCL	13218	0.0001	6800	7.80	68.01	4625.79	0.5	2.3	7.2	14	21.1	74.5	143.8
Ag	SOILLAG	15671	0.01	81	0.40	0.72	0.52	0.5	0.5	0.5	0.5	0.5	1	1.8
Ag	SOILPD	4193	0.0001	67	3.17	6.77	45.82	0.5	0.5	3.3	9.25	16	32	16.7
As	ROCK CHIP	33889	0	103000	151.28	1358.70	1846060	1	11	43	170	419	2690	2868.7
As	SED80M	49217	0	3900	6.69	29.13	848.37	2	3	6.95	12.9	20	50	64.9
As	SED80P	10599	0.1	10585	16.66	105.70	11173.20	5	9	19.5	35.5	49	90	228.1
As	SEDBCL	473	0	458	5.30	22.68	514.20	0.01	0.01	0.02	20	26	33	50.7
As	SEDLAG	2103	0.5	1110	55.33	65.59	4302.46	1	40	74	115	147	246	186.5
As	SEDPC	341	0.5	820	47.42	94.37	8905.56	20	20	40	100	175	500	236.2
As	SOIL80M	77795	0	7840	12.01	48.25	2327.71	2	4	9	23	40	131	108.5
As	SOIL80P	49286	0	3500	16.14	46.64	2175.38	2	7	14.5	33	55	160	109.4
As	SOILBCL	276	0.5	270	8.71	23.43	549.07	0.5	0.5	0.5	30	48	80	55.6
As	SOILLAG	15274	0.01	767	33.32	45.25	2047.97	4	14	47	82	114	207	123.8
As	SOILPD	3234	0.0005	1900	36.68	127.12	16159.80	25	0.5	21	25	250	650	290.9
Au	ROCK CHIP	48281	0	16700	1.00	79.10	6256.73	0.005	0.01	0.05	0.29	0.92	7.85	159.2
Au	SED80M	18520	0	850000	101.08	6911.34	47766700	2	2	5	24.5	49	250	13923.8
Au	SED80P	9184	0.025	58400	109.93	1179.56	1391370	1.5	3	9.8	46	160	2160	2469.1
Au	SEDBCL	40594	0	170000	8.79	872.94	762029	0.05	0.35	0.99	3	6.95	47.7	1754.7
Au	SEDLAG	484	0.5	80500	302.41	4452.69	19826500	0.5	2.5	9	10	15	64.8	9207.8
Au	SEDPC	1709	0	995.2	14.35	66.60	4434.97	0.01	0.06	1.64	18.9	66.5	277	147.5
Au	SOIL80M	74709	0	32900	16.33	188.89	35679.50	0	3	6	24	49	213	394.1
Au	SOIL80P	33952	0	7200	17.82	134.41	18066.50	0.5	1.5	5	17.8	49	370	286.6
Au	SOILBCL	34631	0.005	17270	13.75	245.87	60454.10	0.5	1.3	3.49	9.3	19	94.8	505.5
Au	SOILLAG	3970	0.05	862	6.31	36.85	1358.07	0.5	0.5	2	9	15	116	80.0
Au	SOILPD	3486	0.005	26.4	0.81	1.32	1.74	0.05	0.5	1	1.9	2.49	5.7	3.5
Cu	ROCK CHIP	88204	0	710000	2675.08	16667.70	277812000	10	60	299	1610	6370	73800	36010.5
Cu	SED80M	153316	0	57500	42.31	219.09	47998.20	20	25	47	85	119	232	480.5
Cu	SED80P	20928	0.005	20914	51.73	188.28	35447.70	10	25.5	60	114	152	280	428.3
Cu	SEDBCL	10088	0	10080	7.49	108.01	11666.50	0.05	1.39	2.81	5.99	15.105	120.8	223.5
Cu	SEDLAG	2663	2.5	23400	78.34	472.03	222814	15	39	87	148	195	415	1022.4
Cu	SEDPC	294	1	840	65.20	93.64	8769.08	10	35	72	135	175	500	252.5
Cu	SOIL80M	232312	0	184000	96.25	608.61	370409	20	37	83	179	300	958	1313.5
Cu	SOIL80P	83416	0	98400	120.93	1095.20	1199460	15	25	55	124	200	831	2311.3
Cu	SOILBCL	15110	0.002	1800	16.68	45.31	2053.13	15	7.17	14.9	33	55.7	168	107.3
Cu	SOILLAG	16420	0.51	6379	54.08	98.74	9748.80	5	29.5	59	124	190	369	251.6
Cu	SOILPD	4432	0.0005	7600	544.35	1022.64	1045790	0.0025	1.9	507	2290	2860	4190	2589.6
Mo	ROCK CHIP	12580	0	37000	36.20	607.82	369450	2	3	9	19	39	290	1251.9
Mo	SED80M	28527	0.05	118	1.90	2.51	6.32	2.5	1.5	2.5	3	4.6	9	6.9

Table 8.1 (continued)

Element	Sample Type	N	Minimum	Maximum	Mean	Standard Deviation	Variance	Mode	Median	75 percentile	90 percentile	95 percentile	99 percentile	Mean + 2SD
Mo	SED80P	1481	0.1	1467	4.68	38.73	1499.85	5	2.5	4.9	5	8.5	29	82.1
Mo	SEDLAG	795	2	106	7.29	9.08	82.40	2.5	4	8	16	20	39	25.4
Mo	SEDPC	100	1	110	14.31	18.66	348.14	10	10	10	20	40	100	51.6
Mo	SOIL80M	39909	0	485	1.95	4.42	19.58	2	2	2	3	5	9	10.8
Mo	SOIL80P	20835	0	135	2.40	3.11	9.68	1.5	1.5	2.9	5	6.9	12.5	8.6
Mo	SOILBCL	251	1	10	2.66	1.01	1.01	2.5	2.5	2.5	2.5	2.5	5	4.7
Mo	SOILLAG	8162	0.05	86	3.05	3.18	10.08	2.5	2.5	2.9	6	8	13	9.4
Mo	SOILPD	2295	0.0005	141	4.12	13.38	179.13	0.5	0.5	0.5	9	21	71	30.9
Ni	ROCK CHIP	14892	0	11000	57.05	166.25	27640	10	26	54	110	180	525	389.6
Ni	SED80M	56464	0.5	470	19.35	15.52	240.80	20	15	24	37	45	70	50.4
Ni	SED80P	5322	1.5	7550	42.53	176.76	31244.10	35	35	50	64	74	100	396.1
Ni	SEDBCL	70	0.03	55	1.56	7.17	51.46	0.05	0.15	0.49	1.1	1.2	24.872	15.9
Ni	SEDLAG	2248	2.5	287	57.85	42.81	1833.12	10	49	73	117	147	201	143.5
Ni	SEDPC	115	5	900	293.91	252.43	63720.40	200	200	600	1300	2300	6100	798.8
Ni	SOIL80M	48824	0	611	25.60	21.19	448.82	25	20	33	49	61	94	68.0
Ni	SOIL80P	22302	0.01	2400	19.98	41.08	1687.71	15	15	21	30.9	40	130	102.1
Ni	SOILBCL	287	0.17	64	18.48	14.59	212.87	2.5	17	26	39	47	55	47.7
Ni	SOILLAG	11920	1	718	37.07	38.23	1461.36	10	24	48	80	107	185	113.5
Ni	SOILPD	4183	0.0025	9230	208.12	500.97	250968	0.0025	0.547	206	555	1230	2490	1210.1
Pb	ROCK CHIP	77356	0	484000	251.89	4670.66	21815000	2	19	40	119	259	2590	9593.2
Pb	SED80M	127472	0	33000	20.76	99.83	9966.69	10	15	24	38	49	100	220.4
Pb	SED80P	19232	0.2	19218	27.52	179.04	32054.60	10	15	24	39	60	257	385.6
Pb	SEDBCL	51	2.5	110	15.74	30.32	919.18	2.5	5	5	38.75	99.2	110	76.4
Pb	SEDLAG	2660	2	1130	44.91	58.82	3459.22	20	31	54	85	114	260	162.5
Pb	SEDPC	347	1	717	48.73	68.37	4674.96	20	32	50	80	145	352	185.5
Pb	SOIL80M	191379	0	22700	28.52	131.86	17388.10	2	13	25	49	80	275	292.3
Pb	SOIL80P	74753	0	17200	55.21	294.68	86837.20	2	12	25	79	190	760	644.6
Pb	SOILBCL	259	2.5	70	4.60	5.18	26.85	2.5	2.5	5	6	10	19	15.0
Pb	SOILLAG	16487	0.5	990	28.43	44.39	1970.91	2.5	16	39	63	87	193	117.2
Pb	SOILPD	4432	0.0005	52000	360.23	1333.23	1777500	0.005	0.06	96	1350	2000	4200	3026.7
Zn	ROCK CHIP	78819	0	435000	201.72	2400.56	5762690	10	27	84	309	680	2800	5002.8
Zn	SED80M	130661	0	22000	37.51	85.01	7226.32	10	25	45	75	99	190	207.5
Zn	SED80P	19663	0.5	19649	37.38	154.44	23852.30	10	25	43	69	96	202	346.3
Zn	SEDBCL	621	0.11	606	6.29	25.53	651.97	5	0.99	5	17	22	35	57.4
Zn	SEDLAG	2659	2.5	3640	113.76	165.53	27399.30	25	72	127	228	346	720	444.8
Zn	SEDPC	351	1	940	137.76	165.40	27358.50	100	88	150	360	500	700	468.6
Zn	SOIL80M	193440	0	47807	50.52	201.43	40575.70	20	25	44	89	146	439	453.4
Zn	SOIL80P	74731	0	15600	50.33	207.29	42967.40	10	20	40	84	141	520	464.9
Zn	SOILBCL	304	0.11	40	9.09	7.97	63.52	7	7	9	21	25	35	25.0
Zn	SOILLAG	16487	0.5	995	63.55	108.94	11868	30	27	77	152	251	871	281.4
Zn	SOILPD	4405	0.0002	185000	385.29	3664.80	13430700	0.06	0.372	206	810	1789	4400	7714.9

Footnote:
ROCK CHIP: Rock chip, grab, trench and channel samples. SED80M: Minus 80# sieved stream sediment including suspended silt samples. SED80P: Stream sediment samples that include size fractions >80#, bulk alluvial, bulk unsieved sediment, coarse fraction sediment, gravel, orientation sample and >80# sieved samples. SEDBCL: Bulk cyanide leached stream sediment samples. SEDLAG: Lag, ferruginous gravel and magnetic fraction of stream sediment samples. SEDPC: Panned stream sediment concentrates and heavy mineral concentrates. SOIL80M: Minus 80# sieved soil samples. SOIL80P: Soil samples with >80# size fractions, orientation sample, bulk unsieved sample, auger sample and regolith sample. SOILBCL: Bulk cyanide leached soil sample. SOILLAG: Lag in regolith sample. SOILPD: Partial digest samples (mobile ion and pyrophosphate).

Mount Dore Project — district-scale 3D modelling

The Mount Dore Project area is a 175km x 70km block located immediately south of Cloncurry (Figure 9.1). It forms the most prospective corridor within the eastern domains of the Mount Isa Inlier which constitute a world-class copper ± gold ± iron oxide (IOCG) exploration province. The project area is host to significant current and past copper-gold producers such as Osborne, Mount Elliott – Swan, Mount Dore, Selwyn, Kuridala–Hampden and Greenmount.

Significantly, the area also includes the world's highest grade molybdenite-rhenium deposit, the Merlin deposit. The discovery of the Merlin deposit, as well as the Kalman copper-molybdenum-rhenium-gold deposit immediately to the west of the project area, is expected to mark a turning point for North-West Queensland as the region broadens its production base to produce iron ore, molybdenum and rhenium for the first time in its history.

The purpose of the project was to investigate the geological, structural, geophysical, geochemical and hyperspectral characteristics of mineralisation styles in this region, recognising that ore deposits are highly variable in their local characteristics, and to use this to assess the potential for further mineralisation, particularly under cover beyond the exposed sections of the Inlier.

This scale-integrated study of the Mount Dore area provides an example of how open-file geological and geophysical data can be used to develop district-scale 3D models that can then be used for predictive investigations in greenfield areas.

Work on this project was undertaken in four stages: compilation of mineral systems models, geological 3D model construction, geophysical inversion of the model to populate it with rock property values, and a final 3D exploration targeting analysis using a Weights of Evidence (WofE) approach. Detail on each of the stages of the process is presented below.

Compilation of mineral systems models

Data on known mineralisation was integrated into a IOCG mineral system model for the eastern half of the Mount Isa Inlier, defining the geological, geochemical and geophysical characteristics that can be used for quantitative assessments of mineral potential, particularly under cover. This analysis incorporates information from detailed studies of significant deposits and regional studies of mineralising processes. It addresses six fundamental questions regarding:

- the geodynamic and P-T-t history of the system
- the architecture of the system
- fluid characteristics and sources of water, metals, ligands and sulphur
- fluid flow drivers and pathways
- transport and depositional processes
- the effect of later geological processes on the preservation of deposits.

The IOCG mineral systems models developed for the Mount Dore Project are summarised as tables in Chapter 6, along with summaries of other important mineral systems of the region (i.e. structurally-controlled epigenetic Cu±Au deposits and stratabound sediment-hosted Zn-Pb-Ag mineralisation west of the Kalkadoon–Leichhardt Domain, and Ag-Pb-Zn in high-grade metamorphic terranes and structurally-controlled epigenetic Cu±Au±iron oxide mineralisation east of the Kalkadoon–Leichhardt Domain). More detailed reports are found in Appendix 6. Key outputs of these analyses are sets of criteria that can be used for quantitative assessment of mineral potential.

3D geological model construction

As the main controls on mineral deposition in the area are structural and lithological, an understanding of the structural architecture is critical to assessing mineral potential. Consequently, the initial phase of the project involved creating a 3D geological model of the area using the solid geology map and seven interpreted cross-sections created from potential field, seismic and magnetotelluric data. Model construction was undertaken using the SKUA implicit modelling environment within the GoCAD software suite.

Major structural domains were subdivided as fault compartments and incorporated with mapped faults to build a fault network. Ten stratigraphic packages were identified within the region, grouping together rocks of similar physical property characteristics (Figure 9.1). This 3D geological model formed the reference for the 3D geophysical and mineral potential modelling of the project area and has been incorporated into the final, project-wide NWQMEP regional 3D model.

3D geophysical inversion modelling

The GSQ commissioned Mira Geoscience Pty Ltd to develop 3D physical property models that could be used directly to assist mineral targeting and indirectly by influencing interpretation of the regional structural and geological setting. The work flow involved iterative data processing and reconciliation through a number of inversion stages, as follows:

Voxel model preparation

As a basis for inversion modelling, a regional voxet model (900 metres lateral x 200 metres vertical resolution) was produced from the SKUA-derived geological model (Figure 9.2). This discretised model was populated by appropriate rock property (density and magnetic susceptibility) values derived from an assessment of GSQ and other published rock property databases for the region.

Geometry refinement

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. These results were used to improve and prepare the initial voxet model for regional potential field inversions.

Property inversion

A three stage property inversion process was conducted applying VPmg (and finally UBC) to both the magnetic and gravity data.

(i) Optimisation of homogeneous property values — to achieve a better fit to the observed data in each geological package. Homogenous optimisation of properties, especially the magnetic susceptibility, was hindered by the inherent heterogeneity created by clustering multiple lithologies into broad geological domains.

(ii) Optimisation of heterogeneous property values — optimised densities and susceptibilities were used as inputs for VPmg 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 was used to highlight anomalous regions within the geological packages of the 3D density model (Figure 9.3) and magnetic susceptibility model (Figure 9.4). An example in this inversion were zones of heightened density and magnetic susceptibility corresponding to mapped dolerites which were not represented in the simplified geological reference model.

(iii) Production of high resolution upper crustal model — the regional gravity inversion results were interpolated into a high-resolution model (300 metres laterally x 150 metres vertical resolution) of the upper 2.5 kilometres of the crust. 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 (Figure 9.5).

Pseudo-lithology model

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 (Figure 9.6) using statistical software. This process used 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 generated by its properties depending on its proximity to these domains in the parameter space, identifying cells which are more similar to cells in regions other than their own. The pseudo-lithology is useful in testing the validity of the starting model, allowing interpretation of additional geological complexity and

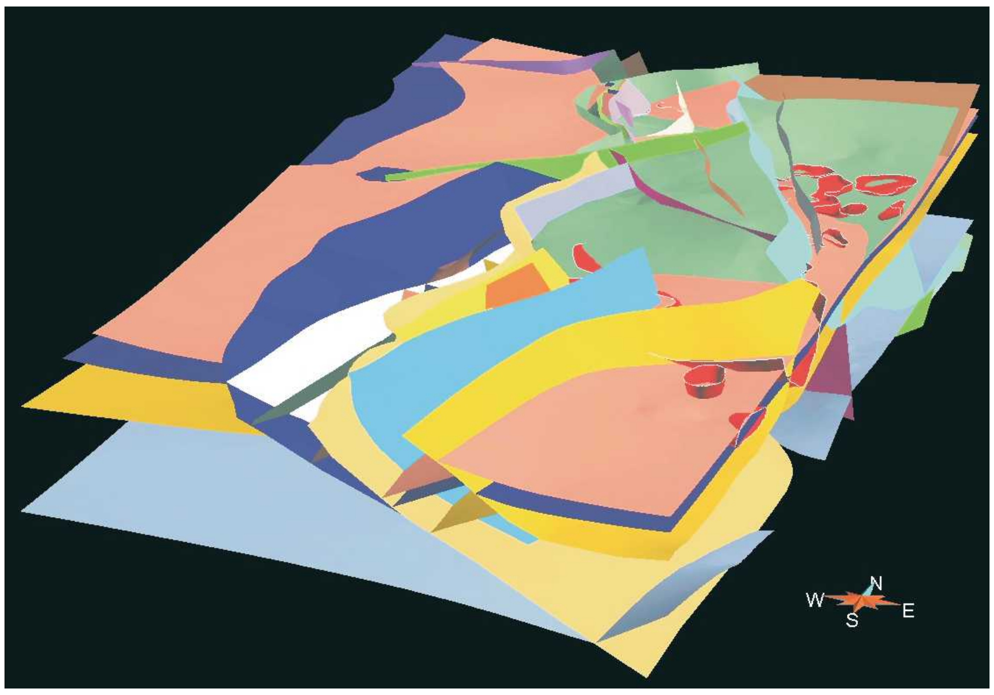


Figure 9.1: Fault and Horizon SKUA model of the Mount Dore region viewed from the south

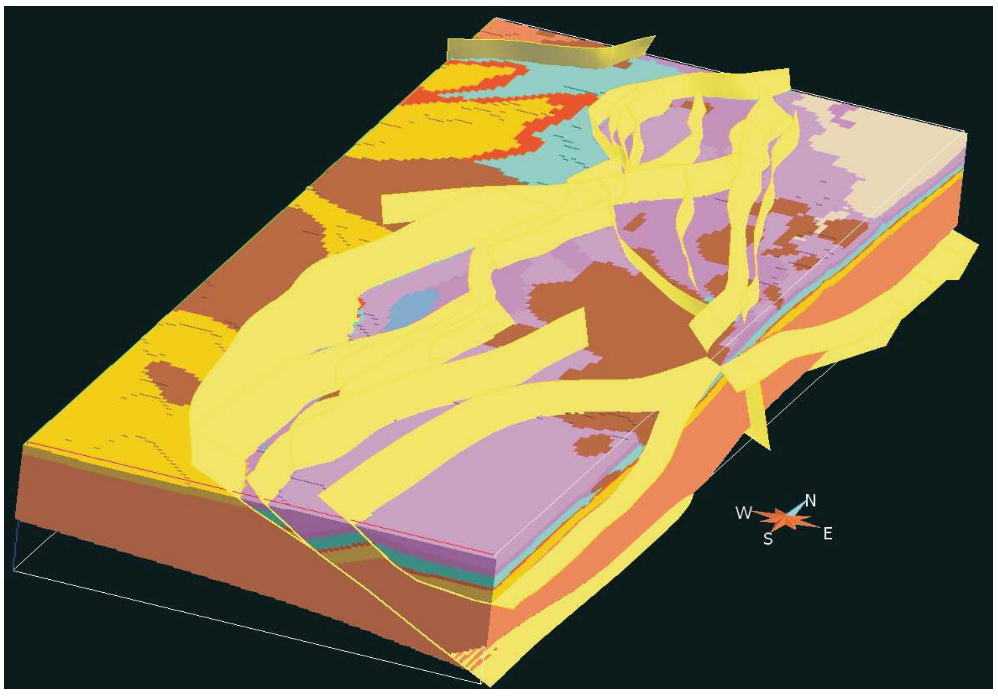


Figure 9.2: Voxet model of the Mount Dore region (900m x 200m) viewed from the south with SKUA faults

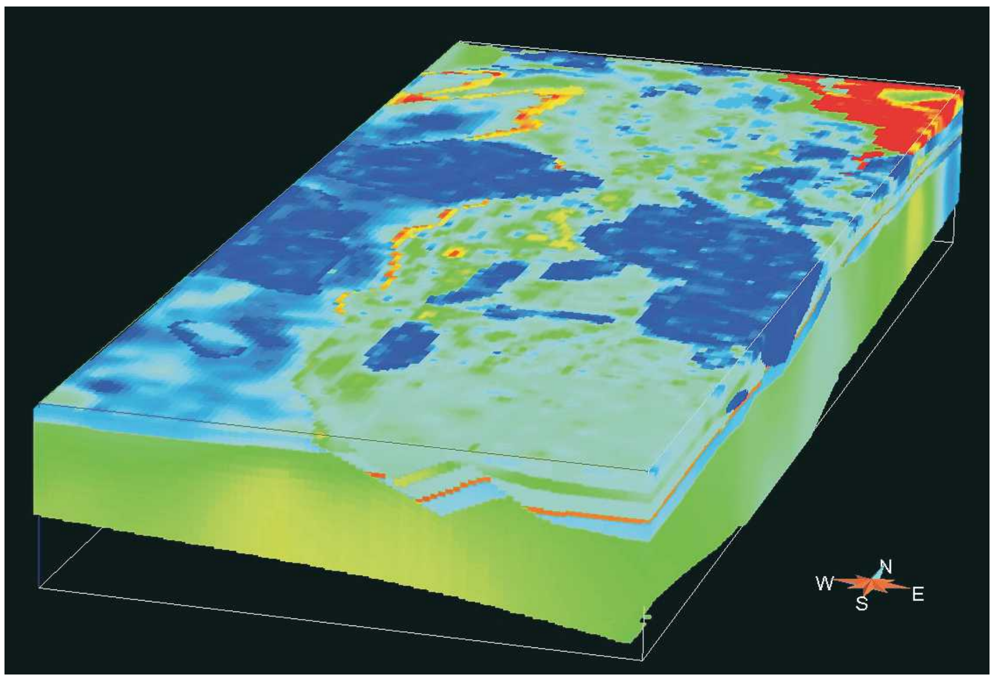


Figure 9.3: Regional density model of the Mount Dore region produced after VPmg homogenous and heterogeneous property inversions

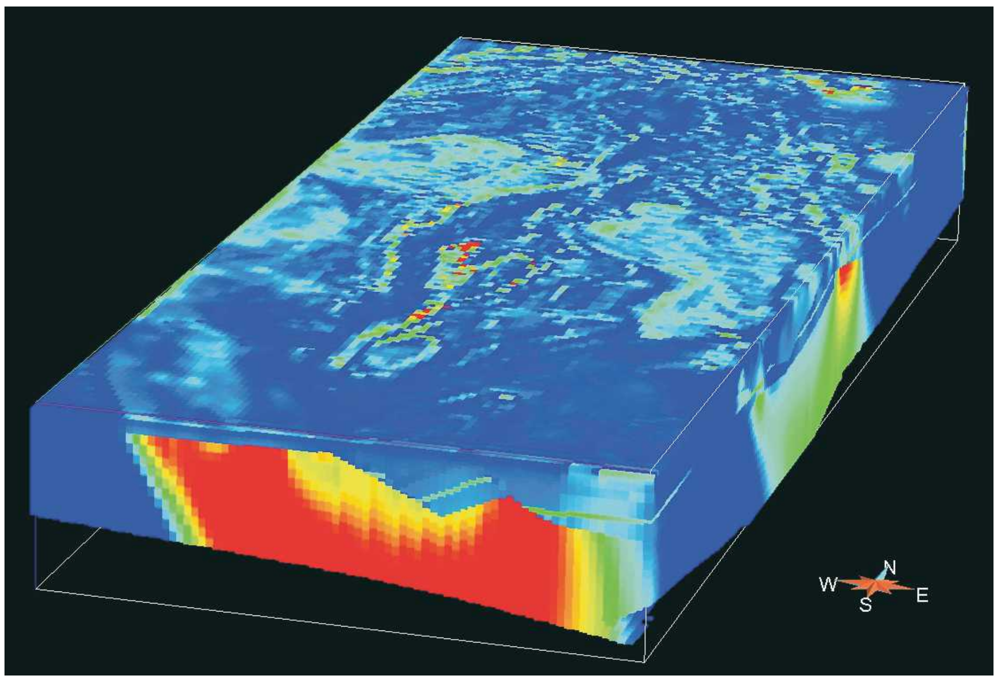


Figure 9.4: Regional magnetic susceptibility model of the Mount Dore region produced after VPmg homogenous and heterogeneous property inversions

identification of 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 9.7). Other reclassified areas can be interpreted as unidentified intrusive bodies or as a metamorphic or alteration overprint.

