The University of Queensland
Australia
CREATE CHANGE

Central Eastern Fold Belt, North West Queensland

Solid Geology Interpretation and Insights from Crustal Architecture

Dr Karen Connors | Associate Professor

The Sustainable Minerals Institute The University of Queensland, Australia

November 2019

This page is intentionally left blank

Contents

Acknowledgements

Data and Support

With thanks to:

Ian Withnall
Paul Donchak
Paul Gow
Rick Valenta

Citation: Connors, K. 2019. Central Eastern Fold Belt, North West Queensland: Solid Geology Interpretation and Insights from Crustal Architecture. The University of Queensland, Report and Digital Data Package CR123565, 57p.
https://geoscience.data.qld.gov.au/report/cr123565

List of Figures and Tables

Figures

Tables

Executive Summary

A comprehensive understanding of the geology, structure and evolution provides the foundation for resource exploration in any region. Exploration in the exposed and near surface regions of Australia, including the Eastern Fold Belt, is maturing and as a result economic discoveries have been decreasing over several decades. The need to explore in areas of deeper cover and/or further from outcrop is currently driving a range of research initiatives and data acquisition programs. The resulting knowledge advancement and growing wealth of precompetitive data acquired by Australian state and federal governments, provide new opportunities for industry but also require detailed interpretation and integration with existing datasets in order to continue to progress our understanding of the fundamental geology of the covered regions.

This project builds on previous BRC projects to produce a detailed and integrated geological and structural interpretation and solid geology map, that extends the highly prospective Eastern Fold Belt (EFB) undercover to the east and south (Figure E.1). This study highlights the importance of understanding not only the near surface distribution of key geological units, but also the architecture of the inherently heterogeneous underlying crust. Crustal strength is controlled by size and distribution of rheological domains and strain will localise along zones of contrasting rheology. While the most recent events or features are typically the most obvious, it is critical to unravel the evolution and to understand the earliest events as the pre-existing architecture will have a significant influence on later events. In general terms, an existing structural zone or orogenic belt commonly provides a rheological contrast that will localise deformation during subsequent events. Likewise, early architecture will influence other geological processes including sedimentation, magmatism, and fluid / alteration events. It has long been recognised that the extensional history during Soldiers Cap Group deposition has had a significant effect on the structure of the Soldiers Cap Domain (east of the Cloncurry Fault Zone) and its mineralised systems, but elucidation of the extensional architecture has been lacking.

The main aim of this project was to produce a new solid geology interpretation of the central EFB (Figure E.1) resulting in an improved understanding of the structural complexity, as well as the context and controls on mineralisation, and to provide a basis for interpretation of permit and mine scale exploration datasets in the area. The plan view datasets such as the magnetic, HyMap, radiometric, and drilling data highlight the folded patterns of the near surface geology in plan view, but integration with the seismic data has made the difference in providing a clearer picture of the 3D geometry and history of the major structures. The seismic lines are of variable quality but provide critical information at depth, especially on the geometry of the shallow crust. For example, the numerous small anticlines (3-4 km wavelength) separated by dominantly east-dipping faults developed within the Soldiers Cap Group units (line 94MTI-01; Figure E.2b), do not directly correspond to the three large folds mapped at surface (Figure E.2a). In cross section view on the seismic line, these faulted anticlines are typical of a set of inverted normal faults. Shortening of a wedge-shaped growth package against a normal fault results in an anticline adjacent to the fault and a much smaller or no syncline.

