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3D mineral potential of the Quamby area

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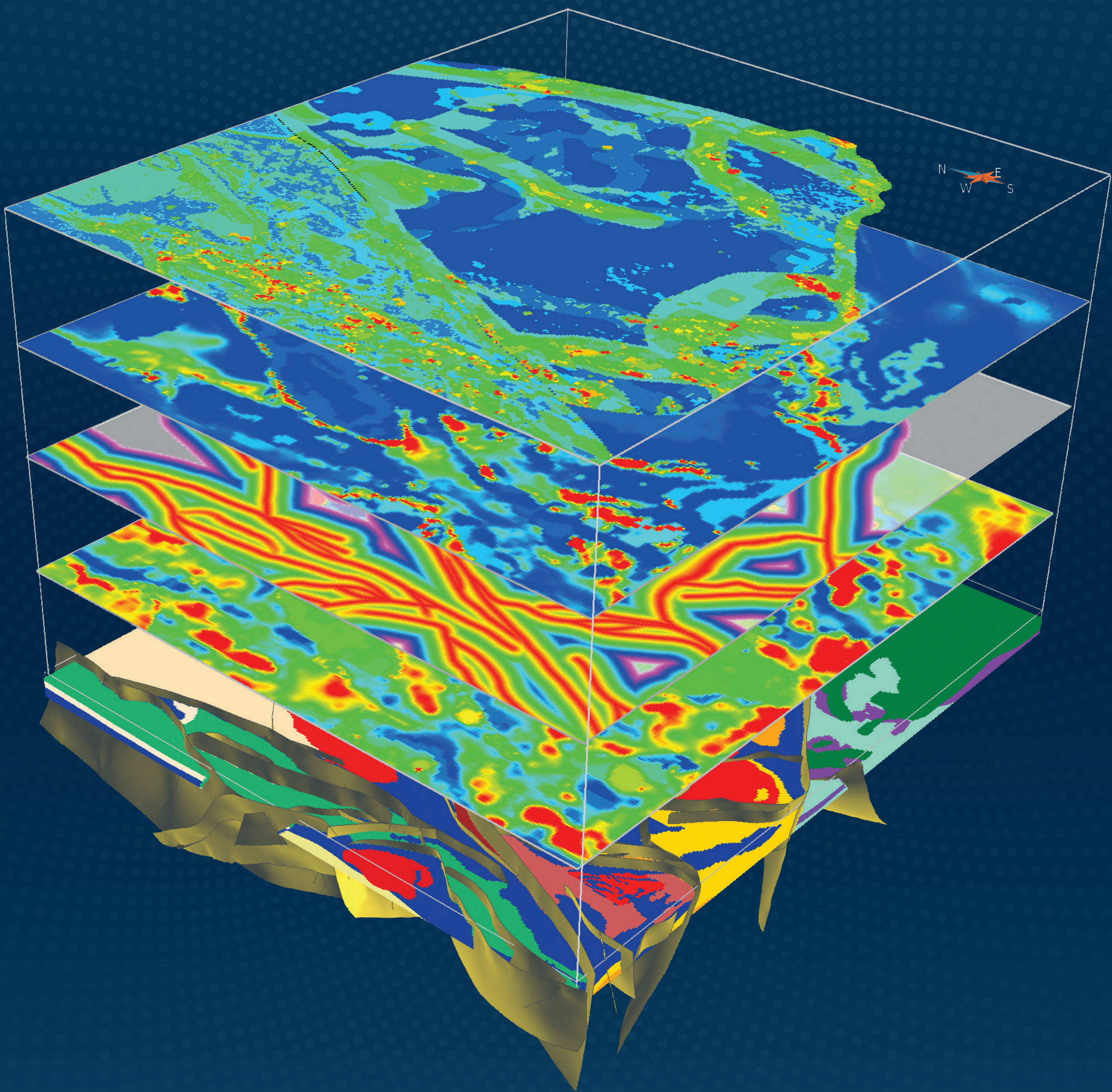

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Queensland Government

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Cover: Quamby 3D model with several key input datasets

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Contents

Figure

Table

Appendices

DVD contents

Summary

3D geological and geophysical modelling was used in conjunction with mineral potential modelling to assess unrealised Cu-Au potential in the Quamby area in the Eastern Succession of the Mount Isa Inlier. This report documents the process used by the Geological Survey of Queensland, including 3D modelling and geophysical inversion, to create a Common Earth Model (CEM) for 3D mineral potential modelling over the Quamby Project area. The area is divided into three main geological domains — the Mary Kathleen, Constantine and Soldiers Cap Domains (adapted from the North-West Queensland Mineral and Energy Province Report (NWQMEPR), Geological Survey of Queensland, 2011b).

The Quamby Project area contains the major operating Ernest Henry Cu-Au mine as well as other significant Cu-Au projects and is highly prospective for a range of mineralisation styles including Cu±Au±Fe deposits and stratabound sediment-hosted Cu deposits. Mesozoic and Cenozoic sediments cover more than 70% of the project area. Although interpreted cover depths are generally less than 150m, much of the area remains under-explored.

A 3D geological model was created using GOCAD and SKUA software incorporating new interpretations from recent mapping by the Geological Survey of Queensland (Geological Survey of Queensland, 2011b) as well as drillhole and seismic data. This 3D model was used as a starting model to constrain potential field inversions yielding 3D physical property models (density and magnetic susceptibility).

The 3D physical property models show the distribution of the density and magnetic susceptibility properties within the topmost 2.5km of the crust within the project area. These property distributions can be used to directly assist exploration targeting and allow interpretation of the regional structural and geological setting. In particular the property models can be used to define structural breaks and alteration pathways.

Literature reviews were undertaken over the major Cu-Au deposits within the Quamby Project area with relevant data having been collated into Appendix 2. Available information on mineralisation, including depositional environment, fluid source and geophysical characteristics within both the Mary Kathleen and Constantine Domains (the project area's two main prospective domains), was used to create targeting criteria, called evidential properties, which were tested using a Weights-of-Evidence (WoE) approach.

A Common Earth Model (CEM) was prepared at the same resolution as the physical property models mentioned above. This CEM contains the lithological and physical rock properties from the inversions and properties representing the identified targeting criteria for Au-Cu mineralisation. For the WoE modelling the CEM also contains training cells, representing known mineral occurrence sites.

The Weights-of-Evidence modelling method assesses the relationship between the identified evidential properties and the training cells. The evidential properties within the study area found to have a strong association with mineralisation include the geological complexity, distance to faults and fault curvature, geochemical anomalies and anomalous regions within the density and magnetic susceptibility models (derived from the inversions). 3D mineral potential models were created by combining the statistically significant evidential properties for each domain.

The 3D mineral potential models represent the relative probability of each individual cell within the model hosting Cu-Au mineralisation. Mineral potential models were generated separately for the Mary Kathleen and Constantine Domains as the style of mineralisation and significant evidential properties were different in each domain.

As well as highlighting locations of known mineralisation, the mineral potential models show extensions along trends and define high potential areas under shallow cover in previously unexplored regions.

Introduction

Modern mineral exploration requires a multi-disciplinary approach using a range of techniques and data sources and a thorough understanding of relevant mineral systems. Using this approach, targeting strategies developed in exposed data-rich terranes of the Mount Isa Inlier can be extrapolated into adjacent lesser known areas, where prospective bedrock is concealed by Mesozoic and Cenozoic cover beyond the reach of typical exploration drillholes. This report details the application of this concept to the Quamby region of north-west Queensland.

The Quamby Project area is 93.6km long by 81km wide, extending east from the Mount Rose Bee Fault and north from Cloncurry in north-west Queensland (Figure 1) within the bounds of the 2011 North-West Queensland Mineral and Energy Province Report (Geological Survey of Queensland, 2011b). Proterozoic outcrop varies from good to poor in the west and south-west to concealed in the north-east. Mesozoic and Cenozoic sediments cover more than 70% of the area. Interpreted cover depths are generally less than 150m, but increase significantly to the east. Consequently, much of the area has been under-explored.

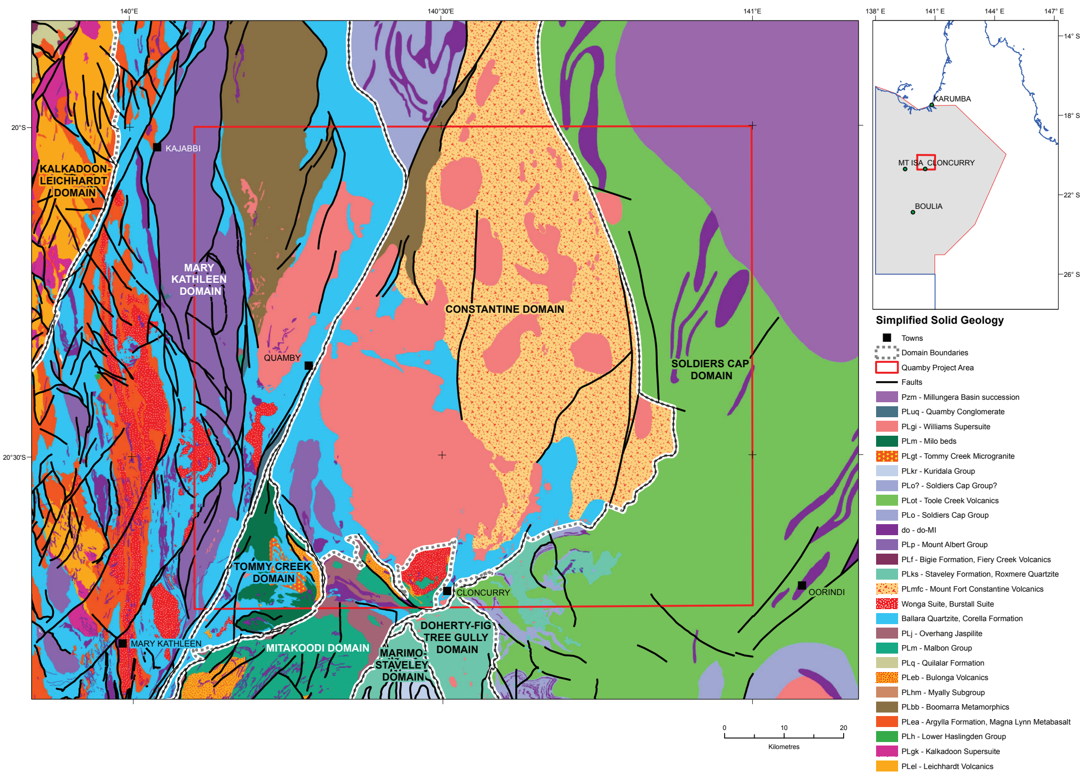

Figure 1: Location of the Quamby Project area (red rectangle)

The project area includes the major operating Ernest Henry Cu-Au mine as well as significant Cu-Au projects such as the recently operating E1 Camp/Mount Margaret mine, Rocklands and Roseby projects, and the Dugald River Ag-Pb-Zn deposit. The region remains highly prospective for a range of mineralisation styles including Cu±Au±iron oxide deposits, stratabound sediment-hosted Cu deposits, sediment-hosted Ag-Pb-Zn deposits, Au and Cu veins, Cu skarns, roll-front uranium in Mesozoic sediments, and magnetite-hematite in Cu±Au±iron oxide deposits, ironstone lenses and banded ironstones.

The primary objective of modelling in the Quamby region was to provide geologically and geophysically constrained 3D property models that could be employed in regional mineral exploration targeting. A 3D geological model of the project area was constructed in GOCAD and then used to constrain 3D density and magnetic susceptibility geophysical inversions. The results of the geophysical inversion were combined into a Common Earth Model (CEM) which also incorporated mineral exploration targeting criteria and known mineral occurrences.

A data-driven 3D Weights-of-Evidence study was undertaken using the CEM to statistically assess the spatial relationship between the exploration criteria (developed from literature research and previous studies undertaken in the area) and known copper and gold mineral occurrences. The Weights-of-Evidence modelling was used to produce 3D mineral potential models representing the relative probability of each individual cell within the model hosting mineralisation.

This report summarises the exploration significance of the mineral potential modelling and is accompanied by a large set of digital products on the included DVDs, including a GIS package, GOCAD project and 3D model objects in various formats as well as report appendices discussing, in detail, the geological setting, mineral systems/styles and known mineral occurrences.

Geological setting

The Quamby Project area lies within the so-called ‘Eastern Succession’ of the Mount Isa Inlier, encompassing seven geological domains which were defined in the Geological Survey of Queensland’s North-West Queensland Mineral and Energy Province Report (Geological Survey of Queensland, 2011b). The report presented a geodynamic synthesis of the Mount Isa region, and included a significant revision of the stratigraphic framework for the area which has been adopted for the current study. The subdivision of the inlier into domains was based on a combination of geophysical character, metamorphic grade, basin evolution, structural grain and geochronology. The domains replace the previously defined subprovinces within the Eastern Succession shown in the earlier North-West Queensland Mineral Province Report (Queensland Department of Mines and Energy & others, 2000).

Geological domains

The Mary Kathleen, Constantine and Soldiers Cap Domains were the main areas of focus in this study, with only the northern edges of the Tommy Creek, Doherty – Fig Tree Gully and Mitakoodi Domains captured within the southern margin of the project area (Figure 2). Extended descriptions of the stratigraphic framework of the project area and domains are found in Appendix 1.

The new term, **Constantine Domain**, is introduced to replace the Canobie Domain presented in the North-West Queensland Mineral and Energy Province Report (Geological Survey of Queensland, 2011b). The primary reason for this change is due to the tenuous association of the name with a variety of geological and geographic entities, such as the Triassic Canobie Depression, the Proterozoic (maximum depositional age of ~1590Ma) Canobie Succession and the Canobie Station location. The new name, Constantine Domain, better represents the location and geological association of the domain, which is interpreted to be dominated by the Mount Fort Constantine Volcanics. This report also proposes a new domain, the **Donors Hill Domain**, located to the west of the Constantine Domain replacing the western extent of the Soldiers Cap Domain surrounding the Constantine Domain.

The **Mary Kathleen Domain** in the west of the Quamby project area is interpreted to be underlain by a largely unexposed felsic volcanic-dominated basement of Leichhardt Volcanics (dated at ~1860Ma) and overlying the Argylla Formation (dated at ~1780Ma). The latter gives way to the coeval Boomarra Metamorphics which are exposed in the north. These units are overlain by the carbonate-siliciclastic Ballara Quartzite/Corella Formation package and, in the west of the model, the Mount Albert Group. The Mary Kathleen Domain is intruded by a series of ~1740Ma Wonga – Burstall Suite plutons including the large Dipvale Granodiorite. The eastern boundary of the Mary Kathleen Domain with the Constantine, Tommy Creek and Mitakoodi Domains is the Pilgrim and Quamby Fault zones.

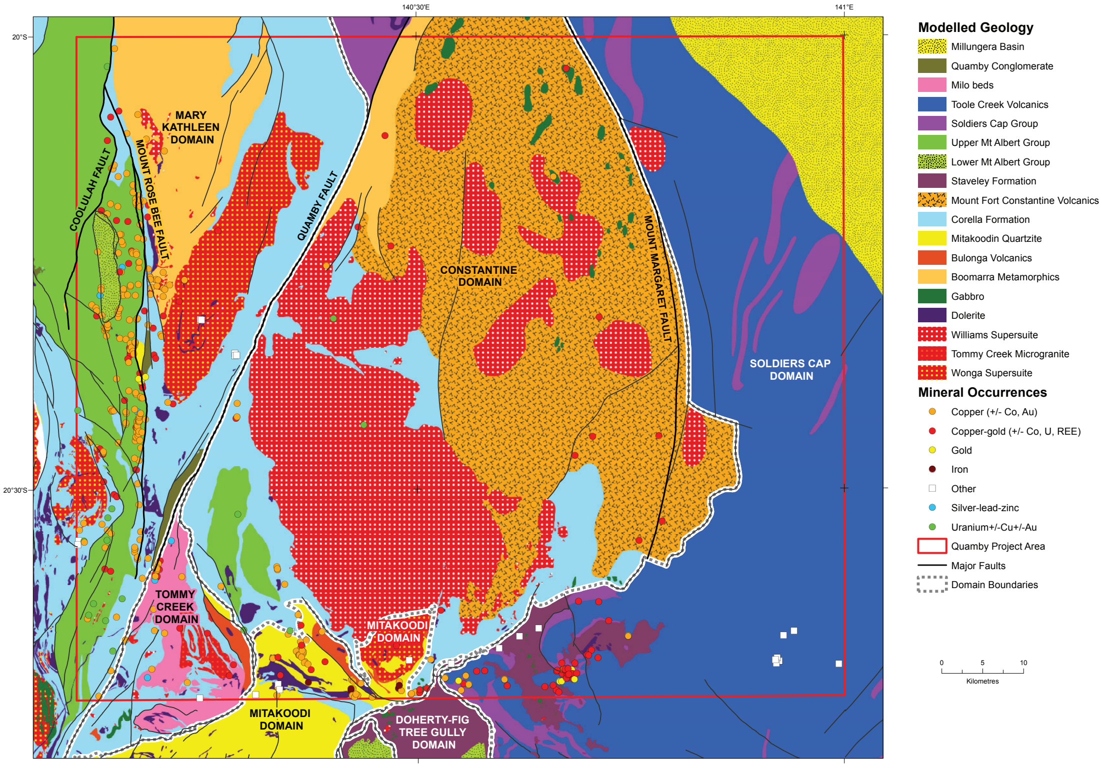

Figure 2: Geological domains of the Quamby Project with modelled geology (derived from the simplified solid geology from NWQMEPR), with major faults and all known mineral occurrences discriminated by commodity.

The **Constantine Domain** is mostly covered by Mesozoic and Cenozoic sediments, with Proterozoic units only outcropping in the south. The basement of the Constantine Domain and the Mary Kathleen Domain are believed to be similar, consisting of the Leichhardt Volcanics and the Argylla Formation. In the north of the Constantine Domain, the basement sequence additionally consists of the Boomarra Metamorphics overlying these units. These units are overlain by the Corella Formation and felsic to intermediate volcanics assigned to the Mount Fort Constantine Volcanics which host the Ernest Henry deposit. The Constantine Domain is intruded by both Wonga–Burstall Suite and Williams Supersuite plutons with the large Malakoff Granite dominating the southern section of the domain. The eastern margin of the Constantine Domain with the Soldiers Cap Domain is defined by the Mount Margaret Fault. The southern margin of the Constantine Domain with the Mitakoodi Domain is marked by the Highway Thrust.

The **Soldiers Cap Domain**, like the Constantine Domain, is nearly entirely covered by Mesozoic and Cenozoic sediments with only small areas of Proterozoic exposure in the south of the project area. Basement in the Soldiers Cap Domain is believed to be the ~1760Ma felsic-dominated Bulonga Volcanics which is overlain by the calc-silicates of the Staveley Formation (including rocks previously mapped as the Doherty Formation). The Staveley Formation is in turn overlain (probably mainly structurally) by the Soldiers Cap Group, comprising the meta-turbidites of the Llewellyn Creek Formation and Mount Norna Quartzite and the uppermost finer grained meta-sediments and mafic lavas and sills of the Toole Creek Volcanics. The Millungera Basin is a recently discovered succession located in the north-east of the Quamby Project area which unconformably overlies the Soldiers Cap Group. The Soldiers Cap Domain is intruded by granitic and mafic rocks of the Williams Supersuite, emplaced over a protracted period from ~1540–1500Ma.

The youngest sedimentation recorded in exposed rocks of the project area was the ~1660–1610Ma deposition of the calcareous Milo beds in the **Tommy Creek Domain**.

Deformation history

A major regional extensional tectonic event at ~1740Ma is thought to separate deposition of the Leichhardt/Argylla/Ballara/Corella package of rocks from that of the younger Staveley/Mount Albert Group/Soldiers Cap Group package of rocks. This event (the Wonga Event; see Pearson & others, 1992) is interpreted to have been accompanied by intrusion of the Wonga–Burstall Suite of granitoids, and also perhaps by eruption of the Mount Fort Constantine Volcanics within the Constantine Domain. Deformation and metamorphism related to this extensional event is restricted almost entirely to the Mary Kathleen Domain, although the Double Crossing Metamorphics and Gin Creek Granite within the Marimo–Staveley Domain (south of the project area) record metamorphism and intrusion during the same event. The Wonga Event was accompanied by a metamorphic peak, but Rubenach & others (2008) questioned the regional extent of the accompanying metamorphism.

Sedimentation in the youngest Eastern Succession sequences was brought to a halt by the ~1600–1570Ma ***Early Isan Orogeny*** (D_1) accompanied by N–S to NW–SE directed crustal shortening. In the Mitakoodi and Soldiers Cap Domains crustal shortening was accommodated by movement along shallow, west dipping decollements (e.g. the Overhang Shear Zone) and nappe development in the hanging walls of the decollements. The peak of the accompanying high temperature, low pressure metamorphism occurred at ~1570–1580Ma (Rubenach & others, 2008).

These events were succeeded by further regional shortening of the ***Middle Isan*** (D_2) and ***Late Isan Orogenies*** which spanned the 1570–1500Ma time period. The former was characterised by strong E–W compression producing the strong N–S structural grain of the Mary Kathleen and Soldiers Cap Domains, while the latter was dominated by brittle wrench style faulting.

Stress field rotation during these episodes has resulted in complex east-trending and northerly trending interference fold patterns in parts of the Soldiers Cap Domain. 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-Naraku Supersuite were intruded over a protracted period (mainly between ~1550 and 1500Ma), and were only locally affected by wrench faulting of the Late Isan Orogeny.

The age of Canobie Succession is uncertain but the rocks have undergone deformation and low grade metamorphism, presumed to be related to one of the later phases of the Isan Orogeny. Palaeozoic deformation is inferred to have affected at least the eastern part of the Soldiers Cap Domain as the eastern margin of the overlying Millungera Basin is deformed by east-dipping post-Middle Devonian thrusts identified in the Isa–Georgetown deep seismic reflection profile.

Mineralisation

The Quamby Project area is host to a number of different mineralisation styles, with epigenetic Cu±Au±iron oxide (combining iron oxide Cu-Au (-U-REE) and structurally controlled Cu-Au) and stratabound sediment hosted Cu mineralisation styles comprising the majority of the known deposits in the area (as shown in Figures 3 and 4). Other mineralisation styles within the area include shear hosted hydrothermal, vein calcite ± Cu, sediment hosted Pb-Zn-Ag and limestone deposits. The project area lies completely within the Cloncurry 1:250 000 map sheet area and known mineralisation has been previously compiled and field checked during the mineral occurrence mapping program (Denaro & others, 2004), with active prospects and mines updated regularly as part of the Queensland Minerals release. Current known resources within the project area are listed in Table 1.

Copper mineralisation within the project area was discovered around 1865 and gold mineralisation in 1867, with small scale mining starting soon after. Historical gold mining ended in the early 1940s, while copper mining continued in some capacity through to recent times. Copper was the main commodity mined, followed by gold, limestone, silver and uranium in more recent times. Currently there are four operating mines within the project area — Ernest Henry (Cu, Au and Mt), Mount Margaret (Cu, Au), Castlereagh (gravel), Great Australia (Cu), with the Lorena (Au) mine currently on care and maintenance (as of December 2012). Advanced projects include the Roseby Group Copper Project and the Dugald River deposit within the Mary Kathleen Domain and the Rocklands Group Copper Project within the Mitakoodi Domain.

The majority of company exploration in the Constantine Domain has been focused on Ernest Henry style mineralisation using geophysical methods to target similar style deposits undercover. In the Mary Kathleen Domain within the western part of the project area, exploration has been focussed on structurally-controlled fault and shear zone-hosted Cu±Au mineralisation and stratabound Cu using surface geochemical methods (soil, stream and rock chip sampling and RAB drilling) and surface expressions of copper mineralisation. Very little company exploration has been undertaken in the Soldiers Cap Domain due to the increasing depth of cover to the east.

Key references discussing the major deposits in the project area have been included in this report as Appendix 2.