Exploration targeting

A WofE approach was chosen to assess the potential for further economic mineralisation using the existing location of IOCG mineralisation as training data. A Common Earth Model (CEM) of the Mount Dore region was prepared with a cell resolution of 300m x 300m x 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 the NWQMEP study — outlined 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 (Table 9.1). Exploration criteria with large weights in the WoE study can be used as an exploration tool, increasing predictive

Table 9.1: Exploration criteria and associated weights

Exploration Criteria	W +	W -	Contrast	Stud. Contrast	Range start	Range end
Coincident Gravity High-Magnetic High	2.29	-0.2	2.49	5.9	0.81	0.246
Distance C-Sharp Filter ISO <35	2.88	-0.91	3.79	11.09	0m	300m
Distance to Crustal faults	0.74	-0.32	1.06	3.12	0m	964m
Distance to faults intersecting mafics	1.12	-0.29	1.41	4	0m	921m
Fault Roughness	2.79	-0.17	2.96	6.63	0	0.00015
Geological Complexity	1.8	-0.35	2.15	6.09	0.107	0.0198
Normalised Susceptibility	3.25	-0.14	3.39	7.03	0.372	0.0884
Regional Density Model	3	-0.08	3.08	5.11	0.426	0.32
Uranium divided by Thorium	2.12	-0.58	2.7	8.1	1.289	0.274
Distance to Gold Anomaly <150	5.16	-0.29	5.45	14.15	0m	304m
Distance to Copper Anomaly <2000	5.72	-0.75	6.47	19.35	0m	250.7m

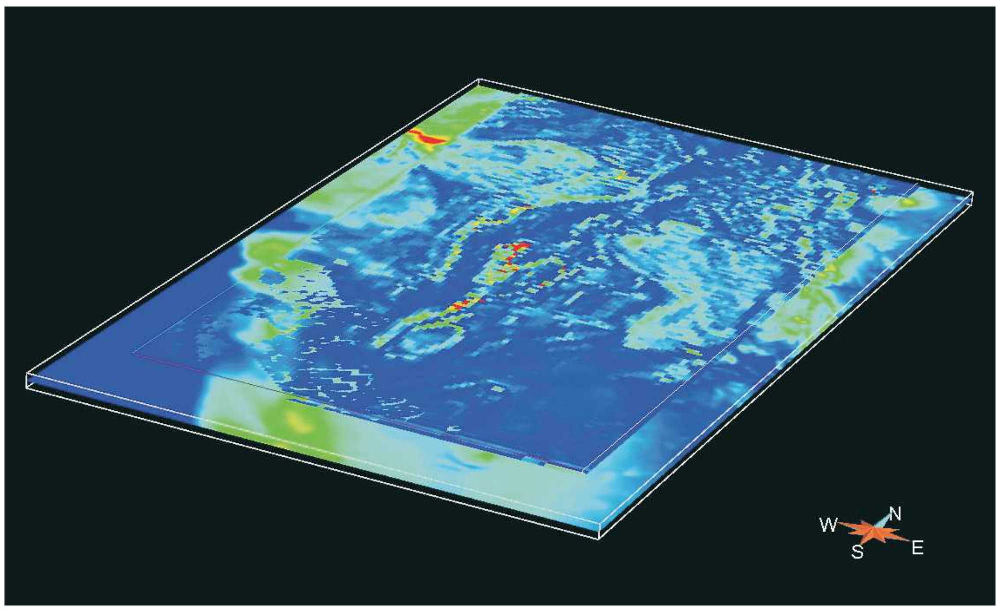


Figure 9.5: High resolution (300m x 150m) upper crustal magnetic inversion model

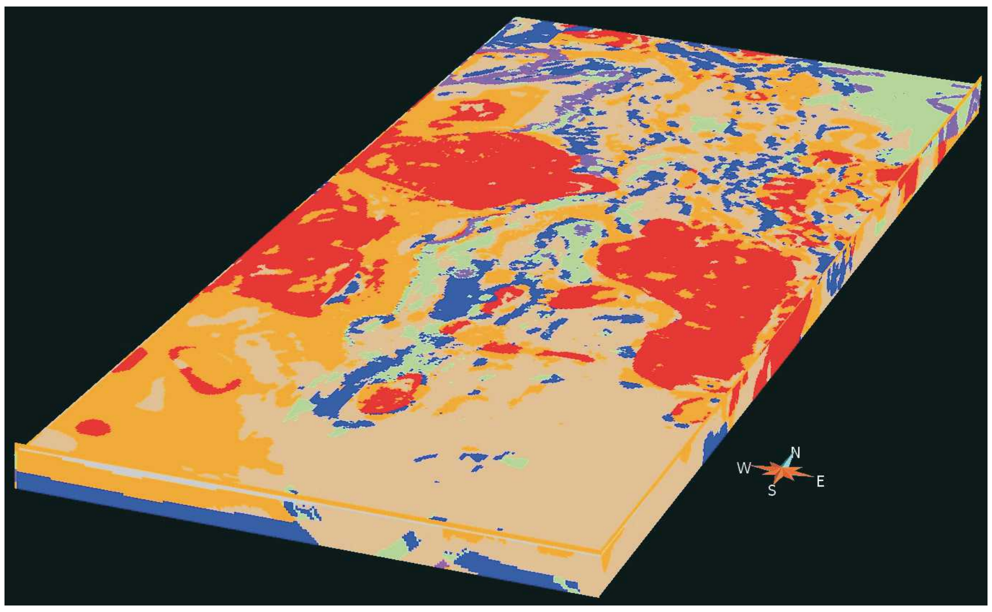


Figure 9.6: Pseudo-lithology model defined by 3D statistical property classifications of three major rock properties (magnetic susceptibility, density and conductivity) that populate upper crustal model

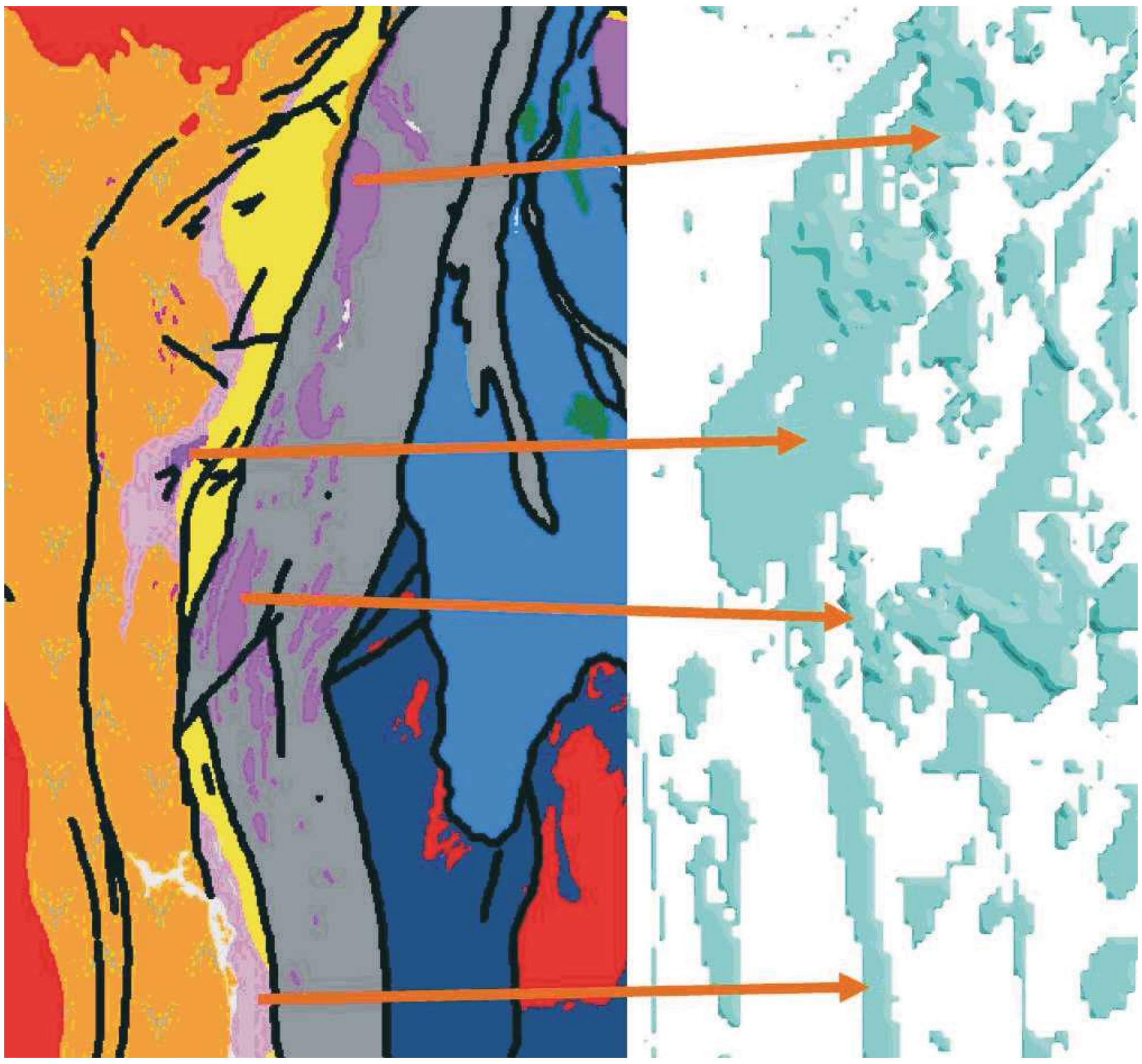


Figure 9.7: Geology map (left) and volumes of changed pseudo-lithology (right). The reclassification is due to small intrusives that didn't appear in the initial regional modelling.

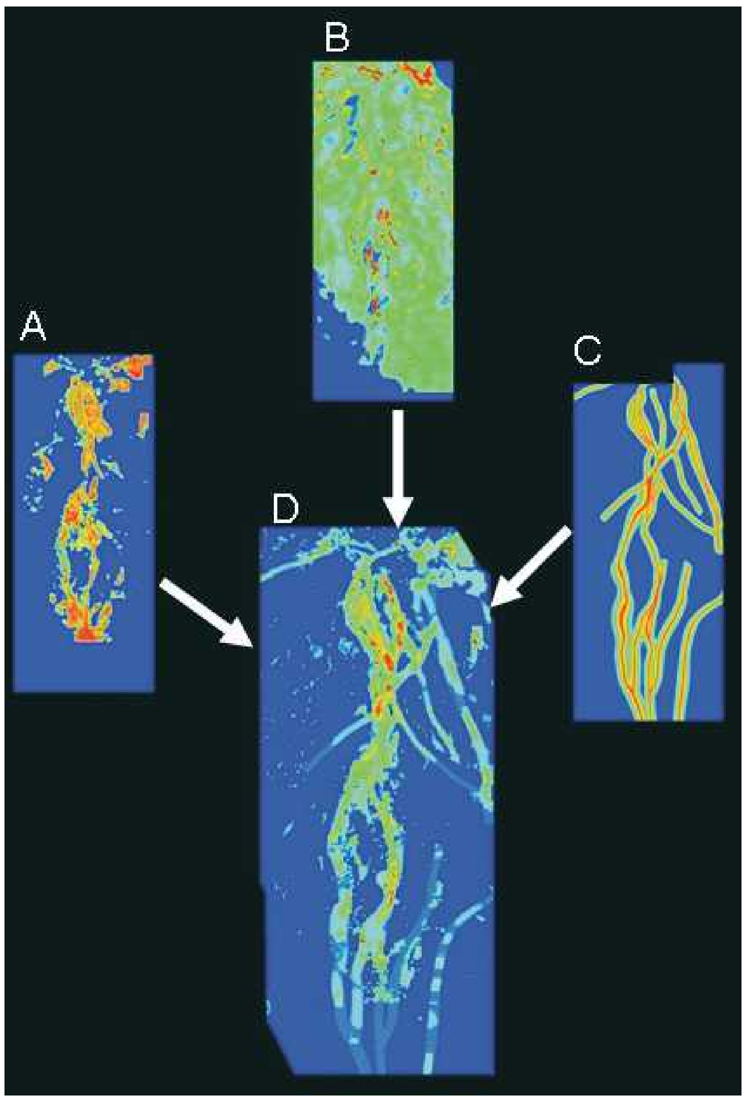


Figure 9.8: Three exploration criteria: Distance to conductive bodies (A), Coincident Magnetic and gravity anomalies (B) and Distance to crustal scale faults (C), and the Mineral Potential Index (D)

capabilities by increasing the understanding of specific district controls on the ore forming system (Figure 9.8).

Eleven of the exploration criteria exhibited significant correlation with known mineralisation in the Mount Dore area and were used to calculate a Mineral Potential Index (MPI) which represents the relative chance of each individual cell within the model hosting IOCG mineralisation (Figure 9.9). A separate MPI was created for undercover greenfields regions as several of the exploration criteria, such as surface geochemistry, require outcropping geology.

Refer to Appendix 6 for a detailed report of the Mount Dore Project.

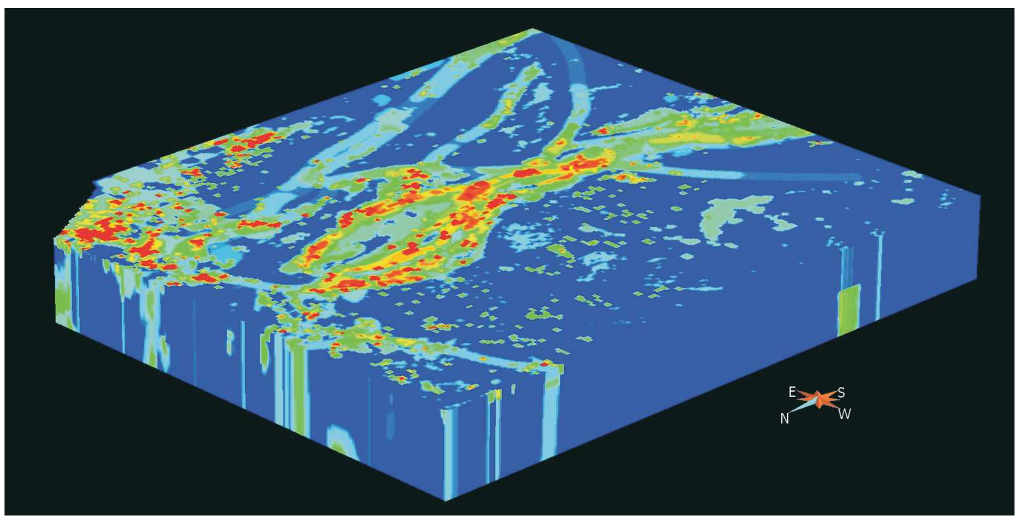


Figure 9.9: Mineral potential index for the northern section of the Mount Dore region where hot colours represent high mineral potential derived from the WofE modelling.

Satellite, airborne, and subsurface spectral data, Mount Isa

Spectral data for the Mount Isa region is now available at a range of scales from regional to prospect, and provides geologically oriented information that extends beyond that provided by traditional datasets such as Landsat.

ASTER satellite data

The Japanese ASTER multispectral sensor was launched in 1999 on NASA's Terra satellite (http://asterweb.jpl.nasa.gov/). Since then, ASTER has built up a comprehensive library of multispectral data, enabling a wide area mosaic covering the entire Mount Isa Inlier to be completed (Figure 10.1). ASTER has six bands in the Short Wavelength Infra-Red (SWIR) and three in the visible region of the spectrum, where many clay and mica minerals, and iron oxides have characteristic absorption features. Although ASTER's band coverage can enable mineral groups to be identified, it is generally insufficient to determine mineral types. Nevertheless, fourteen separate image maps were derived for the whole mosaic area, and these provide information on surface materials, geological textures and vegetation (Table 10.1). The images are available in GIS-compatible format for easy integration with other datasets to assist mineral exploration as well as land management applications.

Airborne hyperspectral data

Airborne hyperspectral systems such as HyMap have much greater spectral and spatial resolution than ASTER, providing even more information to geologists. The Department funded an airborne data collection program in 2006 and 2007, using HyVista Corporation's HyMap sensor. Approximately 19 000km^2 of coverage was obtained in the Mount Isa region (Figure 10.1). The data were processed at CSIRO in Perth, where systematic approaches were developed to produce a standard suite of images characterising the surface materials. Over 350 images are available from the Mount Isa region (Cudahy & others, 2008).

In the Mount Isa area, the survey lines were located along significant structural features such as the Termite Range, Pilgrim, and Cloncurry Faults. The surveys also covered major mineralised regions such as the iron oxide-copper-gold province south of Cloncurry, and a good representation of the diversity of Mount Isa's geology.

The Hyperspectral-derived images assist explorers to assess their tenements in terms of mineralisation models, fluid flow pathways, and chemical reactivity between mineral-rich fluids and host rocks of various compositions. Such considerations enable the exploration geologist to ask the right questions about possible alteration haloes and the mineral expression of chemical and temperature gradients. Hyperspectral surveys identify both the distribution and composition of a suite of minerals across the landscape. Direct mineral mapping is now possible, as demonstrated by the over 25 000km^2 of hyperspectral survey-derived mineral maps of Mount Isa and beyond in north Queensland. The mineral map products from

Table 10.1: List of image products from the ASTER mosaic of the Mount Isa Region, available in ecw and jp2 formats from http://c3dmm.csiro.au/NGMM/
(select the 'Precompetitive Data Download' option)

ASTER Satellite Images		
False colour	Ferric oxide abundance	AlOH group
Green vegetation	Ferrous iron abundance	AlOH group composition
CSIRO regolith ratios	Opaque group	Advanced argillic group
Ferrous iron with MgOH	Fe-OH group	MgOH group
Ferric iron with MgOH		MgOH group composition

Table 10.2: List of image products from the hyperspectral survey, available in ecw and jp2 formats from http://c3dmm.csiro.au/NGMM/
(select the 'Precompetitive Data Download' option)

Airborne HyMap Images		
Natural colour	White mica abundance	MgOH content (abundance)
False colour	White mica composition	MgOH composition
Green vegetation	White mica crystallinity	MgOH and ferric iron
Dry vegetation	Al smectite content (abundance)	MgOH and ferrous iron
Ferric oxide content (abundance)	Al smectite composition	Amphibole-chlorite
Ferrous iron abundance (in silicates and carbonates)	Kaolin content (abundance)	Epidote content (abundance)
Opaque group	Kaolin crystallinity	Hydrated silica
Water and mica		

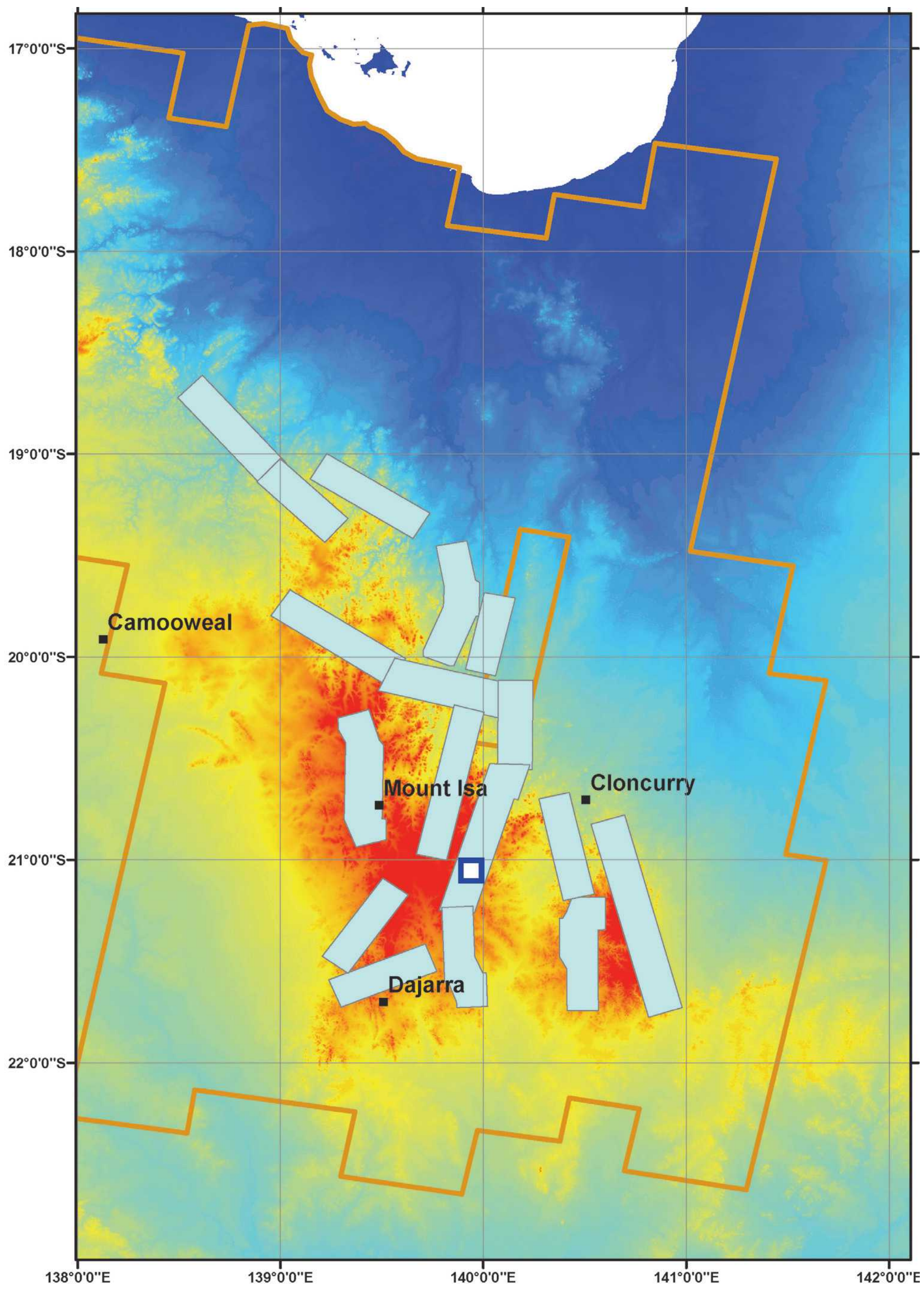


Figure 10.1: The airborne Hyperspectral coverage in the Mount Isa region comprises seventeen 15km-wide swaths within the footprint of an extensive regional ASTER mosaic (large polygon). Blue square shows location of Figure 10.2. Underlying image shows topography (Blue = low; red = high).

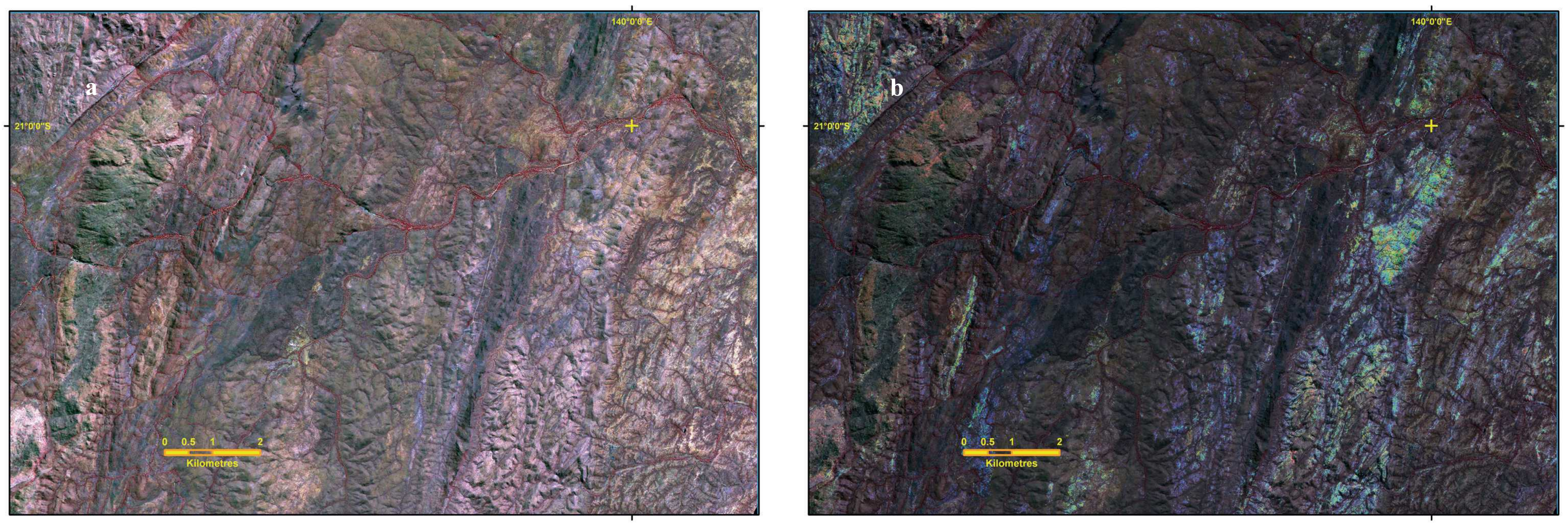


Figure 10.2: a) False colour composite image from Hyperspectral survey shows the Fountain Range Fault crossing the north-west corner of the image, and the Pilgrim Fault (NNE grey zone in the east). b) White mica distribution image for the same area, derived from Hyperspectral data, shows high abundance in red and low in blue; black = not detected. The Wonga Batholith in the west is characterised by high mica abundance.

Figure 10.3: Core is cleaned and annotated with depth information before being scanned by HyLogger™ to determine Visible to Short Wavelength Infra-Red spectra. The HyLogger™ is operated by the Geological Survey of Queensland at the Exploration Data Centre, Zillmere, Brisbane.

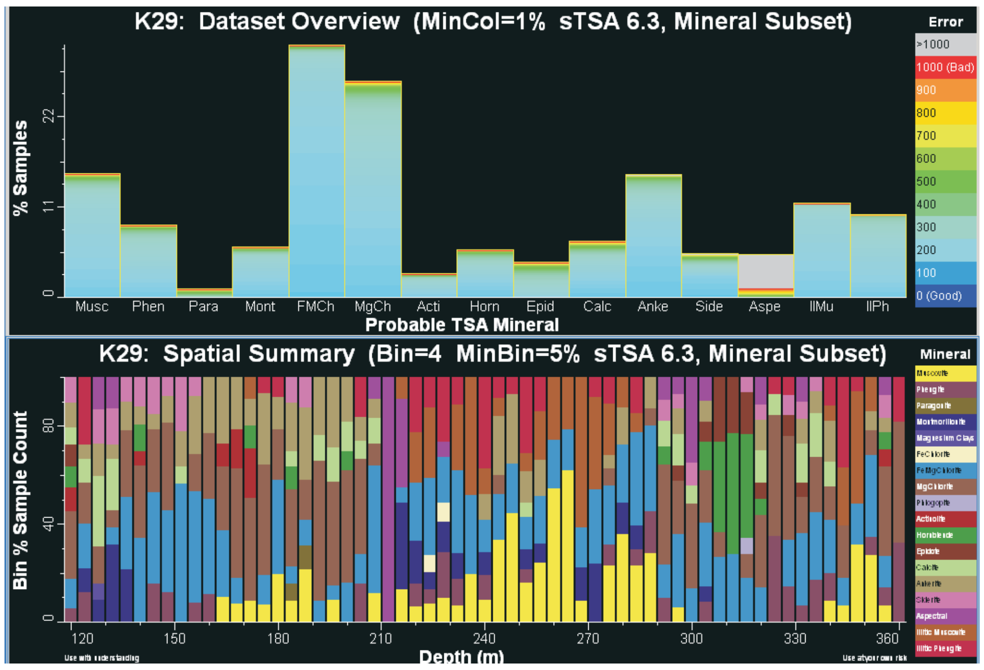


Figure 10.4: Overview display in TSG software shows mineral abundance and downhole distribution (Depth on horizontal axis).

these surveys are now available at no charge via web download from http://c3dmm.csiro.au/NGMM/.

Subsurface spectral data

Satellite and airborne surveys characterise the topmost few millimetres of the landscape. With HyLogger™ (Figure 10.4), the spectral characteristics of core can be measured in a similar fashion. When airborne and HyLogger™ data are used together, the distribution of minerals in 3D can be studied.

HyLogger™ data includes high resolution photography of the core as well as spectral information, and is displayed using proprietary TSG software (http://www.ausspec.com/TSG.htm). The software enables the rapid display of downhole mineralogy (Figure 10.4), and also allows other datasets such as assays to be depicted. Only a small number of drillholes from the Mount Isa region have been scanned by HyLogger™ at present. However, as the archive of spectral data expands through the HyLogger™ program, better knowledge of the 3D geology of the region will support further successful exploration. The HyLogger™ data will be made available through the National Virtual Core Library, an initiative of AuScope http://nvcl.csiro.au/Default.aspx.

The spectrally-derived images from ASTER, HyMap and HyLogger™ display mineral distribution and composition at various resolutions and provide geologists with quantitative and objective information to examine geology from regional to prospect scales.

Energy resources of North-West Queensland

The North-West Queensland Minerals and Energy Province (NWQMEP) contains large sedimentary basins ranging in age from the Neoproterozoic to the present. They have been sporadically explored and studied by exploration companies, government agencies and research organisations over the last 80 years, particularly for minerals and petroleum.

Juxtaposition of these basins to early gold fields (Palmer River, Cape York) and, later, the Mount Isa and Cloncurry mineral fields has kept a focus on a lookout for available energy resources in the region.

Future opportunities for coal seam gas, shale gas and geothermal energy are just some of the projects that await development in an area that is still considered vastly underexplored.

Exploration history

Early encounters with post-Proterozoic geology in the NWQMEP were associated with the drilling of water bores. Most of these bores were shallow but some reached considerable depth, occasionally encountering basement.

Basic geological units were established for these strata, particularly those exposed at the surface (Eromanga and Carpentaria Basins) partly based on correlation with units of similar age described in the east of the State.

Petroliferous materials were occasionally encountered in some of these water bores, prompting an interest in petroleum exploration.

In 1928, Longreach Oil Wells Ltd drilled a hole near the (Longreach) Town Water Bore No. 2 (to the east of the study area) which had been exuding blobs of paraffin wax from the Eromanga Basin. No economic resources were encountered and activities ended in 1934 (Denmead, 1960).

In 1954, Frome Broken Hill Company carried out geological, gravity and aeromagnetic surveys and drilled FBH 1 (Wyaaba 1) in the Carpentaria Basin (Meyers, 1969). Some years later Comalco Aluminium Limited also explored the area near the coast (McConachie & others, 1990).

In 1960, Conorada Petroleum Corporation intersected a thin layer of sediments of the Galilee Basin (Moolayember Formation) beneath the Eromanga Basin in exploration well CPC Oonooroo 1 (McPhee, 1960). Evidence of the possible occurrence of sediments older than the Jurassic within the sequence was based on recently acquired company-derived gravity surveys. In the same year Magellan Petroleum Company drilled MPC Corfield 1 that intersected the Early Permian Aramac Coal Measures (Harris, 1960).