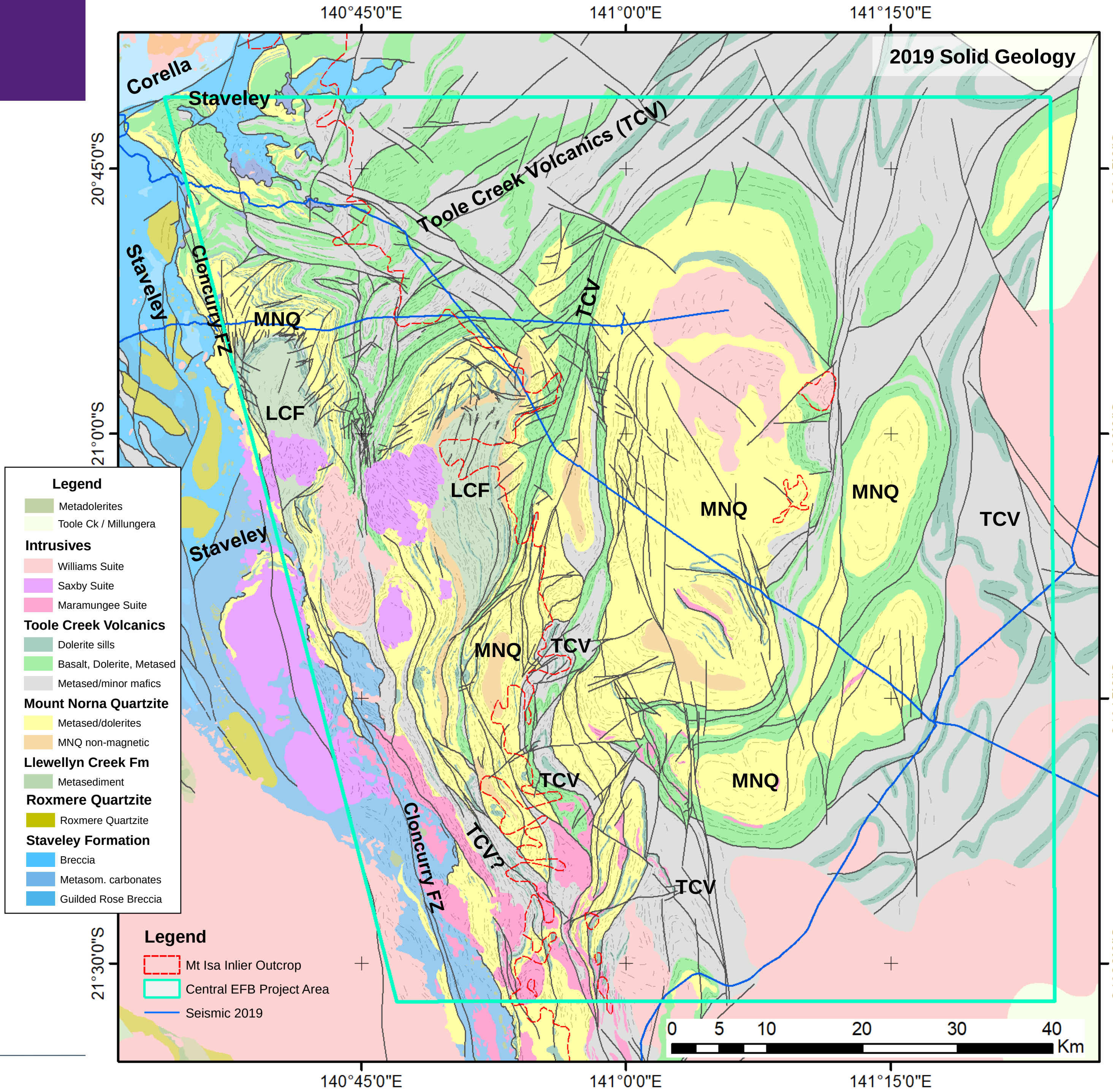


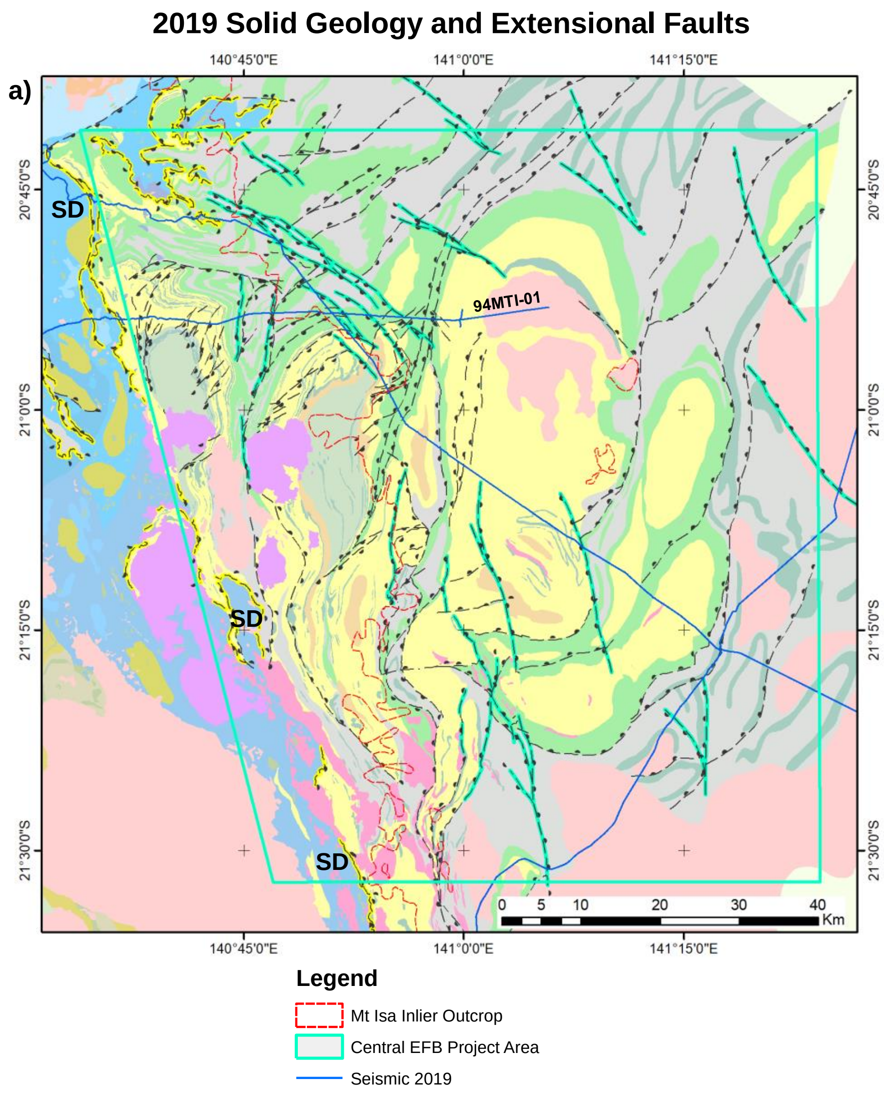
Figure E.1. 2019 solid geology interpretation with faults (medium black lines) and trend lines (fine dashed line). The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. Seismic lines are in blue. The Soldiers Cap Group includes the Toole Creek Volcanics (TCV), Mount Norna Quartzite (MNQ), and Llewellyn Creek Formation (LCF).