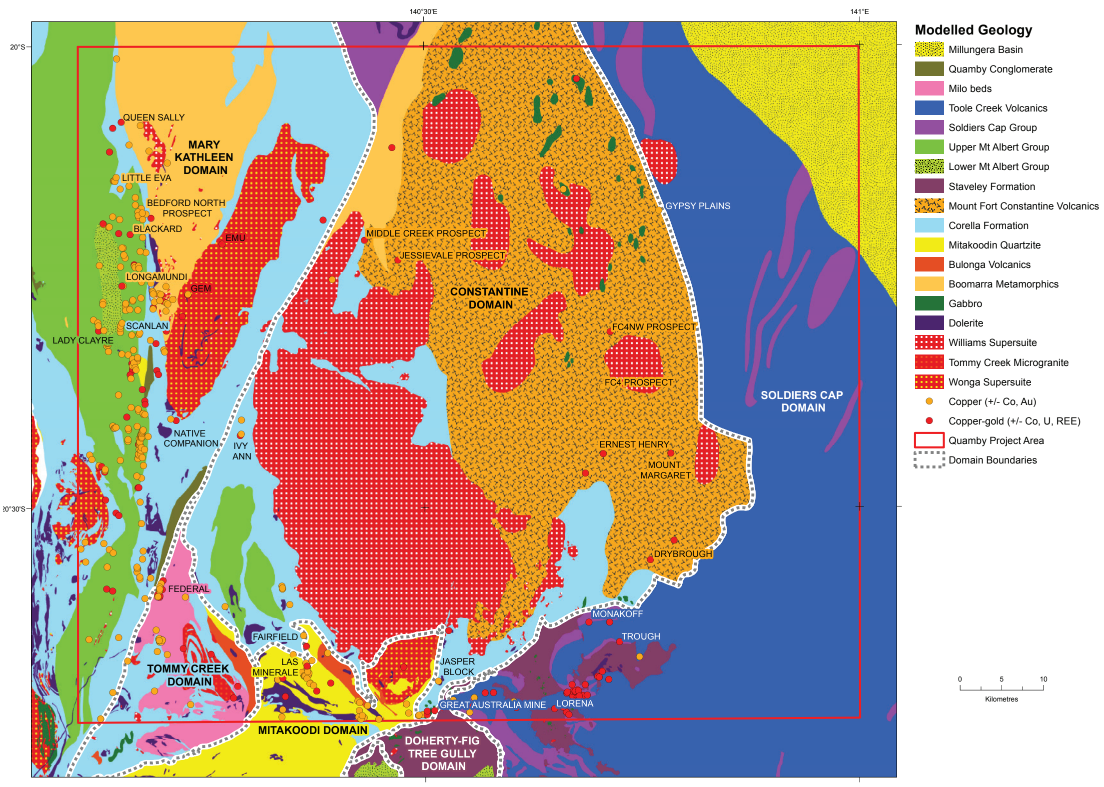

Figure 3: Location of copper-gold and copper deposits (including operating mines) and mineral occurrences in the Quamby Project area

Table 1: Current resources within the project area as of December 2012 (Geological Survey of Queensland, 2011a)

Deposit name	Inferred Resource	Indicated Resource	Measured Resource
Ernest Henry	13Mt @ 1.2% Cu, 0.6g/t Au and 26% Magnetite (1.15% Cu equivalent cutoff)	71Mt @ 1.3% Cu, 0.7g/t Au and 28% Magnetite (1.15% Cu equivalent cutoff); Probable reserve of 74Mt @ 0.95% Cu, 0.5g.t Au and 23% Magnetite (included within combined measured and indicated resource)	4Mt @ 1.3% Cu, 0.7g/t Au and 32% Magnetite (1.15% Cu equivalent cutoff)
Monakoff (includes Monakoff East)	1Mt @ 1.2% Cu and 0.4g/t Au (0.5% Cu cutoff) Uranium: 1 902 000t @ 0.0183% U_3O_8 (0.5% Cu cutoff)	2Mt @ 1.4% Cu and 0.4g/t Au, including a probable reserve of 1.9Mt @ 1.35% Cu and 0.43g/t Au (0.5% Cu cutoff)	
E1 Camp/Mount Margaret (including E1 North, South and East)	1.4Mt @ 0.6% Cu and 0.2g/t Au (0.3% cutoff) Uranium: E1 North – 7.93Mt @ 0.0151% U_3O_8; E1 South – 10.3Mt @ 0.0099% U_3O_8; E1 East – 8Mt @ 0.0113% U_3O_8 (0.5% Cu cutoff)	25Mt @ 0.7% Cu and 0.2g/t Au, including a probable reserve of 17Mt @ 0.75% Cu and 0.22g/t (0.3% Cu cutoff)	9Mt @ 0.9% Cu and 0.3g/t Au, including a proven reserve of 9.2Mt @ 0.87% Cu and 0.25g/t Au (0.3% Cu cutoff)
Great Australia	800 000t @ 0.14g/t Au and 1.57% Cu (0.5% Cu cutoff)	1.4Mt @ 0.13g/t Au and 1.53% Cu (0.5% Cu cutoff)	
Lorena	A Lode – 177800t @ 9.8g/t Au		B Lode – 95 000t @ 7.2g/t Au
Roseby Copper Project			
Ivy Ann	Primary ore – 2 100 000t @ 0.49% Cu and 0.06 g/t Au (0.3% Cu cutoff); Oxide ore – 1 240 000t @ 0.55% Cu and 0.08g/t Au (0.3% Cu cutoff)	Primary ore – 5 400 000t @ 0.6% Cu, and 0.08g/t Au (0.3% Cu cutoff)	
Lady Clayre	Oxide ore – 340 000t @ 0.51% Cu and 0.16g/t Au; Primary ore – 10 400 000t @ 0.54% Cu and 0.18g/t Au (0.3% Cu cutoff)	Primary ore – 3 600 000t @ 0.6% Cu and 0.24g/t Au (0.3% Cu cutoff)	
Bedford (includes Bedford North and South)	Oxide ore – 240 000t @ 1.12% Cu and 0.21g/t Au; Primary ore – 400 000t @ 0.83% Cu and 0.16g/t Au (0.3% Cu cutoff)	Primary ore – 1 300 000t @ 10.4% Cu and 0.21g/t Au (0.3% Cu cutoff)	
Blackard	Native Copper, Transitional and Sulphide ore – 42 740 000t @ 0.59% Cu (0.3% Cu Cutoff)	Native Copper, Transitional and Sulphide ore – 6 630 000t @ 0.60% Cu (0.3% Cu Cutoff)	Native Copper, Transitional and Sulphide ore – 26 980 000t @ 0.68% Cu (0.3% Cu cutoff)
Scanlan	Native Copper, Transitional and Sulphide ore – 3 810 000t@ 0.60% Cu (0.3% Cu Cutoff)	Native Copper, Transitional and Sulphide ore – 18 390 000t @ 0.65% Cu (0.3% Cu Cutoff)	
Longamundi	10 400 000t @ 0.66% Cu (0.3% Cu cutoff)		
Charlie Brown	700 000t @ 0.4% Cu (0.3% Cu cutoff)		
Little Eva	Oxide ore – 7 700 000t @ 0.39% Cu and 0.09g/t Au; Primary ore – 22 600 000t @ 0.49% Cu and 0.11g/t Au (0.2% Cu cutoff)	Primary ore – 41 400 000t @ 0.48% Cu and 0.08g/t Au; includes probable reserves of 13.69Mt at 0.69% Cu and 0.13g/t Au (0.2% Cu cutoff)	Primary ore – 36 300 000t @ 0.63% Cu and 0.08g/t Au – includes proved reserves of 1.77Mt at 1.03% Cu and 0.12g/t Au. (0.2% Cu cutoff)
Legend	Native Copper ore – 7 080 000t @ 0.59% Cu; Transitional ore – 550 000t @ 0.54% Cu; Sulphide ore – 9 800 000t @ 0.51% Cu (0.3% Cu cutoff)		
Great Southern	6 000 000t @ 0.61% Cu (0.3% Cu cutoff)		
Salebury	Salebury Oxide Zone – 12 200t @ 0.4 g/t Au and 0.87% Cu; Salebury Primary ore – 152 700t @ 0.71% Cu and 0.41 g/t Au (0.5% Cu cut-off)	Salebury Oxide Zone – 32 400t @ 0.45g/t Au and 0.82% Cu; Salebury Primary ore – 968 000t @ 0.93% Cu and 0.57g/t Au (0.5% Cu cut-off);	
Rocklands Group Copper Project (Las Minerale, Rocklands Central and South and Le Meridian)	1 100 000t @ 1.06% Magnetite, 0.8% Cu, 0.0281% Co and 0.1% Au (0.8% Cu eq cutoff)	16 400 000t @ 1.32% Magnetite, 0.81% Cu, 0.0367% Co and 0.19% Au (0.8% Cu eq cutoff)	13 800 000t @ 3.53% Magnetite, 1.1% Cu, 0.0597% Co and 0.19% Au (0.8% Cu eq cutoff)
Gem	491936t @ 0.51% Cu and 0.19g/t Au (0.2% Cu cutoff)		

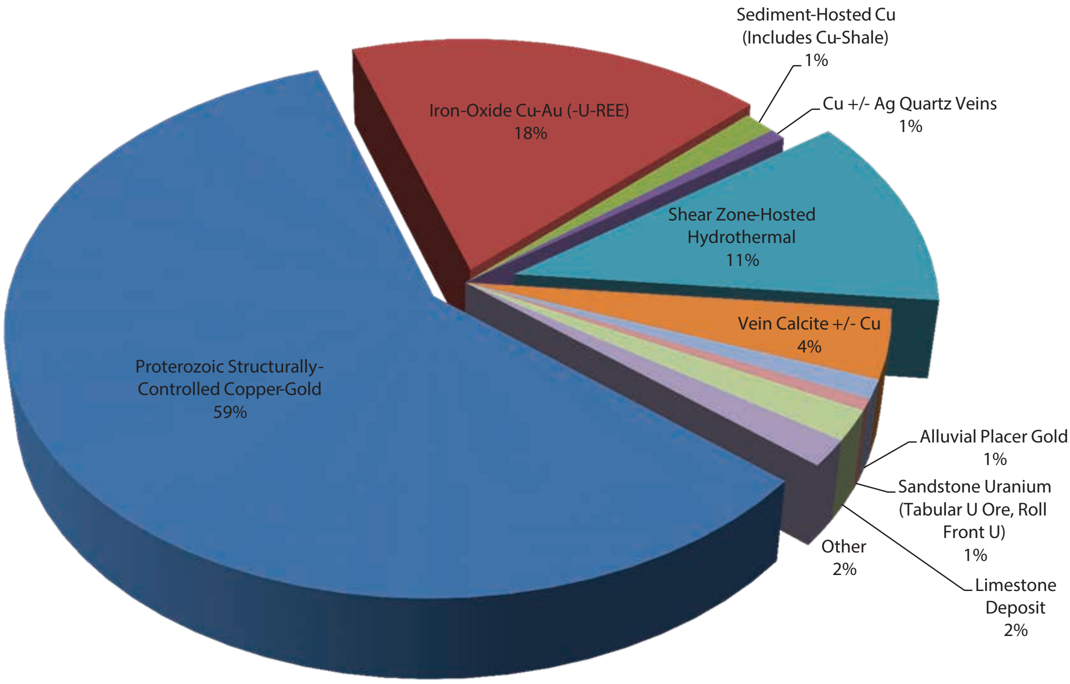

Figure 4: Pie chart of mineral occurrences by deposit model, with data taken from the MINOCC database over the Quamby Project area (Geological Survey of Queensland, 2011a). The other categories on the pie chart include copper skarns, epithermal, uranium veins, mesothermal veins, metamorphic-related (slate belt veins) and mesothermal veins.

Mineralisation styles

The exploration criteria for mineralisation targeting within the Quamby project area was developed from literature research of studies within the Mount Isa Eastern Succession (specifically structurally-controlled epigenetic Cu±Au±iron oxide) and previous detailed studies over the Mount Dore 3D model area, contained in the North-West Queensland Mineral and Energy Province Report (Geological Survey of Queensland, 2011b). The criteria focused on two main mineralisation styles — 1) structurally-controlled epigenetic Cu±Au±iron oxide mineralisation (Ernest Henry, E1 Camp etc.) and 2) sediment hosted stratabound Cu mineralisation (Blackard, Scanlan etc.). These two mineralisation styles are the dominant mineralisation styles in the project area, with all of the known copper-gold resources in the area related to one of these mineralisation styles.

A summary of the current understanding of the controlling factors for both mineralisation styles being assessed within the Quamby Project area is below.

Structurally-controlled epigenetic Cu±Au±iron oxide

- Mineralising fluids may be complex and heterogeneous in view of their possible interactions with a variety of wall rocks. Fluid pathways and sites of fluid mixing are much more important than fluid sources for controlling the distribution of deposits. A common mineralising process can generate deposits in a variety of host rocks depending on the fluid pathways (Mustard & others, 2005a,b).
- Cu and Au anomalism in soils, rock chips and RAB holes and the presence of sulphides appear to be the most direct geochemical and mineralogical signals of potential Cu-Au targets. Although deposits may also exhibit strong anomalism in elements such as Co, Mo, Ba, U, Ag, Pb, Zn, Bi, As, Ni, Se, Hg, Te, Sn, W, Ca, Mn, Y, F, Cl and heavy REEs, related geochemical anomalies are commonly not much more broadly developed than the Cu and Au anomalism (Queensland Department of Mines and Energy & others, 2000).

- 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.

- Exploration for Ernest Henry and Starra style deposits should focus on recognition of oxidised corridors in relation to structurally-defined targets, but recognition of truly large deposits (Ernest Henry and larger) may require recognition in the 3D model of both oxidised and reduced corridors (Oliver & others, 2005). This can be identified through geophysical interpretation: strongly magnetic and higher density response = magnetite alteration; moderate magnetic + high density response = pyrrhotite alteration; low magnetic + high density response = hematite alteration.

- Iron oxide-copper-gold deposits are generally marked by coincident magnetite and hematite-sulphide anomalies in potential field inversion modelling of density and magnetic susceptibility from gravity and magnetic data (Chopping & others, 2010). High density, low magnetic susceptibility zones could represent hematitic targets.

- There is a strong positive correlation between copper endowment and geological complexity. Geological complexity is a measure of the combination of faults and lithological boundaries (Ford, 2006; Ford & Blenkinsop, 2008b).

- Fractal measurements of fault roughness indicate that the roughest faults in the Mount Isa Inlier (for example, Mount Gordon and Mount Isa Faults) are endowed with orders of magnitude more metal/km^2 than the smoothest faults. Intermediate roughness faults (for example, Fountain Range, Mount Remarkable, Cloncurry, Pilgrim and Termite Faults) have significant to no mineral endowment (Blenkinsop & others, 2005a,b)

- The presence of major basement crustal structures can be delineated by abrupt gravity gradients. Reactivated north–south and east-north-east oriented basement structures have a district-scale control on localising fluids responsible for Cu-Au mineralisation (Mustard & others, 2005a,b). In some places, the only evidence for these fertile deep crustal structures is the alignment of deposits (Davidson & Large, 1998).

- Stress partitioning, stress anomalies and failure seem to be regionally important guides. Broad-scale mechanical/numerical analyses of parts of the fault arrays most favourable for failure in tension or extensional shear failure (Weights-of-Evidence, UDEC, FLAC) can be used to identify sites of strain partitioning, stress anomalies and failures using 2D and 3D prospect data from 1:100 000 to 1:10 000 scales (Murphy & others, 2008).

- In the Eastern Succession, clustering of copper deposits shows a high correlation with the clustering of mafic intrusives (Ford & Blenkinsop, 2008b). Mafic intrusives play a potential role in Cu-Au deposition by providing rheological contrast and/or a potential source of sulphur (Mustard & others, 2005a,b). Metals may have been transported and deposited from magmatic-hydrothermal fluids on crystallisation of the mafic rocks, or from metamorphic fluids that subsequently leached them (Blenkinsop, 2005). Oliver & others (2008) showed a close spatial relationship between Cu-Au mineralisation and mafic rocks (<500m) and, in particular, with faults connected to mafic rocks within a 1km buffer. Proximity to gravity gradients (basement architecture) and gravity highs (mafics in crust) are important targeting criteria (Blenkinsop, 2005).

- The deposits are hosted by a variety of rock types, ranging from epigenetic and syngenetic ironstone, through carbonaceous phyllite, quartz-mica schist, black shale and meta-arkose, to intermediate metavolcanic rocks and amphibolites (Kositcin & others, 2009). Cover Sequence 3 and the upper units of Cover Sequence 2 (terminology of (Queensland Department of Mines and Energy & others, 2000) are the preferred hosts (Blenkinsop, 2005). Strong rock property contrasts in association with fault offsets are an important component.

- The Staveley Formation (including some rocks previously mapped as Corella or Doherty Formation) – Soldiers Cap Group contact plays a significant role, possibly by localising faulting, fluid flow and juxtaposing lithologies of contrasting rheology, geochemical character and oxidation state (Blenkinsop, 2005; Mustard & others, 2005b). This contact is characterised by juxtaposition of calc-silicate and meta-sedimentary lithologies.

- Many of the more significant Cu-Au-iron oxide deposits in the Eastern Succession are hosted in, or are spatially related to, large, hydrothermal breccia systems. These breccias generally have a close spatial relationship with felsic-mafic intrusions of the Williams – Naraku Batholith (Cleverley & Oliver, 2005).
- In many deposits, there is an early albitic alteration assemblage that is overprinted by later K±Fe-bearing or calcic skarn assemblages (Kositcin & others, 2009).
- Potassic alteration and uranium anomalism, commonly associated with oxidised styles of Cu-Au mineralisation, can be expressed by radiometric anomalies, identifiable from the interpretation of airborne or ground radiometric data in areas lacking post-mineralisation cover (Queensland Department of Mines and Energy & others, 2000).
- Hyperspectral mineral maps, alone or in combination with other geophysical data (for example, magnetics or radiometrics), can be used to detect not only possible host rocks, but also alteration assemblages and their spatial distribution. A good knowledge of the mineralisation-related alteration assemblage and its spatial distribution, in combination with a good knowledge of the geology (calibration) of the investigated area, is required (Laukamp & others, 2008; Murphy & others, 2008).
    - Amphibolites can be separated from other mafic units (for example, gabbros and dolerites) using mineral maps derived from hyperspectral data ("MgOH content", "MgOH composition", "amphibole/chlorite" and "Fe^{2+} associated with MgOH")
    - Spatial relationships of sodic-calcic and potassic alteration can be detected with mineral maps derived from hyperspectral data:
        - Na(-Ca)-alteration: "white mica composition", "white mica abundance";
        - K-alteration in mafics: "MgOH content", "MgOH composition", "amphibole/chlorite" and "Fe^{2+} associated with MgOH" combined with "white mica composition" and "white mica abundance")
        - ASTER band 8 data can be integrated with magnetic and K-radiometric data to form a sodic-calcic mineral index that highlights albite-actinolite-magnetite assemblages, many of which are spatially coincident with copper mineralisation (Austin, 2008). Sodic-Calcic Alteration Index = 2nd derivative of magnetic intensity/[K radiometrics + ASTER Band 8].
- Butera & others (2005) considered the key criteria for undercover exploration to be:
    - gravity highs (reflecting mafics)
    - magnetic highs
    - north- and north-east-trending faults (magnetic worms or lineaments).

Sediment hosted stratabound Cu mineralisation (Cu only deposits)

- The deposits are all hosted within the Mount Roseby Schist (part of the Mount Albert Group) which through recent work by the Geological Survey of Queensland (2011b) has been interpreted as a time equivalent of the Coocerina Formation and the Lady Clayre Dolomite.
- Most deposits are expressed by a copper flower vegetation anomaly (Gidyea trees) — HyMap or ASTER imagery may highlight other areas of Cu anomalism.
- The deposits formed during the weathering of stratiform and stratabound bornite-chalcopyrite protore within the stratigraphy originally assigned to the Corella Formation — now mapped as Mount Roseby Schist (Rabone & others, 2004).
- These deposits are characterised by near surface oxide zones, around 0–30m deep, with minor malachite and cupriferous goethite. The oxide mineralisation is treated as waste due to the refractory nature of the goethite. The supergene zone varies between depths of 100m and 240m below surface and is dominated by native copper, with minor chalcocite and traces of other Cu minerals. Below this, the supergene zone passes into the primary sulphide system composed of chalcopyrite, chalcocite, bornite and minor pyrite (Universal Resources Limited, 2009).

- Native copper (supergene zone) is restricted to a distinct domain (referred to as the “native copper domain” by Altona Mining Limited) underlying the oxide-carbonate domain and overlying fresh bedrock. This domain is clay-rich, associated with Ca-Na-K depletion, reduced bulk density, low rock competency and increased porosity (Rabone & others, 2004).
- Isotopic studies using oxygen and carbon isotopes on calcite indicate that precipitated fluids were derived from the dewatering of calcium-rich rocks (Rabone & others, 2004).

Targeting criteria

Based on literature research and previous targeting criteria developed for epigenetic Cu mineralisation in the Mount Dore area, key targeting criteria for both mineralisation style and geological domain were assessed. Specific criteria for epigenetic Cu mineralisation were created for both Mary Kathleen and Constantine Domains as each domain has different controlling factors related to known mineralisation (i.e. different host rocks or geophysical characteristics). No specific targeting criteria were developed for the Soldiers Cap Domain due to the lack of known mineral occurrences and geological understanding in the area.

Targeting criteria for epigenetic Cu±Au±iron oxide mineralisation (Constantine Domain)

1. Elevated copper values in soil, rock chips and regolith drillholes
2. elevated gold values in soil, rock chips and regolith drillholes
3. proximity to Corella or Staveley Formation calc-silicate rocks
4. proximity to mafic intrusives and to faults intersecting mafic intrusives
5. lithological character (dominantly Cover Sequence 3)
6. rheological contrasts between lithological units
7. gravity (gradients)
8. high conductivity values indicative of sulphide zones at depth
9. proximity to major crustal scale faults; preferably N–S (350°–015°) and ENE (040°–075°) faults
10. bends on north–south and east – north-east faults
11. intersections of second-order cross structures with crustal scale faults
12. radiometrics (high U/Th, high U^2/Th and high K)
13. zones of magnetite, albitic, hematitic (red rock) and potassic alteration
14. proximity of Williams and Naraku batholiths and related brecciation
15. proximity to coincident high magnetics/high gravity (magnetite) and to coincident low magnetic/high gravity (hematite) zones
16. moderate-high magnetic/high gravity (pyrrhotite) zones
17. zones of high geological complexity
18. breccia zones
19. degree of clustering and alignment of Cu mineralisation.

Targeting criteria for stratabound sediment-hosted Cu mineralisation (Mary Kathleen Domain)

1. Lithological contact with Mount Roseby Schist
2. gravity low and coincident EM response
3. magnetic high
4. copper geochemical anomalies in stream, soil and bedrock sampling

5. elevated K and U in ternary radiometric response.
6. clay alteration seen in MMR/RMIP, EM and IP responses.

Targeting criteria for epigenetic Cu±Au±iron oxide mineralisation (Mary Kathleen Domain)

1. Presence of Mount Albert Group or Corella Formation
2. magnetic high combined with electromagnetic response
3. copper geochemical anomalies in stream sampling
4. Cu and Au geochemical anomalies in soil
5. spatial relationships of sodic-calcic and potassic alteration via HyMap survey (Pilgrim Fault survey) along with corresponding Aster coverage may be indicative of albite-actinolite-magnetite assemblages and Cu mineralisation
6. distance to Mount Roseby Fault Zone.

The targeting criteria above were generated from the previous section discussing the current understanding of mineralisation in the Quamby Project area and these were separated into single properties that can be tested on a regional scale over the project area using a Weights of Evidence approach in a 3D environment.

Geological modelling

3D geological modelling of the Quamby area was undertaken to provide a geological constraint on potential field inversions, incorporating the Geological Survey of Queensland's (GSQ) current structural and geodynamic understanding of the regional geology. The 3D model of the Quamby project area was built in GOCAD and SKUA using a combination of available datasets and the GSQ's current interpretations of the sub-surface geology. The final product was a robust model incorporating rock property data (density and magnetic susceptibility), lithology and geological boundaries, serving as the input product for geophysical inversion and mineral potential targeting studies. The 3D model was designed to cover an area slightly larger than the project area to reduce boundary effects during inversions, and is now available as either a vector (surface) or raster (voxet) model product.

Data compilation

Initial work on the Quamby project involved a review of the current ideas of the geological framework of the area and a compilation of the available data. The datasets used in the construction of the Quamby model included: new geological mapping and interpretation released as part of the North-West Queensland Mineral and Energy Province Report (NWQMEPR; Geological Survey of Queensland, 2011b), the 3D model constructed as part of the NWQMEPR and previous models (Jupp & others, 2009), Deep Seismic sections, magnetotelluric data, gravity and magnetic datasets, including various filtered images and worms (multi-scale edge detection) and geological cross-sections. Field work was undertaken in the area in May and June 2011 to collect samples for physical property measurement (density and magnetic susceptibility) and to better define major units to be modelled, together with fault orientations and relationships and inferred subsurface geometries. A workflow was developed to integrate the field-measured magnetic susceptibility data and the density measurements conducted in-house into the 3D model as an initial starting point to better constrain the potential field inversions.

The solid geology mapping product released as part of the NWQMEPR utilises new geological mapping of outcropping areas and extends this out under cover based on interpretation of potential field data, drill-hole data and regional seismic data. Within the Quamby region there are 117 mapped stratigraphic units and subunits, many of which are discontinuous or are small local localised

Table 2: List of modelled lithostratigraphic units in the Quamby project and brief descriptions

Modelled Unit	Description
Cover	All Phanerozoic (Post-Proterozoic) units including Eromanga and recent cover
Millungera Basin	Lithologies within the newly discovered Millungera Basin in the north-eastern section of modelled region
Quamby Conglomerate	Regionally discrete unit within Mary Kathleen Domain
Milo Beds	Regionally discrete unit within Tommy Creek Domain
Toole Creek Volcanics	Regionally broad unit in Soldiers Cap Domain
Staveley Thrust	Structural repeat of Staveley Formation lithology due to thrusting
Kuridala Group	Regionally discrete group in south analogous to Soldiers Cap Group
Soldiers Cap Group	Regionally broad unit in Soldiers Cap Domain, including Mount Norna Quartzite and Llewellyn Creek Formation
Upper Mount Albert Group	Subset of broad Mount Albert Group including Coocerina Formation, Dugald River Shale, Lady Clayre Formation, Mount Roseby Schist and undifferentiated Mount Albert Group lithologies
Lower Mount Albert Group	Subset of broad Mount Albert Group quartzites including Deighton Quartzite, Knapdale Quartzite and the White Blow Formation lithologies
Staveley Formation	Regionally broad unit in east of model including the Gilded Rose Breccia
Mount Fort Constantine	Brecciated felsic to intermediate volcanic lithology in central Constantine domain
Corella Formation	Regionally extensive modelled unit including Corella Formation, Mount Philp Breccia and Lime Creek Metabasalt
Mitakoodi Formation	Regionally discrete unit within Mitakoodi Domain including Chumvale Breccia, Mitakoodi Quartzite, Overhang Jaspilite and the Wakeful Metabasalt
Bulonga Volcanics	Felsic volcanic and metavolcanics lithologies located within Mitakoodi and Soldiers Cap Domain
Boomarra Metamorphics	Regionally discrete group in north of model within Mary Kathleen Domain
Argylla Formation	Regionally extensive unit underneath western section of model; does not outcrop in modelled area but does to the west
Leichhardt Volcanics	Regionally extensive unit underneath western section of model; does not outcrop in modelled area but does to the west
Basement	Represents crystalline basement lithologies below Leichhardt in east of model and Bulonga in west of model

lithological variations, non-continuous across broad areas. For practical modelling purposes these units were simplified and grouped into lithological packages. These groupings were based on economic, geological and geophysical factors. The divisions between geological subunits that had been distinguished during mapping at the surface (e.g. Corella/b is described as a laminated calc-silcate granofels with localised calc-silcate breccia, while Corella/c is described as a laminated calc-silcate granofels with minor mica schists) could not be modelled in three dimensions and so they were grouped back into major unit boundaries. Additionally, units with comparable petro-physical properties were grouped together as these could not be discriminated in the geophysical inversion process (i.e. the Lower Mount Albert Group is a subset of quartzites including Deighton Quartzite, Knapdale Quartzite and the White Blow Formation lithologies). Within the project area there were 15 stratigraphic lithologies and 8 intrusive units identified as appropriate units for modelling and/or prospectivity assessment (Tables 2 and 3).

Four new geological cross-sections were produced using these simplified geological groupings based on interpretations from the NWQMEPR, available geophysical data sets and expert knowledge within the GSQ. These cross-sections were used as an initial skeleton for the 3D modelling and to test the broad geodynamic assumptions made across the region.

Table 3: List of modelled intrusive bodies in the Quamby project

Modelled Intrusive	Description
Malakoff Granite	Williams-Naraku aged granite in central Constantine Domain
Williams Granite	Williams-Naraku Supersuite granites including Mount Margaret Granite.
Williams Granite (High Mag)	Williams-Naraku Supersuite granites identified during mapping as having high magnetic susceptibility.
Williams Granite (Low Mag)	Williams-Naraku Supersuite granites identified during mapping as having low magnetic susceptibility.
Tommy Creek Microgranite	Microgranite in Tommy Creek Domain.
Mount Godkin Granite	Wonga aged granite in west of model.
Levian Granite	Wonga aged granite to south of Malakoff Granite.
Dipvale Granodiorite	Wonga aged granodiorite in Mary Kathleen Domain.