The Bureau of Mineral Resources (BMR) carried out mapping of the Georgina Basin during the late 1950s – early 1960s. In 1962, Phillips Petroleum Company drilled the first hole, PPC Black Mountain 1 in the Georgina Basin (Green & others, 1963).

Australian Aquitaine Petroleum Pty Ltd drilled two wells, AAP Fermoy 1 and AAP Mayneside 1 in 1966, and discovered oil shale in the Toolebuc Formation at depth. Their attention shifted to Julia Creek where the formation outcropped. In 1968 a Departmental Reserve was proclaimed where a number of joint ventures carried out exploration and analysis but activities were abandoned in 1969 (Swarbrick, 1974).

During the 1970s, joint mapping by the Bureau of Mineral Resources and the GSQ, including shallow and deep stratigraphic drilling, advanced the understanding of the stratigraphy of the basins (Casey, 1970; Gray & Swarbrick, 1975; Smart & others, 1980).

In 2009 airborne geophysics and deep seismic transects collected by GA and the GSQ added to the knowledge of the area, including a possible new basin, the the Millungera Basin, concealed beneath the Eromanga Basin to the east of the Mount Isa Inlier. It is yet to be conclusively drilled.

Geology

At the end of the Proterozoic Eon, the Mount Isa Inlier had become part of a stable crust of folded and metamorphosed strata of continental thickness.

During the Middle Cambrian to Middle Ordovician, carbonate-dominated marine sediments of the Georgina Basin accumulated in shallow seas that transgressed from the south across this crust.

The Thompson Orogen that formed immediately to the south during the late Ordovician caused varying degrees of deformation and metamorphism to both the Mount Isa Inlier and Georgina Basin.

In the late Carboniferous the central and south-western sections of the Thomson Orogen began to sag and large shallow depressions started to accumulate continental sediments.

In the NWQMEP, sedimentation included fluvioglacial and fluvial deposits, followed by fluvial and coal measure deposition. During this time, activation at the boundary between the Mount Isa Inlier and the Thompson Orogen produced contemporaneous faulting resulting in the development of the Lovelle Depression on the downside of the Cork Fault.

A hiatus in the Early to Late Middle Permian was followed by further coal measure deposition which spread across the whole Galilee Basin.

A further hiatus in the Early Triassic was followed by terrestrial sedimentation in the Middle Triassic.

A major hiatus through the Late Triassic and early Early Jurassic was followed by a major new sag phase that developed across a large area of Queensland during the Jurassic. In the NWQMEP this resulted in the deposition of the basal Eromanga Basin units.

During the Cretaceous, eustatic sea-level changes caused wide-spread inundation by the sea, with marine sediments accumulating in both the upper Eromanga and Carpentaria Basins.

During the Tertiary, a sag phase developed over the compacting Carpentaria Basin leading to the formation of the Karumba Basin, an Oligocene to Recent basin with a thin sequence (<300m) of fluvial, minor shallow–marine, and lacustrine sediments (Day & others, 1983).

Georgina Basin

The Georgina Basin is a Neoproterozoic to early Palaeozoic (Cambrian/Ordovician) basin straddling the Queensland to Northern Territory border (Figure 11.1).

In Queensland it outcrops from north of Camooweal to the Simpson Desert and in a belt between Duchess and east of Boulia. In the south, the basin extends beneath the Eromanga Basin.

Basement rocks of the Arunta Complex, Mount Isa Inlier and 'Aljawarra Craton' underlie it (Tucker & others, 1979).

Structure

The Toko Syncline is bounded to the south-west by the Toomba Fault, a large fault with a reverse vertical displacement of approximately 6.5km and lateral displacement of approximately 4km (Draper, 2007). Movement along this fault has disrupted the Palaeozoic strata of the hanging wall and created potential traps along its length.

Faulting within the Burke River Structural Belt is thought to have a dominantly vertical character (Draper, 2007).

Stratigraphy

The Queensland section of the Georgina Basin can be divided into three regions; the Toko Syncline and the Burke River Structural Belt in the south, and the Undulla Sub-basin in the north. Each of these regions have had a different depositional and erosional history.

The stratigraphy of the basin is dominated by rocks associated with a carbonate-shelf environment. Carbonates and dolomites are common throughout the sequence. The stratigraphy has been summarised by Draper (2007). Figure 11.2 shows a stratigraphic column for the basin. Due to low levels of exploration and limited outcrop, stratigraphic relationships across the basin are poorly defined.

The Toko Syncline contains the thickest and most complete succession in the basin and is considered to be the most prospective region. Marine source rocks of Middle Cambrian age are thought to be mature for oil in the shallower sections of the syncline and mature for dry gas in the deeper parts (Draper, 2007). An increase in salinity across an unconformity between the Ordovician Nora and Kelly Creek Formations is thought to be an indicator that the Lower Ordovician and Cambrian sections of the Toko

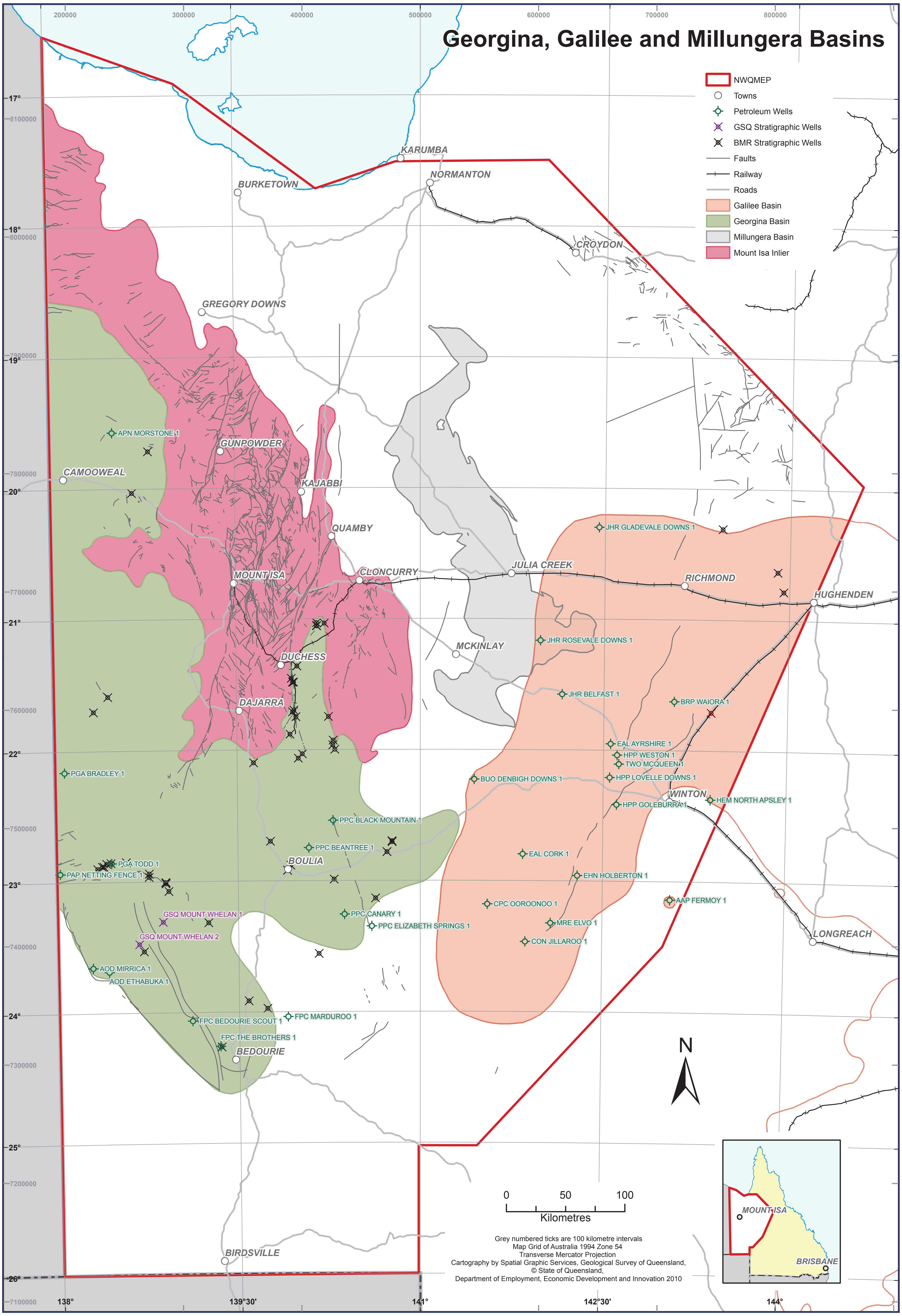


Figure 11.1: Location of the Georgina, Galilee (Lovelle Depression), and Millungera Basins

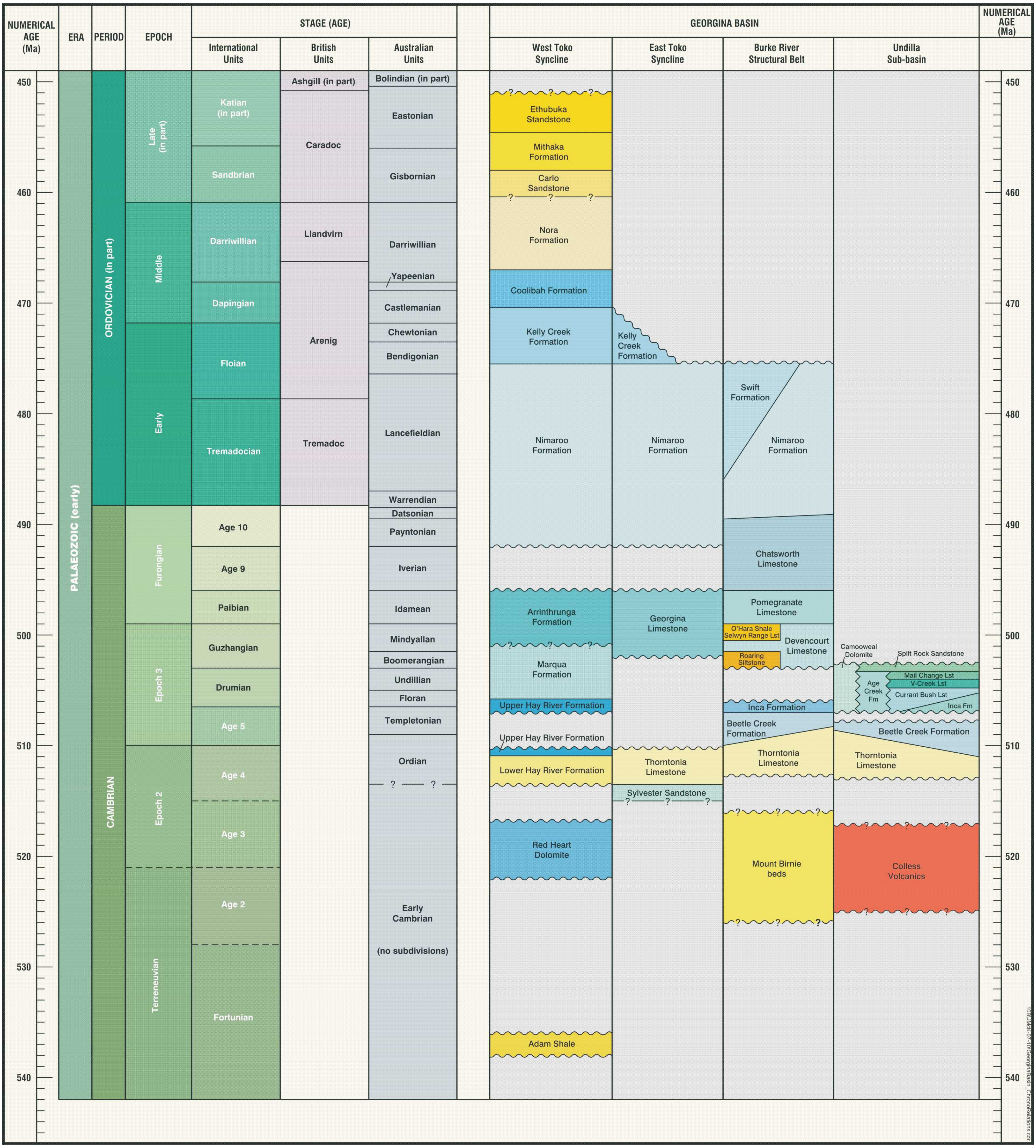


Figure 11.2: Stratigraphy of the Georgina Basin

Syncline have not been water flushed (Mulready, 1975).

Previous exploration

Previous exploration in the Queensland section of the Georgina Basin has focussed on the Toko Syncline and the Burke River Structural Belt.

Within the Toko Syncline, seven petroleum exploration wells have been drilled, testing various traps and depths. In addition, two stratigraphic wells, GSQ Mount Whelan 1 and 2 have been drilled.

The most promising petroleum show occurred in AOD Ethabuka 1. Gas flowed at approximately 6000m^3/day (200MCF/day) from the Ordovician Coolibah Formation.

The exploration well AOD Ethabuka 1 was abandoned prior to reaching its intended target depth due to drilling problems and flooding of the region. A seismic survey conducted in 1999 suggests that AOD Ethabuka 1 was not drilled on the closure of its target structure.

Minor indications have been reported in other wells drilled into the Toko Syncline (see Appendix 7).

Four petroleum exploration wells were drilled within the Burke River Structural Belt. The only indication of petroleum was a bituminous odour from sandstone cored from the Inca Formation in PPC Black Mountain 1.

Phosphate exploration wells (BMR Duchess 16-18 and BMR Urandangi 10) encountered numerous oil stains associated with fracture porosity and calcite veins.

APN Morstone 1 is the only petroleum well drilled in the Undilla Sub-basin. No petroleum shows were recorded during the drilling of this well.

Galilee Basin (Lovelle Depression)

The Galilee Basin is a large, relatively shallow intracratonic basin in central Queensland extending over an area of a quarter of a million square kilometres and reaching a maximum total depth of 3000m.

In the NWQMEP the most westerly of the three main depocentres of the Basin reaches a little over 730m in thickness beneath the overlying Jurassic/Cretaceous Eromanga Basin which reaches thicknesses up to 1400m (Figure 11.1).

Structure

Structural features in the area include the Cork Fault that is suggested to be influenced by its proximity to the Mount Isa Inlier. The Cork Fault runs in a south-west to north-east direction, roughly parallelling the margin of the Thomson Orogeny where it abuts the Proterozoic craton (Kirkegaard, 1974; Hawkins & Harrison, 1978; Murray & others, 1989; Totterdell, 1990; Gray & Foster, 2004).

The Galilee Basin overlies a basement of Thompson Orogen rocks consisting mainly of metamorphosed phyllitic siltstones and micaceous metaquartzites (Devonian?). In the north-west it overlies the Proterozoic Mount Isa Inlier (Hawkins & Harrison, 1978).

Deposition associated with down-faulting during the Permian has caused considerable difference in thickness of the Aramac Coal Measures and Betts Creek beds from east to west across the fault. A half-graben formed on the western flank of the Fault, with thick deposits in the Lovelle Depression and thin and shallow deposits on the Elderslie Ridge.

The Holberton and Wetherby Structures, both faults, roughly parallel the Cork Fault, but all were active at different times.

Stratigraphy

During the late Carboniferous/Early Permian the Galilee Basin accumulated glacial and fluvial deposits that are correlated with the Jochmus Formation recognised in the eastern Galilee Basin. The deposits in the west accumulated at roughly the same time and under similar conditions as those in the east, even though there are some lithologic differences (Hawkins & Harrison, 1978) (Figure 11.3).

The Jochmus Formation was overlain by the Aramac Coal Measures which is also recognised in the east of the Basin. A Middle Permian east–west compression phase, the onset of the Hunter-Bowen Orogeny, caused uplift and erosion and resulted in the coal measures being represented as a thin, irregularly eroded remnant across the whole Galilee Basin.

Deposition of the Betts Creek beds in the Late Permian consisted of accumulation within an alluvial-coastal plain in a low-accomodation basin setting (Allen & Fielding, 2007). This sequence is thought to be correlative with the Bandanna Formation and Colinlea Sandstone in the eastern Galilee Basin, and the Late Permian sequences of the Springsure Shelf and Bowen Basin.

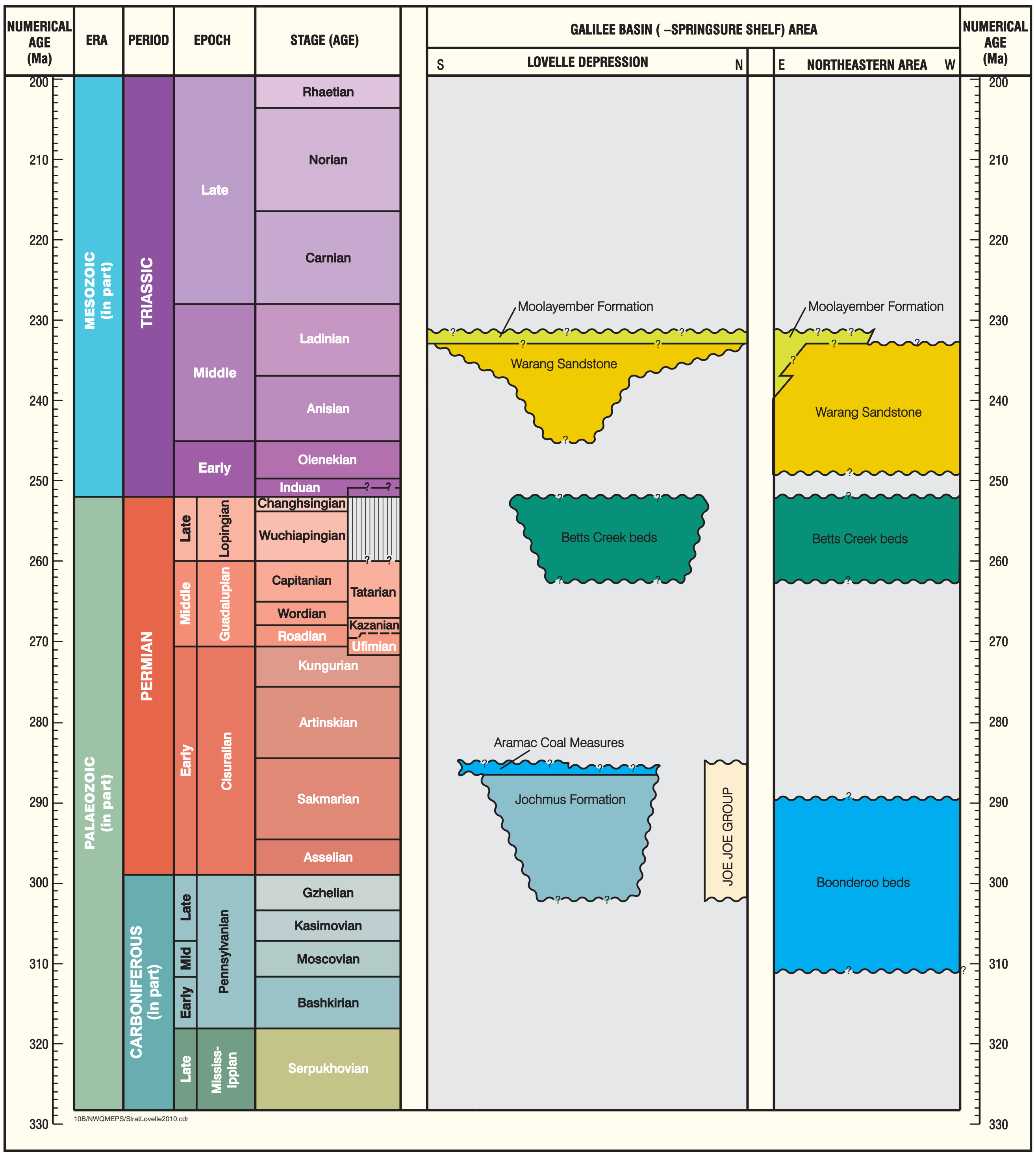


Figure 11.3: Stratigraphy of the Galilee Basin (Lovelle Depression)

These are unconformably overlain by the Early–Middle Triassic Warang Sandstone which is tentatively correlated with the Rewan Formation and Clematis Sandstone in the Basin further east. The Warang Sandstone is conformably overlain by the Moolayember Formation.

Previous exploration

Early seismic surveys identified the Cork Fault, prompting petroleum explorers to drill the western flank. These wells (HPP Lovelle Downs 1 and HPP Weston 1) verified that the formations were thicker to the west.

Later drilling has partially identified the extent of the Aramac Coal Measures and the Betts Creek beds (Figure 11.7).

Government surface mapping and stratigraphic drilling have been used to produce a stratigraphy for the area.

Millungera Basin

A recent deep crustal seismic reflection survey has identified a previously unrecorded succession, the Millungera Basin, beneath the Eromanga and Carpentaria Basins. The survey was conducted under a collaborative program between GA, the GSQ, *pmd**CRC, and Zinifex Pty Ltd that aimed at imaging the structure of the upper crust. Six regional seismic lines were acquired with only one line (07GA-IG1) traversing the width of the basin and two others (06GA-M5 and 06GA-M4) interpreted to cross the margins of the basin (see Chapter 5, this volume).

The extent of the Millungera Basin is loosely defined from seismic, magnetotellurics, airborne magnetics, gravity, and drillhole data. Based on seismic interpretation, the basin geometry consists of broadly-folded reflectors that have a distinct three-fold subdivision. Using average seismic velocities for shallow crustal rocks, the total thickness of the basin is estimated to be 2000–3000m. Although no drillholes have intersected the Millungera succession, the configuration suggests the sequence to be entirely sedimentary due to the lack of any intrusions cross-cutting the strata.

Post-depositional compressional deformation has produced low-amplitude broad folds and several large thrust faults that have propagated along pre-existing deep crustal weaknesses. Modelling of magnetic and gravity data, together with mudlog descriptions from adjacent drillholes and outcrop observations, have identified the presence of granites beneath the Millungera Basin and in adjacent areas.

The stratigraphic position of the Millungera Basin dates the succession as no older than the Isan Orogeny (overlying the Soldiers Cap Formation) and no younger than the Late Jurassic-Early Cretaceous Gilbert River

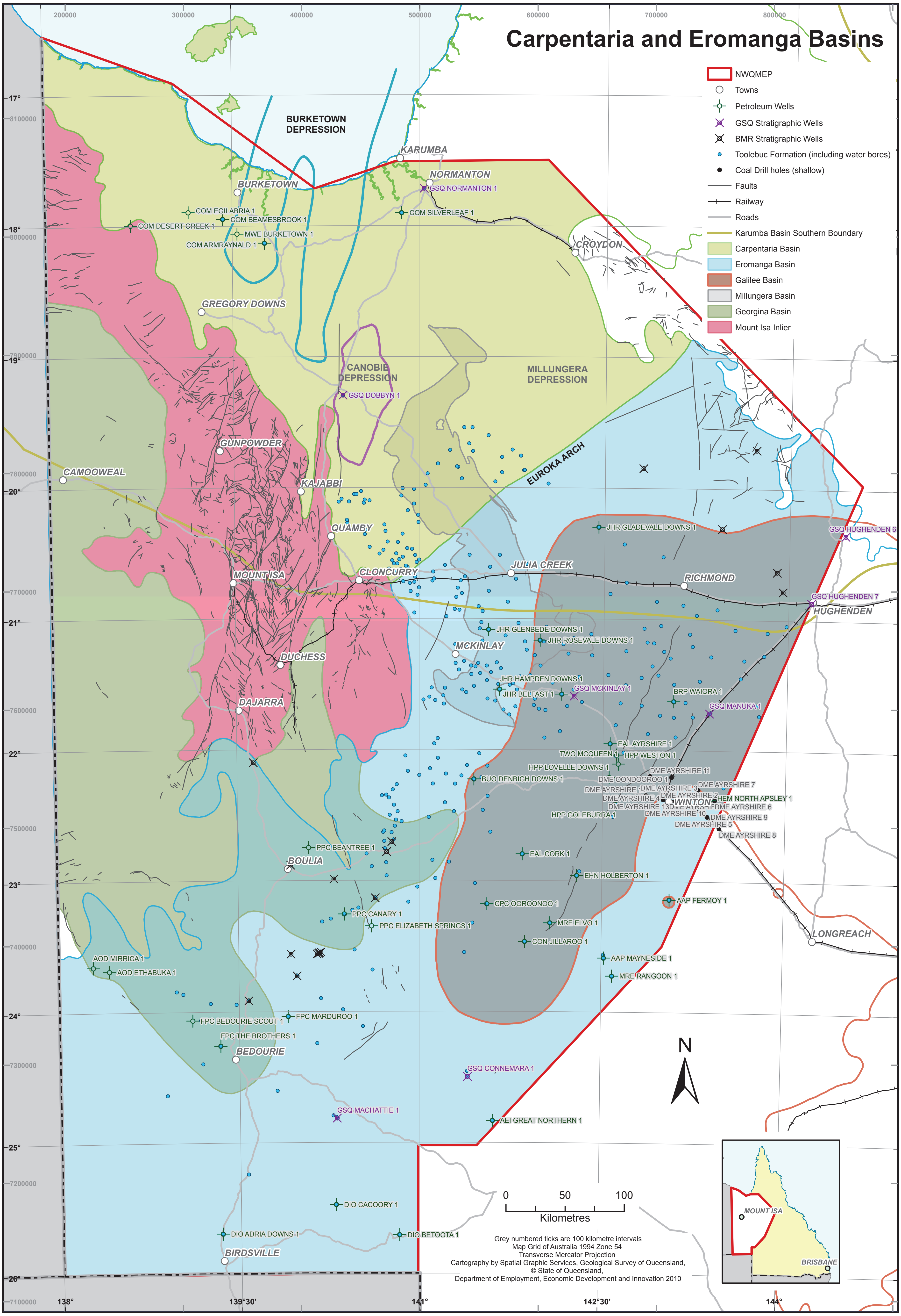


Figure 11.4: Location of the Eromanga, Carpentaria and Karumba Basins

Formation of the Carpentaria Basin (which overlies it).

A preliminary comparison of basins in the region has concluded that the Millungera Basin could well be a sub-basin or extension of the Galilee Basin due to its juxtaposition to the basin and its proximity to the time-equivalent mid-Triassic sequence in the Canobie Depression to the north. However, this does not preclude the possibility that the Millungera succession is older. Thick quartzite and quartzose sandstone beds (brick red in part) were intersected in petroleum wells at the southern margins of the basin and could be representative of the basin fill.

Eromanga Basin

The Eromanga Basin was first defined and named along with the Carpentaria and Surat Basins, as separate depositional and tectonic subdivisions of the Great Artesian Basin (Mott, 1952).

The Eromanga's extent is approximately 1 025 995km^2, covering a large part of western Queensland and extending into the Northern Territory, South Australia and New South Wales. It is therefore one of the largest basins of the world.

The Basin sequences thicken to the south-west in south-west Queensland and South Australia up to about 2700m (Gallagher & Lambeck, 1989). Sequences comprise Jurassic non-marine and Cretaceous non-marine to marine sediments.

The Eromanga Basin in the NWQMEP represents less than a quarter of its full extent (Figure 11.4). Here the sediments tend to be thin and show predictable facies variations towards the basin margins (Vine, 1976).

Structure

The northern Eromanga is interpreted as an intracratonic sag basin (Moore, 1986) with the development of mild Paleogene to present-day folding (Radke, 2009).

Pre-Cainozoic outcrops have resulted from uplifting and truncating of the region, however the rocks exhibit little deformation (John, 1984).

Stratigraphy

The Eromanga Basin sediments can be divided into two major depositional events. The lower, of late Triassic–Jurassic to early Cretaceous age, is predominantly of terrestrial origin and consists of a mix of generally permeable sandstone units with more argillaceous tighter units (in the MWQMEP deposition began in the early Jurassic). The sandstone units are mainly quartzose or sublabile, commonly medium to coarse-grained and non-calcareous. They include some of the main artesian aquifers of the Great Artesian Basin (Figure 11.5).