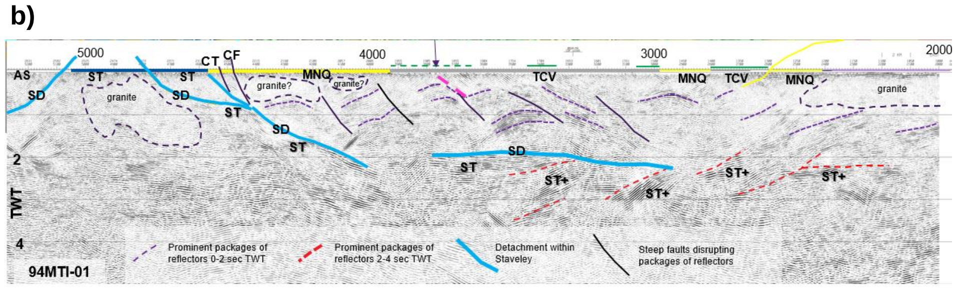
Executive Summary (*continued*)

Mapping along the west of the AOI (Figure E.2a) has defined a sub-horizontal fault zone within the Staveley Formation carbonates and a pervasive flat lying fabric (e.g. Giles et al., 2006a; Rubenach et al., 2008). There has been debate on the extensional vs compressional origin of both features, but the regional upward facing of metasedimentary units prior to D2, the lack of recumbent folds associated with both the fabric and fault zone within the Staveley carbonates, and the consistent younger over older relationship on these faults (Giles et al., 2006b) favours development in an extensional setting (prior to compressional reactivation). The Staveley “detachment” fault(s) (SD; highlighted in yellow) outcrops along the west of the AOI and can be traced at depth in the seismic where it forms a detachment surface at ~2 sec TWT below a set of folds and faults interpreted as inverted normal faults (Figure E.2b). Integrated interpretation of the seismic with the plan view datasets provides the first interpretation of the network of extensional faults in this region (Figure E.2a). The faults mapped in this study are broadly NE-trending and NW-trending consistent with the interpreted ~NW-SE to E-W extension direction for the Calvert / Sybella extension in the Western Fold Belt (e.g. Gordon, 2004 Gibson et al., 2008). Variations in the fault trends reflect both syn-extensional control by the underlying basement and reactivation during Isan Orogeny compression (ca 1610-1500 Ma). The network of extensional faults has been interpreted based on thickness variations in plan view (outcrop or magnetics, radiometric), cross section geometry in seismic (and correlation along strike), and variations in gravity data indicative of increased thickness of mafic igneous units.

Seismic data indicates the presence of three distinct crustal blocks in the mid to lower crust: 1) Mount Isa Province (thick, poorly reflective crust); 2) Numil Province (thinner highly reflective crust), and 3) an intervening competent block of moderately reflective crust that may have originally formed part of Mount Isa or Numil (Figure E.2c). The structural style within the Soldiers Cap Group (SCG) units of the upper ~10 km of crust differs in relation to the underlying basement blocks. For example, the Staveley detachment (SD) is well developed over the competent block, as well as to the west of the AOI overlying the Mount Isa Province (i.e. Marimo – Staveley area). In contrast, the detachment fault is not developed (or not preserved) over the Numil basement terrane. Instead the upper crust is dominated by west-dipping faults many of which extend into the lower crust or directly link with west-dipping fault zones of the underlying basement terrane.

This project provides an understanding of the upper crustal geology and structure as well as the underlying crustal architecture both of which are critical to a minerals system approach to exploration for Broken Hill Type Ag-Pb-Zn massive sulphide as well as IOCG-style Cu-Au deposits in this region. It provides the first interpretation of the ca 1680-1650 Ma extensional fault system of the Soldiers Cap Domain and its control on subsequent shortening during the Isan Orogeny (ca 1610-1500 Ma), and hence provides significant support for exploration in this highly prospective covered region. This project also defines the extent of underlying basement terranes, their control on upper crustal structural evolution and the location of crustal scale structural zones that potentially provide deep-seated fluid conduits. Follow-up work is recommended in order to test this interpretation, including more detailed mapping and integration with prospect and mine scale data. Reassessment of the Soldiers Cap Group stratigraphy and distribution of the three main units is also recommended in several areas.





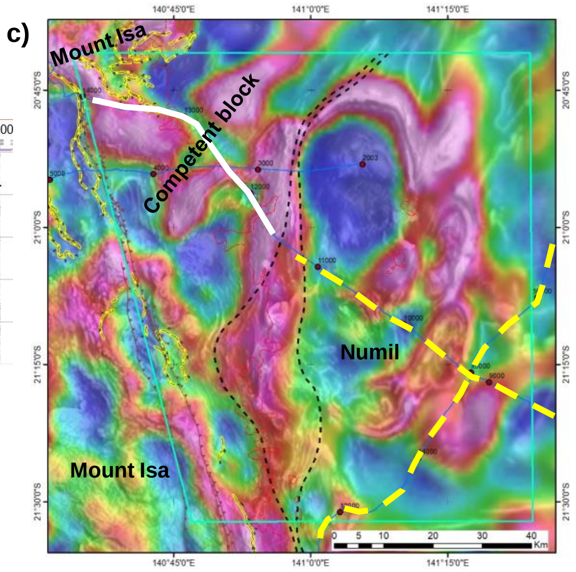


Figure E.2 a) 2019 solid geology map and the extensional fault system. Detachment faults are highlighted in yellow and the main transfer faults in cyan. See Figure E.1 for geological legend. b) Simplified interpretation of seismic line 94MTI01 (location shown in map a). The questions regarding steep geological features in outcrop in comparison to shallow to moderately dipping features in seismic are summarised on page 28, and discussed in more detail for key sections. CF = Cloncurry Fault; CT = Cloncurry Thrust; MNQ = Mount Norna Quartzite; SD = Staveley detachment; ST = Staveley Formation; ST+ = Staveley Formation plus older units; TCV = Toole Creek Volcanics. c) Approximate extent of the basement terranes based on the seismic data overlain on an image combining the gravity (HP40 km of Bouguer) and magnetic data (RTP - AGC 200 and Tilt). The Numil crust is shown in yellow and the competent block is in white. The black dashed line indicates the higher strain zone developed along the west margin of the Numil basement terrane.