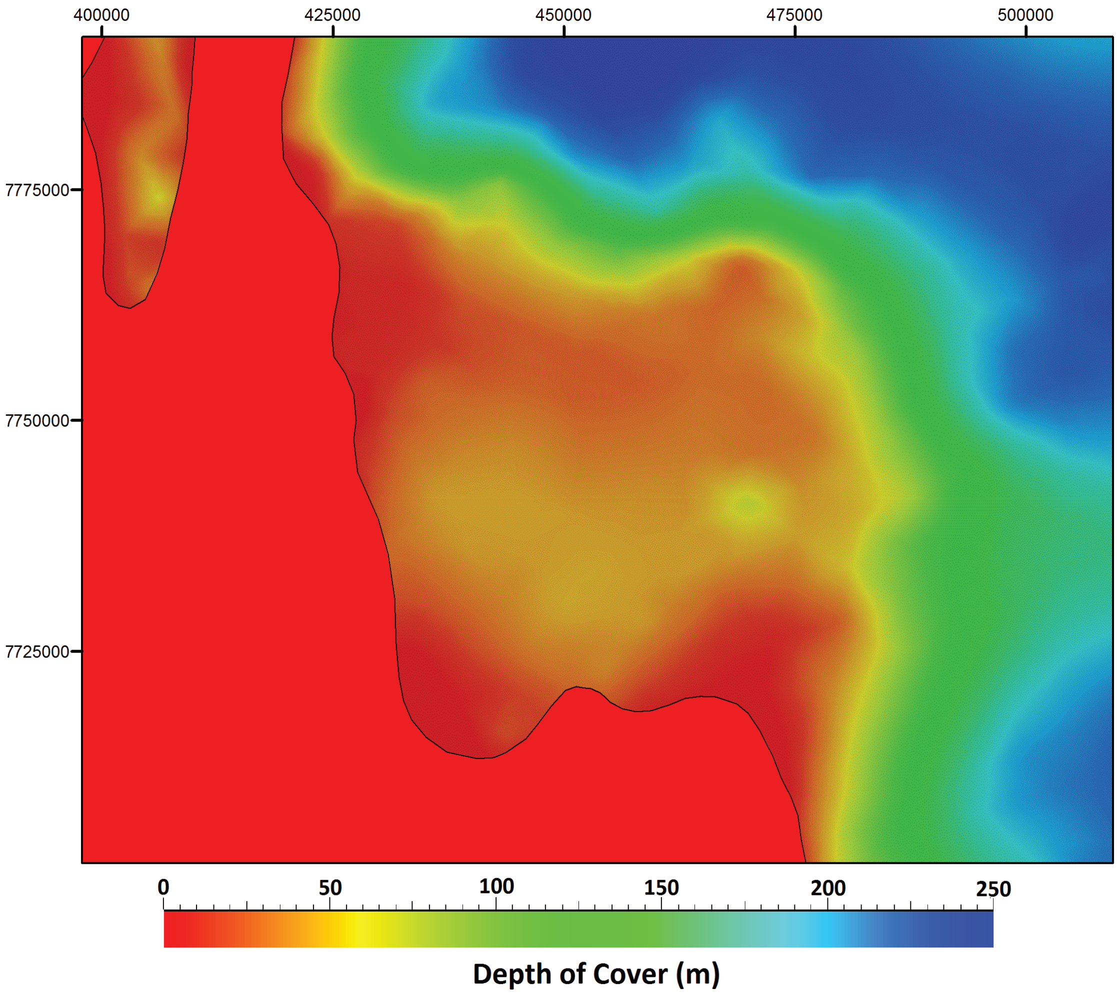

Figure 5: Depth of Phanerozoic cover in the Quamby region. Solid red region in the west is outcropping geology. Depth surface was created from drillhole and water bore basement intercepts and magnetic modelling.

Three-arc second (~90 metres) resolution SRTM (Shuttle Radar Topographic Mission) data (Jarvis & others, 2008) were used to create a topographic DEM (digital elevation model) surface across the modelled area. Additionally, in the undercover regions of the model, a base of cover (top of modelled units) surface was created (Figure 5). For the purpose of this project the cover is defined as any unit younger than Phanerozoic in age because the targeted mineralisation in the Quamby area is Proterozoic in age. The base of the cover surface was constrained by borehole and magnetic depth to source modelling data collected to build the NWQMEPR depth to basement surface. Depth values relative to the surface were corrected using the DEM surface to be relative to the Australian Height Datum

(AHD). A surface was created from these data points to represent the base of the cover sequence. Reported depths from drillhole intercepts were assigned the highest level of confidence and, where they existed, they were used as the main constraint. Where drillhole data did not exist, depths from water bores or magnetic sources from forward modelling were used to constrain the surface. Cover depths are relativity shallow (less than ~100 metres) in the Mary Kathleen Domain and in the southern section of the Constantine Domain. In the northern Constantine Domain and Soldiers Cap Domain cover thicknesses reach over 250 metres in places.

3D model construction

The fault network was first modelled in SKUA, the implicit modelling workflow built into the GOCAD software suite. The SKUA workflow uses both geological data and interpretations to build the fault network. Mapped and interpreted faults of greater than 10 kilometres strike length, or those smaller but deemed important or required for geometric fits, were selected to be modelled. Fault traces (curves representing the fault surface in map view) and fault sticks (curves representing fault interpretations in cross-section) were used to create the fault network. The implicit modelling function of SKUA allows the fault network to be quickly modelled and attempts to discern major and secondary faults (splays) and their intersecting relationships from the raw input data. Incorrect intersection relationships were edited, the network updated, and some manual edits performed to fine-tune the geometry of the final fault network. During the fault network modelling, additional interpretations and fault sticks were added to better constrain the network over multiple iterations. Once the network and geometric relationships were deemed satisfactory, GOCAD surfaces were created from the SKUA fault network. An advantage of building the fault network in SKUA is that the fault network is 'water-tight' (i.e. each fault compartment is fully sealed from the next) making voxet creation and stratigraphic surface cutting easier.

Stratigraphic horizons were then modelled within the fault blocks using GOCAD. The modelling was initially attempted in SKUA, but it was determined that the computational power required for a satisfactory resolution of the large and complex model by implicit means was far above what was available in-house. The GOCAD explicit modelling method allows a suitably complex geological model to be constructed, incorporating regions of varying resolution and reliability. The model is most reliable and has high resolution (i.e. captures more detail) in better-understood and outcropping areas, but geometries become more speculative and lower in resolution in poorly understood or covered areas and at depth (Figure 6). As with the fault modelling, the solid geology map and cross-sections were the main datasets used for the horizon modelling.

Curves representing the base of the modelled horizons, together with the DEM surface in the outcropping regions or the base of cover surface in the undercover regions, were drawn in GOCAD on the cross-sections. Surfaces representing the base of each of these stratigraphic horizons were then created from these curves within each sealed fault compartment. Additional curves along supplementary cross sections and faults were drawn to create a surface skeleton to aid with surface creation and to constrain the thickness and depth of the modelled horizons. Due to the vector nature of triangulated surfaces, areas with greater data density could be modelled with much higher resolution (smaller triangles) than those undercover or at depth.

Once all the stratigraphic horizons were modelled, the granitic intrusions were modelled. Each intrusive body selected was modelled individually with the in-built ellipsoid function in GOCAD. Curves representing the mapped shape of the body and cross-sectional interpretations were translated into a point-set and an ellipsoid was constructed using these points. The final GOCAD surface model incorporates the fault surfaces, DEM and base of cover surface, stratigraphic horizon surfaces and intrusive bodies (Figure 7).

To facilitate potential field inversion and targeting analyses, a raster voxet, or block model, was discretised from the vector surface model. The regional voxet model has voxels (three-dimensional pixels) of 500 metres laterally (X, Y) by 100 metres vertically (Z). The voxet model was created using the DEM, stratigraphic horizons, intrusions and fault surfaces from the vector model to partition the voxet into lithological regions within the model space (Figure 8).

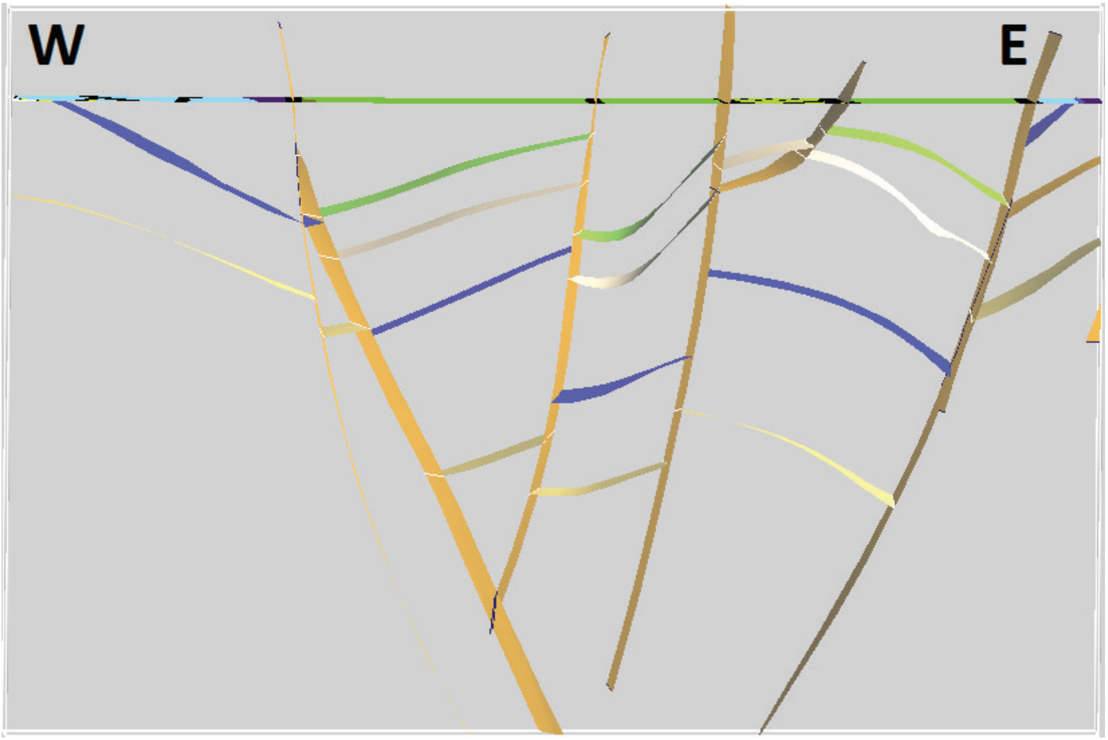

Figure 6: Cross-sectional slice through Quamby 3D model from west to east. Faults are yellow in colour. Stratigraphic surfaces have higher resolution and reliability near-surface than at depth.

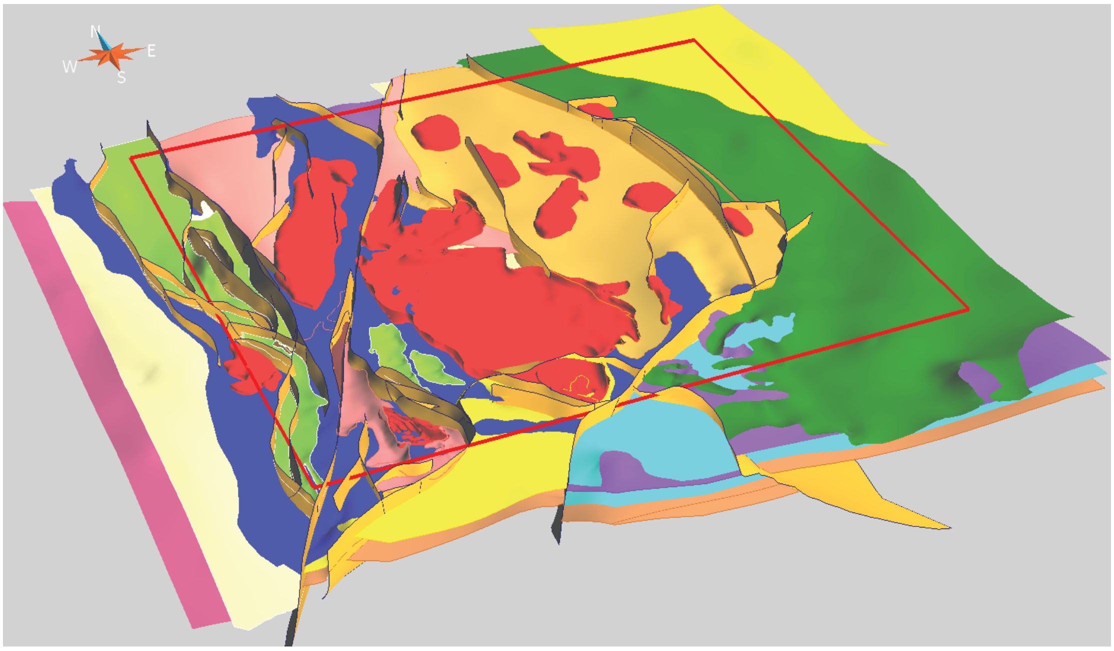

Figure 7: GOCAD surface model of Quamby region viewed from south-west. Red outline is Quamby project area. Surfaces extend outside this boundary to enable building a 'water-tight' model.

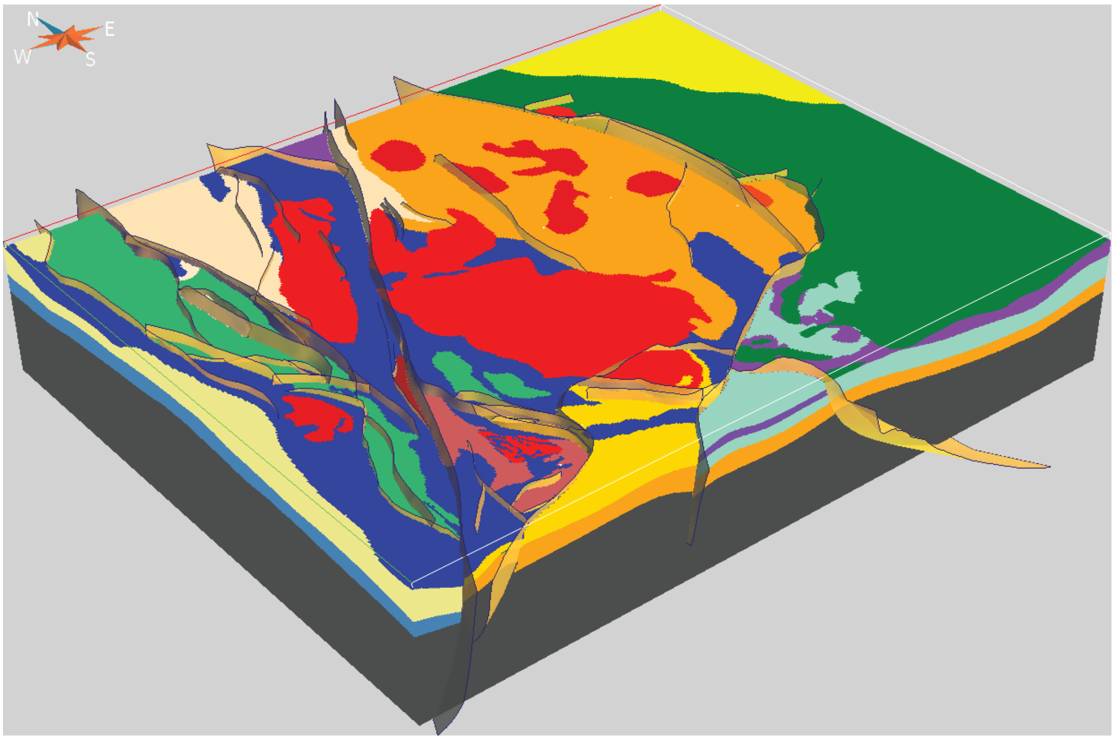

Figure 8: GOCAD voxet model of Quamby region viewed from south-west. Voxet model was constructed from the 'water-tight' surface model

Potential field inversions

The aim of potential field inversions is to create a 3D density or magnetic susceptibility model that can adequately reproduce anomalies consistent with the observed gravity or magnetic data. However without geological constraints the resultant model is non-unique as a near infinite set of models could fit the observed data. Incorporating *a priori* geologic knowledge and combining multiple forms of geophysical data can reduce ambiguity and enhance inversion results, leading to more reliable and robust models. By constraining potential field inversions with a geological model and physical property bounds, the results of the inversions are both geologically and geophysically realistic. Potential field inversion should not be viewed as a single-stage 'black box' technique, but an iterative process where the results of each stage of inversion yield information that is used to build a more robust model for further inversion to create the best geologically and geophysically valid model possible.

Regional inversions were performed on the discretised voxet model created in the GOCAD modelling process. Each region on the model was populated with an integer lithological flag and physical property (density and magnetic susceptibility) values derived from field samples, assessment of GSQ publications, and other literature. Field work was undertaken in the region in May and June of 2011, when *in situ* magnetic susceptibility measurements were undertaken and representative samples of units were collected for density measurement. GPS locations and 10 to 20 magnetic susceptibility measurements were taken across each outcrop with a KT-9 magnetic susceptibility meter to build a statistically representative sample of the unit. Where possible, sledge hammer samples were also collected for density measurement. To reduce the effect of measurement uncertainties on the density values, larger samples in the range of 4 to 8 kilograms were preferred. Density measurements were undertaken in-house following the method of Kueppers & others (2005) and Emerson (1990). Samples were prepared by removing any weathered areas with a rock-saw or sledge hammer and subsequently cleaned of all foreign matter. Samples were weighed, first in air and then suspended in water, using a scientific balance with a sensitivity of 0.1g. The density was then calculated from these values (Equation 1).

$$\rho_{sample} = \frac{m_{air}}{m_{air} - m_{water}} * \rho_{water}$$

Equation 1: Calculation of density from mass in air and mass immersed under water (Kueppers & others, 2005)

The results of the density and magnetic susceptibility measurements were compared to values found in GSQ reports and databases, as well as company reports and literature. Some of the modelled units were found to have relatively homogenous properties, with the recorded and literature values being in good agreement with little spread. Other modelled units contained a diverse lithological range (e.g. the calc-silicates, meta-sediments and volcanics of the Corella Formation), with a consequent larger range in property values. Initial values of the physical properties assigned to these units (Table 4) were designed to take this into account, based on a judgement of the dominant rock types within the modelled unit.

Table 4: List of initial density and magnetic susceptibility properties and ranges for modelled lithologies used for forward modelling

Modelled Lithology	Lithological Index	Density (g/cc)			Magnetic Susceptibility x10^{-3} (SI)		
		Initial	Min	Max	Initial	Min	Max
Cover	1	2.10	2.00	2.30	0	0	0
Malakoff Granite	2	2.65	2.55	2.75	7	0.07	700
Williams Granite	3	2.64	2.54	2.74	50	0.5	1000
Williams Granite (Low Mag)	4	2.65	2.55	2.75	10	0.1	1000
Williams Granite (High Mag)	5	2.65	2.55	2.75	50	0.5	1000
Tommy Creek Microgranite	6	2.60	2.50	2.70	3	0.03	300
Mount Godkin Granite	7	2.66	2.56	2.76	3	0.03	300
Levian Granite	8	2.63	2.53	2.73	0.1	0.001	10
Dipvale Granodiorite	9	2.68	2.58	2.78	20	0.2	1000
Millungera Basin Sequence	10	2.32	2.10	2.60	0.2	0.002	20
Quamby Conglomerate	11	2.40	2.20	2.60	0.2	0.002	20
Milo Beds	12	2.70	2.50	2.90	1	0.01	100
Toole Creek Volcanics	13	2.85	2.60	3.00	20	0.2	1000
Staveley Thrust	14	2.70	2.20	3.20	0	0	1000
Kuridala Group	15	2.60	2.10	3.10	0	0	1000
Soldiers Cap Formation	16	2.60	2.10	3.10	5	0.05	500
Upper Mount Albert Group	17	2.69	2.19	3.19	0	0	1000
Lower Mount Albert Group	18	2.61	2.11	3.11	10	0.1	1000
Staveley Formation	19	2.72	2.22	3.22	0	0	1000
Mount Fort Constantine	20	2.75	2.25	3.25	25	0.25	1000
Corella Formation	21	2.78	2.28	3.28	10	0.1	1000
Mitakoodi	22	2.65	2.15	3.15	0	0	1000
Bulonga Volcanics	23	2.68	2.18	3.18	5	0.05	500
Boomarra Metamorphics	24	2.72	2.22	3.22	5	0.05	500
Argylla Formation	25	2.81	2.31	3.31	25	0.25	1000
Leichhardt Volcanics	26	2.75	2.25	3.25	10	0.1	1000
Basement	27	2.80	2.30	3.30	1	0.01	100

Inversion software

VPmg is a gravity, gravity gradient, magnetic and magnetic gradient 3D modelling and inversion program developed by Fullagar Geophysics (Fullagar & others, 2000; Fullagar & Pears, 2007; Fullagar & others, 2008). VPmg discretises the model space with a set of vertical rectangular prisms, which in plan view appears as a regular grid. Prism tops honour surface topography and internal contacts representing geological boundaries divide each prism into elongated cells. Each prism carries information related to the lithological contact elevations within the prism and the physical property values associated with each lithology. The lithological units can either be homogeneous (uniform in density or susceptibility across the model) or heterogeneous. Full 3D property heterogeneity is achieved by introducing vertical sub-celling within the selected units.

Three different styles of inversion can be performed with VPmg: homogeneous unit property, heterogeneous property and geometric. During homogenous unit property inversions the geometry of the model is fixed. The property value of each lithological unit is varied across the whole model, within a set range, to reduce the misfit between the observed and calculated response. In heterogeneous unit inversions, as in homogeneous inversions, the geometry of the model is fixed. The property value of each sub-cell is allowed to vary within the set range. During geometric inversion the geological boundaries within the prisms are altered while physical properties remain fixed.

Inversion data

The gravity data used for the inversion was from databases maintained by the GSQ including data from government and company gravity surveys. Station spacing was variable with regional spacing at 2 kilometres over most of the region with some 4 kilometre spaced data in the east of the project area. This regional data was infilled with smaller surveys of higher resolution (~40 to 500 metres). Free-air corrected data was used as the input for the forward modelling and inversion, as VPmg uses the surface topography in the modelling and therefore the gravity effect of terrain is modelled. The data was gridded to the model resolution of 500 metres with the data spaced upon the voxel centres and the re-sampled data was positioned on the topography surface (Figure 9).

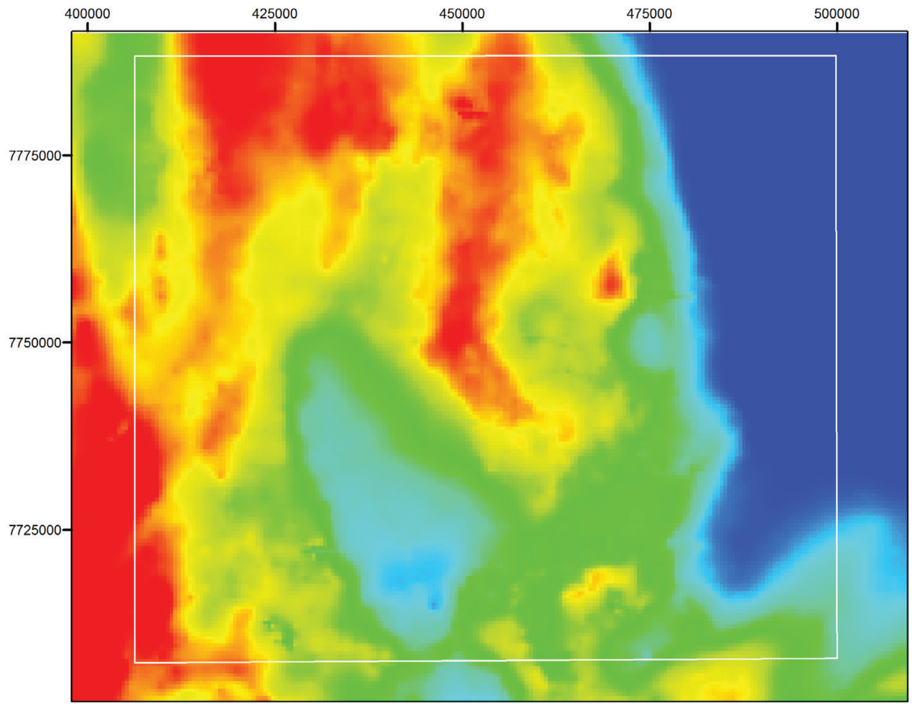

Figure 9: Gridded free-air gravity data over the Quamby region. White rectangle is the defined Quamby project area.

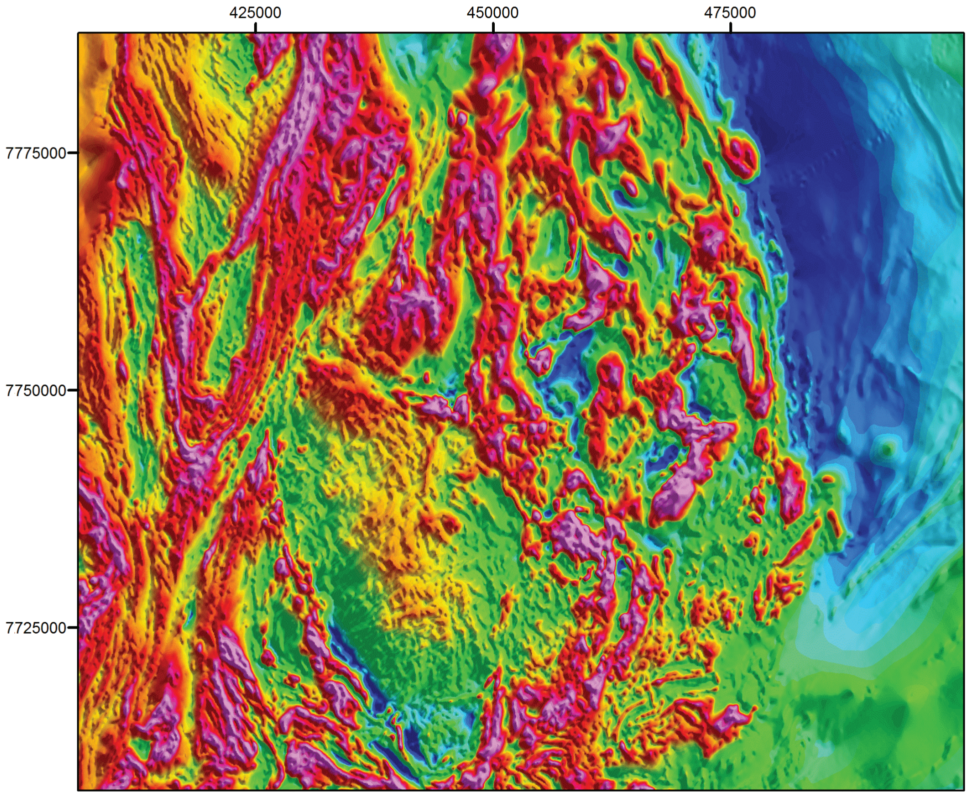

Figure 10: Gridded aeromagnetic data over the Quamby region with sunshade from north-east

The magnetic data used for the inversion was from databases maintained by the GSQ including data from government and company airborne magnetic surveys. The data, cropped from Queensland wide TMI aeromagnetic data is levelled (upward continuation) to an 80 metre flight drape above topography and gridded at 80 metres resolution (Figure 10). This data was re-sampled to a grid spacing of 500 metres with data centred over the voxels. The Quamby project area lies on the edge of the regional Mount Isa Inlier magnetic anomaly. For the purpose of the inversions the regional trend was removed from the magnetic data using Mira Geoscience's Potential Fields add-on module in GOCAD removing the far-field effects.