The upper consists of marine and non-marine sequences. The early Cretaceous marine sequences show a lithological change from quartz rich to being dominated by contemporaneous volcanogenic detritus. During widespread shallow marine conditions, the shaly Toolebuc Formation and Allaru Muststone were deposited. The final stage of the upper sequence is represented by the fluvial Winton Sandstone, a sequence of volcanogenic sandstones and siltstones with minor shales and coals. The late Cretaceous to Palaeogene (Early Tertiary) is marked by a period of deep chemical weathering of the Winton Formation (Gallagher & Lambeck, 1989).

These units grade northwards across the Euroka Arch into units of the Carpentaria Basin (Mond & Yeates, 1973).

Previous exploration

A combined total of 68 stratigraphic boreholes and petroleum wells have been drilled in the Eromanga Basin in the NWQMEP. Most of the exploratory wells in the northern Eromanga Basin were drilled to test structural highs (Casey, 1970). There are abundant water springs and areas of seepage in the marginal areas of the basin. Nearer the centre of the basin the average depth of waterbores is about 500m, with some reaching depths of up to 2000m (Habermehl, 1982).

BMR Springvale 2, 3, 4 and 5 wells were drilled by the Bureau of Mineral Resources in June 1971, to establish the subsurface extent of a svanbergite occurrence. These wells were drilled to shallow depths, typically between 30–100m, and identified the edge of the Eromanga Basin where it overlies the southern Georgina Basin (Senior & Hughes, 1972; Figure 11.1).

Carpentaria Basin

In the Cretaceous a marine inundation related to eustatic sea-level changes associated with break-up of Gondwana commenced in the Carpentaria Basin, possibly as early as the Late Jurassic in the east, and advanced into the Eromanga Basin (Figure 11.4).

Structure

In the NWQMEP, the Carpentaria Basin is bounded by the Mount Isa Inlier to the west, and the Georgetown Inlier to the east. It connects with the Eromanga Basin to the south over the Euroka Ridge, a wide shallowing of the basement between the two Inliers. Only a few holes have penetrated the Eromanga, intersecting a range of rock types including sandstones, quartzites and granites.

The Burketown, Canobie and Millungera Depressions are low areas that that have been suggested to have received pre-Cretaceous sediments prior to the deposition of the Carpentaria Basin.

COM Armraynald 1 intersected sediments in the Burkedown Depression tentatively correlated with the Eulo Queen beds in the east, but palynology is inconclusive. GSQ Dobbyn 1 in the Canobie Depression intersected sediments that show similarities to the Warang Sandstone in the Galilee Basin. It is underlain by the Canobie Sequence of the Soldiers Cap Domain (see Chapter 2, this volume). No deep drilling has occurred in the Millungera Depression.

Perhaps some of these features are more geographical than geological, as stated by Mott (1952) who commented "The Euroka Shelf and Carpentaria Basin were land surfaces until Cretaceous times".

In the west, structural movement has occurred along several north–south faults, the Boomarra Fault, Coolullah Fault and other associated faults. These have created horsts that have been eroded following uplift.

To the north the Carpentaria Basin shows a steady thickening into the Gulf of Carpentaria.

Stratigraphy

With rising sea levels, the area of the Carpentaria Basin became the site of deposition of fluvial and lacustrine sediments of the Gilbert River Formation, followed by marine sediments of the Wallumbilla Formation and the Toolebuc Formation, the latter including limestones and black shales (Figure 11.5).

As the seas receded, deposition included the marginal marine Allaru Mudstone and the Normanton Formation (McConachie & others, 1990; Frakes & others, 1987; Smart & others, 1980).

Previous exploration

Government and university mapping, with gold and water the main drivers, defined the geology of the Carpentaria Basin during the 1950s and 1960s. In the NWQMEP the first petroleum exploration well was Mid-Eastern Exploration's Burkedown No. 1 well drilled in 1964. The GSQ drilled GSQ Normanton 1 and GSQ Dobbyn 1 stratigraphic holes in 1988 (Derrington & Williams, 1988; Williams & Gunther, 1989).

In the late 1980s and early 1990s, Comalco Exploration Limited drilled 4 wells in the basin to investigate a raft of source targets including the Gilbert River Formation, the Eudlo beds and the Mount Isa Basin (Dunster & others, 1989a,b,c; Dunster & others, 1993).

Karumba Basin

The Karumba Basin lies unconformably over the Carpentaria Basin, and has extended over the northern Eromanga during some phases of its development. It has been accumulating from the early Tertiary to the present.

The Karumba Basin was first defined by Doutch (1976) and described in detail by Smart & others (1980).

It consists of a number of depositional cycles separated by periods of local uplift, erosion and weathering.

Rock types include conglomerates, clayey sandstones, sandy claystones. Some limestone development is also present. Extensive weathering profiles have also had a strong effect on the sediments.

The three main events recognised in the Karumba Basin are the early to middle Tertiary Bulimba Cycle, a Middle Tertiary to Pliocene Wyaaba Cycle, and the present Claraville Cycle which began in Pliocene times and is ongoing (Smart & others, 1980).

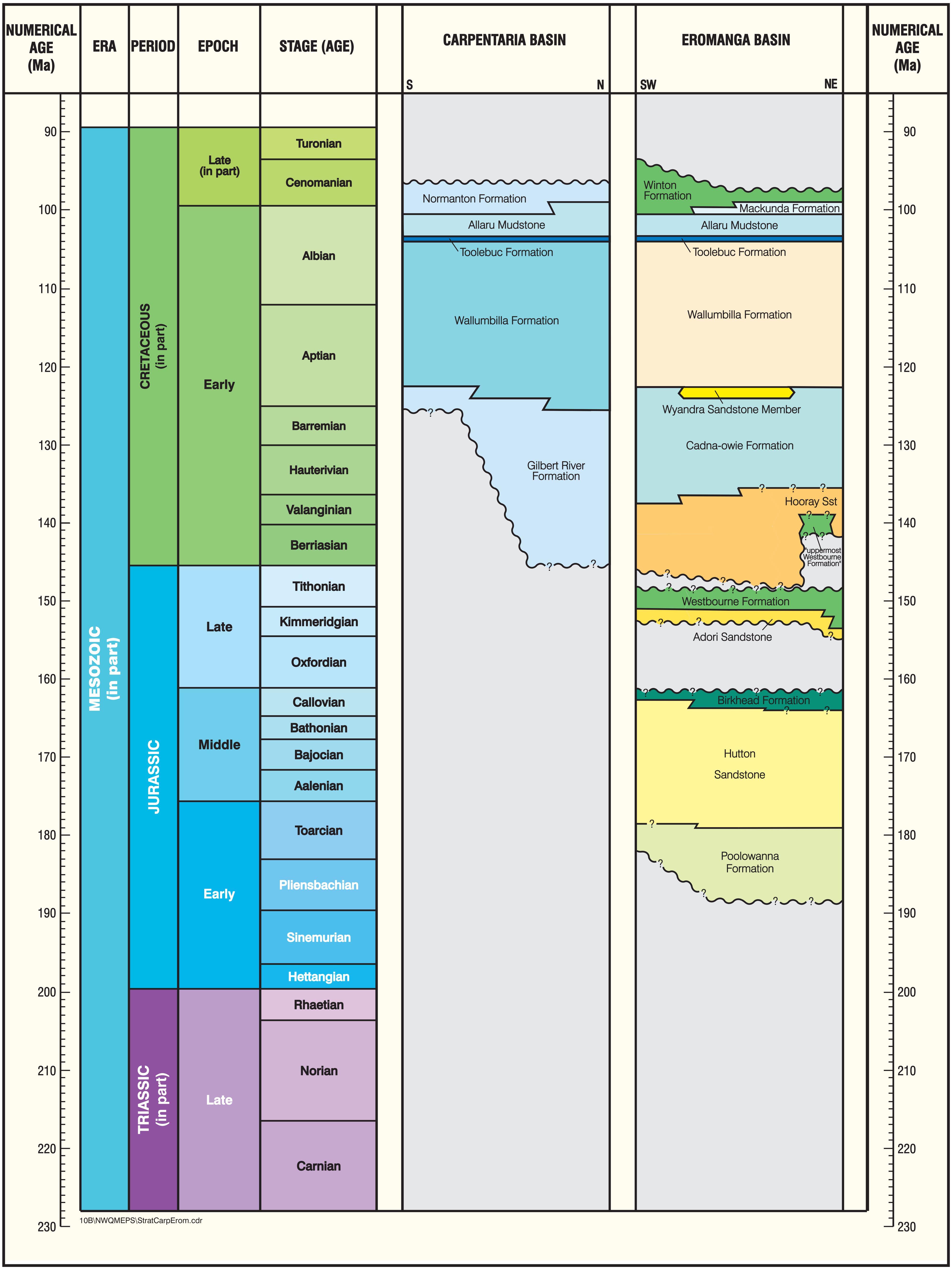


Figure 11.5: Stratigraphy of the Eromanga and Carpentaria Basins in the NWQMEP

Resource Assessment

Petroleum

Georgina Basin

The Georgina Basin is underexplored, with only 11 petroleum exploration wells across its extent (Figure 11.6).

Of these, the only hole to give some indication of hydrocarbons was Alliance Oil Development's Ethabuka 1 drilled in 1974, which flowed at 6000m^3/day from the Coolibah Formation. The significance of this show was never fully evaluated. This hole also provided confirmation of widespread phosphate deposits in the basin, as discovered by Broken Hill Proprietary Ltd while field mapping in 1966.

Magnetics and gravity surveys have been conducted across the extent of the basin. Modern seismic coverage is limited to a survey conducted in 1999 covering the Ethabuka structure. Older seismic lines cover the Burke River Structural Belt (Figure 11.7).

Tests for thermal maturation and TOC contents for samples from AOD Ethabuka 1, AOD Mirrica 1 and FPC The Brothers 1 were conducted by Glikson (1999). All three wells are regarded to be mature to overmature for oil generation, but still within the gas generation window. The high reflectance values may be attributed to hydrothermal processes from fluid migration through the Toomba Fault (Glickson, 1999).

Targets are the Coolibah and Kelly Creek Formations and Georgina Limestone in the north-west of the NWQMEP where the Eromanga's margin overlies the Georgina Basin.

The Undulla Sub-basin is considered to be water flushed (Draper, 2007). The Georgina Basin is currently mined for phosphate (See Chapter 1, this volume).

Galilee Basin

In the Galilee, limited exploration for petroleum has resulted in a scattering of wells across the area. Gas shows have been reported from EAL Ayrshire 1, HPP Weston 1, and BRP Waiora 1.

Formations with the best source potential are the Aramac Coal Measures, the Jochmus Formation, and possibly the underlying basement rocks. The Aramac Coal Measures and the Betts Creek beds are considered to have suitable reservoir rocks (Figure 11.7).

The Aramac Coal Measures have been intersected, at depth, in the centre of the Lovelle Depression at 1600m in HPP Lovelle Downs 1 (272m in thickness) down dip from the Cork Fault, at 1295m in HPP Goleburra 1 (87m in thickness) on the Eldersleigh Ridge, and at 800m in BUO Denbigh Downs 1 (172.3m in thickness) on the western margin of the Basin.

The Betts Creek beds are also thickest down dip from the Cork Fault, at 1458m in HPP Lovelle Downs 1 (142m in thickness), and shallowest on the western margin of the basin at 727m in BUO Denbigh Downs 1 (33m in thickness).

Eromanga Basin

External to the NWQMEP, there have been large oil and significant gas discoveries reservoired in the Eromanga Basin. Within the NWQMEP, exploration levels are low. Many of the wells drilled were targeting the underlying Galilee or Georgina basins. Target formations within the Eromanga Basin include the Toolebuc Formation, Hooray Sandstone, Westbourne Formation, Birkhead Formation, Poolowanna Formation and Hutton Sandstone.

The best probable reservoirs within the basin are the Hooray and Hutton Sandstones, which are also the main continuous aquifers in the region. Hydrocarbon sourced from formations in the axis of the Lovelle Depression may have migrated towards the flanks of the depression, to be reservoired where the Permian formations pinch out, or into the overlying Eromanga Basin sediments.

Limited maturity data are available for the northern Eromanga Basin, however, the basal Jurassic units of the southern Eromanga Basin, where it overlies the Cooper Basin outside of the study area, are known to be mature for oil generation. Study of samples from MRE Elvo 1 shows that the basal Jurassic is marginally mature within the central Eromanga Basin in the NWQMEP.

Good yields are noted over the southern-central portion of the Maneroo Platform, indicating the Birkhead Formation has achieved a maturity level corresponding to oil generation (Hawkins & others, 1991).

Gas shows have been reported in the study area from AEL Ayrshire 1, BUO Denbigh Downs 1, MRE Elvo 1, AAP Fermoy 1, AEI Great Northern 1, CON Jillaroo 1, MRE Rangoon 1, BRP Waiora 1 and HPP Weston 1. Overall, results within the study area for the Eromanga Basin have been disappointing, though numerous hydrocarbon occurrences have been recorded from early petroleum drilling.

The presence of widespread, highly permeable aquifers that could have been flushed by meteoric water over a long period of time could be a prime cause. Despite these unpromising results so far, there are possibilities of stratigraphic traps that have shielded accumulations from flushing.

Coal/Coal Seam Gas/Oil Shale

Galilee Basin

Exploration for coal seam gas has occurred in the eastern Galilee Basin, external to the study area. Many of the gas kicks within the Galilee Basin of the study area have occurred from within coal seams of the Aramac Coal Measures and the Betts Creek beds. These gas kicks could indicate that the western Galilee Basin is prospective for coal seam gas.

Vitrinite reflectances in the Aramac Coal Measures in the Lovelle Trough include HPP Goleburra 1 (0.57–0.68%), MPC Corfield 1 (0.71%), HPP Weston 1 (0.99–1.08%), and HPP Lovelle Downs 1 (1.03–1.17%). BUO Denbigh Downs 1 on the western edge has values from 0.42% to 0.50% but these may be cavings.

Vitrinite reflectances in the Betts Creek beds in the Lovelle Depression include HPP Weston 1 (0.84–0.97%), HPP Lovelle Downs 1 (0.76%), and BUO Denbigh Downs 1 (0.42%).

Eromanga/Carpentaria Basins

The Toolebuc Formation is wide-spread throughout the Eromanga Basin and Carpentaria Basin in the NWQMEP. Bituminous shale is present within the Toolebuc Formation over all of its extent, but thickness and grade show a wide range. Oil grades range from 20L/t to 100L/t, with grade improving away from the Basin margins. The oil produced is relatively high in sulphur, nitrogen and unsaturated compounds. The vanadium content is high and uranium values (which give a gamma-ray anomaly) are up to 200ppm (Smart & others, 1980). Arguably the most economic area lies near Julia Creek (Swarbrick, 1974).

The organic content is largely bituminite/micrinite with minor percentages of liptodetrinite and lamalginite (Sherwood & Cook, 1986), most probably from cyanobacteria (Glikson & Taylor, 1986).

Coal is mainly confined to the Jurassic Birkhead Formation. Dunstan (1920) mentioned coal in a bore to the west of the Coolulah Fault.

Prospectivity in the Millungera Basin

Until a series of drillholes is commissioned to intersect and sample the sequence, neither the economic potential nor the depositional history of this new basin will be realised. The emplacement of high-heat producing granites in the region may allude to an elevated geothermal gradient that could result in increased source rock maturity or provide a renewable source of energy as a geothermal resource (see Chapter 12, this volume).

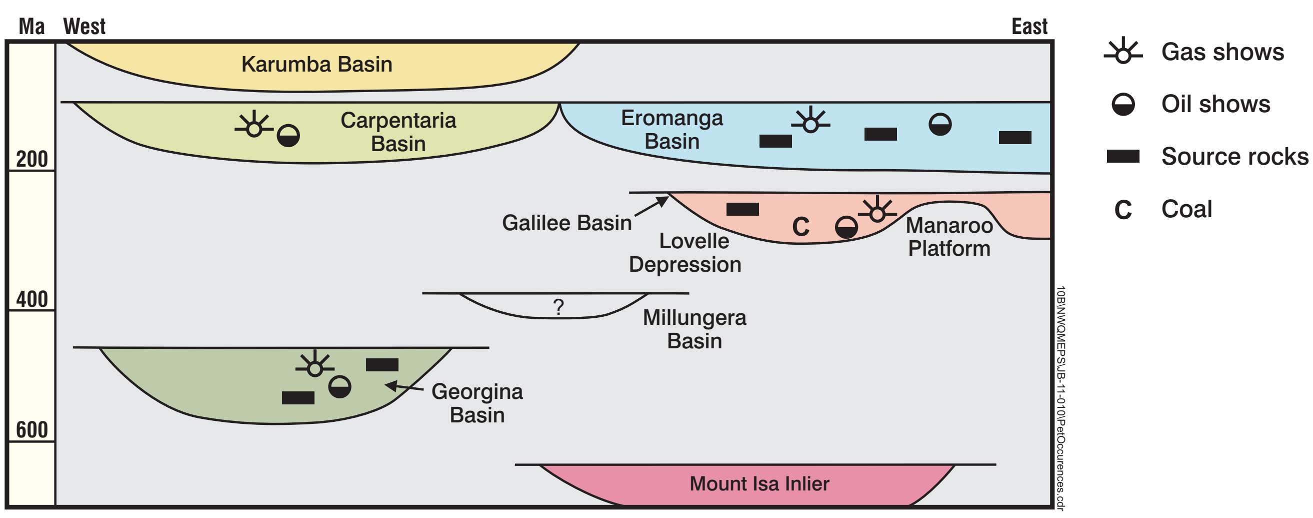


Figure 11.6: Distribution of potential energy resources in the North-West Queensland Mineral and Energy Province

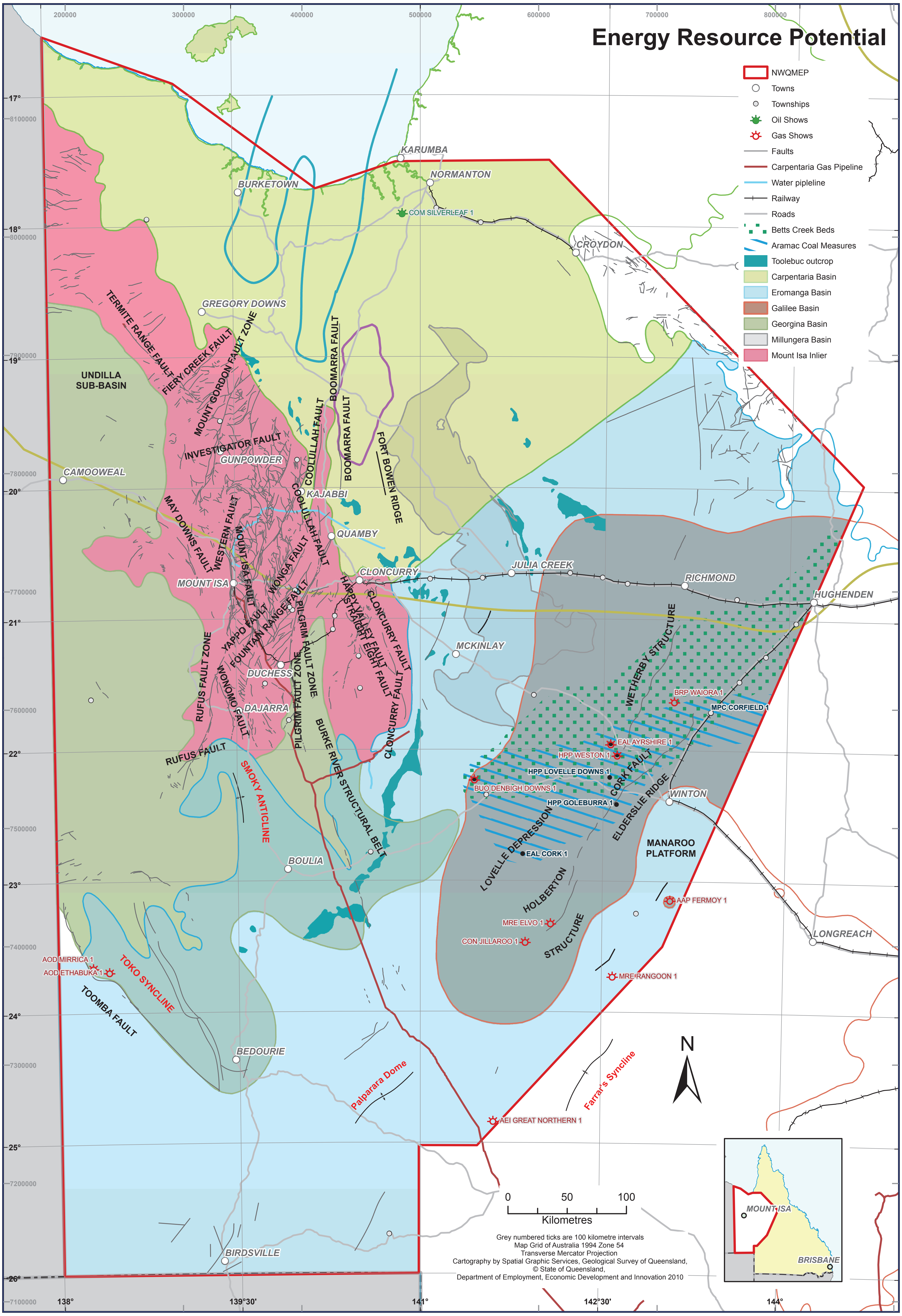


Figure 11.7: Potential energy resources of the North-West Queensland Mineral and Energy Province

Geothermal energy

The geological setting of the NWQMEP suggests that this region could be prospective for geothermal energy. The criteria listed in Table 12.1 was used to assess the geothermal prospectivity for Enhanced Geothermal Systems (EGS) and Hot Sedimentary Aquifers (HSA) within the NWQMEP area.

Using a basin by basin geothermal assessment of the Carpentaria, Eromanga, Galilee, Georgina and Millungera Basins, an overall geothermal prospectivity analysis was undertaken to delineate areas with potential for HSA and EGS. The reader should refer to Appendix 8 for the source data used in this assessment.

Table 12.1: Important criteria for geothermal potential

Enhanced Geothermal Systems (EGS)	Hot Sedimentary Aquifer (HSA)
1. THICKNESS • Sediment thickness greater than *3500m* 2. INSULATING COVER • Cumulative thermal resistance >2000m^{2}K/W • Low thermal conductivity of overlying sediments <3.0W/mK 3. HEAT SOURCE • Target heat source with heat production values >5μW/m^3 • Calculated geothermal gradients >40°C/km from temperature measurements 4. OTHER INDICATORS • Fluoride anomalies ≥4.0 mg/L	1. THICKNESS • Sediment thickness greater than *1000m* 2. HEAT SOURCE • Elevated temperature measurements 3. OTHER INDICATORS • Fluoride anomalies ≥4.0mg/L • Aquifer thickness (400–500m), porosity (>10%) and permeability (>200mD)

Methodology

The information below details the methodology used to estimate values for thermal conductivity, cumulative thermal resistance and heat production values.

Thermal conductivity values

Company lithology logs were used in conjunction with GSQ rock unit picks to estimate the bulk composition of insulating cover for each basin. A weighted thermal conductivity value was calculated using average thermal conductivity data compiled by Huston (2010).

Using thermal conductivity values of sandstone 3.45W/mK and siltstone 2.67W/mK (Huston, 2010),
e.g. 60% sandstone 40% siltstone = 0.6*3.45+0.4*2.67 = 3.13W/mK

Cumulative thermal resistance

The cumulative resistance (R) indicates how effective the entire overlying cover is as an insulator.

$$R = \sum_i \frac{\Delta z_i}{k_i}$$

Where:
R = cumulative thermal resistance
Δz = unit thickness
k = thermal conductivity
i = unit

Heat production values

Using:

$$A = 10^{-5}\rho(9.52c_U + 2.56c_{Th} + 3.48c_K)$$
(Beardsmore & Cull, 2001)

Where:
A = heat production value μW/m^3
ρ = density kg m^{-3}
c_U = concentration of uranium in parts per million
c_{Th} = concentration of thorium in parts per million
c_K = concentration of potassium in weight percentage
Projection: GDA 1994
Source Data: GSQ Geochemistry dataset, extracted August 15th 2010.

Temperature gradients

$$\text{Temperature gradient (°C/km)} = \frac{(T_B - T_A)}{Depth}$$

Where:
T_B = bottom hole temperature
T_A = average air temperature (Source: Bureau of Meteorology)
$Depth$ = kilometres

Basin by basin geothermal assessment

1. Georgina Basin

Thickness

The Basement to the Queensland portion of the Georgina Basin are rocks of the Paleoproterozoic Arunta Block and the Mount Isa Inlier (Tucker & others, 1979). Both the Arunta Block and Mount Isa Inlier have been intruded by multiple phases of felsic intrusions as seen in the granitic basement intersections at PGA Bradley 1 (886.0m), PAP Netting Fence 1 (2007.0m), AOD Mirrica 1 (3263.0m), PGA Todd 1 (1384.0m) and GSQ Mount Whelan 1 (606m) (Figure 12.1).

The deepest part of the basin is best preserved in the Toko Syncline where limestone, siltstone and sandstone sequences unconformably overly Neoproterozoic rift sequences and could potentially provide thermal insulation to heat sources (GSQ Mount Whelan 1, PGA Bradley 1, PGA Todd 1) (Ambrose & Putman, 2007).

Insulating cover

Thermal insulation of overlying stratigraphy was assessed using existing well data and is based on estimated thermal conductivity (W/mK) of formations that contribute to the cumulative thermal resistance of the entire overlying basin sequences (Figure 12.2). The Marqua beds, Ethabuka Sandstone, Mithaka Formation, Nora Formation, Ninmaroo Formation and the Georgina Limestone are considered thermal insulators as they are likely to have thermal conductivity values less than 3.0W/mK, however their distribution and thickness varies greatly across the basin. Within the Toko Syncline, a basin thickness of 886m and 3260m was intersected in the PGA Bradley 1 and AOD Mirrica 1 wells (Figure 12.1). The cumulative thermal resistance was estimated for two wells, one drilled though the Toko Syncline (AOD Mirrica 1) and was ~1140m^{2}K/W, and the other drilled further to the north (PGA Bradley 1) was ~240m^{2}K/W (Figure 12.2).

Potential heat source

Cull (1982) identified the Queensland portion of the Georgina Basin as having elevated heat flow (79.7±3.1mW/m^2), based on thermal conductivity measurements and heat production values calculated from granitic basement encountered in GSQ Mount Whelan 1. The heat production value calculated for granitic basement intersected at GSQ Mount Whelan 1 was 10.78±1.0μW/m^3 (Cull, 1982). Heat production values calculated from the Napperby, Southwark and Mount Webb granite suites of the Arunta Block are between 6.0–7.6μW/m^3 (Wyborn & others, 1988). Geothermal gradients calculated from scattered well temperature measurements are less than 32°C/km, which is typical for sedimentary basins. This discrepancy between elevated heat flow calculations (Cull, 1982) and mediocre geothermal gradients could be due to a) accelerated broad scale denudation of high heat producing granite suites during increased tectonic activity during the Palaeozoic (McLaren & others, 2003) or b) well temperatures were measured before thermal equilibrium was reached.

Other indicators

Aquifers present within the Georgina Basin consist of limestone, sandstone and dolomite, however the porosity and permeability steadily decreases with depth. The Carlo Formation has a porosity and permeability of 24% and 700mD respectively (Bradshaw & others, 2009). The Kelly Creek Formation and Arrinthrunga Formation were also noted by Randal (1978) as being drilled successfully as water bores.