The University of Queensland Australia | Create Change

Chapter 1

Introduction

1.0 Introduction

Background

An updated solid geology interpretation has been produced for a >7100 km^2 area covering the central part of the Eastern Fold Belt (EFB) southeast of Cloncurry, Queensland. This work builds on a series of industry-supported, solid geology interpretation projects completed by the WH Bryan Mining & Geology Research Centre (BRC) as well as Geological Survey of Queensland products. The BRC projects have been focused on enhancing base metal prospectivity in the Eastern Fold Belt and have been pragmatically-oriented, specifically focused within practically-explorable depths in both outcropping and covered areas. BRC's 2D and 3D interpretations in the Cloncurry-Osborne region (Deep Mining Queensland (DMQ); Murphy et al., 2017), around and south of Cannington (Southern Eastern Fold Belt (SEFB); Hinman et al., 2018), and around Ernest Henry (Ernest Henry; Valenta, 2018) have advanced the tectono-magmatic-stratigraphic understanding and significantly enhanced mineral prospectivity. These projects were carried out with the generous financial support of the DNRME under the umbrella of the IPI and SREP New Discovery Program initiatives.

The giant Ernest Henry and Cannington base metal deposits lie north and south, respectively, of the Area of Interest (AOI; highlighted in cyan on Figure 1.1) which includes the Eloise Cu-Au-Ag and Maronan Pb-Ag (and Cu-Au) mines, and is considered to be highly prospective for both Broken Hill Type Ag-Pb-Zn massive sulphide and IOCG-style Cu-Au deposits. Several significant deposits in this region, including Osborne, Eloise, Ernest Henry and Cannington, were discovered under shallow cover in the 1980's and 1990's based on the increased availability of widespread airborne magnetic datasets during that period. Much of the prospective area in this region is under deeper cover (200-400m or greater) and current exploration must focus on improved interpretation of geology, structure, alteration and mineralisation in areas of deeper cover using all the available data, new technology, and practical application of a mineral systems approach.

This project has been modelled on recent Industry-University-Government collaborations (e.g. Deep Mining Queensland, Murphy et al., 2017 and Solid Geology Interpretation of the southern Eastern Fold Belt, Hinman et al., 2018) in which Industry partners have, without-cost, made available their extensive and extensively-invaluable drilling, geological and geophysical datasets to the research project under the proviso that the data remains confidential to the Project but that derivative products can be released to the exploration community as pre-competitive, enhanced datasets that will advance prospectivity and lead to future discovery. The Confidentiality Agreements and Data Disclosure Agreements signed with South32, Minotaur Exploration and Sandfire Resources for the solid geology interpretation of the southern EFB (Hinman et al., 2018) remain active and apply to this project. These three companies are active miners, explorers and/or tenement holders in the region and have generously contributed detailed data to the improved understanding of the geology and structure of the Cloncurry region. The drilling and magnetic data provided by these companies has significantly improved the results of this project.

Aims and Methodology

The main aim of this project has been to produce a new solid geology interpretation resulting in an improved understanding of the structural complexity, as well as the context and controls on mineralisation, and a basis for interpretation of new exploration datasets in the area. However, a fundamental understanding of the nature and evolution of the underlying basement (composition, fabric, major boundaries, etc.) is first required in order to more confidently interpret the near surface geology and structure. Although the older units of the Eastern Fold belt (e.g. Mary Kathleen and Mitakoodi domains) and basement units (Kalkadoon-Leichhardt Domain) to the west are reasonably well known, their extent beneath the Soldiers Cap Group is unknown. Staveley Formation is the only pre-SCG unit that is exposed within the SC domain and it is only found along the western boundary. Fortunately, several seismic lines cut across the project area and link to the regional seismic lines of northwest Queensland. Although the data is of variable quality and consideration must be given to linking outcrop geology with seismic data, the seismic has provided key information on two critical scales for a mineral systems approach: 1) the structural geometry of the Soldiers Cap Group in the upper ~10km of crust; and 2) the extent and structure of the underlying basement terranes.

The datasets were complied into an ArcGIS project and interpretation was completed in ArcMap. The key datasets are included in the accompanying ArcGIS project. The iterative interpretation process involved checking and integration of constraints from all of the datasets, including the seismic and proprietary drilling data. A brief search and review of CR reports was conducted in key areas to extract additional constraints on geological units. A more thorough search and compilation of maps and data from CR reports should be conducted as part of future work, in order to increase the resolution of the interpretation and integrate it in more detail with permit and mine scale geology.

Detailed and accurate interpretation of the seismic data is beyond the scope and budget of this project. However, this dataset provides some fundamental constraints to the interpretation of the solid geology and highlights the extent of underlying basement terranes. Therefore a simplified, first-pass interpretation has been completed using tiff images of the seismic data. The quality of these images limits the accuracy of the interpretation. Further insights and improved accuracy of the location and geometry of faults and horizons can be achieved using a seismic interpretation software package, and by dedicating a suitable time period for this interpretation.