3D density inversion

The geological model, as a voxet model in GOCAD, was exported into VPmg format for inversion. Initially a 3D forward model was run to check the starting model and properties for misfit issues. Each lithological region of the voxet was populated with the constant density properties displayed in Table 4. VPmg was used to compute the gravity and magnetic response of the model and compare against the observed data. Following this, the bulk properties were optimised using a homogenous unit property inversion. The homogenous unit property inversion runs the forward model as before, and then modifies the bulk unit property values to lower the misfit between the observed and calculated response. These optimised properties were then used as the basis for heterogeneous unit inversions, where the value of the property of each cell of the unit is permitted to vary within the set range for the unit to reduce the misfit.

Forward modelling

The forward modelled gravity response from assigned densities and the starting model created in GOCAD is presented in Figure 11. The RMS (root mean square) misfit across the model is 11.14mgal

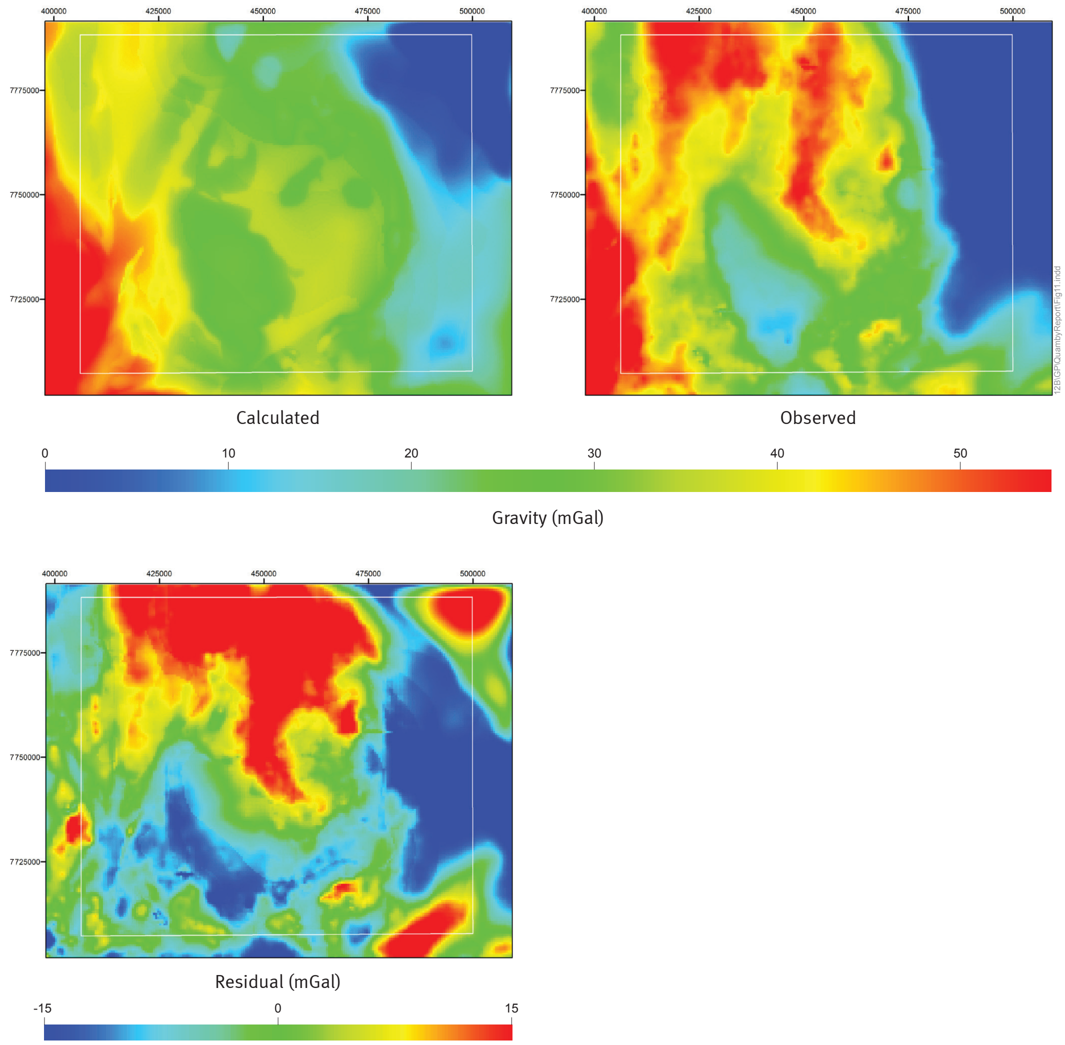

Figure 11: Comparison of calculated gravity from initial forward model and observed data. Residual grid is the resultant of the observed grid minus calculated grid. Therefore a positive residual means the observed data is higher than the calculated and a negative residual means the calculated is higher than the observed.

with large areas of misfit occurring in the north and east of the model. The dynamic range (difference between maximum and minimum data values) of the observed gravity is 99.6mgal and therefore this misfit represents 11.2% of the dynamic range. These large areas of residual misfit may be related to improper density property values being used or geometric problems with the model.

The residual misfits in the initial forward modelling were examined and the model adjusted accordingly over multiple inversion iterations. The starting densities of lithologies in the east, including the Millungera basin, Soldiers Cap and Toole Creek Volcanics, were judged to be creating an unacceptable residual anomaly and were modified. These new property values are listed in Table 5. The large residual anomaly in the north of the model was created by the calculated gravity being lower than that observed. The residual was judged to be a result of excess thickness of the Corella Formation unit, and this was reduced accordingly (Figure 12).

The revised forward density model (Figure 13) has a lower RMS misfit of 9.93 mgal (10% of the dynamic range of the observed anomaly). The lower residual in the forward model was considered acceptable for the initiation of the inversion process to further refine the model. By refining the initial model with a lower residual, the subsequent homogenous unit inversion (see below) was better able to optimise the density values across the entire model without being trapped within local minima in the misfit.

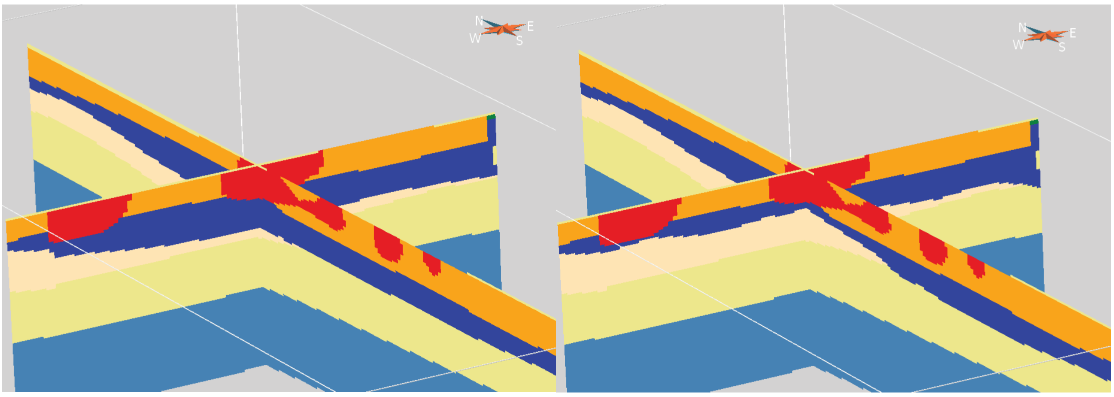

Figure 12: Cross-sectional view of model showing variation in Corella thickness (dark blue unit). Initial model on left has a thicker Corella unit where the two sections meet than the revised model on right.

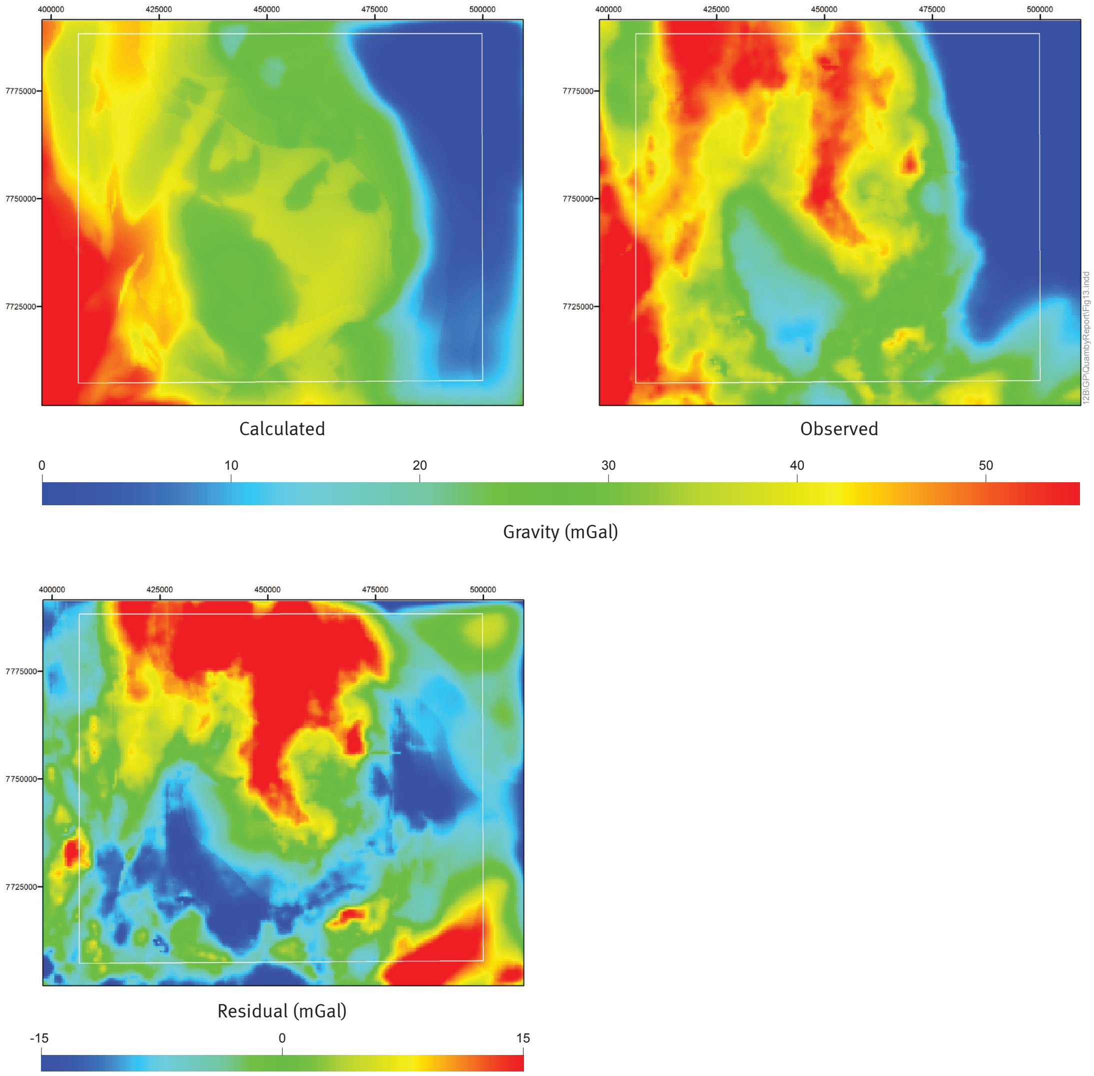

Figure 13: Comparison of calculated and observed gravity from revised forward model and observed data

Property optimisation

Homogenous unit inversion is an iterative process designed to reduce the residual misfit by optimising the bulk value of the properties of each unit. Multiple iterations of fixing the density of certain lithologies and allowing others to explore solutions within their bounds allows the user, with the aid of the inversion program, to find the most suitable starting densities (Table 5). This property optimisation stage reduced the residual misfit to 6.87mgal (6.9% of the dynamic range of the observed anomaly; Figure 14).

Table 5: Comparison of density values and ranges used in initial and revised forward models and the resultant optimised densities from the homogenous unit inversion.

Modelled Lithology	Initial Forward Model			Revised Forward Model			Optimised Density g/cc
	Density g/cc	Min	Max	Density g/cc	Min	Max	
Cover	2.10	2.00	2.30	2.10	2.00	2.30	2.139
Malakoff Granite	2.65	2.55	2.75	2.65	2.55	2.75	2.551
Williams Granite	2.64	2.54	2.74	2.64	2.54	2.74	2.634
Williams Granite (Low Mag)	2.65	2.55	2.75	2.65	2.55	2.75	2.696
Williams Granite (High Mag)	2.65	2.55	2.75	2.65	2.55	2.75	2.654
Tommy Creek Microgranite	2.60	2.50	2.70	2.60	2.50	2.70	2.604
Mount Godkin Granite	2.66	2.56	2.76	2.66	2.56	2.76	2.675
Levian Granite	2.63	2.53	2.73	2.63	2.53	2.73	2.619
Dipvale Granodiorite	2.68	2.58	2.78	2.68	2.58	2.78	2.72
Millungera Basin Sequence	2.32	2.10	2.60	2.55	2.40	2.70	2.521
Quamby Conglomerate	2.40	2.20	2.60	2.40	2.20	2.60	2.40
Milo Beds	2.70	2.50	2.90	2.70	2.50	2.90	2.70
Toole Creek Volcanics	2.85	2.60	3.00	2.70	2.45	2.85	2.647
Staveley Thrust	2.70	2.20	3.20	2.70	2.50	2.90	2.661
Kuridala Group	2.60	2.10	3.10	2.60	2.50	2.70	2.576
Soldiers Cap Formation	2.60	2.10	3.10	2.60	2.50	2.70	2.575
Upper Mount Albert Group	2.69	2.19	3.19	2.69	2.19	3.19	2.668
Lower Mount Albert Group	2.61	2.11	3.11	2.61	2.11	3.11	2.586
Staveley Formation	2.72	2.22	3.22	2.72	2.22	3.22	2.755
Mount Fort Constantine	2.75	2.25	3.25	2.75	2.25	3.25	2.806
Corella Formation	2.78	2.28	3.28	2.78	2.28	3.28	2.674
Mitakoodi	2.65	2.15	3.15	2.65	2.15	3.15	2.667
Bulonga Volcanics	2.68	2.18	3.18	2.68	2.18	3.18	2.639
Boomarra Metamorphics	2.72	2.22	3.22	2.72	2.22	3.22	2.881
Argylla Formation	2.81	2.31	3.31	2.81	2.31	3.31	2.83
Leichhardt Volcanics	2.75	2.25	3.25	2.75	2.25	3.25	2.796
Basement	2.80	2.30	3.30	2.80	2.30	3.30	2.756
Below Model	2.72	2.22	3.22	2.72	2.22	3.22	2.647

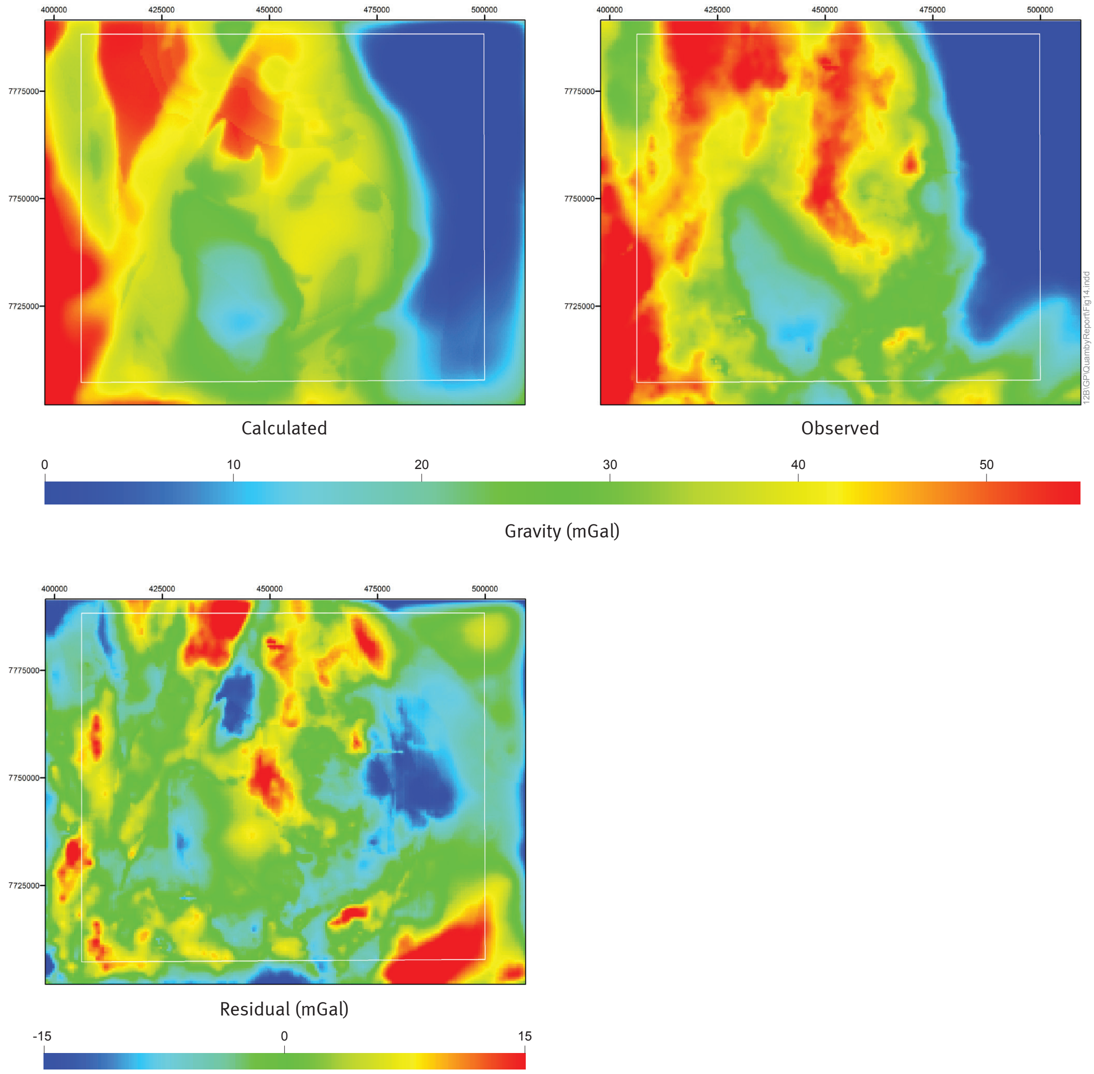

Figure 14: Comparison of calculated gravity from density property optimisation (homogenous unit inversion) and observed data.

Heterogeneous unit density inversions

The results of the homogenous unit inversions were used as the input for heterogeneous gravity inversion to adjust the densities within the lithologies subject to the lower and upper bounds for each lithology. Homogeneous units were divided into sub-cells for heterogeneous unit inversion. The vertical prisms of the VPmg model, used in the forward modelling and property optimisation, maintain the 500 metre horizontal (X,Y) resolution of the input voxet. Within the vertical prisms all lithologies, except the Basement unit, were discretised into 100m intervals in the Z direction. These new cells maintained their initial lithological information, but their properties were allowed to vary independently of others during the inversion process within the set bounds. Within the Basement unit the uppermost cells were initially discretised into 100m intervals, with this thickness progressively increasing using a 1.3 multiplier for successive sub-cells down to the bottom of the model.

With VPmg the heterogeneous unit inversion can be run either via a conventional (least squares) inversion method or via a stochastic inversion method. Conventional inversion produces smooth distributions of density or susceptibility, while in stochastic inversion the property variations are erratic. The conventional inversion method was used in this study, as an aim of the inversion was to define anomalous property areas created which may represent alteration overprints or unrecognised intrusive bodies. Those zones demanding unexpected or anomalous property variations were identified during the subsequent mineral potential targeting exercise. While the figures presented in the following pages provide an impression of the inverted results, the full model is best assessed in a 3D modelling package.

Final 3D density model

The final 3D density model of the Quamby project region (Figure 15) is the ultimate product of several generations of iterative inversion. During the inversion process the allowed density range of units was increased or decreased while others were fixed. This process yielded information regarding the sensitivity of the densities of individual lithological units. This information and the obtained results were fed back into the inversion process to better constrain the model geologically and geophysically

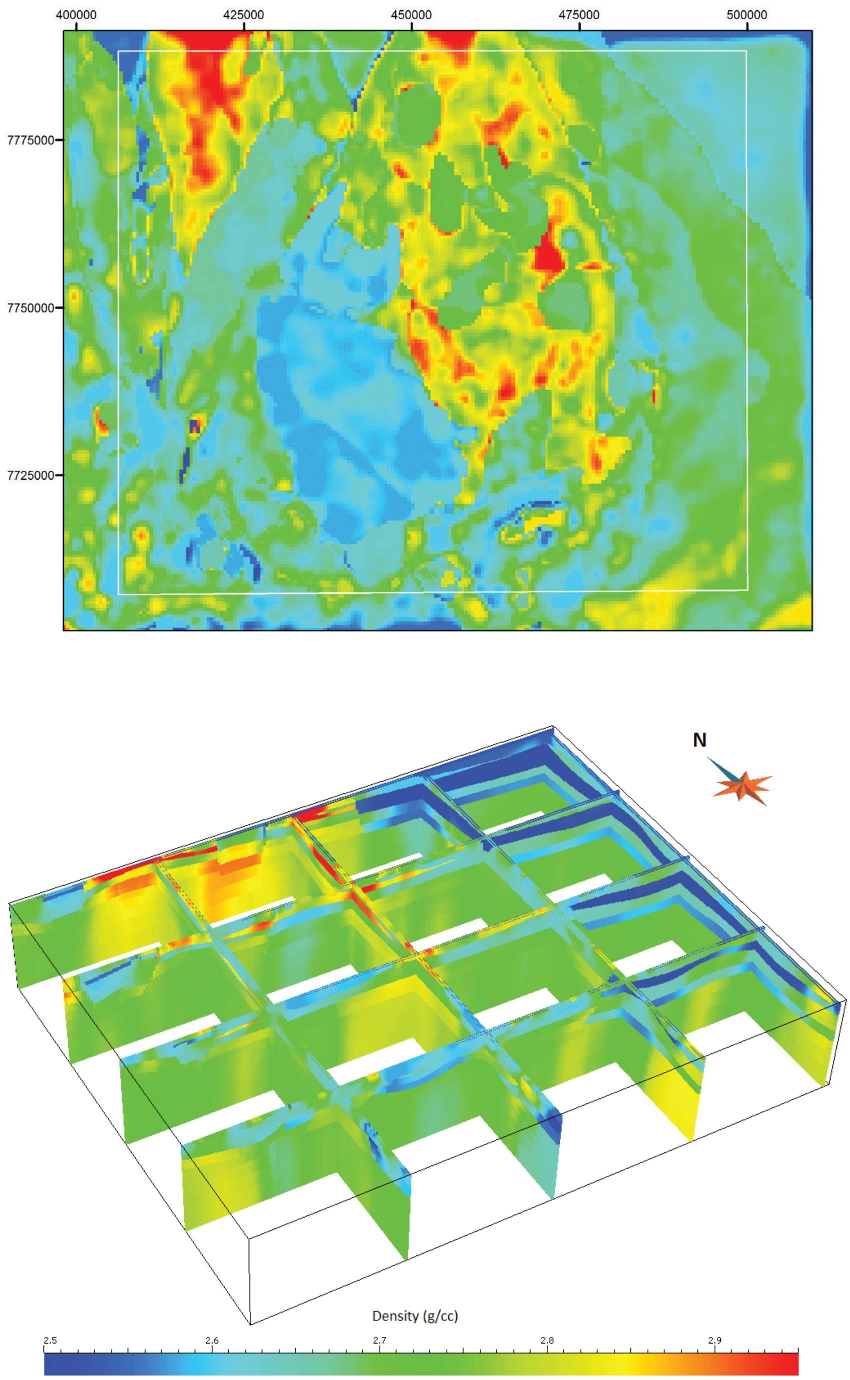

Figure 15: Top view and fence diagram of final 3D density model created from the iterative inversion process

and eventually produced the final 3D density model. The RMS misfit of the final 3D density model is 0.32mgal (0.3% of the dynamic range of the observed anomaly; Figure 16).