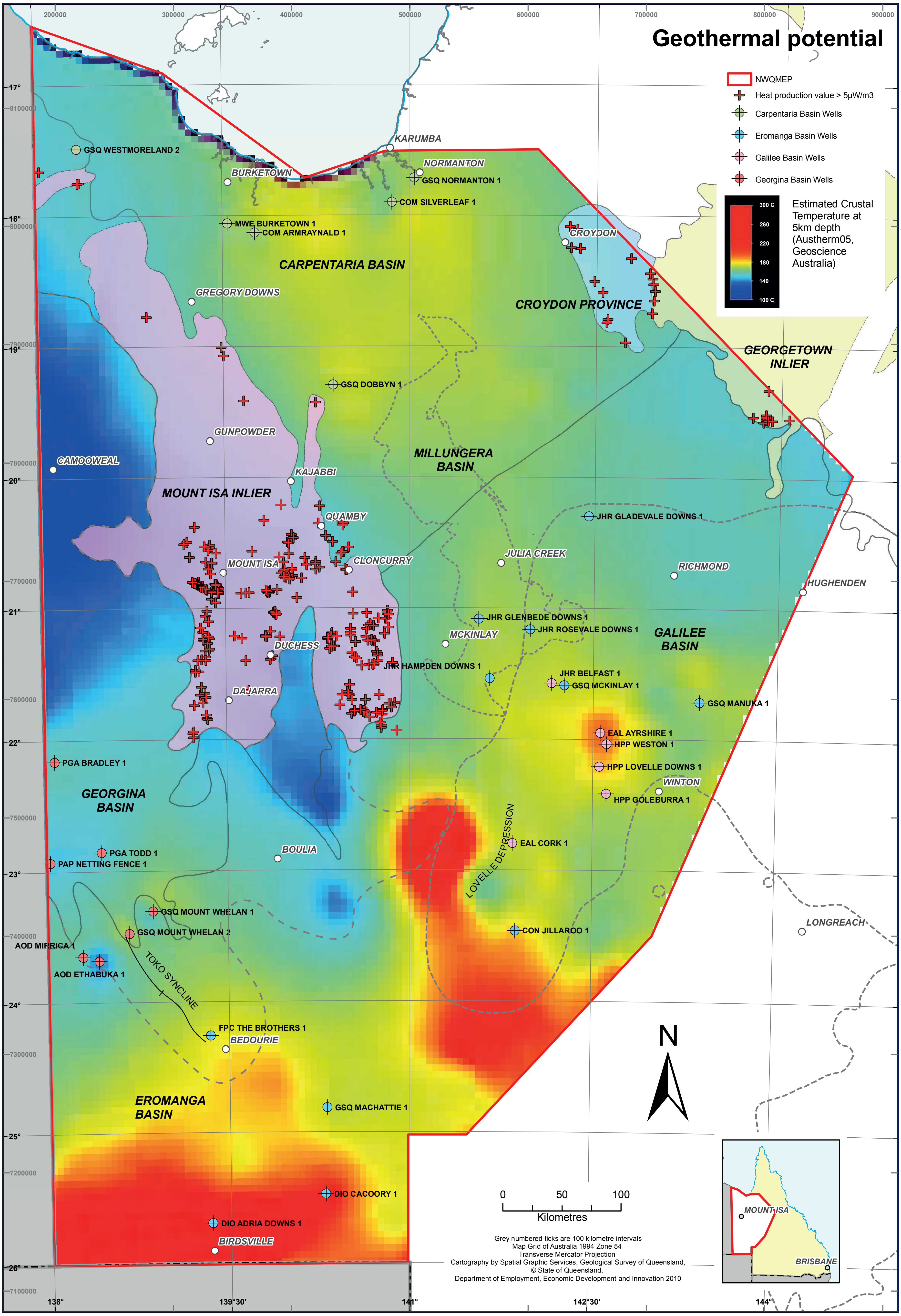


Figure 12.1: NWQMEP area showing well locations, outcropping high heat producing (HHP) intrusives and basin outlines. NOTE: Only the basin areas within the NWQMEP area were considered in this assessment.

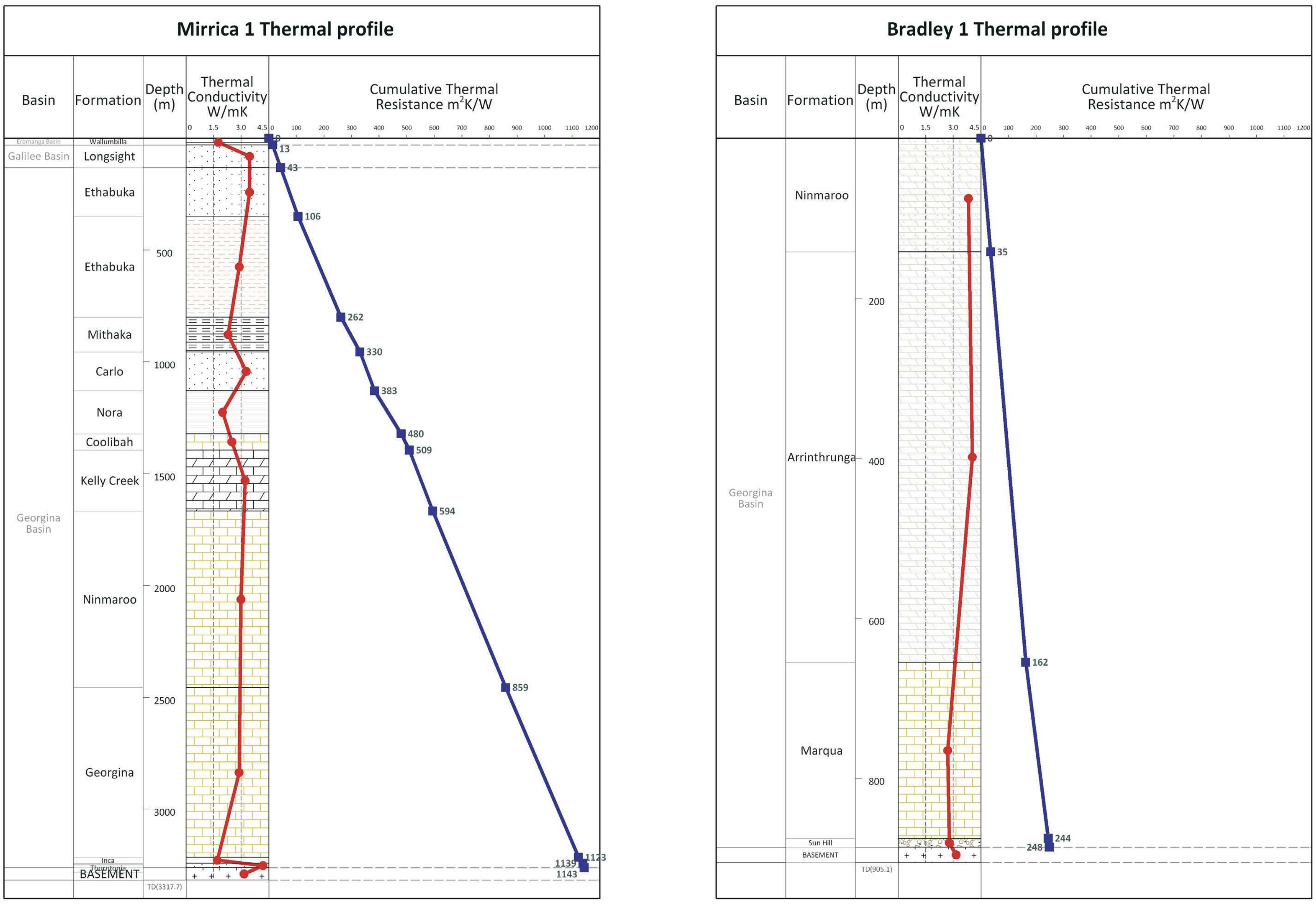


Figure 12.2: Thermal profile of the Georgina Basin estimated from AOD Mirrica 1 and PGA Bradley 1 rock types. Weighted thermal conductivity values were calculated from Huston (2010). Refer to Appendix 8 for the raw data.

2. Millungera Basin

Thickness

The recently discovered Millungera Basin (Mesoproterozoic – Late Jurassic?) unconformably overlies Paleoproterozoic Mount Isa Inlier and unconformably underlies the Late Jurassic–Cretaceous Carpentaria Basin. Whilst no drilling has definitively penetrated the basin, average seismic velocities for shallow crustal rocks suggests a maximum thickness of 2000–3000m (Hutton & others, 2010). Unpublished modelling by GA (Korsch & others, unpublished data) suggests the basin could be up to 6500m thick.

Insulating Cover

The insulating characteristics of the Millungera Basin are unknown.

Potential heat source

Table 12.2 illustrates the heat production values calculated from potassium, thorium and uranium concentrations of granitic bodies interpreted to underlie the Millungera Basin. Values greater than 5μW/m^3 were highlighted as potentially significant heat sources of elevated heat flow in the area. The heat production capacity of the granites intruded into the Mount Isa Inlier (interpreted as basement beneath the Millungera Basin) is significant with heat production values well above the 5μW/m^3 (Table 12.2). This suggests the radiogenic decay of these granites is a significant contributor to the anomalous heat flow in the area (Cull, 1982).

Table 12.2: Characteristics of high heat producing granites in the basement to the Millungera Basin (Withnall & others, 2002, Bain & Draper, 1997; Geoscience Australia stratigraphic database, 2010)

Intrusion	Basement Block	Age	Heat production value μW/m^3	Composition
Williams Batholith	Mount Isa Inlier	Mesoproterozoic	Ave: 6.72 Max: 18.50 No. samples: 136	Granite, granodiorite; minor leucogranite, pegmatite
Naraku Batholith	Mount Isa Inlier	Mesoproterozoic	Ave: 7.50 Max: 37.03 No. samples: 27	Granite, aplite, pegmatite

Whilst the Millungera Basin is likely to contain elevated heat flow, there is insufficient data to fully assess the geothermal potential for EGS and HSA. Further work is required in the area to assess the likelihood of a sedimentary thickness greater than 3.5 km and the presence of aquifers.

3. Galilee Basin — northern

Thickness

The Late Carboniferous to Late Triassic Galilee Basin underlies the Eromanga Basin and overlies the Mount Isa Inlier and Thomson Orogen. The deepest part of the basin is within the Lovelle Depression where quartzite and phyllite basement was intersected at 2007m and 1964m at HPP Lovelle Downs 1 and HPP Weston 1 respectively. The deepest part of the Galilee Basin within the study area is the Lovelle Depression where approximately 1375m of Eromanga Basin sedimentary rocks and approximately 630m of the Galilee Basin were intersected in HPP Lovelle Downs 1.

Insulating cover

The insulating capacity of the Galilee Basin is estimated in Figure 12.3 and is based on rock types intersected in JHR Belfast 1 and HPP Lovelle Downs 1. The Moolayember Formation, Betts Creek beds and Aramac Coal Measures contain siltstones and carbonaceous coaly material which could contribute to the thermal resistance of the stratigraphic profile. The Winton Formation, Mackunda Formation, Allaru

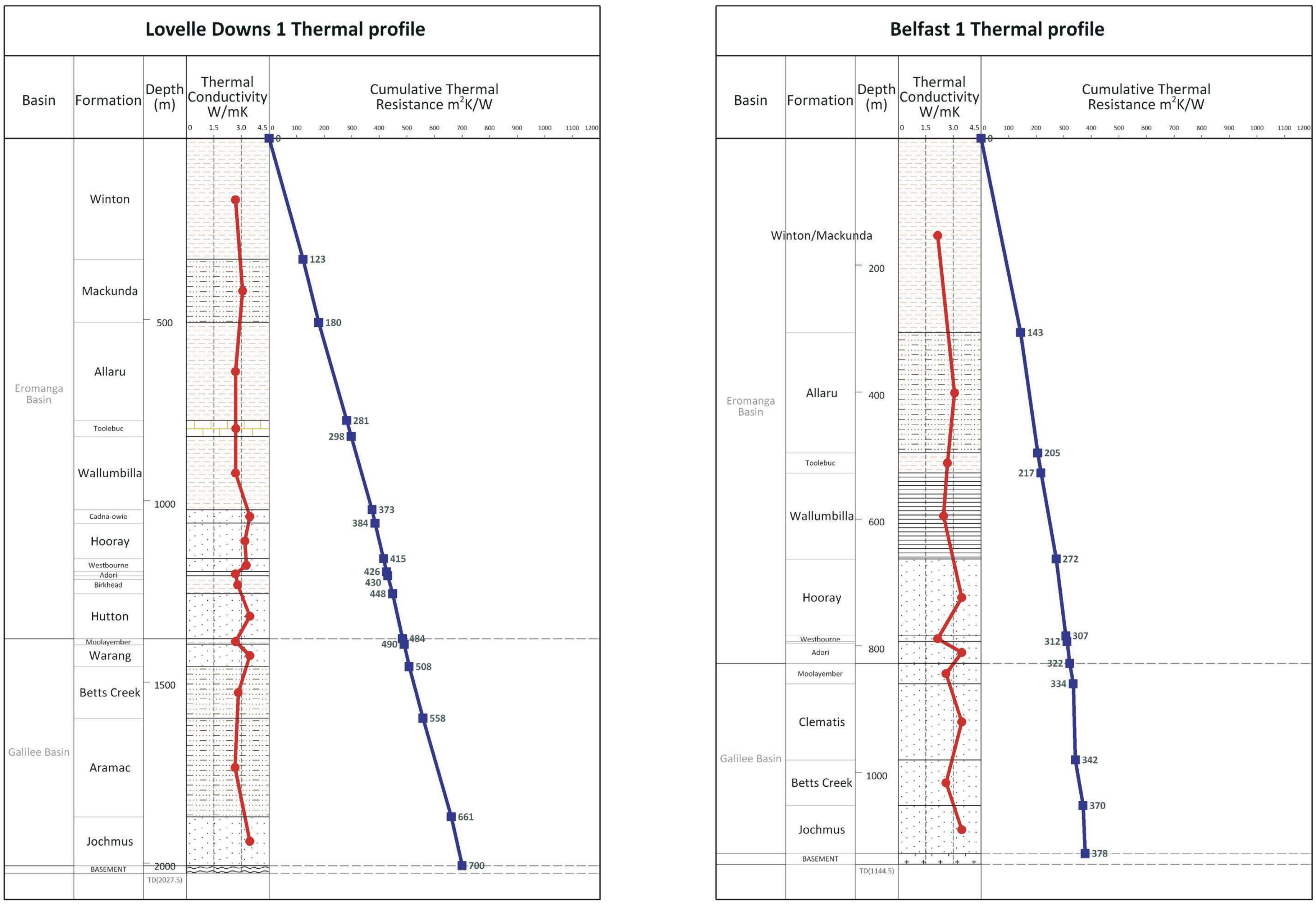


Figure 12.3: Thermal profile of the Galilee Basin estimated from HPP Lovelle Downs 1 and JHR Belfast 1 bulk rock types. Weighted thermal conductivity values calculated from Huston (2010). Refer to Appendix 8 for the raw data.

Table 12.3: Geothermal gradients calculated from petroleum well temperature data based on mean surface temperature 23°C

Operator	Well Name	Total Depth (m)	Depth of temperature measurement (m)	Temperature (°C)	Hours after Circulation	Gradient (°C/km)	Temperature Method
HPP	Weston 1	1982.7	1981.2	115.6	16.0	47.22	wireline logging
JHR	Belfast 1	1144.2	1144.2	74.4	7.5	45.83	wireline logging
HPP	Goleburra 1	1581.3	1571.9	93.3	9.0	45.38	wireline logging
HPP	Lovelle Downs 1	2027.5	2027.5	113.3	9.0	45.05	drill stem test
BUO	Denbigh Downs 1	1008.9	1007.1	64.4	25.0	42.14	drill stem test

Mudstone, Toolebuc Formation, Wallumbilla Formation and Westbourne Formation within the Eromanga Basin stratigraphy also contribute to the cumulative thermal resistance. The cumulative thermal resistance value for the Galilee Basin estimated from HPP Lovelle Downs 1 and JHR Belfast 1 is 700m²K/W and 378m²K/W respectively (Figure 12.3).

Potential heat source

Granites within the Mount Isa Inlier have a high heat producing capacity (Table 12.2) however the heat producing capacity of the Thomson Orogen underneath the Basin is poorly defined. Granitic basement (possibly Mount Isa intrusives) was intersected in JHR Belfast 1 at 1127.8m and JHR Gladevale Downs 1 at 490m. Estimated geothermal gradients calculated from wells in the Lovelle Depression are up to 46.22°C/km (Table 12.3) indicating this part of the basin contains an elevated heat flow.

Other indicators

There is limited permeability data available for aquifers within the Lovelle Depression however the Warang and Clematis Sandstones are known aquifers in the remainder of the Galilee Basin (Bradshaw & others, 2009).

4. Carpentaria Basin

Thickness

The southern Carpentaria Basin in the NWQMEP thickens away from COM Silverleaf 1 (652m) and GSQ Normanton 1 (635.6m) and reaches 833m in the south-west at GSQ Dobbyn 1. In the north-east of the basin, basement intersected at MWE Burketown 1 (874m), COM Armraynald 1 (572m) and COM Egilabria 1 (~310m) consisted of carbonaceous cherts, dolostones and quartzites.

Insulating cover

The key insulator rock types of the Carpentaria Basin are within the Allaru Mudstone, Toolebuc Formation and Wallumbilla Formations. These units are up to 500m thick (GSQ Dobbyn 1) and consist of interbedded siltstone and mudstone with thermal conductivity values likely to be less than 2.67W/mK. Figure 12.4 highlights the thickness and thermal properties for rock types of the Carpentaria Basin. Based on the thermal conductivity of each rock unit, the cumulative thermal resistance of the basin cover was estimated for GSQ Normanton 1 and GSQ Dobbyn 1 to be between 230–291m²K/W, (Figure 12.4).

Potential heat source

Temperature measurements from well data and ground water bores have delineated the Carpentaria Basin as an area of elevated heat flow. Geothermal gradients above 40°C/km calculated from elevated temperatures were measured at GSQ Dobbyn 1, COM Armraynald 1 and COM Silverleaf 1 (Table 12.4). In addition, geothermal gradients calculated from temperature measurements taken from 22 static water bores averaged 72.14°C/km (after Habermehl, 2001). The origins of this heat anomaly have been postulated to be meteoric in origin however the underlying granitic basement

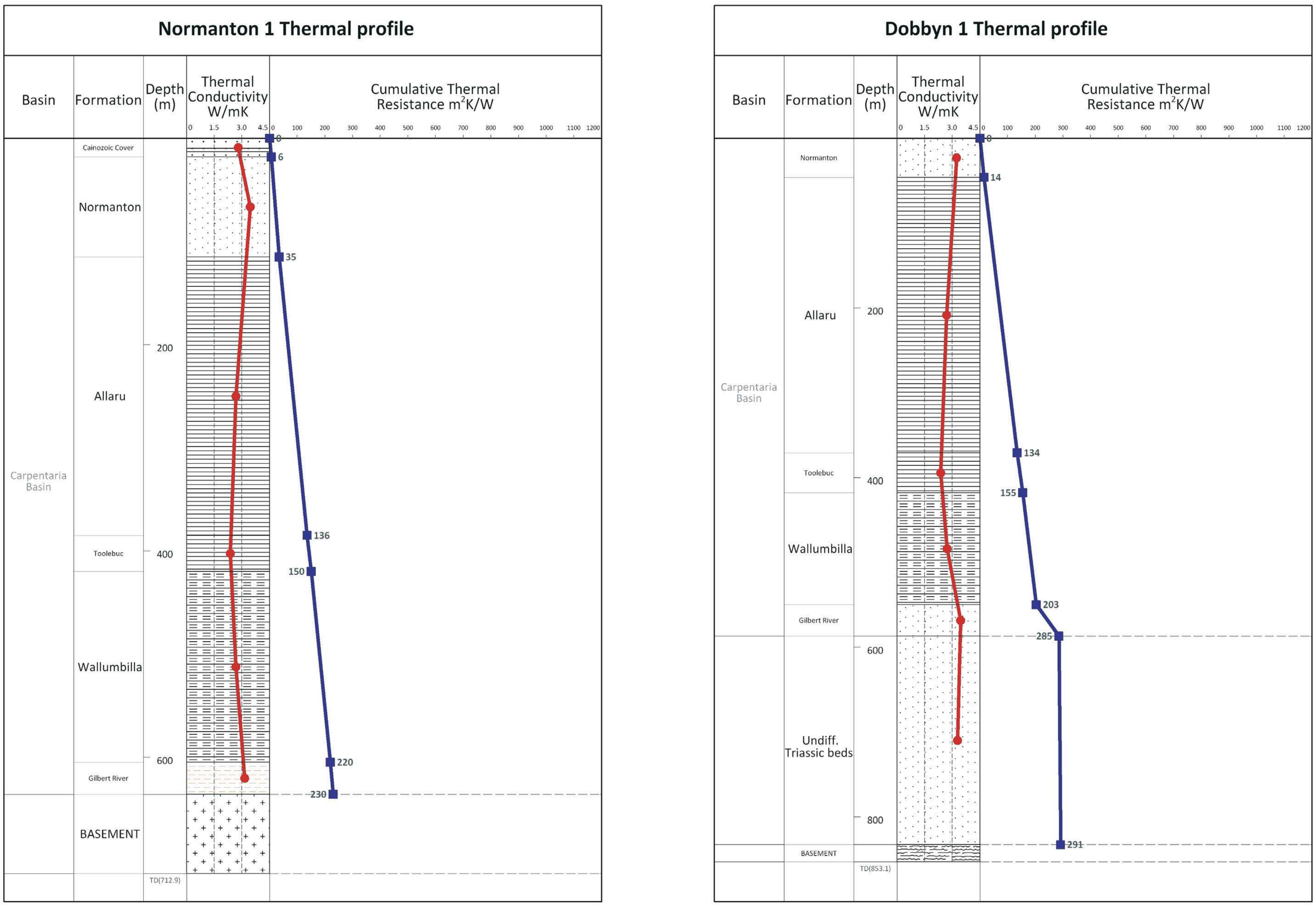


Figure 12.4: Thermal profile of the Carpentaria Basin estimated from GSQ Normanton 1 and GSQ Dobbyn 1 bulk rock types. Weighted thermal conductivity values calculated from Huston (2010). Refer to Appendix 8 for the raw data.

Table 12.4: Geothermal gradients calculated from petroleum well temperature data based on mean surface temperature 25°C

Operator	Well Name	Total Depth (m)	Depth of temperature measurement (m)	Temperature (°C)	Hours after Circulation	Gradient (°C/km)	Temperature Method
GSQ	Normanton 1	712.9	712.9	65	NS	56.11	wireline logging
GSQ	Dobbyn 1	853.1	853.1	69	NS	51.58	wireline logging
COM	Armraynald 1	638	634	53.7	NS	45.27	not specified
COM	Silverleaf 1	681	681	54.4	NS	43.17	not specified

Table 12.5: Characteristics of high heat producing granites in the basement to the Carpentaria Basin (Withnall & others, 2002; Bain & Draper, 1997; Geoscience Australia stratigraphic database, 2010)

Intrusion	Basement Block	Age	Heat production value μW/m^3	Composition
Wonga Batholith	Mount Isa Inlier	Paleoproterozoic	Ave: 8.57 Max: 15.39 No. samples: 91	Granite, xenolith and gneissic granite
Naraku Batholith	Mount Isa Inlier	Paleoproterozoic	Ave 7.50 Max:37.03 No. samples: 27	Granite, aplite, pegmatite
Ewen Batholith	Mount Isa Inlier	Paleoproterozoic	Ave: 4.82 Max: 8.43 No. samples: 4	Leucogranite, porphyritic granite and granodiorite
Esmeralda Supersuite	Croydon Province	Mesoproterozoic	Ave 4.66 Max: 10.28 No. samples: 21	Granite, porphyritic in parts

complexes could be a contributing factor. Figure 12.1 highlights the location of these petroleum wells.

Table 12.5 illustrates the high heat producing capacity of basement intrusives interpreted to underlie the basin. Granitic basement was intersected at 632m in GSQ Normanton 1 where a temperature measurement of 65°C was recorded at 712.95m depth (Table 12.4). The Mount Isa Inlier and the Toolebuc Formation in the Carpentaria Basin are considered prospective for uranium (Huston, 2010). Anomalously high uranium concentrations include E1, Westmoreland, Valhalla deposits and the exhausted Mary Kathleen Mine (von Gnielinski, 2010).

Other Indicators

Significant fluoride concentrations have also been encountered in the Carpentaria Basin, with values in excess of 4.0mg/L consistently recorded within the NWQMEP area (Evans, 1996). These elevated fluoride values were attributed by Evans (1996) to groundwater interactions with fluoride rich granitic basement.

5. Eromanga Basin — northern

Thickness

The Eromanga Basin succession thickens to the south-west with 351.4m intersected at JHR Glenbede Downs 1, 1493.5 at DIO Adria Downs 1 and 1566.6m at Jillaroo 1 (Figure 12.1).

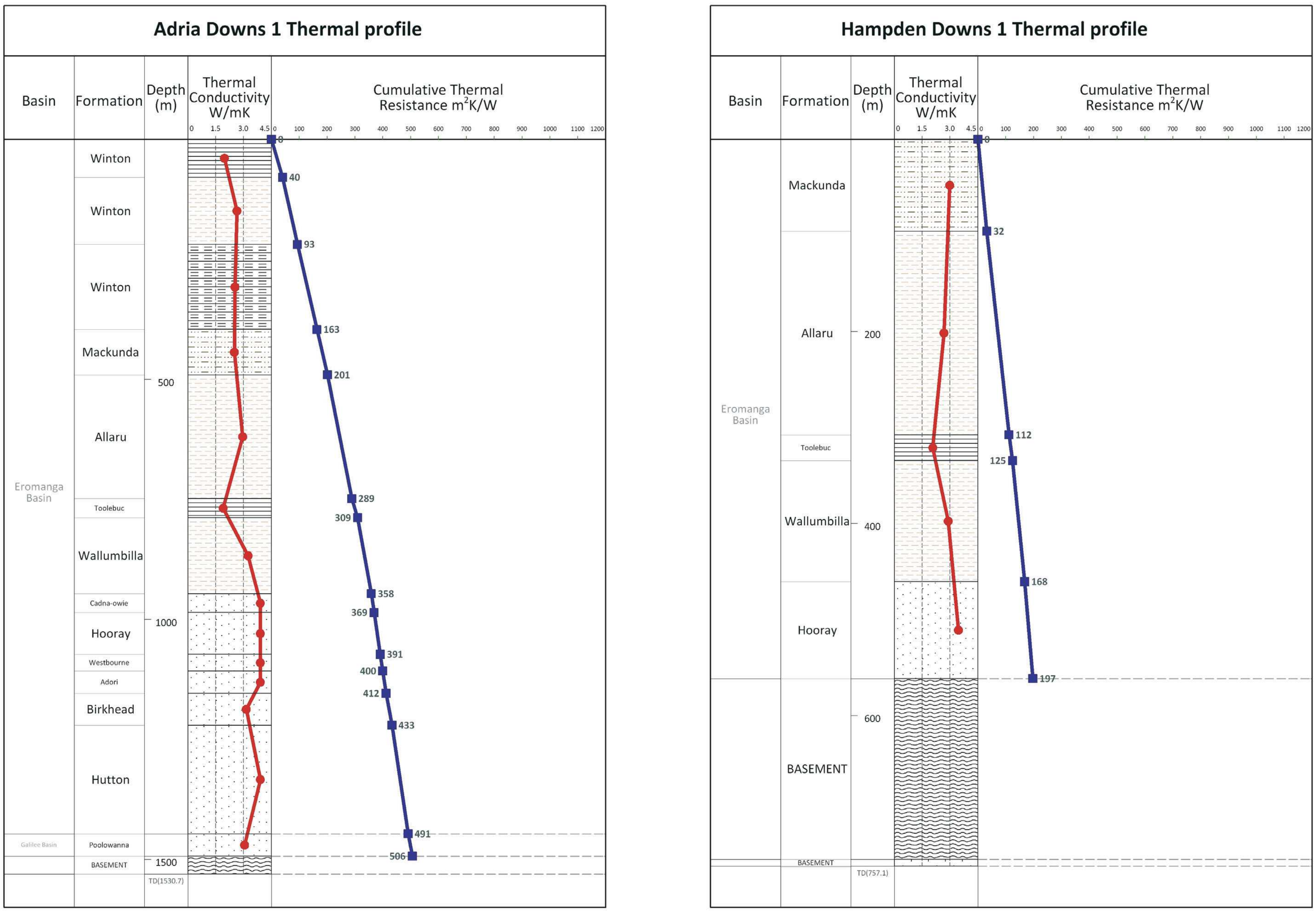


Figure 12.5: Thermal profile of the Eromanga Basin estimated from DIO Adria Downs 1 and JHR Hampden Downs 1 bulk rock types. Weighted thermal conductivity values calculated from Huston (2010). Refer to Appendix 8 for the raw data.