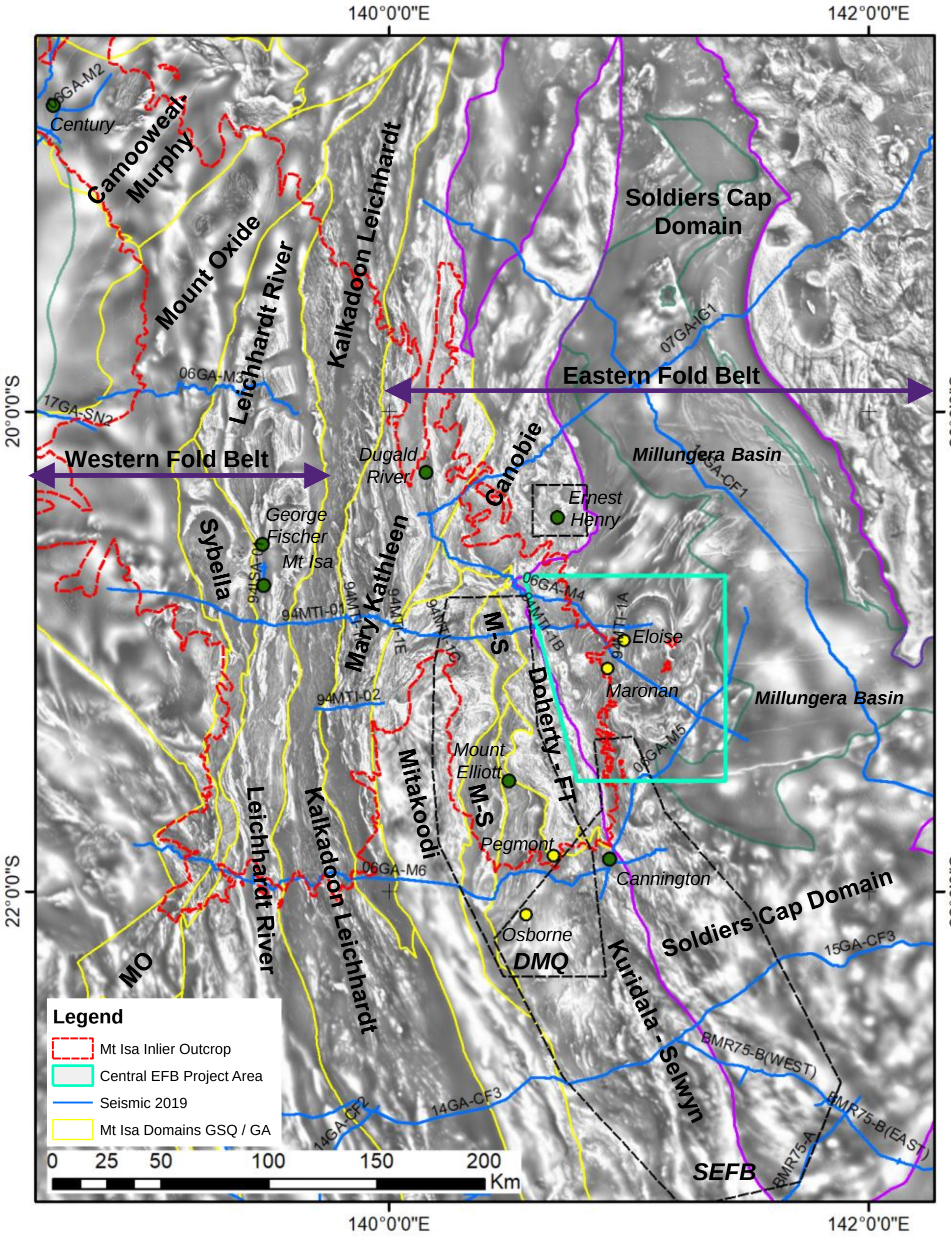


Figure 1.1. Regional location map showing the project area (cyan outline) relative to the previous Ernest Henry, DMQ, and SEFB projects (black dashed outline) overlain on grey scale image of RTP (AGC 200 and Tilt). The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. Mount Isa Province domains are shown in yellow with Soldiers Cap Domain highlighted in purple, and the overlying Millungera Basin is in green (Australian Geological Provinces dataset). The seismic lines are in blue. M-S = Marimo-Staveley domain; MO= Mount Oxide domain. Green dots = giant ore deposits and yellow dots = medium to large deposits mentioned in text.

Key questions

The solid geology interpretation of the central part of the EFB is focussed on the structurally complex Soldiers Cap Group (SCG) which is exposed in the west of the AOI (west of red dashed boundary) and extends to the east under cover that is largely Mesozoic within the AOI but includes the Millungera Basin in the east (Figure 1.2). The SCG comprises the Llewellyn Creek Formation (LCF), Mount Norna Quartzite (MNQ) and Toole Creek Volcanics (TCV). The Proterozoic Time-Space Chart for the Mount Isa region correlates these three units with the Kuridala (Starcross), Mount Hope Sandstone and Answer Slate, respectively (Figure 1.3; see also Murphy et al., 2017; Hinman et al., 2018). The only unit older than the SCG that is exposed in the Soldiers Cap Domain is the Staveley Formation which is in faulted contact with the MNQ along the western boundary and locally the TCV in the northwest (areas highlighted by ovals on Figure 1.2). Original 250K mapping distinguished the LCF, MNQ and TCV north of ~ 21°S but higher grade, and higher strain units of the SCG south of this area were undivided. 2015-2016 100K map sheets have distinguished the three units throughout the project area assisted by potential field datasets and further geological traverses. However, a few areas may require further review and are discussed below in this report.

Review of the existing interpretation and published papers at the start of this project led to several questions which guided the initial interpretation process. These questions include:

- What forms basement beneath the SCG in the Soldiers Cap Domain?
- The Staveley Formation outcrops along the west of the Soldiers Cap Domain (SCD) but how far does it extend to the east beneath the SCG?
- The Llewellyn Creek Formation (LCF) is exposed in the core of the two large anticlines (Snake Creek (S) and Middle Creek (M)) but where the Staveley Formation outcrops on the western margin of the domain, the LCF is missing and part, and locally all, of the Mount Norna Quartzite (MNQ) is also absent. What is the extent of the LCF and what controls it?
- How well do we understand the stratigraphy of the Soldiers Cap Group? Are the observed / interpreted variations in rock type the result of local overturning of stratigraphy on fold limbs, could overturned stratigraphy be present on a more regional scale, and/or is the SCG stratigraphy more complex than we currently understand? For example, the LCF is locally overturned in the south of the Snake Creek anticline (Cloncurry 100K map sheet; GSQ, 2015) and seismic shows that the TCV dips to the SE projecting beneath the older MNQ on the east limb of the Weatherly Creek syncline (W).
- Is the NNW-trending belt of pelitic units (marked by "??" between ~21°15'S and ~21°30'S) part of LCF as currently interpreted or could all or part of these pelitic units be TCV or MNQ? If this belt of pelitic rocks is LCF then it represents the core of an overturned anticline with a highly thinned west limb comprising downward-facing MNQ structurally overlain by LCF, and underlain by the Staveley Formation carbonates and detachment fault (see area highlighted by arrows). This geometry is possible and in fact is similar to that of the Snake Creek anticline to the north. However, this geometry is not consistent with that along strike to the south of the AOI where the geometry on seismic line 06GA-M5 and the geology from outcrop and drilling indicates a very thick upward-facing section of MNQ that is stratigraphically overlain by TCV (see Figure 4.7 below).