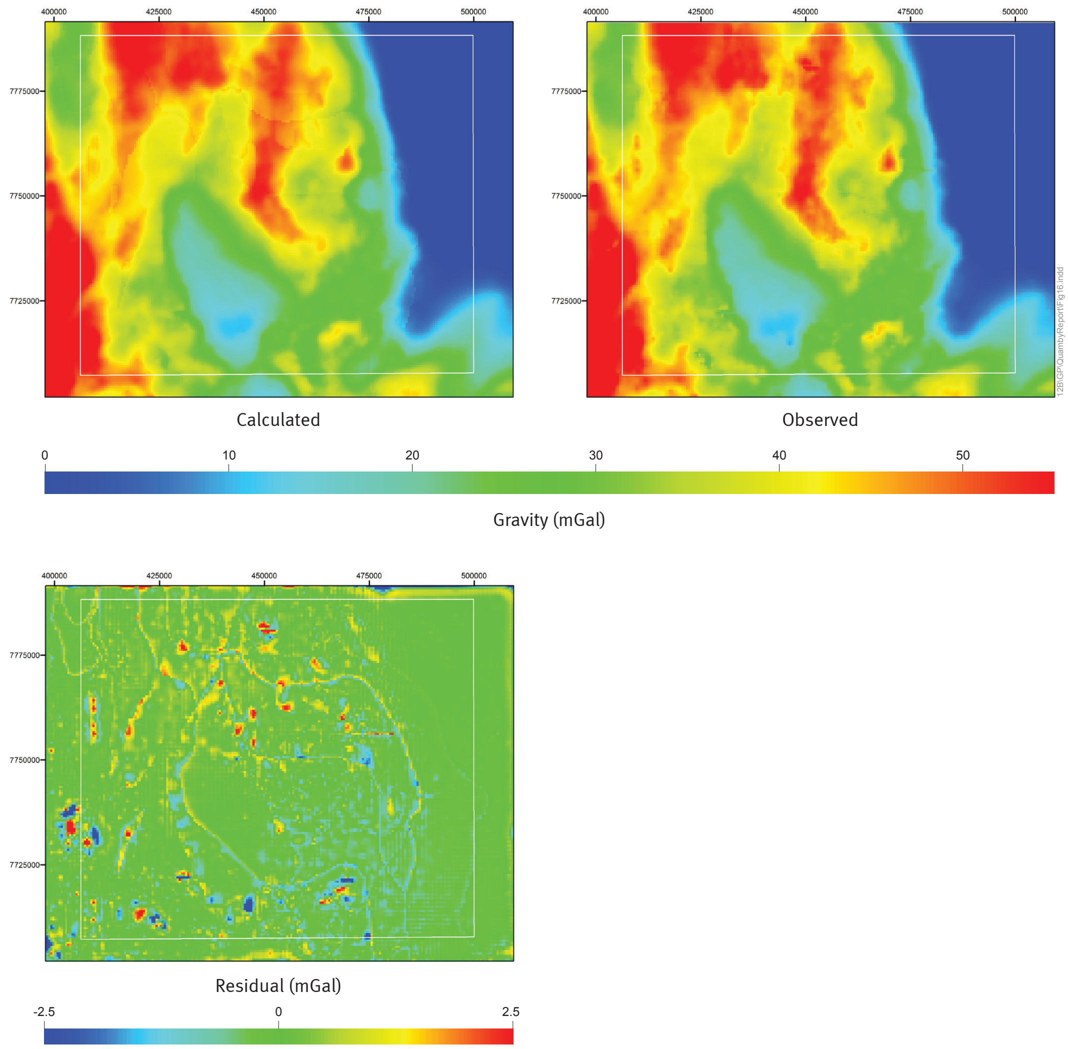

Figure 16: Comparison of calculated gravity from final 3D density model (after homogenous unit inversion and heterogeneous inversion) and observed data. Note change of residual scale bar from previous examples.

3D Magnetic susceptibility inversion

Magnetic susceptibility data was extracted from GSQ and company reports and collected *in situ* in the field. There was a far greater amount of magnetic susceptibility data available than density data, but the population distributions were large within units and ambiguous between units. Similar population characteristics existed between some lithologies while others seemed to have a bimodal distribution. Starting properties and ranges are listed in Table 4. The cover unit was set at 0 SI while most lithologies were given a large range to ensure that the property optimisation was able to explore the entire range of possibilities within the model space.

Forward modelling

Due to the inherent heterogeneity and large range of magnetic susceptibility values compared to the variations in density within units, the forward modelling and homogenous unit inversion was not able to reproduce the observed magnetic response of the model. The observed TMI, with regional removed, has a dynamic range of 2500nT ignoring outliers. The forward model has a RMS misfit of 459.59nT (18.4% of the dynamic range of the observed data; Figure 17).

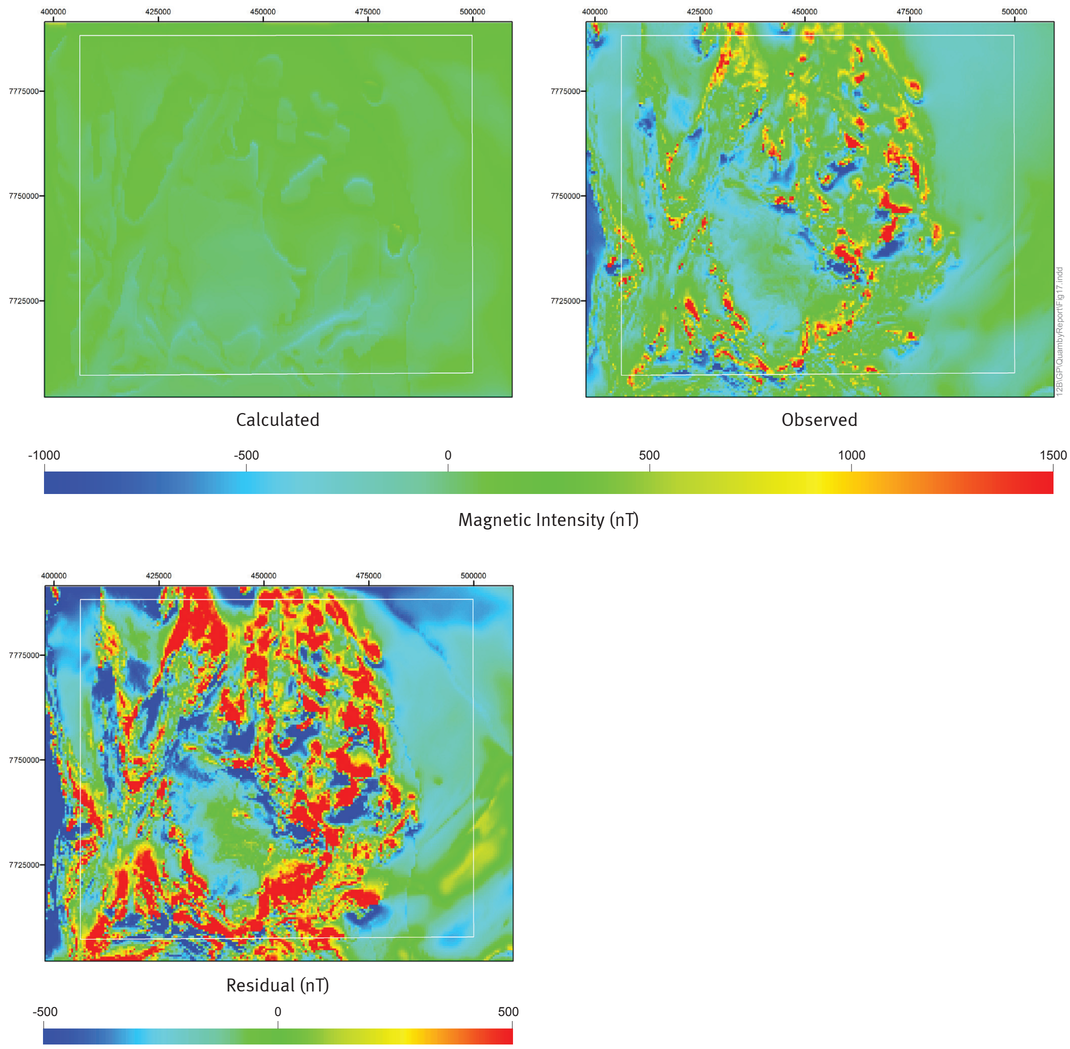

Figure 17: Comparison of calculated magnetic data from initial forward model and observed data. Residual grid is the resultant of the observed grid minus calculated grid. Therefore a positive residual means the observed data is higher than the calculated data and a negative residual means the calculated data is higher than the observed data.

Property optimisation

The reduction of misfit achieved during the homogeneous property inversion was only minor with the optimised properties having a RMS misfit of 433.02nT (17.3% of the dynamic range; Figure 18). The resultant optimised properties from inversion are displayed in Table 6.

Several of the units have either reached their lower or upper bounds during the optimisation suggesting, with the low reduction in misfit, that the variability of susceptibility within units in the model far overwhelms the bulk susceptibility distinction between the units. Broadly similar features are seen in the calculated response and in the observed data. However, the vast amount of the observed response must be due to susceptibility variations that exist within the modelled lithologies.

Table 6: Comparison of magnetic susceptibility properties used in the forward modelling stage and the optimised magnetic susceptibilities

Modelled Lithology	Initial Magnetic Susceptibility x(10^{-3})			Optimised Magnetic Susceptibility x(10^{-3}) (SI)
	Initial (SI)	Min (SI)	Max (SI)	
Cover	0	0	0	0
Malakoff Granite	7	0.07	700	0.07
Williams Granite	50	0.5	1000	59.449
Williams Granite (Low Mag)	10	0.1	1000	1.919
Williams Granite (High Mag)	50	0.5	1000	57.984
Tommy Creek Microgranite	3	0.03	300	17.901
Mount Godkin Granite	3	0.03	300	16.944
Levian Granite	0.1	0.001	10	0.001
Dipvale Granodiorite	20	0.2	1000	25.948
Millungera Basin Sequence	0.2	0.002	20	0.002
Quamby Conglomerate	0.2	0.002	20	0.002
Milo Beds	1	0.01	100	0.01
Toole Creek Volcanics	20	0.2	1000	0.2
Staveley Thrust	0	0	1000	12.233
Kuridala Group	0	0	1000	9.877
Soldiers Cap Formation	5	0.05	500	0.05
Upper Mount Albert Group	0	0	1000	0
Lower Mount Albert Group	10	0.1	1000	0.1
Staveley Formation	0	0	1000	0
Mount Fort Constantine	25	0.25	1000	64.084
Corella Formation	10	0.1	1000	30
Mitakoodi	0	0	1000	40.671
Bulonga Volcanics	5	0.05	500	0.666
Boomarra Metamorphics	5	0.05	500	35.507
Argylla Formation	25	0.25	1000	0.25
Leichhardt Volcanics	10	0.1	1000	7.375
Basement	1	0.01	100	0.01
Below Model	1	0.01	100	0.603

Heterogeneous unit magnetic susceptibility inversions

The 3D heterogeneous unit magnetic susceptibility inversions were created in a similar fashion to that previously described in the density modelling section, using a VPmg least squares inversion approach and identical discretisation parameters for the model. Due to the inherent heterogeneous nature of magnetic susceptibility within individual lithological units, let alone the expected variations within broadly grouped lithological packages, the accepted magnetic susceptibility ranges for most units were broad (Table 6). Similarly to the heterogeneous density inversion, the permitted ranges of magnetic susceptibility of some units were varied while others were fixed. This process yielded information regarding the sensitivity of the magnetic susceptibility properties of individual lithological units. This information and the obtained results were fed back into the inversion process to better constrain the magnetic susceptibility variations across the model and to produce the final 3D magnetic susceptibility model. While the internal sensitivity of some units outweighs the influence of property variations between other units, it was important during the iterative inversion process to ensure that the bulk of the magnetic anomaly is not accounted for by the internal variations of one single unit.

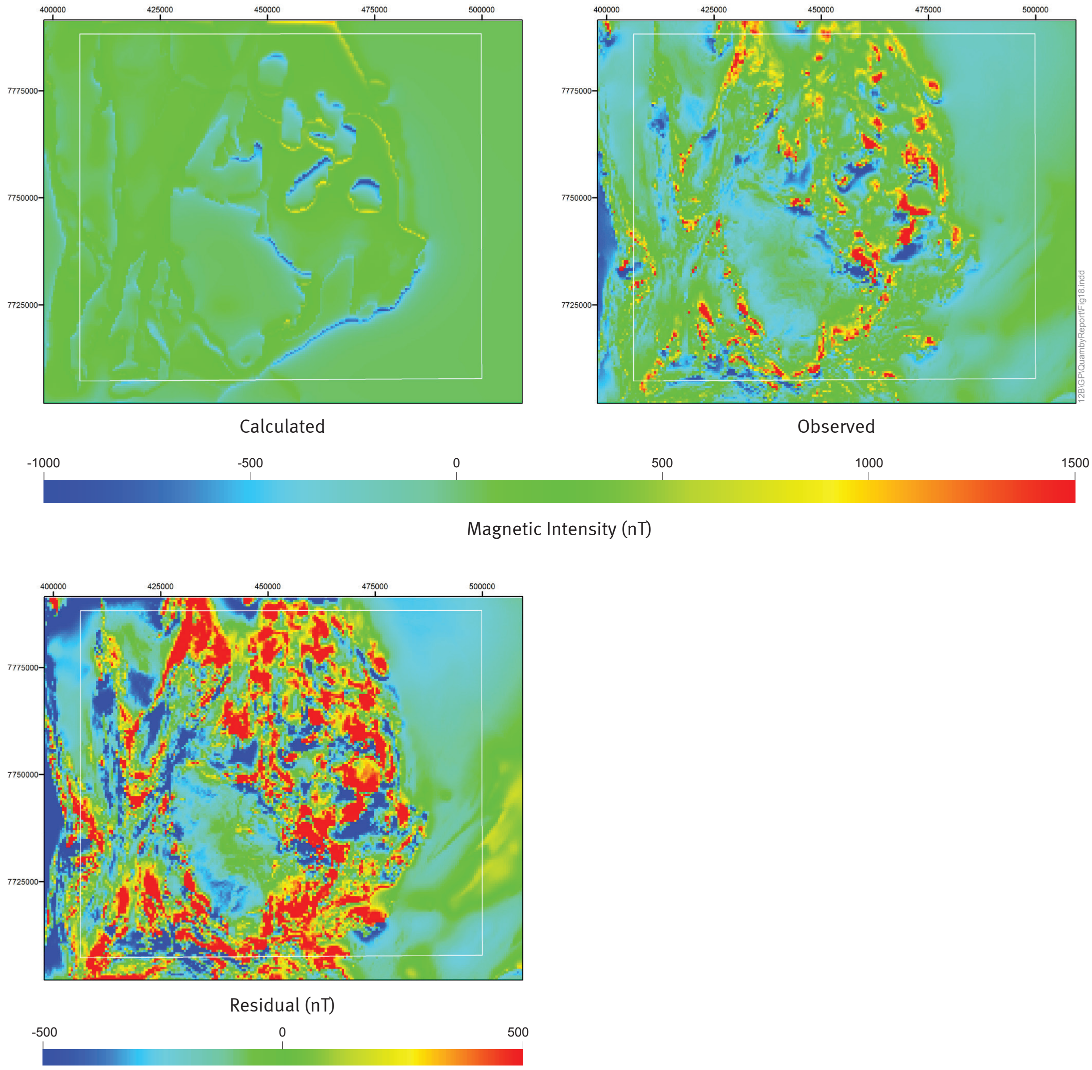

Figure 18: Comparison of calculated magnetic data from magnetic susceptibility property optimisation (homogenous unit inversion) and observed data

Final 3D magnetic susceptibility model

The final 3D magnetic susceptibility model of the Quamby region (Figure 19) is the ultimate product of the iterative inversion process. The RMS misfit has been reduced to 165.5nT (6.6 % of the dynamic anomaly; Figure 20). While this reduction in misfit is not as substantial as that of the density inversion, the high resolution magnetic data (80m grid spacing re-gridded to 500m) contains shorter wavelength (high frequency) elements than the 2–4km spaced gravity data.

The inversion at 500m lateral grid spacing is unable to satisfactorily reproduce the short wavelength component of the observed signal. The residual from the heterogeneous magnetic susceptibility inversion (Figure 20) shows the short wavelength anomalies that were not able to be modelled in the inversion and a north–south regional trend. This is highlighted by the profile across the region (Figure 21); the calculated magnetic response (blue line) captures the same broad, long wavelength anomalies as the observed magnetic response (green line) but does not effectively cover the shorter wavelength anomalies. The residual between the two (red line) shows the short wavelength discrepancies between the calculated and observed responses.

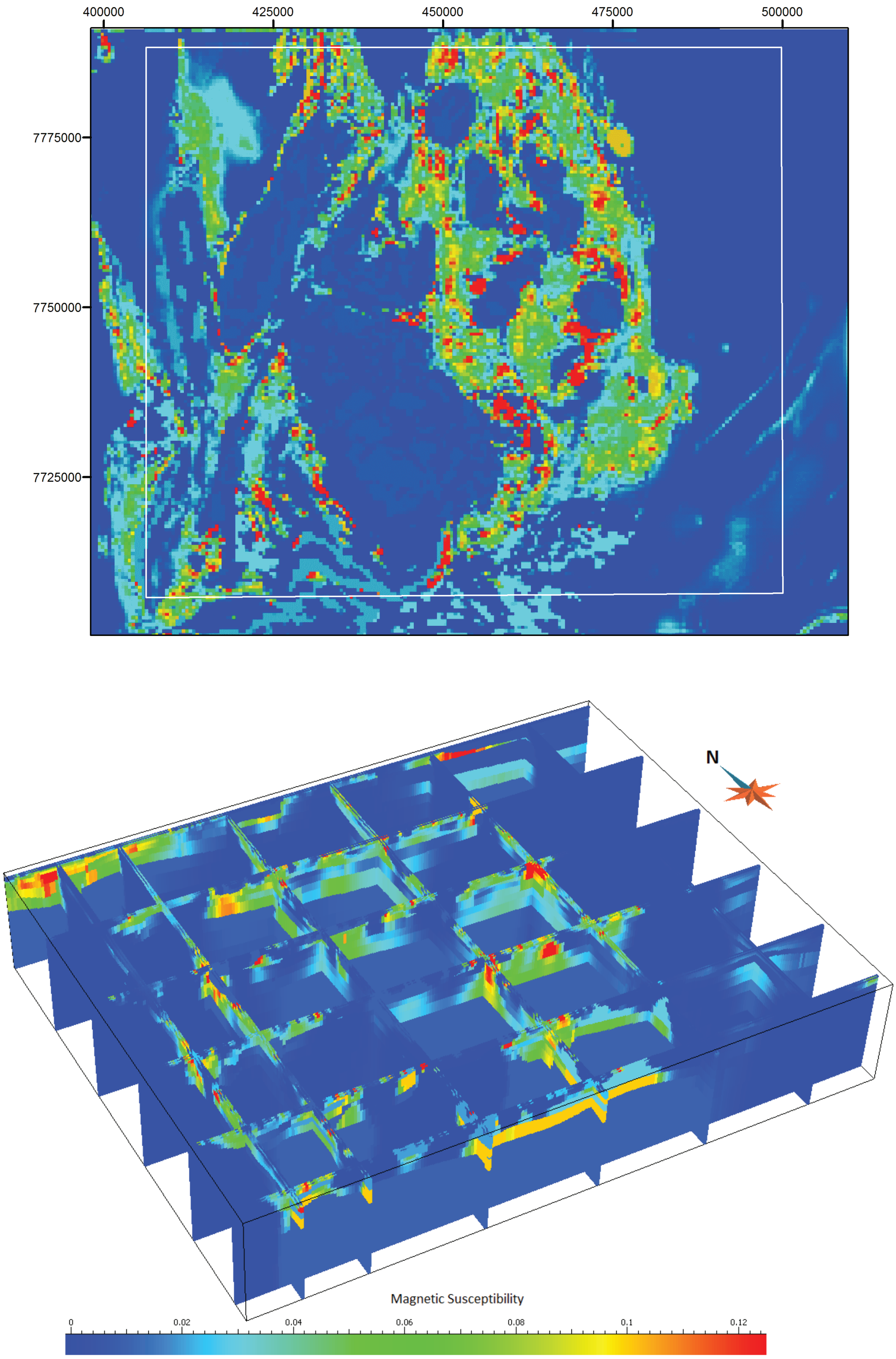

Figure 19: Top view and fence diagram of final 3D magnetic susceptibility model created from the iterative inversion process

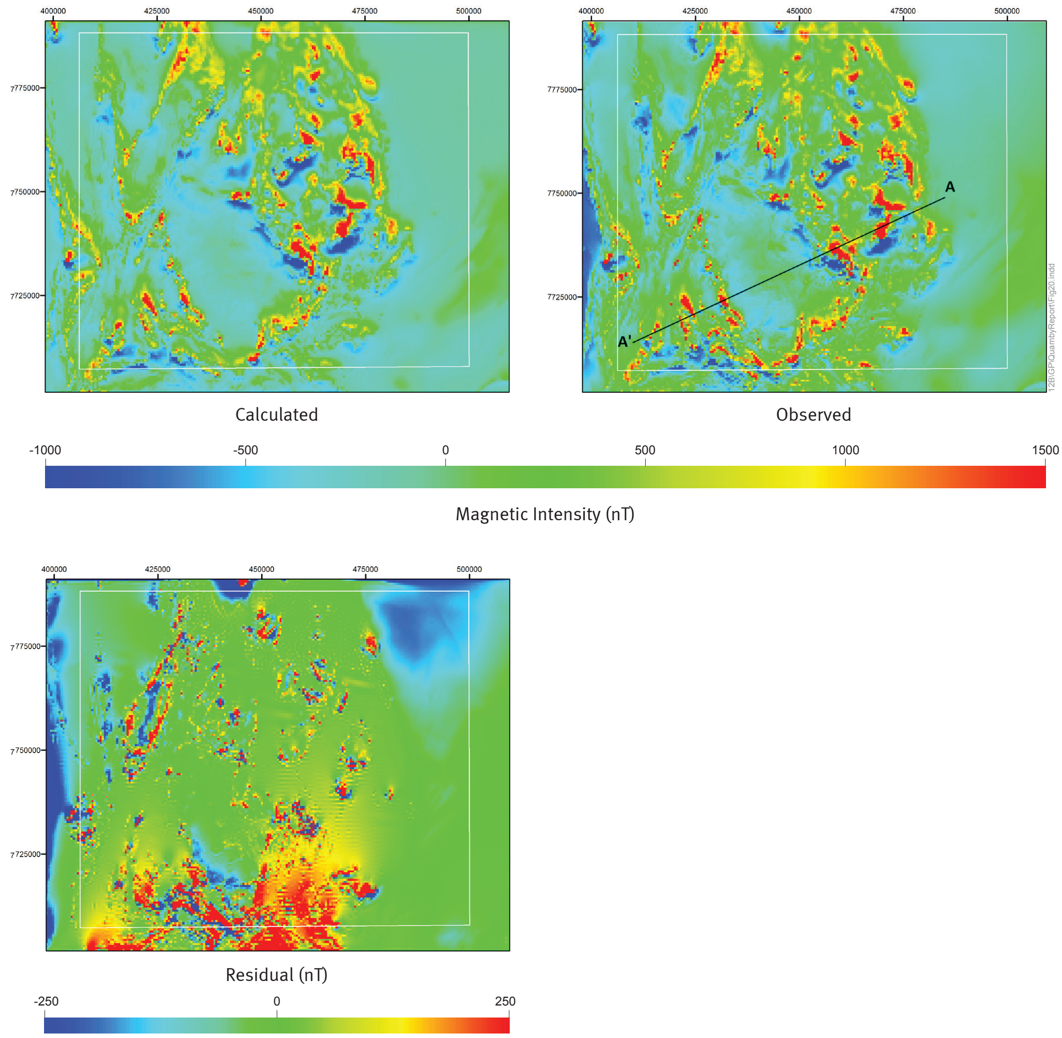

Figure 20: Comparison of calculated magnetic data from final 3D magnetic susceptibility model (after homogenous unit inversion and heterogeneous inversion) and observed data. Note change of residual scale bar from previous examples. Line A–A' on observed data is location of magnetic profile shown in Figure 21.

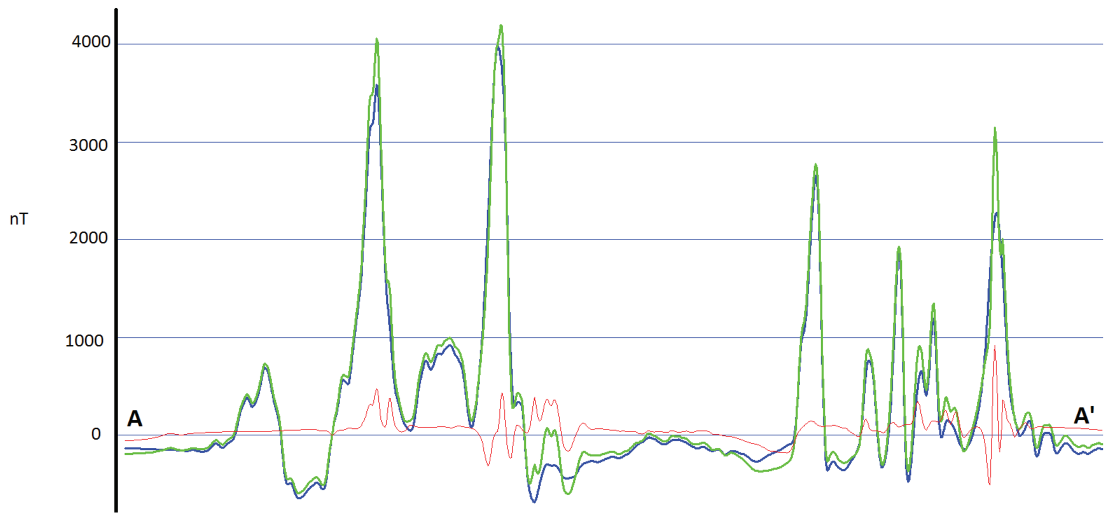

Figure 21: Profile from A–A' (location of profile marked on Figure 20) across the final 3D magnetic susceptibility model calculated (blue), observed (green) and residual (red) grids. Calculated model follows observed data for longer wavelength features, but cannot adequately model the short wavelength features due to the large lateral voxet cell size (500m).

Common Earth Model

A 3D Common Earth Model (CEM; McGaughey, 2006) was constructed from the results of the geological modelling and geophysical inversions. The CEM is a voxet with 250m x 250m x 50m (X, Y, Z) cell resolution, and extends to a depth of 2.5km below AHD. The CEM is smaller than the inversion voxet, clipped to the boundaries defined for the Quamby project area (Figure 1). The initial geological models and the voxets used for the geophysical inversion models cover a larger area than the project area to reduce the edge effects in the inversion when imported into the CEM. The common earth modelling process involves the integration of all available data into a single model consistent with the input data. The common earth modelling process is a multi-disciplinary approach where the geology, geophysics and mineral potential are interpreted together in 3-dimensional space. The resolution for the CEM was chosen based on the sensitivity and availability of the mineral potential targeting criteria and the computational power. The regional inversion results were upscaled into the CEM. The initial CEM contained the modelled lithology, 3D density model and 3D magnetic susceptibility model. Targeting criteria properties for mineral potential derived from the exploration criteria discussed in the mineralisation section above were defined based on available geological, geophysical and geochemical datasets within the CEM. These evidential properties were tested against known mineral occurrences using a Weights-of-Evidence (WoE; Bonham-Carter, 1994) approach, assessing the statistical relationships between the two to generate a mineral potential model across the Quamby region.