The sequences represent deposition of fluvial sediments prior to a marine transgression, marked by the deposition of the Cadna-owie Formation (Draper, 2002). JHR Rosevale Downs 1 and JHR Hampden Downs 1 both intersected ~160m 'metaquartzite' before reaching granite at 750m. The intersected granite have been interpreted as potentially the high heat producing granites of the Williams Batholith or Naraku Batholith (Fitzell, 2010, GSQ internal report). JHR Gladevale Downs 1 intersected granitic basement at 490m, whilst in the south-west of the basin at DIO Adria Downs 1, steeply dipping 'Pre-Permian' quartzite was intersected at 1493.5m.

Insulating cover

Figure 12.5 shows the thermal properties and thicknesses of stratigraphic units intersected in two petroleum wells drilled, one in the north (JHR Hampden Downs 1) and the other in the south (DIO Adria Downs 1) of the Eromanga Basin. Towards DIO Adria Downs 1 in the south-west, the basin deepens to 1500m, however the calculated cumulative thermal resistance values of the overlying stratigraphy indicates thermal resistance values of 500m^{2}K/W which may be insufficient for EGS development.

Potential heat source

The basement to the northern Eromanga Basin includes Proterozoic–Palaeozoic Mount Isa Inlier, Thomson Orogen, Georgetown Inlier,

Table 12.6: Characteristics of high heat producing granites in the basement to the Eromanga Basin (Withnall & others, 2002; Bain & Draper, 1997; Geoscience Australia stratigraphic database, 2010)

Intrusion	Basement Block	Age	Heat production value μW/m^3	Composition
Williams Batholith	Mount Isa Inlier	Mesoproterozoic	Ave 6.72 Max: 18.50 No. samples: 136	Granite and granodiorite, minor leucogranite, pyroxene-bearing granite, microgranite, aplite, pegmatite
Purkin Batholith	Georgetown Inlier	Mid-Late Carboniferous	Ave: 5.33 Max: 8.55 No. samples: 15	Granite, porphyritic biotite microgranite

Table 12.7: Geothermal gradients calculated from petroleum well temperature data using 23°C surface temperature

Name	Operator	Total Depth (m)	Depth Temperature (m)	Temperature (°C)	Hours after Circulation	Gradient (°C/km)	Temperature method
Cacoory 1	DIO	1477.7	1473.7	101.1	10.8	53.00	wireline logging
Rosevale Downs	JHR	769.9	769.3	63.3	6.3	52.42	wireline logging
Gladevale Downs 1	JHR	551.7	551.1	51.7	6.2	52.03	wireline logging
Adria Downs 1	DIO	1530.7	1510.6	101.4	6.5	51.90	wireline logging

Georgina Basin and Galilee Basin sequences (Bain & Draper, 1997; Draper, 2002; Draper, 2007; Boreham & Ambrose, 2007; Wyborn & others, 1988). The suturing and stacking of these complex tectonic blocks have contributed to considerable heat flow in the past. Present day heat flow calculations of 83±18mW/m^2 (which is well above global averages of 60mW/m^2, McLaren & others, 2003) indicates that anomalous heat flow is present in this area (Wyborn & others, 1988; Cull, 1982). Heat production values of the outcropping Williams and Purkin Batholith shown in Table 12.6 indicate the natural decay of uranium, thorium and potassium may provide a significant contributor to the region's heat flow.

Elevated temperatures as high as 32.2°C at 53.64m (Bore RN 1782) have been recorded from water bores and petroleum wells within Eromanga sequences. Geothermal gradients up to 48°C/km were also recorded from petroleum wells as illustrated in Table 12.7.

Other indicators

The stratigraphy of the Eromanga Basin contains a series of stacked aquifers, forming a major component of the Great Artesian Basin (Welsh, 2000). The Hooray Sandstone, Adori Sandstone and Hutton Sandstone are regionally extensive aquifers whilst the siltstones and claystones of the Allaru Mudstone, Toolebuc Limestone and Wallumbilla Formation form low permeable seals (Habermehl, 1986).

Summary table highlighting the geothermal potential for basins within the NWQMEP

Geothermal System	Georgina Basin	Millungera Basin	Galilee Basin	Carpentaria Basin	Eromanga Basin
EGS 1. Thickness 2. Insulating cover 3. Heat Source 4. Other	• Thickness is up to 3330m (AOD Mirrica 1) • Estimated cumulative thermal resistance (AOD Mirrica 1) 1140m^{2}K/W • The high heat producing capacity of felsic intrusives underlying the Georgina Basin, and anomalous heat flow indicates the Georgina Basin could hold potential for EGS development.	• Insulating cover: INSUFFICIENT DATA • Elevated heat flow (Mount Isa Inlier)	• Thickness from well data in the Lovelle Depression (HPP Lovelle Downs 1, EAL Ayrshire 1 and HPP Weston 1) is ~630m. However the overlying Eromanga Basin contributes up to 1375m. • Estimated cumulative thermal resistance (HPP Lovelle Downs 1) is 700m^{2}K/W • High geothermal gradients >40°C/km	• Maximum thickness of the Carpentaria Basin within the NWQMEP is 853.1m (GSQ Dobbyn 1) • Estimated cumulative thermal resistance 290m^{2}K/W (GSQ Dobbyn 1) • Elevated temperatures measured at GSQ Dobbyn 1 (69°C at 853m), at COM Armraynald 1 (43°C at 634m) and at COM Silverleaf 1 (54°C at 681m) • Geothermal gradients calculated from static water bores averaged 72.14°C/km	• Thickness is ~1450m (DIO Adria Downs 1) • Estimated cumulative thermal resistance of 500m^{2}K/W (DIO Adria Downs 1) • Elevated temperatures, geothermal gradients >50°C/km
HSA 1. Thickness 2. Heat Source 3. Other	• Thickness is up to 3330m (AOD Mirrica 1) • Anomalous heat flow 79.7±3.1mW/m^2 • Carlo Sandstone aquifer was intersected in wells proximal to the Toko Syncline and has a maximum thickness of 190m	• Thickness and aquifers: INSUFFICIENT DATA • Elevated heat flow (HHP Granites intruded into Mount Isa Inlier)	• Thickness ~630m (plus 1375m Eromanga Basin, HPP Lovelle Downs 1) • High temperatures measured across the basin • Warang and Clematis Sandstone are aquifers, MORE DATA REQUIRED	• Maximum thickness of the Carpentaria Basin within the NWQMEP is 853.1m (GSQ Dobbyn 1) • The deepest and hottest part of the basin (from available data) is at GSQ Dobbyn 1 where 69°C was reached at 853.1m • Gilbert River Formation, Garraway Sandstone and the Eulo Queen Group are regional aquifers.	• Thickness is ~1450m (DIO Adria Downs 1) • Geothermal gradients >50°C/km • The Birdsville power station (an example of HSA) generates 80kW of power from elevated temperatures at >1200m.

AHMAD, M., WYGRALA,K.A.S., FERENCZI, P.A. & BAJWAH, Z.U., 1993: Pine Creek, Northern Territory. — 1:250 000 Metallogenic Map Series. *Northern Territory Geological Survey Explanatory Notes*, **SE 52-8**.

ALLEN, J.P. & FIELDING, C.R., 2007: Sequence architecture within a low-accomodation setting: An example from the Permian of the Galilee and Bowen basins, Queensland, Australia, *AAPG Bulletin* **91** (11), 1503–1539.

AMBROSE, G.J. & PUTMAN, P.E., 2007: Carbonate ramp facies and oil plays in the Middle–Late Cambrian, southern Georgina Basin, Australia. In: Munson, T.J. & Ambrose, G.J., (Editors): Proceedings of the Central Australian Basins Symposium (CABS), Alice Springs, Northern Territory, 16–18 August, 2005. *Northern Territory Geological Survey, Special Publication* **2**.

ANDREWS, S.J., 1998: Stratigraphy and depositional setting of the upper Mcnamara Group, Lawn Hill region, north-west Queensland. *Economic Geology,* **93**, 1132–1152.

ANON, 2000: A-P 554P, Ethabuka Final Seismic survey report. Held by the Department of Employment, Economic Development and Innovation as CR 31626.

AUSTIN, J.R. & BLENKINSOP, T.G., 2010: Cloncurry Fault Zone: strain partitioning and reactivation in a crustal-scale deformation zone, Mount Isa Inlier. *Australian Journal of Earth Sciences,* **57**, 1–21.

BAGAS, L., 2004: Proterozoic evolution and tectonic setting of the north-west Paterson Orogen, Western Australia. *Precambrian Research,* **128**(3–4), 475–496.

BAGAS, L., BIERLEIN, F.P., ANDERSON, J.A.C. & MAAS, R., 2010: Collision-related granitic magmatism in the Granites-Tanami Orogen, Western Australia. *Precambrian Research,* **177**, 212–226.

BAIN, J.H.C. & DRAPER, J.J., 1997: North Queensland Geology. *Australian Geological Survey Organisation Bulletin* **240**, and *Queensland Geology*, **9.**

BAKER, T., PERKINS, C., BLAKE, K.L. & WILLIAMS, P.J., 2001: Radiogenic and stable isotope constraints on the genesis of the Eloise Cu-Au deposit, Cloncurry District, North-west Queensland. *Economic Geology*, **96**, 723–742.

BAKER, M.J., CRAWFORD, A.J. & WITHNALL, I.W., 2010: Geochemical, Sm–Nd isotopic characteristics and petrogenesis of Paleoproterozoic mafic rocks from the Georgetown Inlier, north Queensland: Implications for relationship with the Broken Hill and Mount Isa Eastern Succession. *Precambrian Research,* **177**, 39–54.

BARNICOAT, A., 2008: The Mineral Systems approach of the pmd*CRC. *Geoscience Australia Record* **2008/0**9, 1–6.

BARRIE, C.T., LUDDEN, J.N. & GREEN, T.H., 1993: Geochemistry of volcanic rocks associated with Cu-Zn And Ni-Cu Deposits in the Abatibi Subprovince. *Economic Geology* **88**, 1341–1358.

BEARDSMORE, G.R. & CULL, J. P., 2001: *Crustal Heat Flow. A Guide to Measurement and Modelling*. Cambridge, New York, Melbourne: Cambridge University Press.

BEARDSMORE, T.J., NEWBERY, S.P. & LAING, W.P., 1988: The Maronan Supergroup: an inferred early volcanosedimentary rift sequence in the Mount Isa Inlier, and its implications for ensialic rifting in the middle Proterozoic of north-west Queensland. *Precambrian Research,* **40–41**, 487–507.

BELL, T.H., 1983: Thrusting and duplex formation at Mount Isa, Queensland, Australia. *Nature,* **304**, 493–497.

BELOUSOVA, E.A., PREISS, W.V., SCHWARZ, M.P. & GRIFFIN, W.L. 2006: Tectonic affinities of the Houghton Inlier, South Australia: U-Pb and Hf-isotope data from zircons in modern stream sediments. *Australian Journal of Earth Sciences*, **53** (6), 971-989.

BETTS, P.G., 1999: Palaeoproterozoic mid-basin inversion in the northern Mount Isa Terrane, Queensland. *Australian Journal of Earth Sciences*, **46**, 735–748.

BETTS, P.G., AILLERES, L., GILES, D. & HOUGH, M., 2000: Deformation history of the Hampden Synform in the Eastern Fold Belt of the Mount Isa Terrane. *Australian Journal of Earth Sciences,* **47**, 1113–1125.

BETTS, P.G. & GILES, D., 2006: The 1800–1100Ma tectonic evolution of Australia. *Precambrian Research*, **144**, 92–125.

BETTS, P.G., GILES, D. & LISTER, G.S., 2004: Aeromagnetic patterns of half-graben and basin inversion: implications for sediment-hosted massive sulfide Pb-Zn-Ag Exploration. *Journal of Structural Geology,* **26**, 1137–1156.

BETTS, P.G., GILES, D. & SCHAEFER, B.F., 2008: Comparing 1800–1600Ma accretionary and basin processes in Australia and Laurentia: Possible geographic connections in Columbia. *Precambrian Research*, **166**, 81–92.

BETTS, P.G., GILES, D., FODEN, J., SCHAEFER, B.F., MARK, G., PANKHURST, M.J., FORBES, C.J., WILLIAMS, H.A., CHALMERS, N.C. & HILLS, Q., 2009: Mesoproterozoic plume-modified orogenesis in eastern Precambrian Australia. *Tectonics,* **28**.

BETTS, P.G., GILES, D., LISTER, G.S. & FRICK, L.R., 2002: Evolution of the Australian lithosphere. *Australian Journal of Earth Sciences,* **49**, 661–695.

BETTS, P.G., GILES, D., MARK, G., LISTER, G.S., GOLEBY B.R. & AILLÈRES L., 2006: Synthesis of the Proterozoic evolution of the Mount Isa Inlier. *Australian Journal of Earth Sciences,* **53**, 187–211.

BETTS, P.G., GILES, D., SCHAEFER, B.F. & MARK, G., 2007: 1600–1500Ma Hotspot track in eastern Australia: Implications for Mesoproterozoic continental reconstructions. *Terra Nova***, 19**, 496–501.

BETTS, P.G., LISTER, G.S. & POUND, K.S., 1999: Architecture of a Paleoproterozoic rift system: evidence from the Fiery Creek Dome region, Mount Isa Terrane. *Australian Journal of Earth Sciences,* **46**, 533.

BETTS, P.G., VALENTA, R.K. & FINLAY, J., 2003b. Evolution of the Mount Woods Inlier, northern Gawler Craton, southern Australia: an integrated structural and aeromagnetic analysis. *Tectonophysics,* **366**, 83–111.

BIERLEIN, F.P. & BETTS, P.G., 2004: The Proterozoic Mount Isa Fault Zone, north-eastern Australia: is it really a ca 1.9Ga terrane-bounding suture? *Earth and Planetary Science Letters,* **225**, 279–294.

BIERLEIN, F.P., MAAS, R. & WOODHEAD, in press: The pre-1.8Ga tectono-magmatic evolution of the Kalkadoon–Leichhardt Belt — Implications for the crustal architecture and metallogeny of the Mount Isa Inlier, north-west Queensland, Australia. *Australian Journal of Earth Sciences.*

BLACK, L.P., GREGORY, P., WITHNALL, I.W. & BAIN, J.H.C., 1998: U-Pb zircon age for the Etheridge Group, Georgetown region, north Queensland: implications for relationship with the Broken Hill and Mount Isa sequences. *Australian Journal of Earth Sciences,* **45**, 925–935.

BLACK, L.P., WITHNALL, I.W., GREGORY, P., OVERSBY, B.S. & BAIN, J.H.C., 2005: U-Pb zircon ages from leucogneiss in the Etheridge Group and their significance for the early history of the Georgetown region, north Queensland. *Australian Journal of Earth Sciences,* **52**, 385–401.

BLAKE, D.H., 1987: Geology of the Mount Isa Inlier and environs, Queensland and Northern Territory. *Bureau of Mineral Resources, Bulletin* **225**.

BLAKE, D.H., BULTITUDE, R.J. & DONCHAK, P.J.T., 1982: *Dajarra, Queensland, 1:100 000 Geological Map Commentary*. Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

BLAKE, D.H., BULTITUDE, R.J., DONCHAK, P.J.T., WYBORN, L.A.I. & HONE, I.G., 1984: Geology of the Duchess–Urandangi Region, Mount Isa Inlier, Queensland. *Bureau of Mineral Resources, Bulletin* **219**.

BLAKE, D.H., JAQUES, A.L. & DONCHAK, P.J.T., 1983: *Selwyn Region, Queensland, 1:100 000 Geological Map Commentary*. Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

BLAKE, D.H. & STEWART, A.J., 1992: Stratigraphic and tectonic framework, Mount Isa Inlier. *In*: Stewart, A.J. & Blake, D.H. (Editors): Detailed Studies of the Mount Isa Inlier. *Australian Geological Survey Organisation, Bulletin,* **243**, 1–11.

BLAKE, D.H., TYLER, I.M. & WARREN, R.G., 2000: *Gordon Downs, Western Australia, 1:250 000 (second edition), Geological Explanatory Notes*, Australian Geological Survey Organisation.

BLENKINSOP, T.G., (Editor), 2005: Total system analysis if the Mt Isa eastern succession — *pmd**CRC I2+3 Project Final Report 2005, 51.

BLENKINSOP, T.G., 2008: Mount Isa Inlier. *Precambrian Research,* **163**, 1–6.

BLENKINSOP, T.G., HUDDLESTONE-HOLMES, C.R., FOSTER, D.R.W., EDMISTON, M.A., LEPONG P., MARK, G., AUSTIN, J.R., MURPHY, F.C., FORD, A. & RUBENACH, M.J., 2008: The crustal scale architecture of the Eastern Succession, Mount Isa: the influence of inversion. *Precambrian Research*, **163**, 31–49.

BLEWETT, R.S., BLACK, L.P., SUN, S.-S., KNUTSON, J., HUTTON, L.J. & BAIN, J.H.C., 1998: U-Pb Zircon and Sm-Nd Geochronology of the Mesoproterozoic of northern Queensland: implications for a Rodinian connection with the Belt Supergroup of North America. *Precambrian Research,* **89**, 101–127.

BOGER, S.D. & HANSEN, D., 2004: Metamorphic evolution of the Georgetown Inlier, north-east Queensland, Australia; evidence for an accreted Palaeoproterozoic terrane? *Journal of Metamorphic Geology,* **22**, 511–527.

BOREHAM, C.J. & AMBROSE, G.J., 2007: Cambrian petroleum systems in the southern Georgina Basin, Northern Territory, Australia. *In*: Munson, T.J. & Ambrose, G.J., (Editors): Proceedings of the Central Australian Basins Symposium, Alice Springs, 16–18th August, 2005. *Northern Territory Geological Survey, Special Publication* **2**, 254–281.

BRADSHAW, B.E., SPENCER, L.K., LAHTINEN, A.C., KHIDER, K., RYAN, D.J., COLWELL, J.B., CHIRINOS, A. & BRADSHAW, J., 2009: *Queensland carbon dioxide geological storage atlas*. Queensland Department of Employment, Economic Development and Innovation.

BROADBENT, G.C., MYERS, R.E. & WRIGHT, J.V., 1998: Geology and origin of shale-hosted Zn-Pb-Ag mineralization at the Century Deposit, North-west Queensland, Australia. *Economic Geology,* **93**, 1264–1294.

BULTITUDE, R., 1982: *Ardmore, Queensland, 1:100,000 Geological Map Commentary*. Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

BULTITUDE, R.J., BLAKE, D.H., MOCK, C.M. & DONCHAK, P.J.T., 1982: *Duchess Region, Queensland, 1:100 000 Geological Map Commentary*. Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

CARSON, C.J., HUTTON, L. J., WITHNALL, I.W, & PERKINS, W.G., 2008a: Summary of results: Joint GSQ-GA geochronology project Mount Isa region URANDANGI, CLONCURRY, DUCHESS and DOBBYN 1:250,000 Sheet areas. *Queensland Geological Record,* **2008/05**.

CARSON, C.J., HUTTON, L.J., WITHNALL, I.W., PERKINS, W.G., DONCHAK, P.J.T., PARSONS, A., BLAKE, P.R. & SWEET, I.P., in preparation: Summary of results: Joint GSQ-GA NGA geochronology project Mount Isa, Lawn Hill and Simpson Desert-Diamantina Regions, 2009–2010. *Queensland Geological Record.*

CARSON, C.J., WORDEN, K., SCRIMGEOUR, I.R. & STERN, R.A., 2008b: The Palaeoproterozoic tectonic evolution of the Litchfield Province, western Pine Creek

Orogen, northern Australia: insight from SHRIMP U-Pb zircon and *in situ* monazite geochronology. *Precambrian Research,* **166**, 145–167.

CASEY, D.J., 1970: Northern Eromanga Basin, *Geological Survey of Queensland Report* **41**.

CHAMPION, D.C., 1991: The felsic granites of far North Queensland. Ph.D thesis Australian National University, Canberra.

CHAPMAN, L.H., 2004: Geology and mineralisation styles of the George Fisher Zn-Pb-Deposit, Mount Isa, Australia. *Economic Geology*, **99**, 233–255.

CHOPPING, R., & HENSON, P.A., (Editors) 2009: 3D map and supporting geophysical studies in the north Queensland region. *Geoscience Australia Record* **2009/29**.

CIHAN, M., EVINS, P., LISOWIEC, N. & BLAKE, K., 2006: Time constraints on deformation and metamorphism from EPMA dating of monazite in the Proterozoic Robertson River Metamorphics, NE Australia. *Precambrian Research,* **145**, 1–23.

CLAOUÉ-LONG, J., EDGOOSE, C. & WORDEN, K., 2008a. A correlation of Aileron Province stratigraphy in central Australia. *Precambrian Research,* **166**, 230–245.

CLAOUÉ-LONG, J., MAIDMENT, D., HUSSEY, K. & HUSTON, D., 2008b. The duration of the Strangways Event in central Australia: Evidence for prolonged deep crust processes. *Precambrian Research,* **166**, 246–262.

COLLINS, W.J. & SHAW, R.D., 1995: Geochronological constraints on orogenic events in the Arunta Inlier — a review. *Precambrian Research,* **71**, 315–346.

COLLINS, W.J., VERNON, R.H. & CLARKE, G.L., 1991: Discrete Proterozoic structural terranes associated with low-P, high-T metamorphism, Anmatjira Range, Arunta Inlier, Central Australia: tectonic implications. *Journal of Structural Geology,* **13**, 1157–1171.

COLLINS, W.J. & WILLIAMS, I.S., 1995: SHRIMP ionprobe dating of short-lived Proterozoic tectonic cycles in the northern Arunta Inlier, central Australia. *Precambrian Research,* **71**, 69–89.

CONNORS, K.A. & LISTER, G.S., 1995: Polyphase deformation in the western Mount Isa Inlier, Australia: episodic or continuous deformation? *Journal of Structural Geology,* **17**, 305–328.

CONNORS, K.A. & PAGE, R.W., 1995: Relationships between magmatism, metamorphism and deformation in the western Mount Isa Inlier, Australia. *Precambrian Research,* **71**, 131–153.

CONOR, C.H.H. & PREISS, W.V., 2008: Understanding the 1720–1640Ma Palaeoproterozoic Willyama Supergroup, Curnamona Province, South-eastern Australia: Implications for tectonics, basin evolution and ore genesis. *Precambrian Research,* **166**, 297–317.

CUDAHY, T., JONES, M., THOMAS, M., LAUKAMP, C., CACCETTA, M., HEWSON, R., RODGER, A. & VERRALL, M., 2008: Next Generation Mineral Mapping: Queensland airborne HyMap and Satellite ASTER Surveys 2006–2008. *CSIRO Exploration and Mining Report* **P2007/364**.

CULL, J.P., 1982: An appraisal of Australian Heat Flow. *BMR Journal of Australian Geology and Geohysics*, **7**, 11–21.

CULPEPER, L.G., DENARO, T.J., BURROWS, P.E. & MORWOOD, D.A., 1999: Mines and mineralisation of the Westmoreland 1:250 000 Sheet area, north-west Queensland. *Queensland Geological Record* **1999/06**.

CULPEPER, L.G., DENARO, T.J., BURROWS, P.E. & MORWOOD, D.A., 2000: Mines and mineralisation of the Dobbyn 1:250 000 Sheet area, north-west Queensland. *Queensland Geological Record* **2000/03**.

DALY, S.J., FANNING, C.M. & FAIRCLOUGH, M.C., 1998: Tectonic evolution and exploration potential of the Gawler Craton, South Australia. *AGSO Journal of Australian Geology & Geophysics,* **17**, 145–168.

DAVIS, B.K., POLLARD, P.J., LALLY, J.H., McNAUGHTON, N.J., BLAKE, K. & WILLIAMS, P.J., 2001: Deformation history of the Naraku Batholith, Mount Isa Inlier, Australia: implications for pluton ages and geometries from structural study of the Dipvale Granodiorite and Levian Granite. *Australian Journal of Earth Sciences,* **48**(1), 113–129.

DAY, R.W., WHITAKER, W.G., MURRAY, C.G., WILSON, I.H. & GRIMES, K.G., 1983: Queensland Geology: A companion volume to the 1:2 500 000 scale geological map (1975), *Publications of the Geological Survey of Queensland,* **383**.

DEB, M., THORPE, R.I., CUMMING, G.L. & WAGNER, P.A., 1989: Age, source and stratigraphic implications of Pb isotope data for conformable sediment-hosted, base metal deposits in the Proterozoic Aravalli-Delhi Orogenic Belt, northwestern India. *Precambrian Research*, **43**, 1–22.

DENARO, T.J., CULPEPER, L.G., BURROWS, P.E. & MORWOOD, D.A., 1999a. Mines and mineralisation, of the Camooweal 1:250 000 Sheet area, north-west Queensland. *Queensland Geological Record* **1999/04**.

DENARO, T.J., CULPEPER, L.G., MORWOOD, D.A. & BURROWS, P.E., 1999b. Mines and mineralisation of the Lawn Hill 1:250 000 Sheet area, north-west Queensland. *Queensland Geological Record* **1999/05**.

DENARO, T.J., CULPEPER, L.G., BURROWS, P.E. & MORWOOD, D.A., 2004: Mines, mineralisation, and mineral exploration in the Cloncurry 1:250 000 Sheet area, north-west Queensland. *Queensland Geological Record* **2004/01**.

DENARO, T.J., CULPEPER, L.G., MORWOOD, D.A. & BURROWS, P.E., 2001: Mines and mineralisation of the Mount Isa 1:250 000 Sheet area, north-west Queensland. *Queensland Geological Record* **2001/03**.

DENARO, T.J., WITHNALL, I.W., CULPEPER, L.G., MORWOOD, D.A. & BURROWS, P.E., 2003a. Mines, mineralisation and mineral exploration in the Urandangi 1:250 000 sheet area, north-west Queensland. *Queensland Geological Record* **2003/02**.

DENARO, T.J., WITHNALL, I.W., CULPEPER, L.G., BURROWS, P.E. & MORWOOD, D.A., 2003b. Mines, mineralisation and mineral exploration in the Duchess and Boulia 1:250 000 Sheet areas, north-west Queensland. *Queensland Geological Record* **2003/04**.

DERRICK, G.M., 1980: *Marraba, Queensland, 1:100 000 Geological Map Commentary*. Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

DENMEAD, A.K., 1960: Occurrence of petroleum and natural gas in Queensland. *Publication of the Geological Survey of Queensland* **299**.

DERRICK, G.M., 1982: A Proterozoic rift zone at Mount Isa, Queensland, and implications for mineralisation. *BMR Journal of Australian Geology & Geophysics,* **7**, 81–92.

DERRICK, G.M. & WILSON, I.H., 1982: Geology of the Alsace 1:100 000 Sheet area (6858), Queensland. *Bureau of Mineral Resources, Record* **1982/6**.

DERRICK, G.M., WILSON, I.H., HILL, R.M. GLIKSON, A.Y. & MITCHELL, J.E., 1977: Geology of the Mary Kathleen 1:100 000 Sheet area, North-west Queensland. *Bureau of Mineral Resources, Bulletin* **243**.

DERRICK, G.M., WILSON, I.H. & SWEET, I.P., 1980: The Quilalar and Surprise Creek Formations — new Proterozoic units from the Mount Isa Inlier (Australia): their regional sedimentology and application to regional correlation. *BMR Journal of Geology and Geophysics,* **5**(3), 215–223.

DERRINGTON, E.A. & WILLIAMS, L.J., 1988: GSQ Normanton 1 – Preliminary lithographic log and composite log. Geological Survey of Queensland Record 1988/13.

DOMAGALA, J., SOUTHGATE, P.N., McCONACHIE, B.A. & PIDGEON, B.A., 2000: Evolution of the Paleoproterozoic Prize, Gun, and Lower Loretta Supersequences of the Surprise Creek Formation and Mount Isa Group. *Australian Journal of Earth Sciences,* **47**, 485–507.

DONCHAK, P.J.T., BLAKE, D.H., JAQUES, A.L. & NOON, T.A., 1983: *Kuridala Region, Queensland, 1:100 000 Geological Map Commentary*. Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

DOUCH, H.F., 1976: The Cainozoic Karumba Basin, northeastern Australia and southern New Guinea. *BMR Journal of Australian Geology and Geophysics* **1**(2), 131–140.