It is not possible to solve all of these questions with the available data in this project, however, various options will be discussed and future work will be recommended.

Report Outline

The remainder of the Introduction section reviews the stratigraphy of the Soldiers Cap Group (SCG), evidence for extension during deposition of the SCG, and then correlation of tectonic events in the EFB. The following sections will first focus on the information available from the regional seismic lines to the north and south of the AOI to provide an understanding of the underlying basement terranes and crustal architecture on a more regional scale. This section includes a brief review of the expected architecture in highly attenuated crust. Then the seismic lines in the AOI will be used to assess the structural geometry of the SCG in the upper ~10km of crust as well as the extent and structure of the underlying basement terranes. The new solid geology interpretation will then be reviewed in light of the insights from the seismic and other key datasets. This section includes a discussion of each tectonic event as well as detailed review of problem areas, and areas with specific questions. The report concludes with a summary of the key results, areas for future work, and other recommendations.

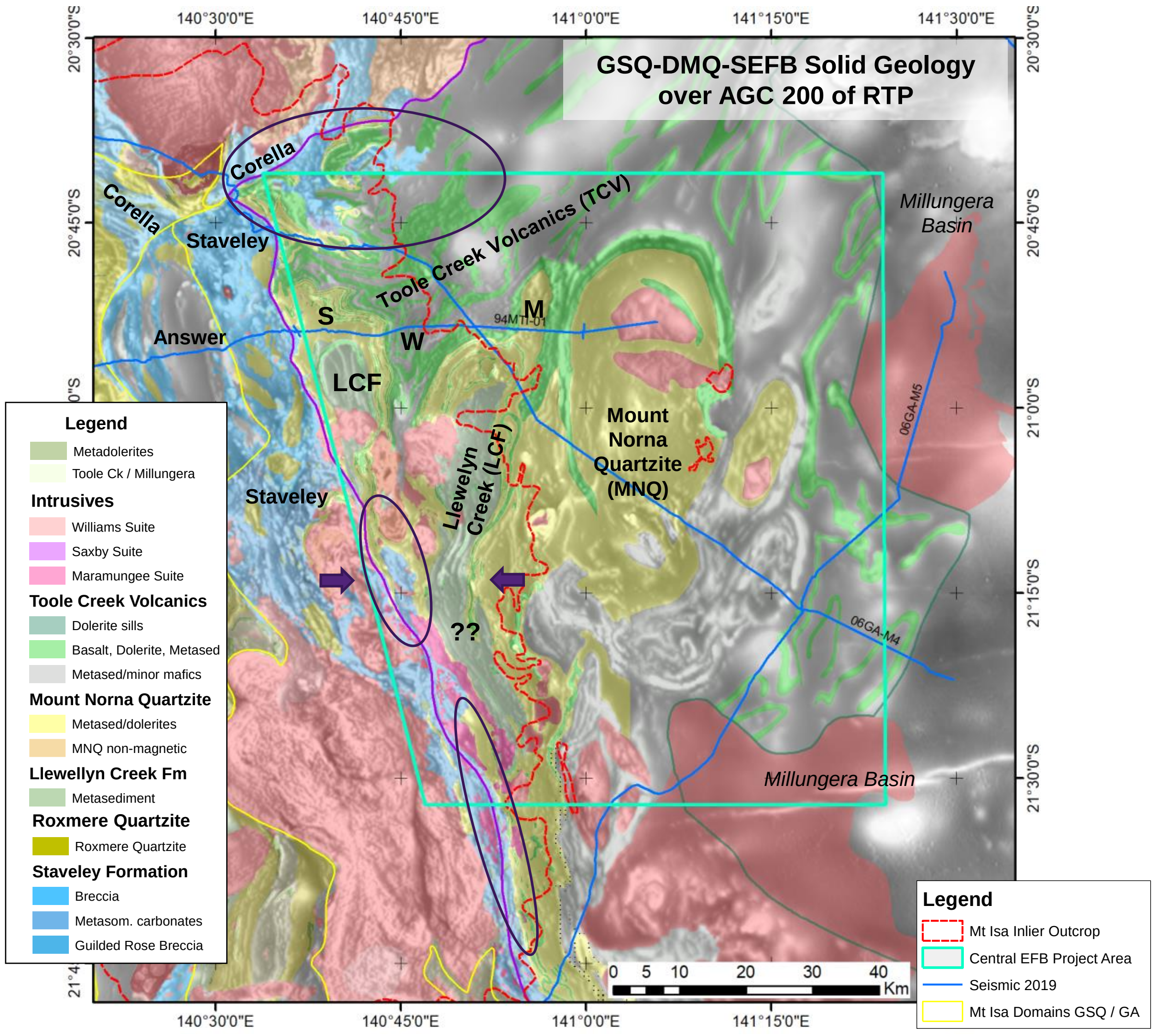


Figure 1.2. Outcrop and solid geology interpretation from GSQ-DMQ-SEFB projects for the project area (cyan outline) with transparent, grey scale image of RTP in the background (AGC 200 and Tilt). The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. Mount Isa Province domains are shown in yellow with Soldiers Cap Domain highlighted in purple, and the overlying Millungera Basin is in green (Australian Geological Provinces dataset). The seismic lines are in blue.