Weights-of-Evidence modelling

The objective of the mineral potential modelling (or exploration targeting) process was to assess the potential for undiscovered gold and copper mineralisation within the Quamby project area. The potential was assessed by the spatial overlap of weighted exploration criteria. These weights were defined by a data driven, Bayesian statistical approach assessing the spatial relationship between training data (known mineral occurrences) and the exploration criteria. Weights-of-Evidence (WoE) is a probabilistic method for combining data in support of a certain hypothesis and has been used as a 2D GIS method in mineral potential mapping for some years. The GOCAD Targeting workflow allows the WoE method to be used within GOCAD in a full 3D volumetric sense. A basic theory of WoE modelling is described below, while a more complete summary of the use of Weights-of-Evidence for mineral potential modelling is described by Bonham-Carter (1994), Kemp & others (1999) and Thiart & others (2006).

Basic principles of Weights-of-Evidence modelling

In order to understand the WoE concept, it is important to be familiar with some of the terminology.

Training cells: Points of known occurrences of a specific condition (e.g. mineral occurrences including current and historical mining operations) within the model. As WoE is a data-driven process this is a required input for modelling.

Evidential properties (exploration criteria): Data (based on the mineral systems conceptual models in this case) which are indicative of the likelihood of the existence of a mineral deposit (e.g. geophysical or geochemical anomalies, distance to faults etc.). These criteria are stored as properties in the CEM. Evidential properties are often continuous or discrete multi-class properties but must be converted into a binary form (presence or absence, using a cut-off value) for WoE modelling.

Weights: Weights provide a measure of spatial association between the training cells and the evidential properties. A positive weight indicates that there are more training cells captured in the region where the evidential property is present or absent than would occur due to chance; conversely a negative value indicates that fewer cells are captured than expected by chance. A value of zero, or very close to zero, indicates that the training cells are distributed randomly with respect to that property. W^+ is used for the weights where the evidential theme is present and W^- is used for where the evidential property is not present.

Contrast: Contrast is defined as the difference between the W^+ and W^- values. It is often plotted as a function of the cut-off values in order to determine the cut-off that maximises the contrast (maximising the spatial association between the evidential property and the known training data).

Prior probability: The probability of occurrence of mineralisation within each cell of the model computed without taking into account any evidential data. For example, if there are 3 training cells in a model with 100 cells, the prior probability is 0.03.

Posterior probability (mineral potential model): The conditional probability of occurrence of mineralisation within a cell given one or more evidential properties. The WoE posterior probability is a property calculated in the process of WoE modelling as a combination of evidential properties, weighted by their spatial correlation with the training cells and indicates the probability of a mineral occurrence.

Each evidential property is tested against the spatial distribution of training cells to evaluate the spatial statistical correlation between the two. These evidential properties are often continuous or discrete multi-class properties (i.e. distance to faults, geochemical assay value) but need to be reclassified into a binary property (i.e. within 500 metres of faults, above certain value of geochemical anomaly) to be used in GOCAD WoE modelling (Figure 22). This is achieved by creating a contrast curve, plotting the contrast for multiple discrete cut-off values (Figure 23). The cut-off value where the contrast is highest (greatest difference between W^+ and W^-) is often chosen as the cut-off value to use for targeting, as it is the best statistical discriminator (ideally, capturing the greatest amount of training cells within the smallest region) of mineralisation (Figure 23; Equation 2).

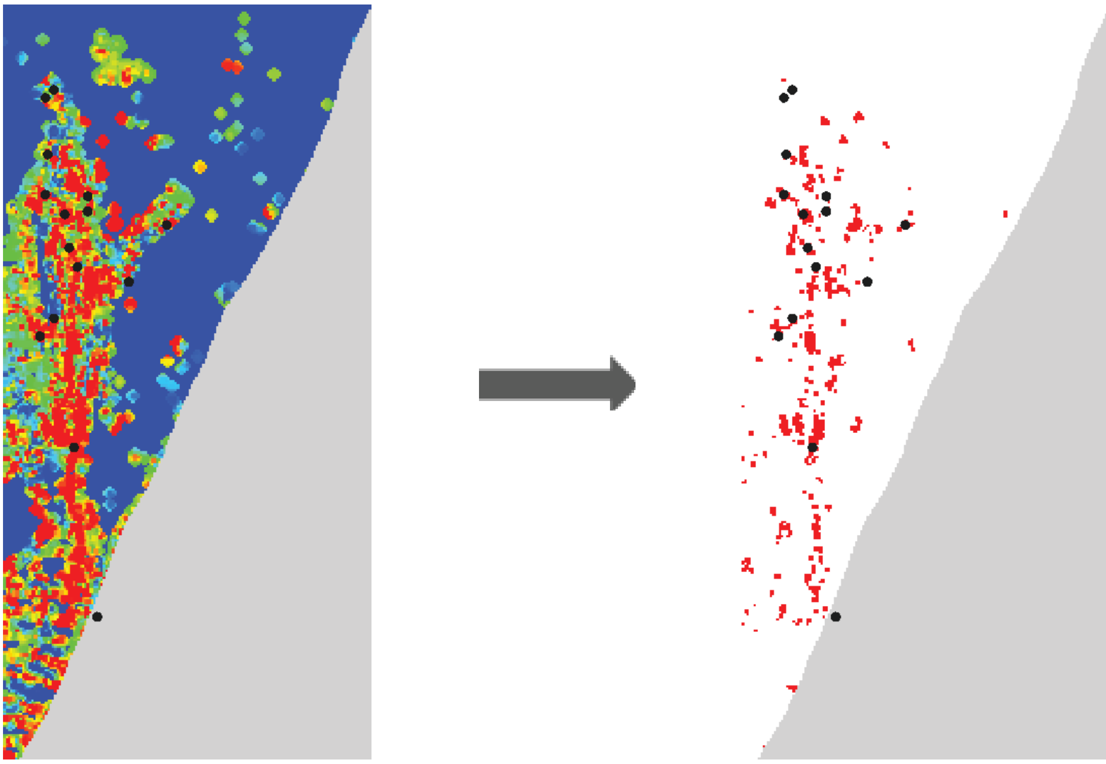

Figure 22: Example of exploration criteria (copper geochemistry) in the Mary Kathleen Domain. The continuous evidential property (left) is required to be converted into a binary evidential property (right) for the weights-of-evidence modelling. This is done using the contrast curve (Figure 23). Training data are plotted as black dots.

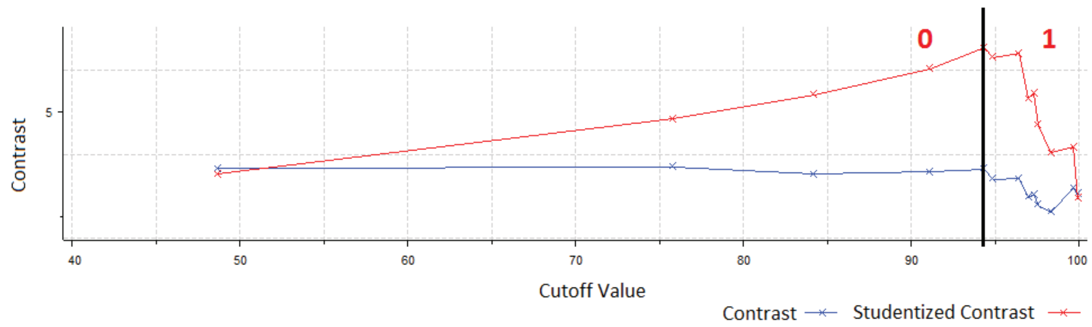

Figure 23: Contrast curve for copper geochemistry in the Mary Kathleen Domain. A set of cut-off values are plotted against the associated contrast (and studentised contrast; being the contrast divided by the standard deviation of the contrast). The cut-off value where the contrast (and/or studentised contrast) is highest is used to reclassify the continuous evidential property into a binary property where cells are within the favourable region (1) or unfavourable region (0).

$$W^{+} = \ln\left[\frac{\left(\dfrac{\text{\# training cells in captured region}}{\text{total \# training cells}}\right)}{\left(\dfrac{\text{\# cells in captured region- \# training cells in captured region}}{\text{total \# cells in model-total \# training cells}}\right)}\right]$$

$$= \ln\left[\frac{\text{\% of training cells captured}}{\text{\% of modelled region with no training cells captured}}\right]$$

Equation 2: Assignment of weights (modified from Kemp & others (1999) and Bonham-Carter (1994))

In an idealised situation a favourable evidential property would have a positive W^{+} (higher than random capture of training data where the evidential property exists) and a negative W^{-} (lower than random capture of training data where the evidential property does not exist). However, sometimes W^{+} can be close to zero, yet W^{-} is strongly negative. This suggests that the presence of the evidential property is not particularly predictive of mineralisation, but the absence of the property provides strong evidence that mineral occurrences are unlikely to be found. Once weights are assigned for the evidential properties, the posterior probability, or mineral potential, is computed by assessing the spatial overlap of the weighted binary evidential criteria.

The WoE theory assumes that evidential properties are conditionally independent of each other (Bonham-Carter, 1994; Agterberg & Cheng, 2002). If multiple evidential properties are based on the same exploration criteria (e.g. different properties based on distance to faults or filters on the geophysical inversion results), this will distort the final result and lead to an over-estimation of the mineral potential in areas where those properties exist. To minimise this over-estimation only one of the properties related to each exploration criteria was used in each computation of mineral potential.

Quamby Weights-of-Evidence modelling

To perform the Weights-of-Evidence modelling in GOCAD, the exploration criteria are required to be represented as evidential properties within the voxet, which in this case was the Quamby Common Earth Model (CEM). The training cells were created in the model using the point locations of operating mines, known resources and significant mineral occurrences from the MINOCC database (Geological Survey of Queensland, 2011a). The MINOCC training data points are for Cu±Au±Fe occurrences within the different domains and have been selected to provide cover over the entire project area. However, training data points are naturally sparser in the eastern part of the project area due to deeper cover and reduced company exploration. The MINOCC points are 2D (X,Y) and were therefore located at the centroid of the grid cell just below the topography in the outcropping region, or below the cover unit in the undercover regions.

Two separate WoE models were generated for Quamby as the conceptual mineralisation model and associated exploration criteria are different between the Constantine and Mary Kathleen geological domains. An additional model was also created for each area without using the geochemical anomalies, as this data was often clustered around known mineral occurrences, creating a bias towards previously explored regions relative to purely greenfields regions. The model volume and training data were identical for all models with only the combination of exploration criteria and the cut-off values changed to generate the mineral potential models.

Exploration criteria

Exploration criteria are geospatial variables thought to be related to gold and copper mineralisation in the Quamby region. The correlation between exploration criteria and known mineralised occurrences is assessed through the Weights-of-Evidence process, and the exploration criteria exhibiting strong correlations to training data are combined to create the mineral potential model. The exploration criteria were based upon the current understanding of the mineralisation in the project area (see Mineralisation Styles section above and references in Appendix 2) outlining the controls on copper and gold mineralisation in the Quamby region. The exploration criteria are represented in the GOCAD model as continuous or discrete variables in the CEM. Where the exploration criteria from the mineral systems study was not a property that could be readily represented within the model, a proxy for this property may be used (e.g. the potassic alteration could not be modelled across the model in 3D, but the potassium channel from the radiometric data was used as an approximation of this variation). Twenty-one properties were created in the CEM for testing in the WoE modelling. Some of these are combinations or variations of each other and not conditionally independent of each other. These were tested to see which had the most significant correlation to the training data. The 21 properties are described below.

Geochemical exploration criteria

Gold and copper anomalism in soils, rock chips and drillholes is obviously considered as important exploration criteria for gold and copper mineralisation. However, the spatial density of this data is extremely high in or around known mineral prospects and mines and relativity low outside of these regions. This may lead to a situation where geochemical anomalism, having a very high contrast, could bias the final mineral prospectivity model to only appear prospective where geochemical data already exists and hide possibly prospective greenfields areas. To avoid this, as already mentioned, models were created with and without geochemical anomalies used as targeting criteria.

Geochemistry data was extracted from the open-file GSQ geochemistry database (Geological Survey of Queensland, 2010) and company reports. Most geochemistry reflects surface sampling (soil and rock chip) but some 3D data (assayed drillholes) exists. For the 3D WoE modelling, the entire voxet must have data, so where 3D data was unavailable, surface data was populated down though the voxet. Each population of data (rock-chip, soil and drillhole) has been derived by different analytical methods from different laboratories. Therefore the results between the populations are not comparable. To make allowance for this, each population was normalised by ranking the value of each sample as a percentile of the whole population. The percentile ranked populations were then combined and gridded in 2D, where data existed. Where no data existed, the grid was given a null value. This 2D grid was placed on the topography surface and populated vertically downwards through the voxet model into 3D space. Where true 3D data (drillhole assays) was available it was used in preference to 2D data. As the WoE method cannot handle null data, any remaining nulls were replaced with a value of 0.

A summary of the geochemical criteria is listed below:

Au_Geochem: Gold geochemical values normalised between 0 and 100

Cu_Geochem: Copper geochemical values normalised between 0 and 100.

Geophysical exploration criteria

The results from the geologically constrained density and magnetic susceptibility inversions were also key targeting criteria for mineralisation. Anomalous properties within the inversion voxet may suggest alteration due to flux of significant volumes of potentially mineralising fluids. Each voxel of the final inversion voxet contains three properties; density, magnetic susceptibility and the lithology integer. Several different datasets were created from the results of both the density and magnetic susceptibility inversion to test which had the best correlation to known mineralisation.

Initially, the absolute value of the density or magnetic susceptibility generated through the inversion process was tested for significance as an exploration criterion. However, as some lithological units had higher or lower mean property values, the variation of property from the expected value was thought to be more relevant to analysing the potential for fluid interaction, alteration and possible mineralisation. A mean value for each lithological unit was calculated and subtracted from the values within each voxel, leaving the variation from the unit mean. Within the inversion process some units had a large range of allowed property variation (e.g. the Corella Formation) while some were relativity constrained (e.g. Lower Mount Albert Group). Therefore, a variation of 0.1g/cc in the Lower Mount Albert Group is far more remarkable than a 0.1g/cc variation in the Corella Formation. The standard deviation of the density and magnetic susceptibility of each unit was calculated and a new property representing the number of standard deviations from the unit mean of each voxel was created. Finally, to test the magnitude variation from unit mean, an absolute value of the number of standard deviations was created. Each set of properties are conditionally dependent as they rely on the same data source. While all were tested in each case, only one density and magnetic susceptibility property could be used in creating the mineral potential model. The final magnetic and density properties chosen for each of the domains are described in later sections. A summary of the tested geophysical criteria is listed below:

Density_prop: Density values resultant from geophysical inversions

Density_dev: Variation of density value from expected value (lithological unit mean)

Density_no_of_std_dev: Number of standard deviations of density value from expected value (lithological unit mean)

Density_no_of_std_dev_ABS: Absolute value of number of standard deviations of density value from expected value (lithological unit mean)

MS_prop: Magnetic susceptibility values resultant from geophysical inversions

MS_dev: Variation of magnetic susceptibility value from expected value (lithological unit mean)

MS_no_of_std_dev: Number of standard deviations of magnetic susceptibility value from expected value (lithological unit mean)

Ms_no_of_std_dev_ABS: Absolute value of number of standard deviations of magnetic susceptibility value from expected value (lithological unit mean).

Potassic alteration and uranium anomalism are commonly associated with oxidised styles of Cu-Au mineralisation. These can be interpreted from airborne radiometric data (Queensland Department of Mines and Energy & others, 2000). The value of the potassium (K) channel of the airborne radiometric data was used as a proxy for the potassic alteration overprint.

The ratios of uranium divided by thorium, and uranium squared divided by thorium, have been used in the past to identify areas of anomalous uranium and both properties were created for the WoE process. During this process it was noticed there was a levelling issue along survey boundaries in the uranium data in the southern Constantine Domain which was exacerbated in the U^2/Th ratio. Hence, the U^2/Th property was not considered reliable in the Constantine Domain. The radiometrics data is a 2D surficial property. To allow for it to be incorporated into the WoE modelling, this property was populated down the Z axis through the model. A summary of the tested radiometric criteria is listed below:

Rad_K: Potassium channel of radiometric data

Rad_UdivTh: Ratio of uranium to thorium radiometric data

Rad_U2divTh: Ratio of uranium squared to thorium radiometric data.

Geological exploration criteria

The proximity to major structures and certain lithological features are thought to be important exploration criteria as these features may represent:

- the source of the metals or ligands
- the source of the fluids
- pathways and structural traps for the mineralised fluids
- a rheological or geochemical contrast that may affect the oxidation state of fluids.

Properties were created in the CEM representing the distance to modelled crustal scale faults and Williams-Naraku aged granites. These properties are summarised below:

Fault_Distance: Distance to nearest fault surface

Dist_Will_Gran: Distance to Williams-Naraku aged granite bodies (only within Constantine Domain). As the zone of interest is outside the granite bodies, not within them, the value of the distance to granite property was manually set very high within the granite bodies to exclude this region.

Faults and lithological boundaries may act as pathways for the large volumes of fluid required to form mineral deposits. The geological complexity is a measurement of the spatial density of faults and lithological boundaries in a region (Ford & Blenkinsop, 2008a;b). More complex regions (those with more interacting surfaces) are thought to have a positive association with mineralisation. The number of intersecting surfaces within each voxel of the CEM was calculated and populated through the CEM using a moving average kernel filter. Three different sized kernels were used with 4x4x2 cells, 5x5x2 cells and 4x4x4 cells. The three properties created with different filters were tested in each case but as they were dependent on the same dataset, only one was used in creating the mineral potential model. The three tested properties are listed below:

Geol_Complex_444: Geological complexity (Count of faults and lithological surfaces per CEM cell) with 4x4x4 moving average filter applied

Geol_Complex_442: Geological complexity (Count of faults and lithological surfaces per CEM cell) with 4x4x2 moving average filter applied

Geol_Complex_552: Geological complexity (Count of faults and lithological surfaces per CEM cell) with 5x5x2 moving average filter applied.

It is thought that the Corella Formation (and the similar calc-silicate rich Staveley Formation in the east) plays a significant role in mineralisation, possibly by localising faulting, fluid flow and the juxtaposition of contrasting lithologies (Blenkinsop & others, 2005c; Mustard & others, 2005b). A property representing the distance to units of the Corella or Staveley Formations was created. The value of this property inside the Corella and Staveley lithologies was 0. A separate property representing this distance to the top and bottom contacts of the Corella and Staveley lithologies was created. These properties are summarised below:

Dist_to_Calc_Sil_inc_inside: Distance to the Corella or Staveley lithology. Property value is 0 within these lithologies.

Dist_to_Calc_Sil_Boundary: Distance to Corella or Staveley lithological boundaries. Distance increase from boundary both within and outside of Corella and Staveley lithologies.

Bends along fault surfaces can play a role in affecting or focusing fluid flow by generating variations in the stress along the structure, creating sites of higher mineral potential (Blenkinsop & others, 2005a).

In previous studies the fault roughness was calculated from the relationship between the actual fault length and ruler fault length (distance between end points). In this study a property representing the curvature of the nodes along the modelled fault surfaces was created. This property assesses the 3D deviation from a flat surface projected from each node. It is minimum (or zero) where little or no deviation exists and highest where the fault deviates from a flat plane. The property was calculated individually on each fault part and then populated into the CEM within a 1500 metre proximity to the modelled faults. Outside this region the property value was set to 0. This property is listed below:

Fault_Curvature: Degree of 3D curvature along modelled faults.

Mineral potential modelling

3D mineral potential models were constructed by combining the weighted statistically significant exploration criteria. These mineral potential models highlight regions of high gold and copper discovery potential in the model — areas which contain multiple favourable exploration criteria. As the conceptual mineralisation model differs between the geological domains, the WoE modelling was conducted independently for each domain. The spatial association between the training cells and the evidential properties was not the same in each domain meaning the cut-offs, weights and favourable criteria in each were different. Separate mineral potential models were therefore created for the Constantine and Mary Kathleen geological domains. Additionally, due to the bias towards well-explored regions in the geochemistry data (high data density around mines and prospects, low data density in greenfields regions) and high contrasts as a result of this bias, a second set of mineral potential models were created without using the geochemistry data.

Constantine Domain

The Constantine Domain lies between the Mount Margaret Fault in the east and Quamby and Fountain Range Faults in the west. To ensure that prospective regions (including anomalous regions of the geophysical inversions along the edge of the Constantine Domain) were captured, a larger region was used for the Weights-of-Evidence modelling. This larger region used for the WoE modelling extends a short distance east into the Solders Cap Domain and south into the Mitakoodi and Tommy Creek Domains. The weights, contrasts and favourable ranges for significant exploration criteria in the Constantine Domain are listed in Table 7. The same favourable ranges and weights are used in the complete model and the subset model (no geochemistry data used).

The exploration criteria with the highest studentised contrast (the contrast divided by the standard deviation of the contrast) are: the geochemistry (Au_Geochem and Cu_Geochem) and the geophysical inversion results (Density_dev and MS_no_of_std_dev_ABS). These exploration criteria form the greatest contributors to the final mineral potential model. The exploration criteria with lower studentised contrast listed above still contributed to the mineral potential model. Some tested exploration criteria (including the Potassium anomaly and distance to calc-silicates) were judged to not have a significant association with the training data in this area and at this scale. These exploration criteria may be significant at a more localised scale or in specific regions of the Constantine Domain.

Complete model

The mineral potential model created in the Constantine Domain using all of the exploration criteria listed in Table 7 is presented as Figure 24. An efficiency of classification plot was generated to determine the effectiveness of the mineral potential model (Figure 25). In this plot, 73% of the training cells are captured in the top 2.5% of the cumulative ranked mineral potential.

Table 7: Statistically significant exploration criteria, associated weights and cut-off values used for the Weights-of-Evidence modelling within the Constantine Domain

	Weights				Favourable Range	
Exploration Criteria	**W^+**	**W^-**	**Contrast**	**Stud. Contrast**	**Range Start**	**Range End**
Au_Geochem	3.726	-0.749	4.475	8.647	100	89.45
Cu_Geochem	3.785	-0.618	4.403	8.507	100	94
Curvature	1.382	-0.318	1.701	3.105	5×10^{-3}	4×10^{-5}
Density_dev	1.525	-0.522	2.046	3.954	0.247	0.055
Dist_Will_Gran	0.467	-0.558	1.025	1.872	0m	3314m
Fault_Distance	0.889	-2.224	3.113	3.008	0m	2192m
MS_no_of_std_dev_ABS	1.652	-0.431	2.083	3.953	27	1.429
Geol_Complex_552	0.544	-0.392	0.935	1.807	1.218	0.0132
Rad_UdivTh	1.742	-0.345	2.087	3.810	1.380	0.248

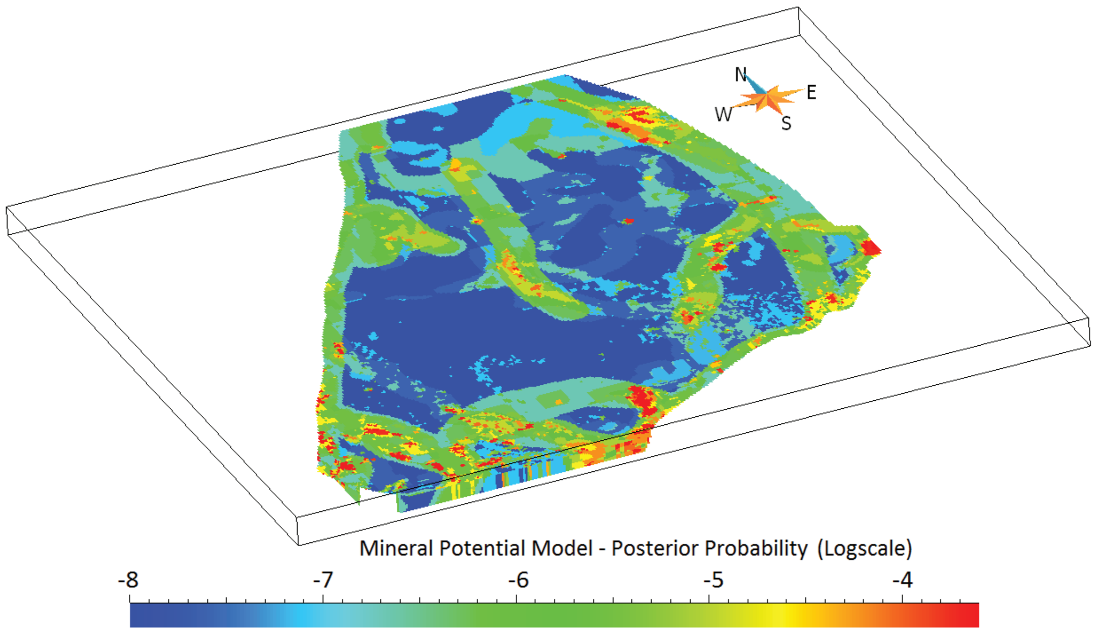

Figure 24: Complete Mineral Potential Model for gold and copper mineralisation in the Constantine Domain using all of the exploration criteria listed in Table 7. Posterior probability displayed on a log scale. Depth section displayed at 50 metres below AHD.

Subset model

The mineral potential model created in the Constantine Domain using all but the geochemical exploration criteria listed in Table 7 is presented as Figure 26. On a regional scale the mineral potential model appears to be very similar to that of the complete model. However, the efficiency of classification plot (Figure 25) does show major differences. For the subset model, 80% of the training cells are captured in the top 21.5% of the cumulative ranked mineral potential (compared to 8% in the complete model). This is due to the large contrast and the spatial bias in the geochemistry data. The geochemistry has a high contrast value as it is naturally more prevalent around previously explored (and often prospective) regions, as is the training data. Due to this fact, the geochemistry data has a high W^+ (the presence of the variable is a good predictor for the presence of mineralisation) but a low W^- (the absence of the variable is not a strong discriminator against the presence of mineralisation).