DRAPER, J.J., (Editor), 2002: Geology of the Cooper and Eromanga Basins, Queensland. *Queensland Minerals and Energy Review Series*, Queensland Department of Natural Resources and Mines.

DRAPER, J.J., 2007: Georgina Basin – an early Palaeozoic carbonate petroleum system in Queensland. *APEA Journal* **2007** (1), 105–124.

DRUMMOND, B.J., GOLEBY, B.R., GONCHAROV, A.G., WYBORN, L.A.I., COLLINS, C.D.N. & MACREADY, T., 1998: Crustal-scale structures in the Proterozoic Mount Isa Inlier of north Australia: their seismic response and influence on mineralization. *Tectonophysics*, **288**, 43–56.

DUTCH, R., HAND, M. & KINNY, P.D. 2008: High-grade Palaeoproterozoic reworking in the south-eastern Gawler Craton, South Australia. *Australian Journal of Earth Sciences,* **55**, 1063–1081.

DUNNET, D., 1976: Some aspects of the Panantarctic cratonic margin in Australia. Philosophic Transactions of the Royal Society of London, A283, 333–344.

DUNSTAN, B., 1920: Geological notes on the Cloncurry Camooweal Burketown Boulia area, *Publications of the Geological Survey of Queensland*, **265**.

DUNSTER, J.N., BARLOW, M.G., MCCONACHIE, B.A. & STAINTON, P.W., 1993: COM Egilabria -1, Well Completion Report, Authority to Prospect 423P, Queensland. Held by the Department of Employment, Economic Development and Innovation as CR24967.

DUNSTER, J.N., MCCONACHIE, B.A. & BROWN, M.G., 1989a: COM Beamsbrook -1, Well Completion Report, Authority to Prospect 373P, Queensland. Held by the Department of Employment, Economic Development and Innovation as CR20566.

DUNSTER, J.N., MCCONACHIE, B.A. & BROWN, M.G., 1989b: COM Armraynald -1, Well Completion Report, Authority to Prospect 373P, Queensland. Held by the Department of Employment, Economic Development and Innovation as CR20579.

DUNSTER, J.N., MCCONACHIE, B.A. & BROWN, M.G., 1989c: COM Silverleaf -1, Well Completion Report, Authority to Prospect 373P, Queensland. Held by the Department of Employment, Economic Development and Innovation as CR20581.

EDMISTON, M.A., LEPONG, P. & BLENKINSOP, T.G., 2008: Structure of the Isan Orogeny under cover to the east of the Mount Isa Inlier revealed by multiscale edge analysis and forward and inverse modelling of aeromagnetic data. *Precambrian Research,* **163**, 69–80.

EESON, B.P. & BURBAN, B., 1985: Final report on Authority to prospect 3742M "Savannah Downs", north Queensland (incorporating the second six-monthly, third six monthly, first annual and second annual report periods). Queensland Metals Corporation. Company report held by the Queensland Department of Employment, Economic Development and Innovation as CR14529.

ESSO EXPLORATION AND PRODUCTION AUSTRALIA INC, 1985: EAL Ayrshire 1, well completion report, Galilee Basin, Qld, Vol. 1 and Vol. 2, Qld, A-P 268P. Company Report held by the Queensland Department of Employment, Economic Development and Innovation as CR14961 .

EVANS, P.A., 1996: Fluoride Anomalies in Aquifers of Queensland Section of the Great Artesian Basin and Their Significance. *In*: *Mesozoic Geology of Eastern Australian Plate*, Geological Society of Australia.

FANNING, C.M., ASHLEY, P.M., COOK, M.D.J., TEALE, G. & CONOR, C.H.H., 1998: A geochronological perspective of crustal evolution in the

Curnamona Province. *In*: Gibson, G.M. (Editor): Broken Hill Exploration Initiative: Abstracts of papers presented at the 4th Annual Meeting in Broken Hill. *Australian Geological Survey Organisation Record,* **1998/25**, 30–35.

FANNING, C.M., REID, A.J. & TEALE, G.S., 2007: A Geochronological Framework for the Gawler Craton, South Australia. *South Australian Geological Survey, Bulletin,* **55**.

FITZELL, M., 2010: Geothermal Exploration Proposal: Millungera Basin North and South. Geological Survey of Queensland Internal Report.

FODEN, J., BUICK, I. S. & MORTIMER, G.E., 1988: The petrology and geochemistry of granitic gneisses from the East Arunta Inlier, central Australia, implications for Proterozoic crustal development. *Precambrian Research* **40/41**, 233–259.

FODEN, J., SANDIFORD, M., DOUGHERTY-PAGE, J. & WILLIAMS, I., 1999: Geochemistry and geochronology of the Rathjen Gneiss: Implications for the early tectonic evolution of the Delamerian Orogen. *Australian Journal of Earth Sciences,* **46**, 377–389.

FORBES, C.J., GILES, D., BETTS, P.G., WEINBERG, R. & KINNY, P.D., 2007: Dating prograde amphibolite and granulite facies metamorphism using in situ monazite U/Pb SHRIMP analysis. *Journal of Geology,* **115**, 691–705.

FOSTER, D.R.W. & AUSTIN, J.R., 2008: The 1800–1610Ma stratigraphic and magmatic history of the Eastern Succession, Mount Isa Inlier, and correlations with adjacent Paleoproterozoic terranes. *Precambrian Research,* **163**, 7–30.

FOSTER, D.R.W. & RUBENACH, M.J., 2006: Isograd pattern and regional low-pressure, high-temperature metamorphism of pelitic, mafic and calc-silicate rocks along an east-west section through the Mount Isa Inlier. *Australian Journal of Earth Sciences,* **53**, 167–186.

FRAKES, A., BURGER, D., APTHORPE, M., WISEMAN, J., DETTMANN, M., ALLEY, N., FLINT, R., GRAVESTOCK, D., LUDBROOK, N., BACKHOUSE, J., SKWARKO, S., SCHEIBNEROVA, V., MCMINN, A., MOORE, P.S., BOLTON, B.R., DOUGLAS, J.G., CHRIST, R., WADE, M., MOLNAR, R.E., MCGOOWRAN, B., BALME, B.E. & DAY, R.A., 1987: Australian Cretaceous shorelines, stage by stage. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **59**, 31–48.

GALLAGHER, K. & LAMBECK, K., 1989: Subsidence, sedimentation and sea-level changes in the Eromanga Basin, Australia. *Basin Research* **2**.

GEOLOGICAL SURVEY OF QUEENSLAND, 2010: *Mineral occurrence and Geology Observations 2010*. Department of Employment, Economic Development and Innovation, digital data released on DVD.

GEOSCIENCE AUSTRALIA, 2010: *Geoscience Australia 'Stratigraphic Units Database' 2010.* http://dbforms.ga.gov.au/pls/www/geodx.strat_units.int.

GEOSCIENCE AUSTRALIA, 2010: The OZCHRON datasets, 2010. http://www.ga.gov.au/oracle/ozchron.

GEORDIE, M., WILDE, A., OLIVER, N.H.S., WILLIAMS, P.J. & RYAN, C.G., 2005: Modeling outflow from the Ernest Henry Fe-oxide Cu-Au deposit: implications for ore genesis and exploration. *Journal of Geochemical Exploration*, **85**, 31–46.

GIBSON, G.M. & HITCHMAN, A.P. (Editors), 2005: *Project I1 Final Report 3D basin architecture and mineral systems in the Mount Isa western succession*. Predictive Mineral Discovery Cooperative Research Centre.

GIBSON, G.M., RUBENACH, M.J., NEUMANN, N.L., SOUTHGATE, P.N. & HUTTON, L.J., 2008: Syn- and post-extensional tectonic activity in the Paleoproterozoic sequences of Broken Hill and Mount Isa and its bearing on reconstructions of Rodinia. *Precambrian Research,* **166**, 350–369.

GILES, D., BETTS, P.G., AILLÈRES, L., HULSCHER, B., HOUGH, M. & LISTER, G.S., 2006: Evolution of the Isan Orogeny at the south-eastern margin of the Mount Isa Inlier. *Australian Journal of Earth Sciences, 53*, 91–108.

GILES, D., BETTS, P. & LISTER, G., 2002: Far-Field continental backarc setting for the 1.80–1.67Ga basins of north-eastern Australia. *Geology,* **30**, 823–826.

GILES, D. & NUTMAN, A.P., 2003: SHRIMP U-Pb zircon dating of the host rocks of the Cannington Ag-Pb-Zn deposit, south-eastern Mount Isa Block, Australia. *Australian Journal of Earth Sciences,* **50**, 295–309.

GLIKSON, A.Y., DERRICK, G.M., WILSON, I.H. & HILL, R.M., 1976: Tectonic evolution and crustal setting of the Middle Proterozoic Leichardt River Fault Trough, Mount Isa Region, north-west Queensland. *BMR Journal of Australian Geology & Geophysics,* **1**, 115–129.

GLIKSON, M., 1999: Report on the thermal maturation of organic matter in the Georgina BasinThermal Maturity. Appendix in Mulready, J., 1975: Well completion report, Ethabuka No. 1, A-P.160P, Queensland. Held by the Department of Employment, Economic Development and Innovation as CR5199.

GLIKSON, M. & TAYLOR, G.H., 1986: Cyanobacterial mats: major contributors to the organic matter in Toolebuc oil shales, *in* Gravestock, D.I., Moore, P.S. & Pitt, G.M. (Editors): Contributions to the geology and hydrocarbon potential of the Eromanga Basin, *Geological Society of Australia Special Publication* **12**, 273–286.

GOLDBERG, A.S., 2010: Dyke swarms as indicators of major extensional events in the 1.9–1.2Ga Columbia supercontinent. *Journal of Geodynamics,* **50**, 176–190.

GONCHAROV, A.G., LIZINSKY, M.D., COLLINS, C.D.N., KALNIN, K.A., FOMIN, T.N., DRUMMOND, B.J., GOLEBY, B.R. & PLATONENKOVA, L.N., 1998: Intra-crustal 'seismic isostasy' in the Baltic Shield and Australian Precambrian cratons from deep seismic profiles and the Kola superdeep bore hole data. *In*: Braun, J., Dooley, J.C., Goleby, B.R., van der Hilst, R.D. & Klootwijk, C.T., (Editors): Structure and evolution of the Australian Continent. *American Geophysical Union Geodynamics Series*, **26**, 119–138.

GORDON, R., 2004: Isan deformation, magmatism and extensional kinematics in the Western Fold Belt of the Mount Isa Inlier. MSc thesis, University of Queensland.

GOSCOMBE, B., 1991: Intense non-coaxial shear and the development of mega-scale sheath folds in the Arunta Block, Central Australia. *Journal of Structural Geology,* **13**, 299–318.

GRAVESTOCK, D.I., MOORE, P.S. & PITT, G.M., 1986: Contributions to the geology and hydrocarbon potential of the Eromanga Basin. *Geological Society of Australia, Special Publication* **12**.

GRAY, A.R.G. & SWARBRICK, C.F.J., 1975: Nomenclature of Late Palaeozoic strata in the northeastern Galilee Basin, Queensland Government Mining Journal, **76** (888), 344–352.

GRAY, D.R. & FOSTER, D.A., 2004: Tectonic evolution of the Lachlan Orogen, southeast Australia: historic review, data synthesis and modern perspectives, *Australian Journal of Earth Sciences*, **51** (6), 773–817.

GREEN, D.C., HAMLING, D.D. & KYRANIS, N., 1963: Completion Report Phillips-Sunray stratigraphic drilling Boulia area, ATP 54P, Queensland.

GREEN, P.M. & BALFE, P.E., 1980: Stratigraphic drilling report – GSQ Mount Whelan 1 and 2. *Queensland Government Mining Journal*, **March 1980**, 162–178.

GREEN, P.M., HAWKINS, P.J., CARMICHAEL, D.C., BRAIN, T.J., SMITH, R.J., QUARANTOTTO, P., GENN, D.L.P., HOFFMANN, K.L., MCKELLAR, J.L., JOHN, B.H. & SHIELD C.J. 1992: An assessment of the hydrocarbon potential of the northern Eromanga Basin, Queensland, Queensland Government Mining Journal, **93** (1085), 37–38.

GREENE, D.C., 2010: Neoproterozoic rifting in the southern Georgina Basin, central Australia: Implications for reconstructing Australia in Rodinia. *Tectonics*, **29**, TC5010, doi:10.1029/2009TC002543 (online).

HABERMEHL, M.A., 1982: The Eromanga Basin within the Great Artesian Basin, *in* Moore, P.S & Mount, J.T. (Compilers): *Eromanga Basin Symposium*, PESA-GSA, 391–393.

HABERMEHL, M.A., 1986: Regional groundwater movement, hydrochemistry and hydrocarbon migration in the Eromanaga Basin. *In*: Contributions to the geology and hydrocarbon potential of the Eromanga Basin. *Geological Society of Australia Special Publication* **12**, 353–376.

HABERMEHL, M.A., 2001: Wire-line logged waterbores in the Great Artesian Basin, Australia — Digital data of logs and waterbore data acquired by AGSO. Bureau of Rural Sciences, Canberra.

HAND, M., MAWBY, J., KINNY, P. & FODEN, J., 1999: U-Pb ages from the Harts Range, central Australia: evidence for early Ordovician extension and constraints on Carboniferous metamorphism. *Journal of the Geological Society,* **156**, 715–730.

HAND, M., REID, A. & JAGODZINSKI, L., 2007: Tectonic Framework and Evolution of the Gawler Craton, Southern Australia. *Economic Geology,* **102**, 1377–1395.

HAND, M. & RUBATTO, D., 2002: The scale of the thermal problem in the Mt Isa Inlier. *Geological Society of Australia Abstracts* **67**, 173.

HARRIS, H.I., 1960: Well completion report, MPC Corfield 1, Magellan Petroleum Corporation. Held by the Department of Employment, Economic Development and Innovation as CR475.

HAWKINS, P.J., GENN, D.L.P. & GREEN, P.M. 1991: Source-rock Evaluation of the Basal Jurassic, Birkhead Formation, and Westbourne Formation, Northern Eromanga Basin. GSQ Record 1991/24.

HAWKINS, P.J. & HARRISON, P.L., 1978: Stratigraphic and seismic investigations in the Lovelle Depression, western Galilee Basin, Queensland Government Mining Journal, **79** (926), 623–650.

HENSEN, P.A. 2005: Chapter 4: An integrated geological and geophysical 3D map for the Mount Isa Western Succession. *In*: Gibson, G.M. & Hitchman, A.P. (Editors): *Project I1 Final Report 3D Basin Architecture and Mineral Systems in the Mount Isa Western Succession* . Predictive Mineral Discovery Cooperative Research Centre, 83–117.

HILL, R.M., WILSON, I.H. & DERRICK, G.M., 1975: Geology of the Mount Isa 1:100,000 Sheet area, north-west Queensland. *Bureau of Mineral Resources, , Record* **1975/175**.

HILL, E.J., LOOSVELD, R.J.H. & PAGE, R.W., 1992: Structure and geochronology of the Tommy Creek Block, Mount Isa Inlier. In Stewart, A.J. & Blake, D.H. (Editors): Detailed studies of the Mount Isa Inlier. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Bulletin* **243**, 329–348.

HILLS, Q.G., 2004: The Tectonic Evolution of the Georgetown Inlier. PhD Thesis, School of Geosciences, Monash University, Melbourne.

HOEK, J.D. & SCHAEFER, B.F., 1998: Palaeoproterozoic Kimban mobile belt, Eyre Peninsula; timing and significance of felsic and mafic magmatism and deformation. *Australian Journal of Earth Sciences,* **45**, 305–313.

HOLCOMBE, R.J., PEARSON, P.J. & OLIVER, N.H.S., 1991: Geometry of a Middle Proterozoic extensional décollement in north-eastern Australia. *Tectonophysics,* **191**, 255–274.

HUSTON, D.L. (Editor), 2010: An assessment of the uranium and geothermal potential of north Queensland. *Geoscience Australia Record* **2010/14**.

HUTTON, L.J., 1973: The geology of the northern part of the Lawn Hill Mineral Field. B.Sc. (Honours) thesis, University of Queensland.

HUTTON, L., FITZELL, M., HOFFMANN, K., WITHNALL, I., STOCKHILL, B., JUPP, B. & DONCHAK, P., 2010: The Millungera Basin — new geoscience supporting exploration. *APPEA Conference 2010: Abstracts* **Volume 1**.

HUTTON, L.J., GIBSON, G.M., KORSCH, R.J., WITHNALL, I.W., HENSON, P.A., COSTELLOE, R.D., HOLZSCHUH, J., HUSTON, D.L., JONES, L.E.A., MAHER, J.L., NAKAMURA, A., NICOLL, M.G., ROY, I., SAYGIN, E., MURPHY, F.B. & JUPP, B., 2009: Geological Interpretation of the 2006 Mount Isa seismic survey. *In*: Camuti, K. & Young, D. (Compilers): Northern Exploration and Mining 2009 and North Queensland Seismic and MT Workshop. *Australian Institute of Geoscientists, Bulletin* **49**, 137–142.

HUTTON, L.J. & SWEET, I.P., 1982: Geological Evolution, Tectonic Style, & Economic Potential of the Lawn Hill Platform Cover, North-west Queensland. *Journal of Australian Geology & Geophysics* **7**, 125–134.

HUTTON, L.J. & WILSON, I.H., 1984: *Mount Oxide Region, Queensland, 1:100 000 Geological Map Commentary*. Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

HUTTON, L.J. & WILSON, I.H., 1985: *Mammoth Mines Region, Queensland, 1:100 000 Geological Map Commentary*. Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

IDNURM, M., 2000: Towards a high resolution Late Palaeoproterozoic – earliest Mesoproterozoic apparent polar wander path for northern Australia. *Australian Journal of Earth Sciences*, **47**, 405–429.

JACKSON, M.J., SCOTT, D.L. & RAWLINGS, D.J., 2000: Stratigraphic framework for the Leichhardt and Calvert Superbasins: review and correlations of the pre-1700Ma successions between Mount Isa and Mcarthur River. *Australian Journal of Earth Sciences,* **47**, 381–403.

JACKSON, M.J. & SOUTHGATE, P.N., 2000: Evolution of three unconformity-bounded sandy carbonate successions in the McArthur River region of northern Australia: The Lawn, Wide and Doom Supersequences I a proximal part of the Isa Superbasin. *Australian Journal of Earth Sciences,* **47**(3), 625–635.

JACKSON, M.J., SOUTHGATE, P.N., BLACK, L.P., BLAKE, P.R. & DOMAGALA, J., 2005: Overcoming Proterozoic quartzite sand-body miscorrelations: integrated sequence stratigraphy and SHRIMP U-Pb dating of the Surprise Creek Formation, Torpedo Creek and Warrina Park Quartzites, Mount Isa Inlier. *Australian Journal of Earth Sciences,* **52**, 1–25.

JACKSON, M.J., SWEET, I.P., PAGE, R.W. & BRADSHAW, B.E., 1999: The South Nicholson and Roper Groups: Evidence for the Early Mesoproterozoic Roper Superbasin. *In:* Bradshaw, B.E. & Scott, D.L (Editors): Integrated basin analysis from the Isa Superbasin using Seismic, Well-log and Geopotential data: an evaluation of the economic potential of the northern Lawn Hill Platform. *Australian Geological Survey Organisation Record* **1999/19**.

JOHN, B.H. 1984: Lithostratigraphy of the Eromanga Basin Sequence in the Richmond 1:250 000 Sheet Area. University of Queensland Honours Thesis.

JOHNSTON, J.D., 1999: Regional fluid flow and the genesis of Irish Carboniferous base metal deposits. *Mineralium Deposita*, **34**, 571–598.

KIRKEGAARD, A.G., 1974: Structural elements of the northern part of the Tasman Geosyncline. *In* Denmead A.K., Tweedale G.W. & Wilson, A.F. (Editors): *The Tasman Geosyncline: A Symposium*, Geological Society of Australia, Queensland Division, Brisbane, 47–62.

KORSCH, R.J., WITHNALL, I.W., HUTTON, L.J., HENSON, P.A., BLEWETT, R.S., HUSTON, D.L., CHAMPION, D.C., MEIXNER, A.J., NICOLL M.G. & NAKAMURA, A., 2009: Geological interpretation of deep seismic reflection line 07GA-IG1: the Cloncurry to Croydon transect. *In*: Camuti, K. & Young, D. (Compilers): Northern Exploration and Mining 2009 and North Queensland Seismic and MT Workshop. *Australian Institute of Geoscientists, Bulletin* **49**, 153–158.

KRASSAY, A.A., BRADSHAW, B.E., DOMAGALA, J. & JACKSON, M.J., 2000: Siliciclastic Shoreline to Growth-Faulted, Turbiditic Sub-Basins: The Proterozoic River Supersequence of the Upper Mcnamara Group on the Lawn Hill Platform, Northern Australia. *Australian Journal of Earth Sciences, 47*, 533–562.

KYLE, J.R., 1994: Short Course on Sediment-Hosted Mineral Deposits. Earth Resources Foundation, The University of Sydney, May 18-19 1994.

LAFRANCE, B., CLARKE, G.L., COLLINS, W.J. & WILLIAMS, I.S., 1995: The emplacement of the Wuluma granite: melt generation and migration along steeply dipping extensional fractures at the close of the Late Strangways orogenic event, Arunta Block, central Australia. *Precambrian Research, 72*, 43–67.

LAING, W.P., 1998: Structural-mesosomatic environment of the east Mt Is Block base-metal-gold province. *Australian Journal of Earth Sciences* **45**, 413–428.

LESLIE, R.B., EVANS, H.J. & KNIGHT, C.L., 1976: Economic Geology of Australia and Papua New Guinea, 3. Petroleum. *AUSIMM Mongraph Series* **7**.

LEISTEL, J.M., MARCOUX, E., THIEBLEMONT, D., QUESADA, C., SANCHEZ, A., ALMODOVAR, G.R., PASCUAL, E. & SAEZ, R., 1998: The volcanic-hosted massive sulphide deposits of the Iberian Pyrite Belt. Review and preface to the thematic issue. *Mineralium Deposita*, **33**, 2–30.

MARK, G., 2001: Nd isotope and petrogenetic constraints for the origin of the Mount Angelay Igneous Complex: implications for the origin of intrusions in the Cloncurry District, NE Australia. *Precambrian Research,* **105**, 17–35.

MARK,G., WILDE, A., OLIVER, N.H.S., WILLIAMS, P.J., RYAN, C.G., 2005: Modeling outflow from the Ernest Henry Fe oxide Cu-Au deposit; implications for ore genesis and exploration. *Journal of Geochemical Exploration* **85** (1) 31–46.

McCONACHIE, B.A., BARLOW, M.G., DUNSTER, J.N., MEANEY, R.A. & SCHAAP, A.D., 1993: The Mount Isa Basin — definition, structure and petroleum geology. *Australian Petroleum Exploration Association Journal*, **33**, 237–257.

McCONACHIE, B.A., FILATOFF, J. & SENAPATI, N., 1990: Stratigraphy and petroleum potential of the onshore Carpentaria Basin, Queensland. *APEA Journal*, **30**(1), 149–164.

McDONALD, G.D., COLLERSON, K.D. & KINNY, P.D., 1997: Late Archean and Early Proterozoic crustal evolution of the Mount Isa Block, North-west Queensland, Australia. *Geology,* **25**, 1095–1098.

McLAREN, S., SANDIFORD, M., HAND, M., NEUMANN, N., WYBORN, L. & BASTRAKOVA, I., 2003: The hot southern continent: heat flow and heat production in Australian Proterozoic terranes, *In*: Hillis, R.R. & Müller, R.D., (Editors): Evolution and Dynamics of the Australian Plate. *Geological Society of Australia Special Publication* **22**.

McPHEE, I., 1960: Well completion report, CPC Oooroonoo 1, Conorado Petroleum Coprporation. Held by the Department of Employment, Economic Development and Innovation as CR548.

MAGEE, C., HUTTON, L.J., WITHNALL, I.W., PERKINS, W.G., DONCHAK, P.J.T., PARSONS, A., BLAKE, P.R., SWEET, I.P. & CARSON, C.J., in preparation: Summary of results: Joint GSQ-GA NGA geochronology project Mount Isa and Lawn Hill Regions, 2008–2009. *Queensland Geological Record.*

MÖLLER, A., HENSEN, B.J., ARMSTRONG, R.A., MEZGER, K. & BALLÈVRE, M., 2003: U–Pb zircon and monazite age constraints on granulite-facies metamorphism and deformation in the Strangways Metamorphic Complex (central Australia). *Contributions to Mineralogy and Petrology,* **145**, 406–423.

MOND, A. & YEATES, A.N., 1973: Bureau of Mineral Resources Geology and Geophysics Record 1973/47.

MOORE, P.S. & MOUNT, T.J., 1982: *Eromanga Basin Symposium*. Proceedings of the Eromanga Symposium, PESA and GSA Branches, 9–11 November, Adelaide, South Australia.

MORIARTY, K.C. & WILLIAMS, A.F., 1982: Hydrocarbon Flushing in the Eromanga Basin – Fact or Fallacy? *in* Moore, S. & Mount, J.T. (Compilers): *Eromanga Basin Symposium*, PESA, GSA, 313–326.

MOTT, W.D., 1952: Oil in Queensland, *Queensland Government Mining Journal*, **53** (612), 848–860.

MULREADY, J., 1975: Well completion report, Ethabuka No. 1, A-P.160P, Queensland. Held by the Department of Employment, Economic Development and Innovation as CR5199.

MURPHY, B., KENDRICK, M., MAAS, R., PHILLIPS, D., JUPP, B., AILLERES, L., SCHAEFER, B., MARK, G., WILDE, A., McLELLAN, J., RUBENACH, M., LAUKAMP, C., OLIVER, N., FORD, A., FISHER, L., KEYS, D., DUCKWORTH, R., NORTJE, G., AUSTIN, J., EDMISTON, M., LEPONG, P., BLENKINSOP, T., FOSTER, D., ROY, I., NEUMANN, N., GIBSON, G., THOMAS, M., SOUTHGATE, P., GESSNER, K., BIERLEIN, F., MILLER, J., WALSHE, J., CLEVERLEY, J., ORD, A. & HUTTON, L., 2008: Mineral system analysis of the Mount Isa – McArthur region, northern Australia. pmd*CRC, Project I7 Final Report, April 2005 – July 2008.

MURRAY, C.G., SCHEIBNER, E. & WALKER, R.N., 1989: Regional geological interpretation of a digital coloured residual Bouguer gravity image of eastern Australia with a wavelength cut-off of 250 km, *Australian Journal of Earth Sciences*, **36** (3), 423–449.

NEEDHAM, R.S. , STUART-SMITH, P.G. & PAGE, R.W., 1988: Tectonic evolution of the Pine Creek Inlier, Northern Territory, *Precambrian Research* **40/41,** 543–564.

NELSON, D.R., MYERS, J.S. & NUTMAN, A.P., 1995: Chronology and evolution of the Middle Proterozoic Albany-Fraser Orogen, Western Australia. *Australian Journal of Earth Sciences,* **42**, 481–495.

NEUMANN, N.L. & FRASER, G.L., (Editors) 2007: Geochronological synthesis and Time-Space plots for Proterozoic Australia. *Geoscience Australia Record* **2007/06**.

NEUMANN, N.L., GIBSON, G.M. & SOUTHGATE, P.N., 2009a: New SHRIMP age constraints on the timing and duration of magmatism and sedimentation in the Mary Kathleen Fold Belt, Mount Isa Inlier, Australia. *Australian Journal of Earth Sciences*, **56**, 965–983.

NEUMANN, N.L, GIBSON, G.M., SOUTHGATE, P.N. & HUTTON, L.H., 2006a. Mount Isa Inlier — Western and Eastern Succession correlations. *In*: *I7 Project Internal Report*. Predictive Mineral Discovery Cooperative Research Centre.

NEUMANN, N.L., HORE, S., FRASER, G.L., 2009b: New SHRIMP geochronology from the Mount Painter Province, South Australia. *In*: Korsch, R.J. (Editor): Broken Hill Exploration Initiative: *Abstracts for the 2009 Conference. Geoscience Australia,* **Record 2009/28**.