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

North West Queensland Proterozoic Time-Space Chart 2018

The Proterozoic Time-Space Chart (Hinman, 2017) highlights the regional correlations of units and events across the Mount Isa Province (see Murphy et al., 2017 for discussion of updated correlations). The Soldiers Cap Group (red box) of the Soldiers Cap Domain is interpreted to range in age from ~1690 Ma to 1650 Ma. Distinct populations of mafic igneous zircons sampled from drainages in the project area indicate pulses of mafic magmatism at ca 1667 Ma and 1630-1625 Ma that have not been directly dated in outcrop (Griffin et al., 2006). The 1667 Ma zircons are associated with increased juvenile input and are interpreted as a “peak” in the high-Fe magmatism of the Toole Creek event and corresponds in time to the later stages of the Sybella extension event. The distinctive 1630-1625 Ma population of zircons classify as derived from mafic rocks with a mantle source (Griffin et al., 2006), and are coeval with renewed extension in the western succession after ca 1640 Ma inversion (cf. Gibson et al., 2018). Although this age matches the Tommy Creek Volcanics, Griffin et al. (2006) interpret the abundance and geographic spread of these age grains to indicate that the Toole Creek mafic magmatism continued (or was renewed) despite the lack of age constraints from outcrop, and that the younger TCV may be present but have not been recognised during mapping in the southwest of the AOI. The drainage study of Griffin et al. (2006) also found abundant and distinct populations of ca 1569-1554 Ma magmatic zircons that they interpreted to indicate a greater age range for the Maramungee suite as well as a more widespread distribution in the southwest of the AOI and also west of Pegmont in the Kuridala-Selwyn domain.

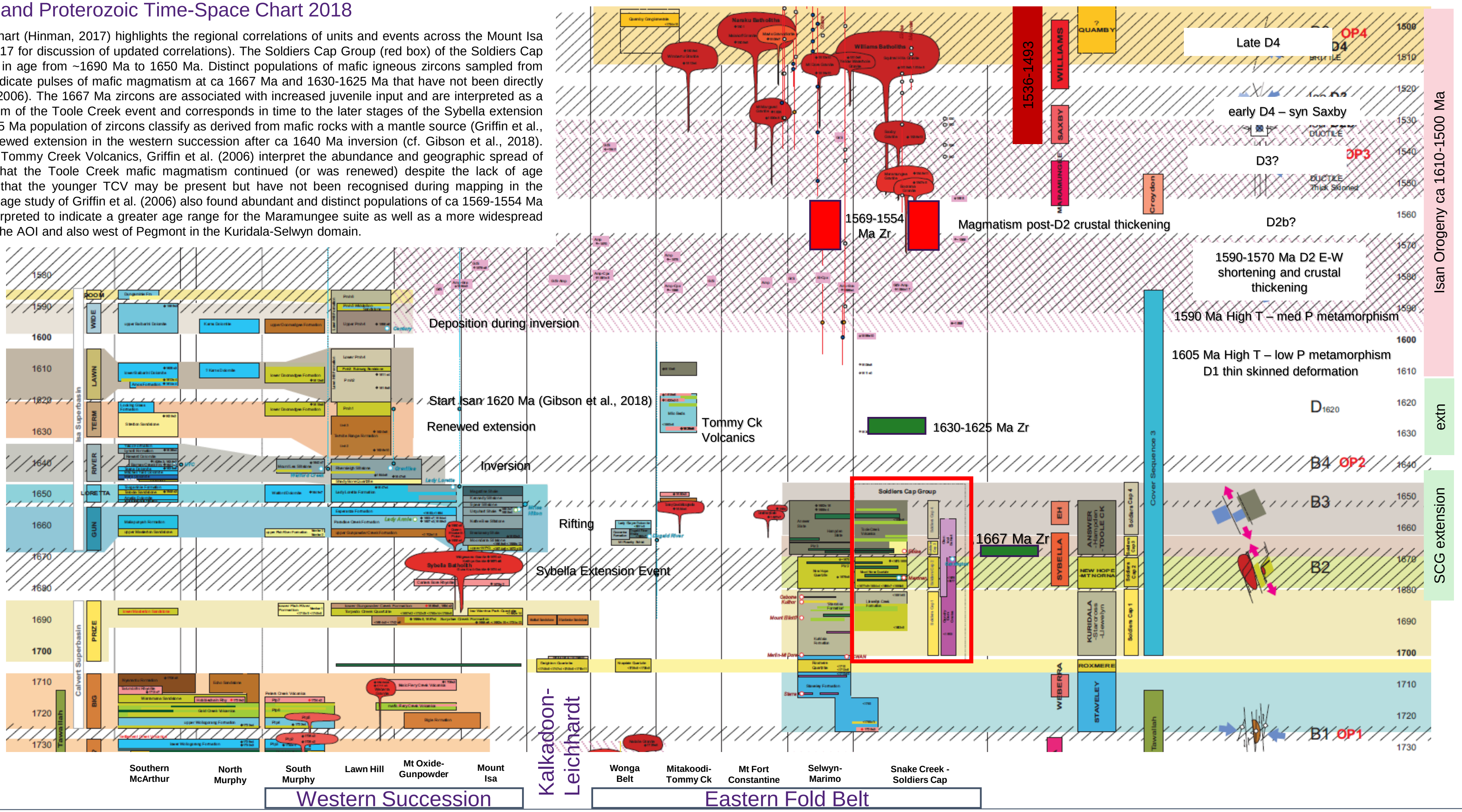


Figure 1.3. Excerpt from the 2018 update of the North West Queensland Proterozoic Time-Space Chart (Hinman, 2017) with annotation highlighting additional datasets and/or interpretations relevant to this project. Additional references: Griffin et al., 2006; Gibson et al., 2018; Porteau et al., 2018. Note that the regions of the Eastern and Western fold belts cover more than 1 domain and do not directly match the domain names on Figure 1.1.