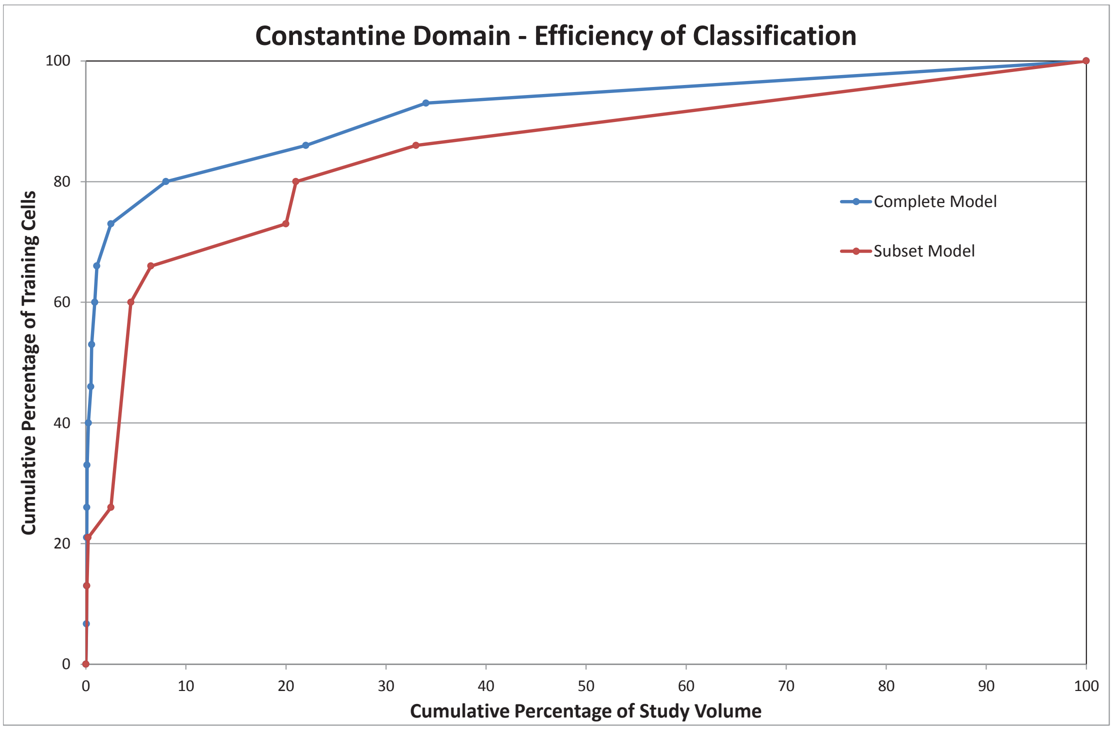

Figure 25: Efficiency of classification plot showing the cumulative percentage of training cells captured versus the cumulative percentage of the study volume (ranked from highest to lowest mineral potential) for the complete model (blue line; Figure 24) and the subset model (red line; Figure 26).

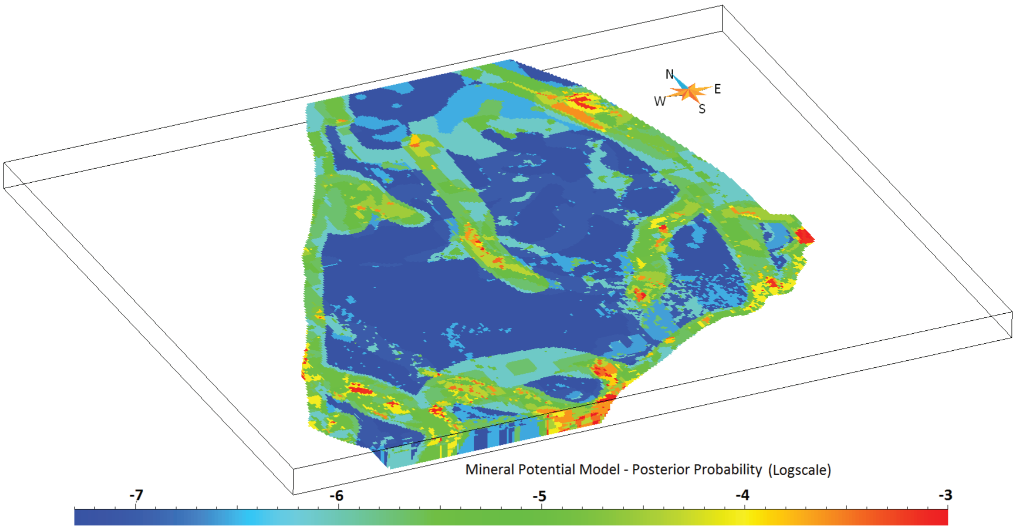

Figure 26: Subset Model Mineral Potential for gold and copper mineralisation in the Constantine Domain using all of the exploration criteria listed in Table 7 apart from the geochemistry data (Au_Geochem and Cu_Geochem). Posterior probability displayed on a log scale. Depth section displayed at 50 metres below AHD.

The geochemistry based exploration criteria have an extremely discriminative favourable range only including the top 5 to 10 percent of the values and as a result, the favourable regions are extremely localised (Figure 27). This, with the high weights, has the effect of pushing the cells where the geochemistry variable is present (including most of the training cells which are mineralised locations usually accompanied by geochemical anomalies) into the top few percent of the cumulative ranked mineral potential model. This effect can be seen in the difference between the two efficiency of classification plots (Figure 25). The presence of the favourable geochemistry variable has shifted the efficiency of classification curve towards the left in the complete model compared to the subset model. However, outside the favourable range of the geochemistry variable, the complete and subset models are comparable to each other.

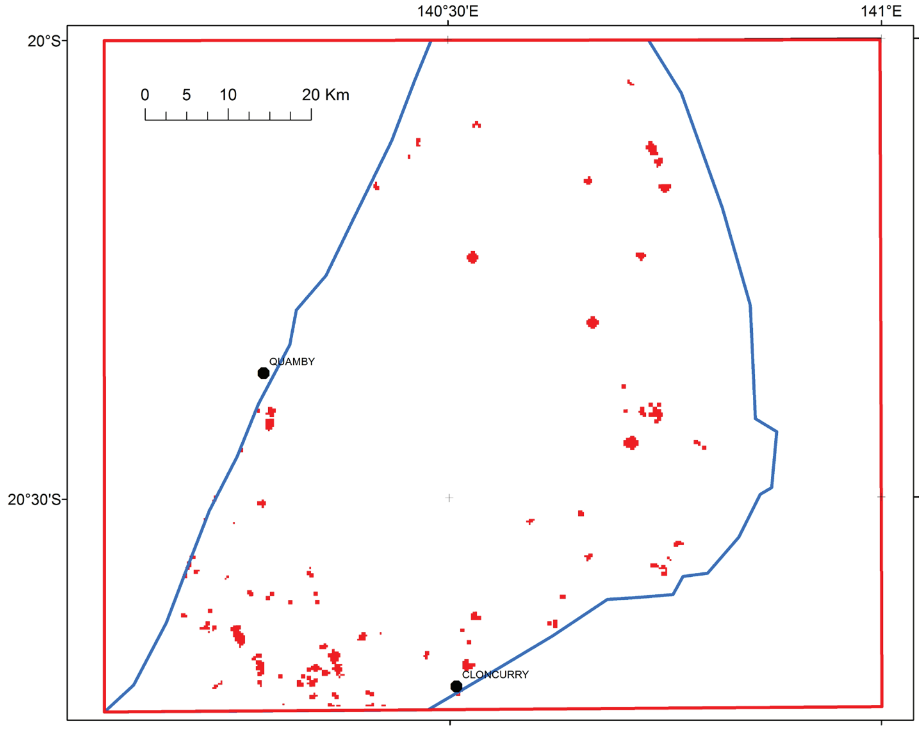

Figure 27: Gold geochemistry binary evidential property (red regions) within Constantine Domain (blue region). The favourable regions are localised very small compared to the whole Constantine Domain region.

Modelling interpretation

Figure 28 shows a plan view section of the Constantine WoE model (at 50 metres below AHD) with the labelled training cells (red spheres) shown. While these section images provide an impression of the results of the mineral potential modelling, the model is best assessed in 3D using a 3D modelling package. A GOCAD project, 3D objects in various formats and 3D pdfs are included in the data packages accompanying this report. A short, non-exhaustive, discussion of some observations regarding the Constantine Domain mineral potential model follows. It is important to note that the mineral potential model should be viewed in the context of the evidential properties that create the potential and not just an exercise in locating the indicated areas of highest potential to focus future exploration.

The complete mineral potential model of the Constantine Domain highlights the Ernest Henry deposit within the south-eastern part of the domain and the continuing trend to the north-east and south-west of the deposit. The trend to the south-west of the deposit follows an inferred fault to the FC9 occurrence, while the north-eastern continuation of the trend matches up with no existing mineral occurrence data point.

The Cormorant and Gypsy Plains prospects along the Mount Margaret Fault in the north of the Constantine Domain model are highlighted by the mineral potential modelling, with the entire fault zone showing high potential along strike with variable potential indicated down the fault plane. The intersection of the Mount Margaret Fault and a smaller fault to the north-east of Cormorant shows a similar response to the nearby Cormorant prospect.

The continuous moderate to high potential between the Great Australia mine, Jasper Block and further north to the historical Australian Margaret mine (not shown on map), highlights the north–north-east trending Turf Club Shear Zone. This shear zone (which was not included as a fault in the 3D model) is believed to control and host mineralisation in the area. While the area is a strong copper geochemical anomaly, the high mineral potential values are also due to the distance from the edge of the Williams Batholith and anomalous variations in the density and magnetic susceptibility models.

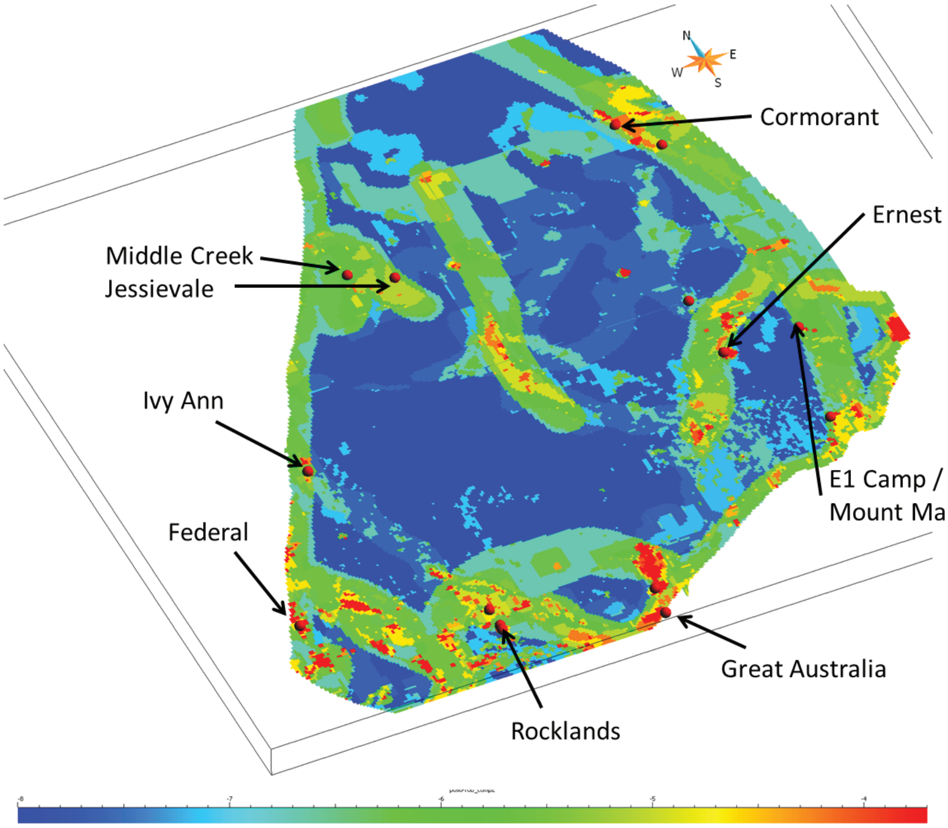

Figure 28: Plan view section of the mineral potential of the complete Constantine WoE model (at 50 metres below AHD) with labelled mineral occurrence points (red spheres)

Within the edge of the Mitakoodi Domain, which was modelled along the southern edge of the Constantine Domain, the Rocklands, Las Minerale and the Fairfield Prospect lie along a north-west trending zone of high mineral potential which extends into the Constantine Domain to the north of the modelled fault. The mineral potential at the Rocklands Prospect is greater at shallower depths within the model when compared to the nearby Fairfield Prospect (as mineralisation outcrops at the surface), while the mineral potential at Rocklands is lower within the subset model due to the removal of surface geochemistry data (a highly weighted key exploration criteria).

The extension of the Constantine model into the Tommy Creek Domain allowed modelling to be undertaken on both sides of the Fountain Range Fault, with mineralisation at the historical Federal mine highlighted on both sides of the fault (therefore also within the Mary Kathleen model). To the north of the mine, along the same fault, heightened mineral potential is created by anomalous variations in magnetic susceptibly and density, along with structural complexity and fault curvature.

To the east of the Middle Creek and Jessievale prospects, a north–south trending concealed thrust fault is highlighted by the model, with two areas showing moderate to high mineral potential visible along strike. The anomalies along the fault appear stronger within the subset model as surface geochemistry has little effect over the complete model due to lack of exploration in the area.

Mary Kathleen Domain

The weights, contrasts and favourable ranges for the most significant exploration criteria in the Mary Kathleen Domain are listed in Table 8. While the exploration criteria tested are the same as that for the Constantine Domain, those found to be statistically significant and their weights, contrasts and cut-off values are different.

Similarly to the Constantine Domain, the exploration criteria with the highest studentised contrast are the Au_Geochem and Cu_Geochem geochemistry data. However, while the result of the magnetic susceptibility inversion still has a significant relationship to mineralisation, none of the properties created from the final 3D density model had a significant relationship, at this scale, within the Mary Kathleen Domain. The fault curvature exploration criteria also had a significant relationship to the mineralisation in the Mary Kathleen Domain. Additionally some exploration criteria that were not very significant in the Constantine Domain (Rad_K and Rad_U2divTh) were found to be more significant in the mineral potential modelling of the Mary Kathleen Domain at this scale.

Complete model

The mineral potential model created in the Mary Kathleen Domain using all of the exploration criteria listed in Table 8 is presented as Figure 29. An efficiency of classification plot was generated to determine the effectiveness of the mineral potential model (Figure 30). In this plot, 79% of the training cells are captured in the top 2.7% of the cumulative ranked mineral potential.

Table 8: Statistically significant exploration criteria, associated weights and cut-off values used for the Weights-of-Evidence modelling within the Mary Kathleen Domain

	Weights				Favourable Range	
Exploration Criteria	**W^+**	**W^-**	**Contrast**	**Stud. Contrast**	**Range Start**	**Range End**
Au_Geochem	2.564	-0.654	3.218	6.020	100	91.38
Cu_Geochem	2.662	-0.984	3.645	6.535	100	94.34
Curvature	1.713	-0.479	2.192	4.059	5×10^{-3}	7×10^{-5}
Fault_Distance	0.587	-0.465	1.052	1.947	0 m	772 m
Rad_K	0.706	-0.516	1.222	2.263	7.84	2.44
MS_no_of_std_dev	0.528	-1.846	2.374	2.287	27	0.58
Geol_Complex_444	0.837	-0.354	1.192	2.206	0.01	0.182
Rad_U2divTh	1.120	-0.318	1.438	2.578	0.34	0.4

Subset model

The mineral potential model created in the Mary Kathleen Domain using all but the geochemical exploration criteria listed in Table 8 is presented as Figure 31. Similarly to the Constantine Domain, the mineral potential model of the subset model appears similar to the complete model (although the complete model has a broader range of posterior probabilities).

However, in the efficiency of classification plot for the subset model (Figure 30) 71% of the training cells are captured in the top 18.6% of the cumulative ranked mineral potential (compared to less than 2.5% in the complete model).

Modelling interpretation

Figure 32 shows a plan view section of the Mary Kathleen WoE model (at 50 metres below AHD) with the training cells (black spheres) shown. Within the Mary Kathleen domain, the Mount Rose Bee Fault (also referred to as the Mount Roseby Fault Zone) is the main structural corridor within the domain and the modelled mineral potential highlights the importance of this structure for mineralisation in the area. Numerous very small and small sized copper and copper-gold occurrences are scattered along the entire length of the fault but the known resources for both sediment hosted and structurally controlled

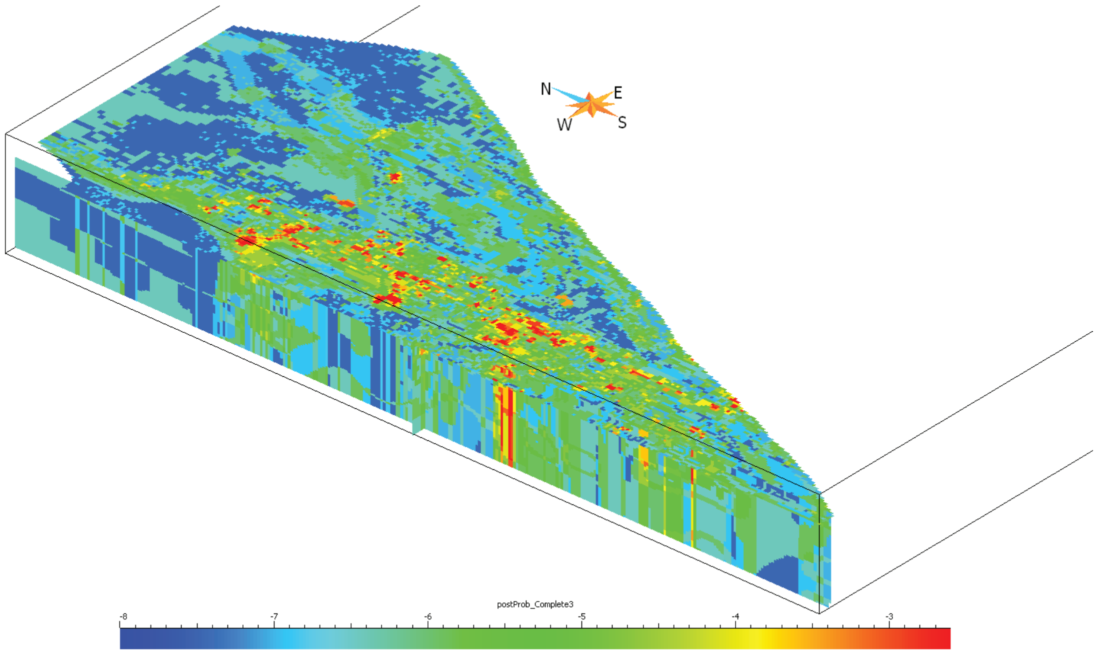

Figure 29: Complete Mineral Potential Model for gold and copper mineralisation in the Mary Kathleen Domain using all of the exploration criteria listed in Table 8. Posterior probability displayed on a log scale. Depth section displayed at 50 metres below AHD.

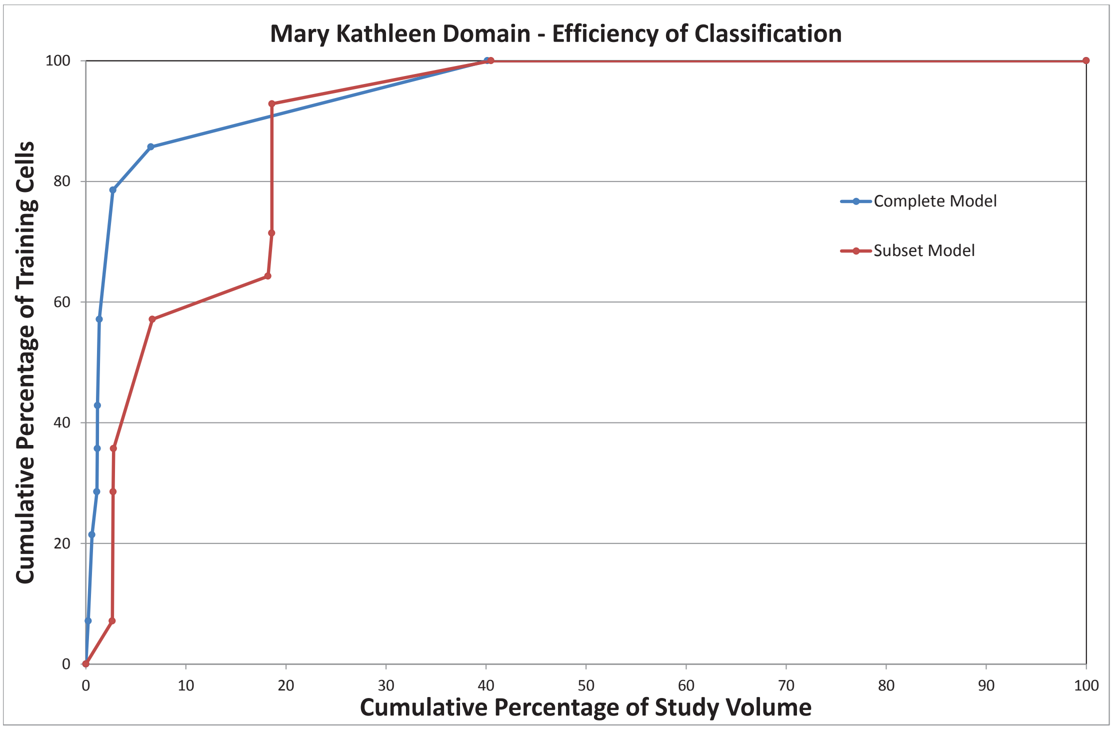

Figure 30: Efficiency of classification plot showing the cumulative percentage of training cells captured versus the cumulative percentage of the study volume (ranked from highest to lowest mineral potential) for the complete model (Figure 29) and the subset model (Figure 31).

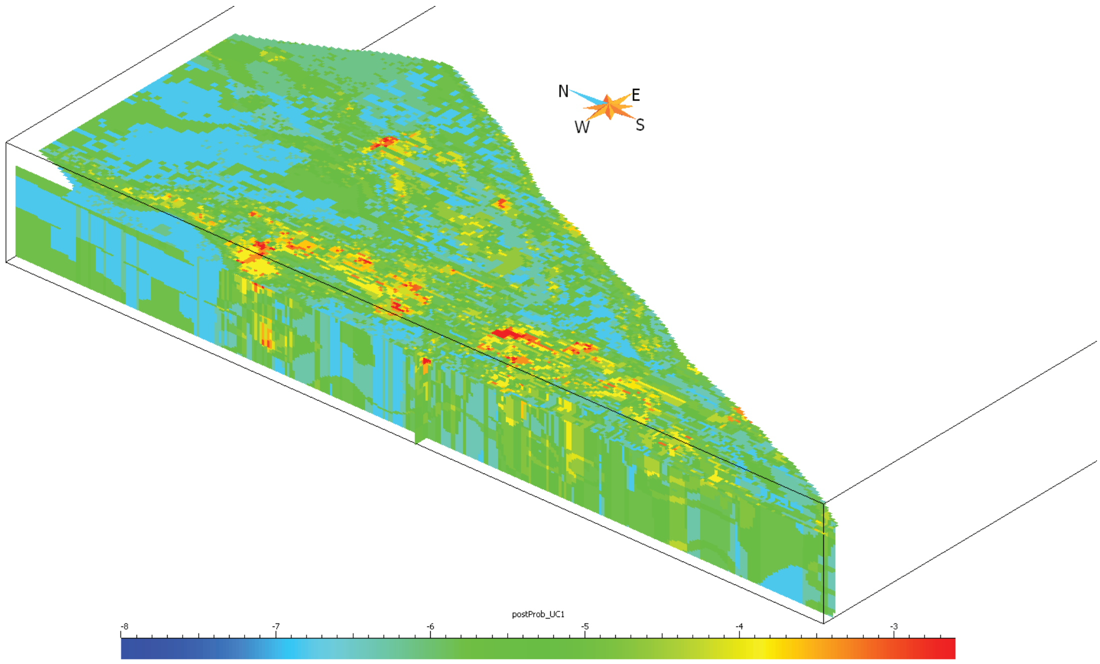

Figure 31: Subset Model Mineral Potential for gold and copper mineralisation in the Mary Kathleen Domain using all of the exploration criteria listed in Table 8 except for the geochemistry data (Au_Geochem and Cu_Geochem). Posterior probability displayed on a log scale. Depth section displayed at 50 metres below AHD.

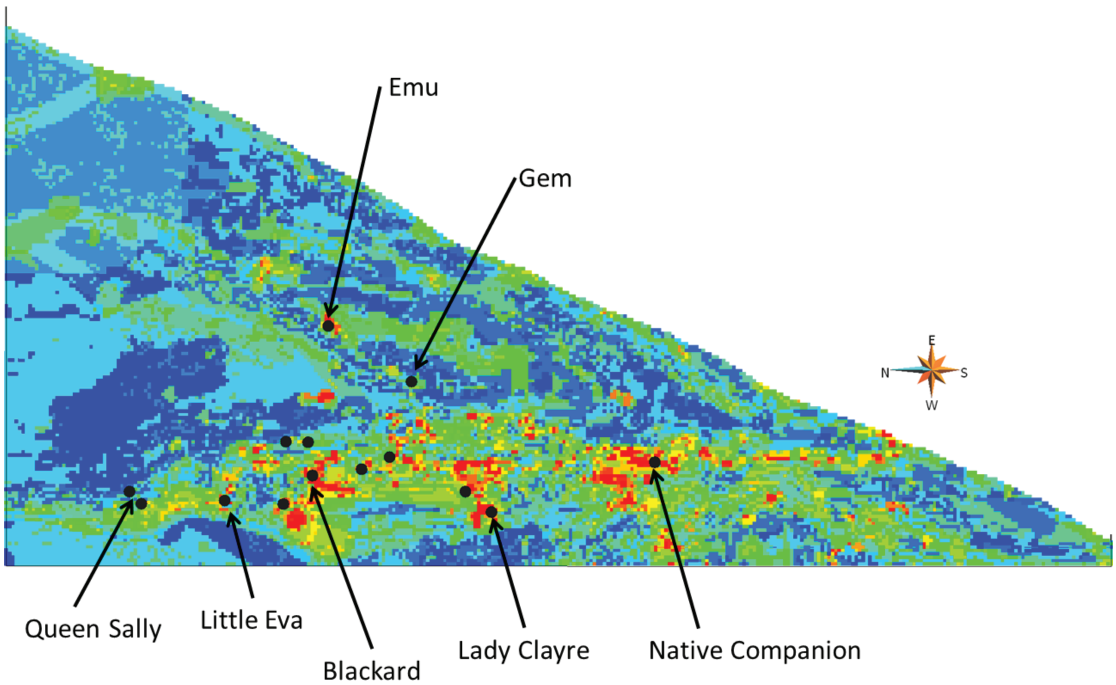

Figure 32: Plan view section of the mineral potential of the complete Mary Kathleen WoE model (at 50 metres below AHD) with labelled mineral occurrence points (black spheres)

Cu±Au±iron oxide deposits are located only within the centre of the domain (from Little Eva in the north to Lady Clayre in the south) known as the Roseby Copper Corridor. The mineral potential model emphasises this prospective zone and possible northern and southern continuations of the Roseby Copper Corridor. Within the Roseby corridor, the mineral potential highlights known mineral occurrences, highlights mineral potential along fault splays to the east of the Mount Rose Bee Fault (east of Lady Clayre) and newer prospective regions to the periphery.