NEUMANN, N.L., SOUTHGATE, P.N. & GIBSON, G.M., 2009c: Defining unconformities in Proterozoic sedimentary basins using detrital geochronology and basin analysis — an example from the Mount Isa Inlier, Australia. *Precambrian Research,* **168**, 149–166.

NEUMANN, N.L., SOUTHGATE, P.N., GIBSON, G.M. & McINTYRE, A., 2006b: New SHRIMP geochronology for the Western Fold Belt of the Mount Isa Inlier: developing an 1800-1650Ma event framework. *Australian Journal of Earth Sciences,* **53**, 1023–1039.

NORMAN, A.R. & CLARKE, G.L., 1990: A barometric response to late compression in the Strangways Metamorphic Complex, Arunta Block, central Australia. *Journal of Structural Geology,* **12**, 667–684.

O'DEA, M.G., BETTS, P.G., MacCREADY, T. & AILLERES, L., 1997a: Sequential development of a mid-crustal fold-thrust complex in the eastern Mount Isa

Inlier, Australia. *Australian Crustal Research Centre Publication* **47**, 28.

O'DEA, M.G., BETTS, P.G., MacCREADY T. & AILLÈRES, L., 2006: Sequential development of a mid-crustal fold-thrust complex: evidence from the Mitakoodi Culmination in the eastern Mount Isa Inlier, Australia. *Australian Journal of Earth Sciences,* **53**, 69–90.

O'DEA, M.G. & LISTER, G.S., 1995: The role of ductility contrast and basement architecture in the structural evolution of the Crystal Creek Block, Mount Isa Inlier, NW Queensland, Australia. *Journal of Structural Geology,* **17**, 949–960.

O'DEA, M.G., LISTER, G.S., BETTS, P.G. & POUND, K.S., 1997b. A shortened intraplate rift system in the Proterozoic Mount Isa Terrane, North-West Queensland, Australia. *Tectonics,* **16**, 425–441.

O'DEA, M.G., LISTER, G.S., MacCREADY, T., BETTS, P.G., OLIVER, N.H.S., POUND, K.S., HUANG, W. & VALENTA, R.K., 1997c: Geodynamic evolution of the Proterozoic Mount Isa Terrane. *In:* Burg, J.P. & Ford, M. (Editors): Orogeny through time. *Geological Society of London, Special Publication* **121**, 99–122.

O'NEIL, B.J., 1989: *The Cooper & Eromanga Basins Australia*. Proceedings of the Cooper and Eromanga Basins Conference, SPE, 26–27 June Adelaide, South Australia.

PAGE, R.W., 1983a. Chronology of magmatism, skarn formation, and uranium mineralisation, Mary Kathleen, Queensland, Australia. *Economic Geology,* **78**, 838–853.

PAGE, R.W., 1983b. Timing of superimposed volcanism in the Proterozoic Mount Isa Inlier, Australia. *Precambrian Research,* **21**, 223–245.

PAGE, R.W., 1988: Geochronology of Early to Middle Proterozoic Fold Belts in Northern Australia: a Review. *Precambrian Research,* **40–41**, 1–19.

PAGE, R.W., JACKSON, M.J. & KRASSAY, A.A., 2000: Constraining sequence stratigraphy in North Australian basins: SHRIMP U-Pb zircon geochronology between Mount Isa and Mcarthur River. *Australian Journal of Earth Sciences,* **47**, 431–459.

PAGE, R.W. & McCREADY, T., 1997: Rocks of Mount Isa Group age in the Eastern Fold Belt. *AGSO Research Newsletter* **26**, 16–17.

PAGE, R.W. & SWEET, I.P., 1998: Geochronology of basin phases in the western Mount Isa Inlier, and correlation with the McArthur Basin. *Australian Journal of Earth Sciences,* **45**, 219–232.

PAGE, R.W. & SUN, S.-S., 1996: Age and provenance of granitic rocks and host sequences in the Mount Isa Eastern Succession. *In*: Baker, T., Rotherham, J., Richmond, J., Mark, G., & Williams, P., (Editors): New Developments in metallogenic research: the McArthur Mount Isa, Cloncurry Minerals Province. *Contributions of the Economic Geology Research Unit,* **55**, 95–98.

PAGE, R.W. & SUN, S.-S., 1998: Aspects of geochronology and crustal evolution in the Eastern Fold Belt, Mount Isa Inlier. *Australian Journal of Earth Sciences*, B, 343–361.

PAGE, R.W. & WILLIAMS, I.S., 1988: Age of the Barramundi Orogeny in northern Australia by means of ion microprobe and conventional U-Pb zircon studies. *Precambrian Research,* **40–41**, 21–36.

PAYNE, J.L., FERRIS, G.M., BAROVICH, K.M. & HAND, M., 2010. Pitfalls of classifying ancient magmatic suites with tectonic discrimination diagrams: An example from the Paleoproterozic Tunkillia Suite, Gawler Craton, Australia. *Precambrian Research*, **177** (3-4), 227–240.

PAYNE, J.L., HAND, M., BAROVICH, K.M. & WADE, B.P., 2008: Temporal constraints on the timing of high-grade metamorphism in the northern Gawler Craton: implications for assembly of the Australian Proterozoic. *Australian Journal of Earth Sciences,* **55**, 623–640.

PEARSON, P.J., HOLCOMBE, R.J. & PAGE, R.W., 1992: Synkinematic Emplacement of the Middle Proterozoic Wonga Batholith into a Mid-Crustal Extensional Shear Zone, Mount Isa Inlier, Queensland, Australia. *In*: Stewart, A.J. & Blake, D. H. (Editors): Detailed Studies of the Mount Isa Inlier. *Australian Geological Survey Organisation, Bulletin,* **243**, 289–328.

PERKINS, C. & WYBORN, L.A.I., 1998: Age of Cu-Au mineralisation, Cloncurry district, eastern Mount Isa Inlier, Queensland, as determined by $^{40}Ar/^{39}Ar$ dating. *Australian Journal of Earth Sciences*, **45**, 233–246.

PETROLEUM RESOURCES ASSESSMENT AND DEVELOPMENT PROGRAM, 1990: Petroleum Resources of Queensland (review to June 30, 1989). *Queensland Resource Industries Review Series*, Department of Resource Industries, Queensland.

PIETSCH, B.A. & EDGOOSE, C.J., 1988: The stratigraphy, metamorphism and tectonics of the Early Proterozoic Litchfield Province and western Pine Creek Geosyncline, Northern Territory. *Precambrian Research,* **40–41**(C), 565–588.

PLUMB, K.A., DERRICK, G.M. & WILSON, I.H., 1980: Precambrian geology of the McArthur River – Mount Isa region northern Australia. *In*: Henderson R.A. & Stephenson P.J. (Editors): *The Geology and Geophysics of North-eastern Australia*. Geological Society of Australia Inc., Queensland Division, 71–88.

*pmd**CRC I7 PROJECT TEAM, 2008: Project I7 Final Report April 2005 – July 2008: Mineral system analysis of the Mount Isa – McArthur region, Northern Australia. Predictive Mineral Discovery Cooperative Research Centre.

POLLARD, P.J., MARK, G. & MITCHELL, L.C., 1998: Geochemistry of post-1540Ma granites spatially associated with regional sodic-calcic alteration and Cu-Au-Co mineralisation, Cloncurry District, north-west Queensland. *Economic Geology,* **93**, 1330–1344.

POLLARD, P.J. & McNAUGHTON, N., 1997: U-Pb geochronology and Sm/Nd isotope characteristics of Proterozoic intrusive rocks in the Cloncurry District, Mount Isa Inlier, Australia. *In: AMIRA P438 Final Report: Cloncurry Base Metals and Gold,* **4**, 19.

POTMA, W.A. & BETTS, P.G., 2006: Extension-related structures in the Mitakoodi Culmination: implications for the nature and timing of extension, and effect on later shortening in the eastern Mount Isa Inlier. *Australian Journal of Earth Sciences,* **53**, 55–67.

QUEENSLAND DEPARTMENT OF MINES & ENERGY, TAYLOR WALL & ASSOCIATES, SRK CONSULTING PTY LTD AND ESRI AUSTRALIA, 2000: *North-West Queensland Mineral Province Report.* Queensland Department of Mines & Energy.

RADKE, B., 2009: Hydrocarbon and Geothermal Prospectivity of Sedimentary Basins in Central Australia; Warburton, Cooper, Perdirka, Galilee, Simpson and Eromanga Basins. Geoscience Australia Record 2009/25.

RANDAL, M.A. 1978: Hydrogeology of the south-eastern Georgina Basin and environs, Queensland and Northern Territory. *Geological Survey of Queensland Publication* **366**.

RASMUSSEN, B., SHEPPARD, S. & FLETCHER, I.R. 2006: Testing ore deposit models using *in situ* U-Pb geochronology of hydrothermal monazite: Palaeoproterozoic gold mineralization in northern Australia. *Geology*, **34**, 77–80.

REID, A., HAND, M., JAGODZINSKI, E., KELSEY, D. & PEARSON, N., 2008: Paleoproterozoic orogenesis in the south-eastern Gawler Craton, South Australia. *Australian Journal of Earth Sciences,* **55**, 449–471.

ROLLINSON, H.R., 1993: *Using geochemical data: evaluation, presentation, interpretation*. Longman Scientific & Technical, John Wiley & Sons, New York.

RUBENACH, M.J., FOSTER, D.R.W., EVINS, P.M., BLAKE, K.L. & FANNING, C.M., 2008: Age constraints on the tectonothermal evolution of the Selwyn Zone, Eastern Fold Belt, Mount Isa Inlier. *Precambrian Research,* **163**, 81–107.

RUTHERFORD, L., HAND, M. & BAROVICH, K., 2007: Timing of Proterozoic metamorphism in the Southern Curnamona Province: implications for tectonic models and continental reconstructions. *Australian Journal of Earth Sciences,* **54**, 65–81.

RYBURN, R.J., WILSON, I.H., GRIMES, K.G. & HILL, R.M, 1983a: *Cloncurry, Queensland, 1:100 000 Geological Map Commentary.* Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

SALISBURY, J.A., TOMKINS, A.G. & SCHAEFER, B.F., 2008: New insights into the size and timing of the Lawn Hill impact structure: Relationship to the Century Zn-Pb Deposit. *Australian Journal of Earth Sciences,* **55**, 587–603.

SCOTT, D.L., BRADSHAW, B.E. & TARLOWSKI, C.Z., 1998. The tectonostratigraphic history of the Proterozoic Northern Lawn Hill Platform, Australia: an integrated intracontinental basin analysis. *Tectonophysics,* **300**, 329–358.

SCRIMGEOUR, I., 2003: Developing a revised framework for the Arunta Region. *In*: Munson, T.J. & Scrimgeour, I., (Editors): Proceedings of the Annual Geoscience Exploration Seminar (AGES) 2003. *Northern Territory Geological Survey, Record* **2003-001**.

SCRIMGEOUR, I.R., KINNY, P.D., CLOSE, D.F. & EDGOOSE, C.J., 2005: High-T granulites and polymetamorphism in the southern Arunta Region, Central Australia: evidence for a 1.64Ga accretional Event. *Precambrian Research,* **142**, 1–27.

SCRIMGEOUR, I. & RAITH, J.C., 2001: High-grade re-working of Proterozoic granulites during Ordovician intraplate transpression, Eastern Arunta Inlier, central Australia. *In*: Miller, J., Holdsworth, R.E., Buick, I.S. & Hand, M. (Editors): Continental Reactivation and Reworking. *Geological Society of London, Special Publication* **184**, 261–287.

SENIOR, B.R. & HUGHES, R.J., 1972: Shallow Stratigraphic Drilling of Radioactive Anomalies at Eyre Creek, Springvale Sheet Area, Western Queensland. Department of National Development. Bureau of Mineral Resources, Geology and Geophysics Record, 1972/19.

SHEPPARD, S., GRIFFIN, T.J., TYLER, I.M. & PAGE, R.W., 2001: High- and low-K granites and adakites at a Palaeoproterozoic plate boundary in north-western Australia. *Journal of the Geological Society,* **158**, 547–560.

SHEPPARD, S., TYLER, I.M., GRIFFIN, T.J., TAYLOR, W.R. 1999: Palaeoproterozoic subduction-related and passive margin basalts in the Halls Creek Orogen, northwest Australia. *Australian Journal of Earth Sciences* **46**(5), 679–690.

SHERWOOD, N.R. & COOK, A.C., 1986: Organic matter in the Toolebuc Formation, *in* Gravestock, D.I., Moore, P.S. & Pitt, G.M. (Editors): Contributions to the geology and hydrocarbon potential of the Eromanga Basin, *Geological Society of Australia Special Publication* **12**, 255–265.

SINGER, D.A., 1995: World class base and precious metal deposits — a quantitative analysis. *Economic Geology*, **90**, 88–104.

SKIRROW, R.G., BASTRAKOV, E., BAROVICH, K., FRASER, G., FANNING, C.M., CREASER, R. & DAVIDSON, G., 2007: The Olympic Cu–Au province: timing of hydrothermal activity, sources of metals, and the role of magmatism., *Economic Geology,* **102**, 1441–1470.

SKIRROW, R.G., JAIRETH, S., HUSTON, D.L., BASTRAKOV, E.N., SCHOFIELD, A., VAN DER WIELEN, S.E. & BARNICOAT, A.C., 2009: Uranium mineral systems: processes, exploration criteria and a new deposit framework. *Geoscience Australia Record* **2009/20**.

SMART, J., GRIMES, K.G., DOUTCH, H.F. & PINCHIN, J., 1980: The Mesozoic Carpentaria Basin and the Cainozoic Karumba Basin, North Queensland, *BMR Bulletin* **202**.

SMITHIES, R.H. & BAGAS, L., 1997: High pressure amphibolite-granulite facies metamorphism in the Paleoproterozoic Rudall Complex, central Western Australia. *Precambrian Research,* **83**, 243–265.

SOUTHGATE, P.N., BRADSHAW, B.E., DOMAGALA, J., JACKSON, M.J., IDNURM, M., KRASSAY, A.A., PAGE, R.W., SAMI, T.T., SCOTT, D.L., LINDSAY, J.F., McCONACHIE, B.A. & TARLOWSKI, C., 2000: Chronostratigraphic basin framework for Paleoproterozoic Rocks (1730–1575Ma) in northern Australia and implications for base-metal mineralisation. *Australian Journal of Earth Sciences,* **47**, 461–483.

STEWART, G.A., 1954: Geomorphology of the Barkly region. *In* Survey of the Barkly Region, 1947-48. *CSIRO Land Research Series*, **3**, 42–58.

STEWART, A.J. & BLAKE, D.H. (Editors), 1992: Detailed studies of the Mount Isa Inlier. *Bureau of Mineral Resources, Australia, Bulletin* **243**.

STEWART, J.R. & BETTS, P.G., 2010: Late Palaeo-Mesoproterozoic plate margin deformation in the southern Gawler Craton: insights from structural and aeromagnetic analysis. *Precambrian Research,* **177**, 55–72.

SWAIN, G., BAROVICH, K., HAND, M., FERRIS, G. & SCHWARZ, M., 2008: Petrogenesis of the St Peter Suite, Southern Australia: Arc Magmatism and Proterozoic Crustal Growth of the South Australian Craton. *Precambrian Research, 166*, 283–296.

SWARBRICK, C.F.J., 1974: Oil shale in Queensland, *Geological Survey of Queensland Report* **83**.

SWEET, I.P. & HUTTON, L.J., 1982: *Lawn Hill Region, Queensland, 1:100 000 Geological Map Commentary.* Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

SWEET, I.P., MOCK, C.M. & MITCHELL, J.E., 1981: *Seigal, Northern Territory, Hedleys Creek Queensland., 1:100 000 Geological map commentary*. Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

SZPUNAR, M., HAND, M., BAROVICH, K.M. & JAGODZINSKI, E., 2007: Age and provenance of the Hutchison Group, southern Gawler Craton, South Australia. *In* Deformation in the Desert Conference 2007, GSA Conference Abstract Series,Geological Society of Australia Specialist Group, Tectonics and Structural Geology, 30.

TANG, J.E.H., 2004: Geochemistry processing methodology and its application to base metal exploration. Northern Queensland Exploration and Mining 2004 Extended Abstracts, *Australian Institute of Geoscientists Bulletin* **40**, 53–56.

TOTTERDELL, J.M., 1990: Notes to accompany a 1:500 000 scale Permian structure map of Australia, BMR Record 1990/40.

TUCKER, D.H., WYATT, B.W., DRUCE, E.C., MATHUR, S.P. & HARRISON, P.L., 1979: The upper crustal geology of the Georgina Basin region. *BMR Journal of Australian Geology and Geophysics*, **4**, 209–226.

TYLER, I.M., PAGE, R.W. & GRIFFIN, T.J., 1999: Depositional age and provenance of the Marboo Formation from SHRIMP U-Pb zircon geochronology: Implications for the early Palaeoproterozoic tectonic evolution of the Kimberley region, Western Australia. *Precambrian Research,* **95**, 225–243.

VINE, R.R., 1976: Eromanga Basin. *In* LESLIE, R.B., EVANS, H.J. & KNIGHT, C.L., 1976: Economic Geology of Australia and Papua New Guinea, 3. Petroleum. *AUSIMM Mongraph Series* **7, 306–**309.

von GNIELINSKI, F.E., (Compiler) 2010: *Queensland Minerals 20109. A Summary of major mineral resources, mines and prospects*. Department of Employment, Economic Development and Innovation.

VRY, J., COMPSTON, W. & CARTWRIGHT, I., 1996: SHRIMP II Dating of zircons and monazites: reassessing the timing of high-grade metamorphism and fluid flow in the Reynolds Range, northern Arunta Block, Australia. *Journal of Metamorphic Geology,* **14**, 335–350.

WADE, B.P., BAROVICH, K.M., HAND, M., SCRIMGEOUR, I.R. & CLOSE, D.F., 2006: Evidence for Early Mesoproterozoic arc magmatism in the Musgrave Block, Central Australia: implications for Proterozoic crustal growth and tectonic reconstructions of Australia. *Journal of Geology,* **114**, 43–63.

WALSHE, J.L., COOKE, D.R. & NEUMAYR, P., 2005: Five questions for fun and profit: A mineral systems perspective on metallogenic epochs, provinces and magmatic hydrothermal Cu and Au deposits. *In*: Mao, J. & Bierlein, F.P. (Editors): *Mineral Deposit Research: Meeting the Global Challenge*. Springer, Berlin, 477–480.

WALTHO, A.E. & ANDREWS, S.J., 1993: The Century zinc-lead deposit in north-west Queensland. *In*: *Proceedings Centenary Conference*. The Australasian Institute of Mining and Metallurgy, Melbourne*,* 41–61.

WELSH, W.D., 2000: *GABFLOW: A steady state groundwater flow model of the Great Artesian Basin*. Bureau of Rural Sciences, Canberra.

WIGHTMAN, D, 1995: EPM 9298 "Gidya" annual and final report for the period ending 30 March 1995. North Ltd. Company report held by Queensland Department of Employment, Economic Development and Innovation as CR26411.

WILLIAMS, L.J. & GUNTHER, L.M., 1989: GSQ Dobbyn 1 — Preliminary lithographic log and composite log. Geological Survey of Queensland Record 1989/22.

WILLIAMS, P.R. 1989: Nature and timing of early extensional structures in the Mitakoodi Quartzite, Mount Isa Inlier, north-west Queensland. *Australian Journal of Earth Sciences,* 36, 283-296

WILLIAMS, P.R. & BLAKE, D.H., 1992: Black Mountain — a strike-slip pull-apart structure in the Quilalar Fault System, Mount Isa Inlier. *In*: Stewart, A.J. & Blake, D. H. (Editors): Detailed Studies of the Mount Isa Inlier. *Australian Geological Survey Organisation, Bulletin,* **243**,191–197.

WILSON, I.H, DERRICK, G.M., HILL, R.M., DUFF, B.A., NOON, T.A. & ELLIS, D.J., 1977: Geology of the Prospector 1:100 000 Sheet area (6857), Queensland. *Bureau of Mineral Resources, Record* **1977/4**.

WILSON, I.H. & GRIMES, K.G., 1984: *Myally, Queensland, 1:100 000 Geological Map Commentary.* Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

WILSON, I.H. & GRIMES, K.G., 1986: *Coolullah, Queensland, 1:100 000 Geological Map Commentary*. Bureau of Mineral Resources, Geology and Geophysics, Australia, Canberra.

WILSON, I.H., HILL, R.M., NOON, T.A., DUFF, B.A. & DERRICK, G.M., 1979a: Geology of the Kennedy Gap 1:100 000 Sheet area (6757), Queensland. *Bureau of Mineral Resources, Record* **1979/24**.

WILSON, I.H., NOON, T.A., HILL, R.M. & DUFF, B.A., 1979b: Geology of the Quamby 1:100 000 Sheet area (6957), Queensland. *Bureau of Mineral Resources, Record* **1979/56**.

WITHNALL, I.W., 1996: Stratigraphy, structure and metamorphism of the Proterozoic Etheridge and Langlovale Groups, Georgetown region, north Queensland. *Australian Geological Survey Organisation, Record* **1996/15**.

WITHNALL, I.W., HUTTON, L.J., GARRAD, P.D., JONES, M.R. & BLIGHT, R.L. 2002: *North Queensland Gold and Base Metal Study Stage 1 Preliminary data release – Georgetown GIS*. Geological Survey of Queensland, Department of Natural Resources and Mines, digital data released on CD-ROM.

WITHNALL, I.W., MACKENZIE, D.E., DENARO, T.J., BAIN, J.H.C., OVERSBY, B.S., KNUTSON, J., DONCHAK, P.J.T., CHAMPION, D.C., WELLMAN, P., CRUIKSHANK, B.I., SUN, S.S. & PAIN, C.F., 1997: Georgetown Region. *In*: Bain, J.H.C. & Draper, J.J. (Editors): North Queensland Geology. *Australian Geological Survey Organisation, Bulletin* ***240*** *and Queensland Geology,* **9**, 19–116.

WORDEN, K.E., CARSON, C.J., CLOSE, D.F., DONNELLAN, N. & SCRIMGEOUR, I.R., 2008: Summary of results. Joint NTGS-GA geochronology: Tanami Region, Arunta Region, Pine Creek Orogen and Halls Creek Orogen correlatives, January 2005 – March 2007. *Northern Territory Geological Survey, Record* **2008-003**.

WYBORN, L., 1998: Younger ca 1500Ma granites of the Williams and Naraku Batholiths, Cloncurry District, eastern Mount Isa Inlier: geochemistry, origin, metallogenic significance and exploration indicators. *Australian Journal of Earth Sciences,* **45**, 397–411.

WYBORN, L.A.I., BASTRAKOVA, I.V., HENSLEY, C. & BUDD, A.R., 2001: Mount Isa Inlier Synthesis. *In*: Budd, A.R. Wyborn, L.A.I., & Bastrakova I.V.,: The Metallogenic Potential of Australian Proterozoic Granites. *Geoscience Australia Record* **2001/12**.

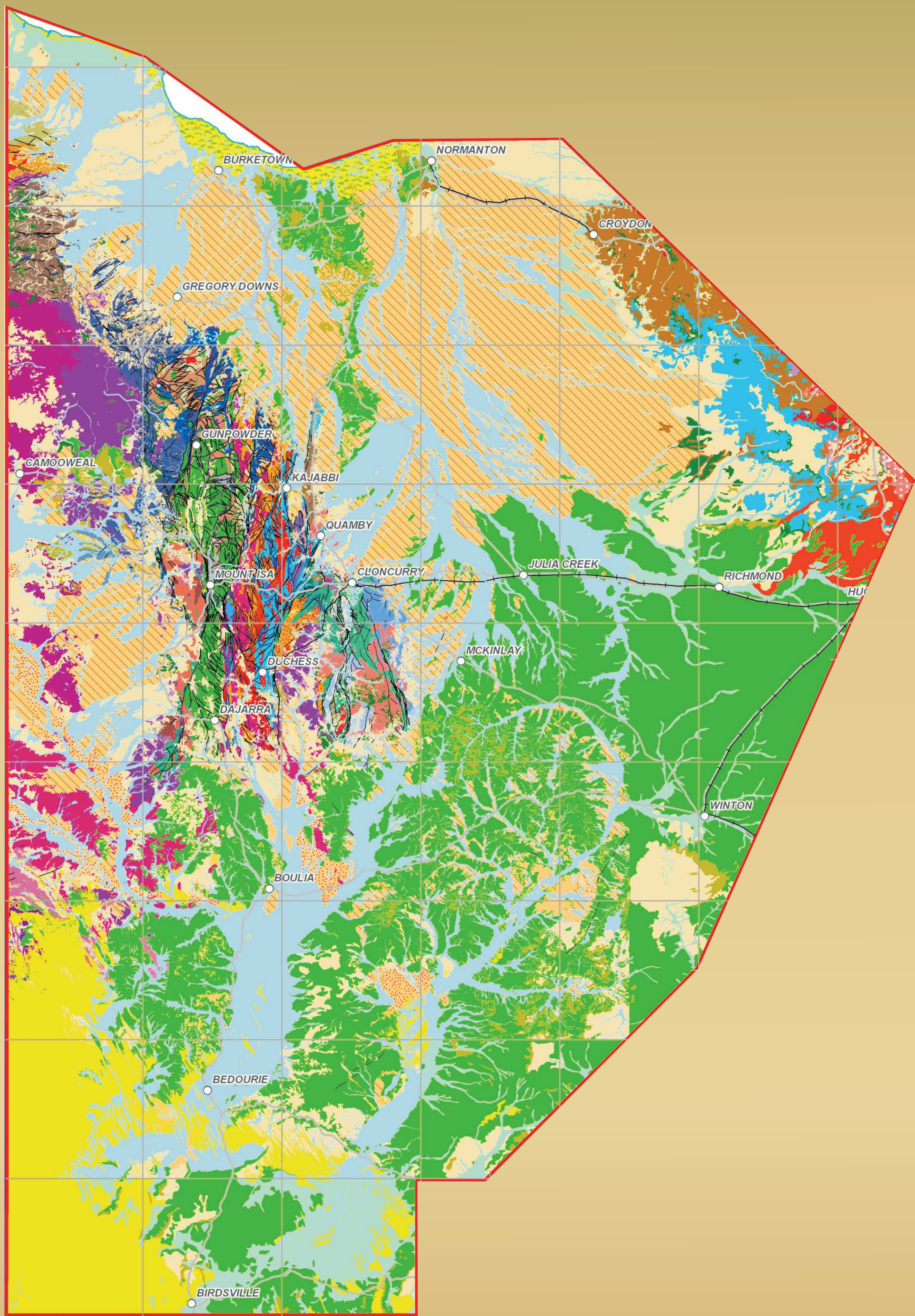
WYBORN, L.A.I., HEINRICH, C.A. & JAQUES, A.L., 1994: Australian Proterozoic mineral systems: essential ingredients and mappable criteria. *Australasian Institute of Mining & Metallurgy, Publication Series* **5**(94), 109–115.

WYBORN, L.A.I. & PAGE, R.W., 1983: The Proterozoic Kalkadoon and Ewen Batholiths, Mount Isa Inlier, Queensland: source, chemistry, age and metamorphism. *BMR Journal of Australian Geology & Geophysics,* **8**, 53–69.

WYBORN, L.A.I., PAGE, R.W. & McCULLOCH, M.T., 1988: Petrology, geochronology and isotope geochemistry of the post-1820Ma granites of the Mount Isa Inlier: mechanisms for the generation of Proterozoic anorogenic granites. *Precambrian Research,* **40-41**, 509-541.

ZHANG, Y., ROBERTS, P.A. & MURPHY, B., 2010: Understanding regional structural controls on mineralization at the century deposit: A numerical modelling approach. *Journal of Geochemical Exploration,* **106**(1–3), 244–250.

ZHAO, J.-X. & McCULLOCH, M.T., 1995: Geochemical and Nd isotopic systematics of granites from the Arunta Inlier, central Australia: implications for Proterozoic crustal evolution. *Precambrian Research,* **71**(1–4), 265–299.



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