The high mineral potential surrounding the historical Native Companion mine to the south of the main Roseby corridor deposits is due mainly to the presence of the geological complexity, radiometric response and fault curvature evidential properties. This area has a number of very small historical mineral occurrences all along the southern extension of the Mount Rose Bee Fault with only minimal surface company exploration undertaken in this area, as recent exploration has been focused on developing known mineral resources and reserves further north.

The Gem deposit, located to the east of the Roseby deposits and hosted by the Dipvale Granodiorite (part of the Wonga-Burstall Igneous Event), only has a minor response from the potential modelling. The Emu prospect which is similar in nature to the Gem deposit has a stronger response, owing to geological complexity and surface geochemistry. As the majority of the training cells were located within the Roseby Copper corridor, the mineralisation system at Gem (which is located within the granodiorite as opposed to sediments) may be considered foreign to the rest of the Mary Kathleen Domain. As the mineral potential modelling is assessing areas where similar anomalous conditions exist, it would be expected that the Gem deposit would not appear as a highly prospective region.

Conclusions

This report follows the workflow used in Geological Survey of Queensland (2011b); building a geological 3D model, refining the model through geophysical inversions creating a robust geologically and geophysically validated Common Earth Model which is subsequently used for mineral potential modelling. This workflow can be downscaled from a regional study and applied to district or even camp scale studies.

3D geological modelling to 20km depth was undertaken to test the Geological Survey of Queensland's current structural and geodynamic understanding of the regional geology and to provide a geological constraint for potential field inversions. The use of geological constraints reduced the non-uniqueness associated with the inversion process and produced a model consistent with both the geological interpretations and potential field data.

Regional geologically constrained potential field inversions of the magnetic and gravity data across the modelled region yielded 3D density and magnetic susceptibility property models. The 3D property models were used to assess anomalous property distributions both throughout the whole model and within lithological regions. Zones of anomalously high or low properties compared to the mean enclosing lithological unit value can be interpreted either as unrecognised intrusive bodies, zones of metamorphism or alteration, or as errors in the initial model. The process of creating and concentrating an economic ore deposit requires a set of anomalous conditions (e.g. metal availability, fluid transport pathways, favourable structural, chemical and lithological depositional environments etc) and therefore areas where the initial model was unable to account for the observed geophysical anomaly are of primary interest in the prospectivity studies and regional exploration. The 3D density and magnetic susceptibility models were a key input into the Common Earth Model for the mineral potential modelling to identify statistically significant exploration criteria.

The mineral potential of the Quamby region was evaluated using a Weights-of-Evidence approach to assess the statistical significance of mineral exploration criteria using their spatial relationship with the locations of known mineralisation. Within the Constantine Domain the exploration criteria based on the geochemistry and the geophysical inversion results had the greatest spatial correlation with known mineralisation. In the Mary Kathleen Domain the exploration criteria based on the geochemistry, fault curvature and the magnetic susceptibility values had the greatest spatial correlation with the known mineralisation. For both the Constantine and Mary Kathleen Domains two mineral potential models were created: (i) using the complete set of significant exploration criteria, and (ii) using a subset of the exploration criteria excluding the geochemistry. The latter models (excluding the geochemistry) remove the bias introduced by the inherent confinement of most geochemistry data to exposed areas close to known mineralisation, enabling a more balanced mineral potential assessment of covered greenfields areas which comprise more than 70% of the project area.

The mineral potential models over both domains highlight the location of known mineralisation (including the training data) but also show potential extensions of the known mineralisation along strike (e.g. Ernest Henry, Mount Rose Bee Fault). The modelling also highlighted areas, for example in the central Constantine Domain, with no known occurrences and minimal geochemistry, which have not been adequately explored to date.

The mineral potential models over the Constantine and Mary Kathleen domains are a product of a number of hypotheses based on literature research and previous WoE modelling over the Mount Dore project area. Initially the exploration criteria were developed to be modelled over the entire project area as a whole (for structurally-controlled epigenetic Cu±Au±iron oxide). However, during the process of the WoE modelling it was realised that the statistical significance, and the strength of association, of the evidential properties across the two domains was not consistent (e.g. the density inversion did not show a relationship to mineralisation within the Mary Kathleen domain but did within the Constantine Domain). In addition, previously held ideas about mineralisation across the Eastern Succession which was used for the Mount Dore WoE modelling to the south of this project area were not as important or relevant within this project area.

Variations of the evidential properties in either domain or changes in scaling (regional >camp > prospect) will have significant changes in the final model results. The level of modelling for the Quamby project is at a regional scale and modelled results should not exclusively be used for target generation.

Future work over the Quamby project area and improvements to the 3D model would benefit from the inclusion of detailed geophysical surveys, in particular electromagnetic (EM) surveys and the extension of the model further to the east into the Soldiers Cap Domain to model similar mineralisation styles under deeper cover.

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Appendix 1
Stratigraphic framework of Quamby Project area

Basement succession

The Quamby Project area lies in the northern exposed segment of the Mount Isa Eastern Succession. The project area comprises a sequence of meta-sedimentary and igneous cover rocks (containing elements of "Cover Sequence 2" and "Cover Sequence 3" of Blake, 1987) overlying significantly older Paleoproterozoic crystalline basement rocks. The latter are exposed to the west of the Quamby region as a north trending belt of broadly coeval granitoids and felsic volcanics of the ***Kalkadoon Granodiorite*** and ***Leichhardt Volcanics*** respectively. The Leichhardt Volcanics typically comprise a sequence of grey quartz feldspar porphyry, recently dated at 1864±3Ma (Magee & others, 2012). They are intruded by Kalkadoon Suite granitoids of varying composition with an age range between 1856Ma to 1862Ma (Wyborn & Page, 1983; Magee & others, 2012). These rocks form the central north-trending basement "spine" of the inlier exposed within the Kalkadoon–Leichhardt Domain immediately to the west of the Quamby Project area. The nature of the crystalline basement underlying the Quamby Project area is uncertain — the Kalkadoon–Leichhardt sequence is assumed to form the basement package in the western part of the project area closest to the exposed regional basement culmination, but further east the nature of the basement rocks is unknown. However, for the purposes of the model building process, the basement rocks are assumed to be of similar composition and age to the Kalkadoon–Leichhardt sequence.

Early extension-related volcanism and sedimentation

The oldest of the cover sequence rocks unconformably overlying inferred basement within the Eastern Succession is represented by the ***Argylla Formation*** — a felsic volcanic-dominated sequence marking a significant regional extensional event. The unit comprises typically brick-red felsic porphyries and minor sediments dated at 1777±3Ma, 1778±3Ma, 1782±3Ma, and 1779±3Ma (Neumann & others, 2009a). This sequence is only exposed in the western part of the project area (the Mary Kathleen Domain) and is interpreted to form the basal cover sequence layer within the central part of the project area, the Constantine Domain, previously referred to as the Canobie Domain (Geological Survey of Queensland, 2011; see discussion in main body of report). The Argylla Formation is not interpreted to extend into the eastern and southern parts of the project area (the Soldiers Cap and Mitakoodi/Tommy Creek Domains respectively).

Overlying the Argylla Formation in the central north part of the project area (i.e. Mary Kathleen Domain east of the Mount Rose Bee Fault and northern Constantine Domain) are the poorly-exposed ***Boomarra Metamorphics***. These rocks may overlie the Argylla Formation with possible conformity as the lower unit of the Boomarra Metamorphics (consisting of felsic granofels) has been correlated with the top of the Argylla Formation (Geological Survey of Queensland, 2011). The upper unit of the Boomarra Metamorphics consists predominantly of quartzite and the formation has a maximum depositional age of 1767±4Ma (Neumann & others, 2009a).

A younger, extension-related, felsic volcanic-dominated cover sequence, the ***Bulonga Volcanics***, is interpreted to directly overlie crystalline basement in the eastern and southern parts of the project area, where Argylla Formation deposition is interpreted to be largely absent (probably due to structural or fault controls). The Bulonga Volcanics extend far to the south where they are extensively exposed within the regional-scale Mitakoodi Anticlinorium, the dominant structural feature of the Mitakoodi Domain of the Eastern Succession. The Bulonga Volcanics in this area were previously mapped as Argylla Formation (Derrick, 1980) due to lithological and geophysical similarities, before recent age dating gave an age of ~1760Ma (Neumann & others, 2009a) establishing these rocks as a younger volcanic sequence. This is also supported by a lack of significant mafic volcanism within the Argylla Formation, contrasting with the eruption of the mafic Marraba Volcanics marking the end of Bulonga felsic volcanism in the Duck Creek area. However, due to the lithological similarities of the two felsic units, small unmapped areas of Argylla Formation may exist in the Mitakoodi Domain within or underlying the mapped area of Bulonga Volcanics. The overlying ***Marraba Volcanics*** were previously equated to the Eastern Creek Volcanics in the western part of the Mount Isa Inlier (within the Leichhardt River Fault Trough; Queensland Department of Mines and Energy & others, 2000) but due to age constraints from the underlying and overlying formations (indicating rapid eruption) they are much younger than the Eastern Creek Volcanics (Geological Survey of Queensland, 2011).

As regional extension relaxed, Argylla and Bulonga/Marraba volcanism was succeeded in the Eastern Succession by widespread deposition of sag-phase blanket of quartzose to feldspathic sand assigned to the ***Ballara Quartzite*** (in the Mary Kathleen Domain west of the Pilgrim and Rose Bee Fault systems) and the ***Mitakoodi Quartzite*** (outlining the Mitakoodi Anticlinorium in the Mitakoodi Domain to the east of Pilgrim/Rose Bee Fault system). Small areas of Mitakoodi Quartzite also occur north of the Mitakoodi Anticlinorium in the Constantine Domain. The Ballara Quartzite is less feldspathic than the Mitakoodi Quartzite and may include parts of the underlying Argylla Formation or Boomarra Metamorphics (in a thickened sequence mapped to the south-east of Dobbyn). The Mitakoodi Quartzite has a depositional age of ~1755Ma (Neumann & Fraser, 2007; Geoscience Australia, 2010) determined from zircon ages as well as from minor rhyolite within the unit. The Ballara Quartzite has a maximum depositional age of 1767±4Ma (Neumann & others, 2009a) and a tuff layer within the sequence dated at 1755±3Ma (Page, 1988).

A shallow (locally evaporitic) carbonate shelf environment succeeded Mitakoodi/Ballara deposition, and is represented by the ***Corella Formation*** comprising calcareous siltstone, limestone, calcareous scapolitic granofels, quartzite, amphibolite, shale, and local metabasalt. This unit is one of the most extensive of the calc-silicate units which comprise the Eastern Succession, and was deposited within the Mitakoodi, Tommy Creek, Mary Kathleen and Constantine domains. Around the regional hinge of the Mitakoodi Anticlinorium (within the Mitakoodi Domain), the Corella Formation is separated from the underlying Mitakoodi Quartzite by the distinctive ***Overhang Jaspilite***, a unit composed of argillaceous sediments and limestone (locally stromatolitic), prominent iron rich jaspilite beds and the siliceous ***Chumvale Breccia*** (Geological Survey of Queensland, 2011). The Overhang Jaspilite unit has not been dated but is believed to be partially equivalent to the Corella Formation. The Corella Formation has yielded maximum depositional ages of 1770±5Ma and 1776±3Ma (Neumann & others, 2009a), with the upper age limit for the formation constrained by the Wonga and Burstall intrusive events. The Corella Formation is believed to be an equivalent of the Quilalar Formation in the Mount Oxide and Leichhardt River Domains of the Mount Isa Western Succession (Derrick & others, 1980; Neumann & others, 2006).

Wonga Extension

Deposition of Eastern Succession cover sequences was terminated by a period of significant extension around 1740Ma, accompanied by extrusive and intrusive magmatism. This extensional event is expressed as a low angle crustal detachment (tightly folded by later east–west Isan Orogeny shortening) exposed mainly within the core of the north-trending Mary Kathleen Domain. This detachment is intruded by broadly syntectonic foliated granitoids of the ***Wonga Suite*** as well as bimodal largely unfoliated intrusives of the ***Burstall Suite***, which intrude rocks of the Argylla and Corella Formations. Within the Quamby Project area, the Wonga Suite is represented by the ***Dipvale Granodiorite*** (in the Mary Kathleen Domain) and the ***Levian Granite*** in the southern part of the Constantine Domain. The Dipvale Granodiorite consists of pervasively foliated medium-grained hornblende-biotite granodiorite to monzodiorite and has been dated at 1746±7Ma (Davis & others, 2001). The Levian Granite has been dated 1746±8Ma (Page & Sun, 1998) and is composed of a strongly deformed magnetite-bearing felsic porphyry, fine grained pink-grey granite and a medium grained biotite granite.

The Burstall Suite of bimodal intrusives is coeval with these Wonga Suite intrusives, and is represented by the ***Mount Godkin Granite*** within the Quamby Project area. The Mount Godkin Granite is a multiphase intrusive consisting of granite, quartz diorite and quartz monzonite, altered endoskarn-bearing metagranite, aplite and microgranite and leucogranite and pegmatite.

To the east of the Mary Kathleen Domain, the Wonga extension event was associated with another period of felsic volcanism associated with eruption of the ***Mount Fort Constantine Volcanics*** (Geological Survey of Queensland, 2011) within the Constantine Domain. This felsic to intermediate sequence hosts mineralisation at the Ernest Henry mine, and is interpreted from drillhole information to continue north of the mine to make up the majority of the magnetic rocks undercover within the domain. The volcanics have been dated at 1746±9Ma and 1742±6 (Page & Sun, 1998) and are interpreted to overlie the Corella Formation.

South of the Quamby Project area, a Wonga-aged extensional core-complex style system is exposed as the ***Double Crossing Metamorphics*** enveloping the ***Gin Creek Granite***. The metamorphics consist of low-grade chlorite schists to migmatitic gneisses yielding maximum deposition ages of 1743± 17Ma (Magee & others, 2012) and 1752± 4Ma (Carson & others, 2011) suggesting temporal equivalence to rocks of the Bulonga–Marraba package. The Gin Creek Granite has yielded a Wonga Suite age of 1741±7Ma (Page & Sun, 1998).

Post-Wonga cover sequences

Calvert Superbasin equivalents

Development of the Calvert Superbasin (~1730–1670Ma) is recognised in the Mount Isa Western Succession as a period of sandstone deposition (e.g. Surprise Creek and Torpedo Creek Formations) accompanied by local bimodal volcanism (Fiery Creek Volcanics). In the Eastern Succession at this time, resumption of sedimentation is marked by deposition of mixed carbonates and siliciclastics of the ***Staveley Formation***. This unit comprises siltstone, sandstone, sandy carbonate and calc-silicate rocks exposed mainly to the south of the Quamby Project area, in the Marimo–Staveley, Doherty – Fig Tree Gully and Soldiers Cap Domains. In the eastern half of the project area, the unit is interpreted to exist at depth in the Soldiers Cap Domain (beneath the younger ***Soldiers Cap Group***). Eastern segments of the Staveley Formation exposed in the Doherty – Fig Tree Gully and Soldiers Cap Domains are metasomatised and significantly higher in metamorphic grade (reaching amphibolite facies) than areas to the west. These higher grade rocks form a package of calc-silicate rocks lithologically similar to, but significantly younger than, the Corella Formation with which they were initially correlated and mapped separately as the now-obsolete Doherty Formation.

South of the project area, the Staveley Formation is overlain by isolated areas of cross-bedded fine-grained quartzose to feldspathic sandstone of the ***Roxmere Quartzite***. The sandstones occur either as discrete structurally emplaced blocks or in-place stratigraphic packages with a gradational stratigraphic contact with the underlying Staveley Formation. Maximum depositional ages for the lower grade western portion of the Staveley Formation (within the Marimo–Staveley Domain) cluster around 1740–1750Ma (Neumann, unpublished data; Magee & others, 2012), similar to detrital zircon ages from the higher grade eastern part of the unit (within the Doherty – Fig Tree Gully Domain). The Roxmere Quartzite has maximum depositional ages of approximately 1710Ma (Neumann, unpublished data; Carson & others, 2011), consistent with a relatively young (post-Corella Formation) age for this package of rocks.

Temporal equivalents of the Staveley–Roxmere sequence are interpreted to be exposed within the western part of the Quamby Project area as the ***Knapdale Quartzite*** (part of the lower Mount Albert Group). The unit is comprised of pink feldspathic and micaceous sandstone and quartzite and has a maximum depositional age of 1728±5Ma (Carson & others, 2008) and is equivalent to the Prize Supersequence in the Calvert Superbasin (Geological Survey of Queensland, 2011).

Late to Post-Calvert Superbasin Successions

In the Western Succession, significant regional extension saw the end of Calvert Superbasin sedimentation, followed by development of the Isa Superbasin (accompanied by deposition of the ore-bearing Mount Isa Group). In the Eastern Succession, extension occurred slightly earlier and was associated with severe localised downthrows along major crustal-scale faults. Drowning of the relatively shallow Staveley–Roxmere shelfal environment was accompanied by widespread siliciclastic turbidite deposition and some mafic volcanism of the Soldiers Cap and Kuridala Groups. The Soldiers Cap/Kuridala depositional event is thought to have occurred during late Calvert to early Isa Superbasin time (Geological Survey of Queensland, 2011).

Within the Quamby Project area, the ***Soldiers Cap Group*** is interpreted to exist in the north-east and south-east of the modelled area (within the Soldiers Cap and Fig Tree Gully Domains), where it represents the youngest Proterozoic stratigraphic element. The unit is widespread to the south and east of the project area and its contacts with underlying units are commonly structural, resulting from major basin inversion during the early phase of the Isan Orogeny. In places the older Staveley Formation has been exhumed and thrust over younger Soldiers Cap sequences (e.g. in the central southern segment of the modelled area).

The **Soldiers Cap Group** comprises three formations: the ***Llewellyn Creek Formation***, ***Mount Norna Quartzite*** and ***Toole Creek Volcanics***. The Llewellyn Creek Formation and the Mount Norna Quartzite form the lower part of the group and consist of pelitic and psammitic metasedimentary rocks, with metamorphic grade increasing from greenschist to gneiss and migmatites south of the Snake Creek area. Detrital zircons from both the Llewellyn Creek Formation and Mount Norna Quartzite have given maximum depositional ages of ~1685Ma (Neumann & others, 2009b), with high grade rocks mapped near the Cannington mine giving similar maximum depositional ages.

The Toole Creek Volcanics form the upper part of the Soldiers Cap Group and consist of basalt flows and intervening carbonaceous rocks which were intruded by mafic sills. The lower Soldiers Cap Group has been intruded with mafic sills which are thought to be at least partly related to the Toole Creek Volcanics. Age dating from a sandstone within the lower part of the Toole Creek Volcanics yielded a maximum depositional age of 1658±5Ma (Carson & others, 2008) which suggests a disconformity between the Mount Norna Quartzite and this unit.

The **Kuridala Group** forms a central metamorphic belt (the Kuridala–Selwyn Domain) south of the project area. The unit is a temporal equivalent of the Soldiers Cap Group and contains similar lithologies. It includes the pelite/psammite dominated ***Starcross Formation*** at the base, the younger quartzite-dominated ***New Hope Sandstone*** and the upper ***Hampden Slate***. The Starcross Formation has yielded a maximum depositional age of 1663±21Ma (Carson & others, 2011), while the New Hope Sandstone has yielded a maximum detrital age of ~1667Ma (Geoscience Australia, 2010). The Hampden Slate is considered to be equivalent to the Toole Creek Volcanics and contains metadolerite sills similar to those intruding that unit and the underlying Mount Norna Quartzite.

These upper fine-grained carbonaceous sections of the Soldiers Cap and Kuridala Groups are thought to be stratigraphically equivalent to the lithologically similar ***Answer*** and ***Marimo Slates*** which are exposed east of the Mitakoodi Anticlinorium (in the Marimo–Staveley Domain) south of the project area.

Further temporal equivalents of the Soldiers Cap – Kuridala succession occur in the western part of the project area in the Mary Kathleen Domain and include the ***Coocerina Formation*** (overlying the older Knapdale Quartzite) and the overlying ***Lady Clayre Formation*** (part of the Upper Mount Albert Group). Rocks previously mapped as Corella Formation, including the Dugald River Shale Member (host to the Ag-Pb-Zn deposit of the same name), have been assigned to a new formation called the ***Mount Roseby Schist***. The Mount Roseby Schist is thought to be a temporal equivalent of the Coocerina Formation. The Dugald River Shale Member of the Mount Roseby Schist has a maximum depositional age of 1686±7Ma (Carson & others, 2011), and the Lady Clayre Formation has a maximum depositional age of 1691±9Ma (Carson & others, 2011), possibly indicating a correlation with the Gun Supersequence of the Mount Isa Group.

Tommy Creek and Canobie Successions

The ***Tommy Creek Microgranite*** intrudes into the Corella Formation within the Tommy Creek Domain and is composed of weakly foliated equigranular to porphyritic leucocratic microgranite. Recent SHRIMP dating of the microgranite gave ages of 1650±3Ma and 1653±4Ma (Geoscience Australia, 2010) and can be correlated with the Mount Isa Group within the Leichhardt River and Kalkadoon–Leichhardt Domains (Jell, 2013).

The ***Milo beds*** within the Tommy Creek Domain are correlated with the upper McNamara Group (within the Term or Lawn Supersequences) and represent one of the youngest parts of the Mount Isa Province. The beds are composed of impure carbonates, carbonaceous shales and volcaniclastics and have varying ages between 1660±6Ma (Geoscience Australia, 2010) and 1610±6Ma (Carson & others, 2011).

Within the Donors Hill Domain (previously part of the Soldiers Cap Domain *in* Geological Survey of Queensland, 2011) north of the project area, a sedimentary unit intersected in drillhole GSQ Dobbyn 1 was recently dated with detrital zircons giving the succession a maximum depositional age of 1592±5Ma (Carson & others, 2011). This unit of metasandstone or siltstone (with a schistose texture) is now referred to as the ***Canobie Sequence*** and is younger than the Soldiers Cap Group. This young sequence may extend over a significant part of the Soldiers Cap Domain and further to the east towards Georgetown (Geological Survey of Queensland, 2011).

The ***Quamby Conglomerate*** within the Mary Kathleen Domain occurs within small grabens along the Rose Bee and Pilgrim Faults and has been assigned a Mesoproterozoic age based on paleomagnetic data (Idnurm & Wyborn, 1998). Age dating of monazite has given ages between 1580Ma and 1490Ma, with the younger limit uncertain due to the nature of monazite formation (Jell, 2013).

Post-Orogenic Proterozoic intrusives

In eastern parts of the Mount Isa Province, the waning of the Isan Orogeny was characterised by extensive emplacement of ~1550–1500Ma trondhjemite–tonalite–granodiorite (TTG) intrusions, which were derived from high-pressure (>8–10kbar), high temperature, partial melting of garnet-bearing mafic, mantle-derived rocks (Page & Sun, 1998; Pollard & others, 1998; Wyborn, 1998; Mark, 2001).

The ***Williams, Naraku and Wimberu Batholiths***, consisting of potassium-rich, 'A-type,' granitoids, were assigned to the ***Williams Supersuite*** , with emplacement ages ranging from ~1540–1500Ma. Units within the supersuite were εNd(t) values of granites within the supersuite range from –1 to –3.8 (Page & Sun, 1998; Mark, 2001) and reflect fractionation and localised magma mixing and mingling (Pollard & others, 1998). Elevated LILE and HFSE concentrations, enrichment in Co and Sr and negative Ba, Nd, Sr, Eu, and Ti anomalies suggest that these granites were derived from hot mantle material sourced from depths of <30km (Jell, 2013).

Only representatives of the Williams and Naraku Batholiths occur within the Quamby Project area, with the Wimberu intrusives occurring further to the south. Within the project area, the main Williams Supersuite granitoids include the Malakoff Granite, the Mount Margaret Granite and the Mavis Granodiorite. The ***Mount Margaret Granite***, dated at 1530±8Ma (Page & Sun, 1998), outcrops within the eastern part of the Quamby Project area, in the Constantine Domain. The Mount Margaret Granite is one of the oldest intrusives of the Williams Supersuite in the project area and is composed of granite and albitised granite.

The ***Malakoff Granite*** (also within the Constantine Domain) has been dated at 1505±5Ma (Page & Sun, 1998) and is composed of pink medium-grained granite with minor granodiorite. The Malakoff Granite is mostly undeformed and is believed to postdate the Isan Orogeny (Geological Survey of Queensland, 2011).

The ***Mavis Granodiorite*** has been modelled as part of the Dipvale Granodiorite (previously called the Capsize Creek Complex) in the Quamby 3D model but recent age dating from the eastern margin of the intrusive gives an age of 1501±6Ma (Davis & others, 2001), with the contact between the two intrusives poorly defined. The Mavis Granodiorite is composed of medium grained hornblende-biotite granodiorite which has been strongly deformed, comparable to deformation evident in the Dipvale Granodiorite.

Unnamed intrusions within the Williams Supersuite which are undercover have been defined based on their magnetic response from regional magnetic data. In the central part of the project area (Constantine Domain), the intrusions have a low to moderate magnetic response, while in the north-east corner of the project area (Soldiers Cap Domain) interpreted intrusives have a moderate to high magnetic response.

Within the project area mafic phases of the Williams Supersuite have been linked to Iron Oxide Copper–Gold (IOCG) mineralisation (Butera & others, 2005), with mineralising fluids believed to be generated through magma mixing and mingling. Magnetic highs proximal to felsic plutons have been interpreted to be mafic bodies at depth associated with felsic intrusives (Butera & others, 2005). Olivine gabbro to norite intrusives within the northern concealed part of the Constantine Domain have been tentatively given a 1550–1500Ma age range (Geological Survey of Queensland, 2011).

Sedimentary basins

Younger sedimentary cover within the Quamby Project area consists of Jurassic–Cretaceous sediments of the Eromanga and Carpentaria Basins overlying the recently discovered Millungera Basin in the north-eastern corner of the project area. The Millungera Basin was first discovered from the deep seismic reflection survey conducted by Geoscience Australia and the Geological Survey of Queensland in 2006 and 2007 (Jell, 2013). The basin is interpreted to be approximately 3km thick, with three sequence stratigraphic cycles inferred. No age dating results were recovered from recent drilling into the basin (Jell, 2013) but seismic interpretation indicates that it unconformably overlies the Soldiers Cap Group and is unconformably overlain by the Gilbert River Formation (Late Jurassic – Early Cretaceous) within the Carpentaria Basin.

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Appendix 2
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