Stratigraphy of the Soldiers Cap Domain

This project is focussed on the structurally complex Soldiers Cap Group which is exposed along the western edge of the Soldiers Cap Domain (west of red dashed boundary; Figure 1.2) and extends to the east under cover. The stratigraphy comprises the Llewellyn Creek Formation, Mount Norna Quartzite and Toole Creek Volcanics which are now interpreted to correlate with the Kuridala – Starcross formations, New Hope Quartzite and Answer-Hampden Slates of the Selwyn-Marimo Domain (Murphy et al., 2017). The Kuridala Formation overlies the Staveley Formation to the west within the Selwyn-Marimo region, but the base of the Llewellyn Creek Formation is not exposed in the Soldiers Cap Domain (Figure 1.4). The SCG is also correlated with the ca 1700-1610 Ma Etheridge Group of the Etheridge Province (Georgetown Inlier) ~300km to the east (e.g. Gibson et al., 2018; Nordsvan et al., 2018 and references therein).

The Staveley detachment fault system

The Staveley Formation is widespread along the west of the project area (Figure 1.2), where it is separated from the overlying Mount Norna Quartzite or Toole Creek Volcanics by a low-angle fault zone, locally known as the Cloncurry Thrust (or Overthrust) and other related faults (Figure 1.2). In addition, a pervasive bedding-parallel fabric has been mapped by many workers (Table 1.2 below), which is developed within upward facing units and lacks recumbent folds favouring an extensional origin (Giles, 2000; Rubenach et al., 2008). Although the low-angle faults localised in the Staveley Formation are commonly interpreted as D1 thin-skinned thrusts (e.g. Giles et al., 2006a; Murphy et al., 2017), the excised stratigraphy, lack of recumbent folds, and regional upward facing of metasedimentary units prior to D2, favour their origin as a set of extensional structures. These structures can be traced over a wide area and are herein interpreted as extensional detachment faults reactivated during the Isan Orogeny and informally referred to as the Staveley detachment faults or fault system. The MNQ and TCV, or their equivalents, are consistently found in the hangingwall of the detachment fault system (e.g. Giles et al., 2006a) and the Llewellyn Creek Formation is absent.

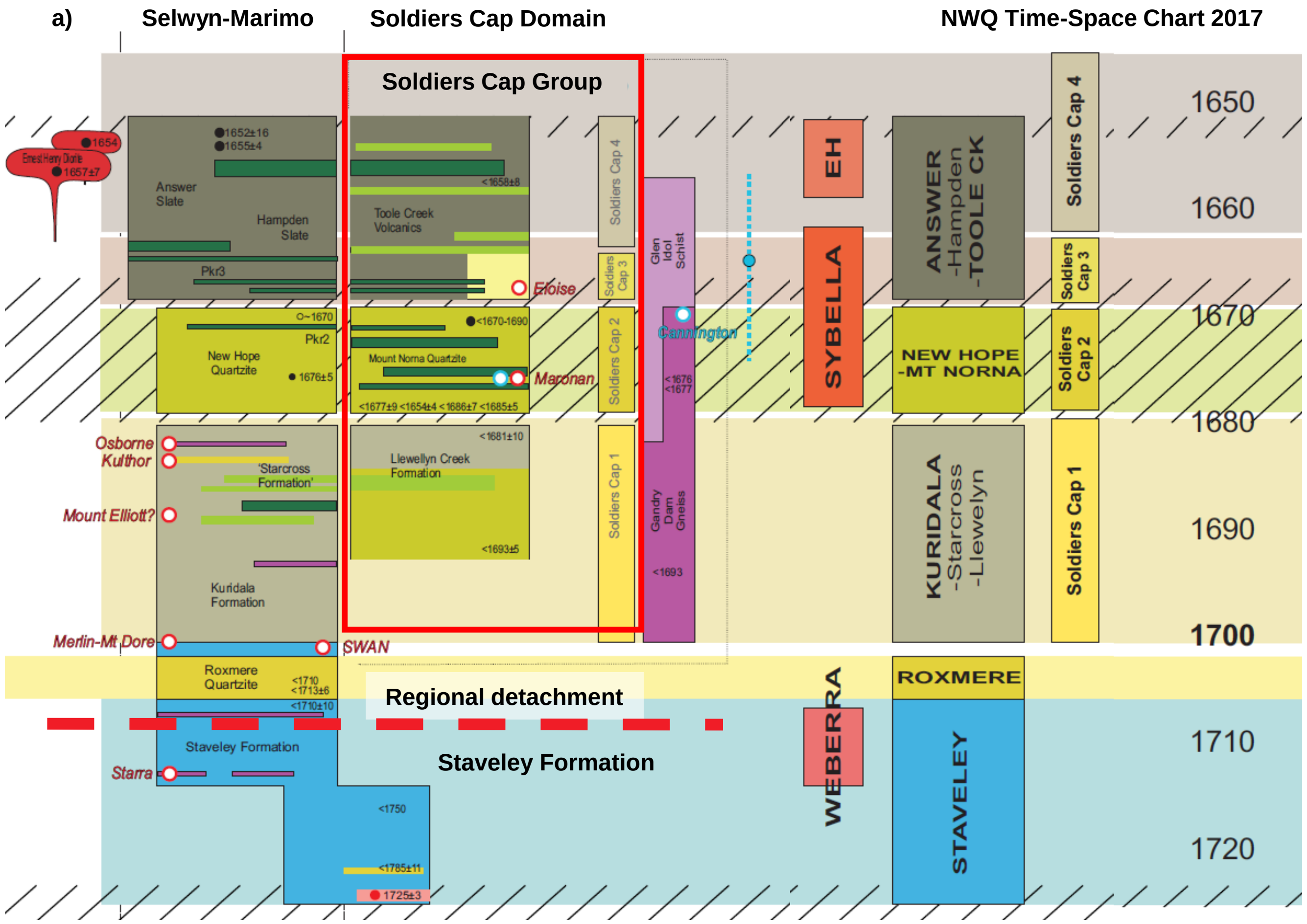


Figure 1.4. Excerpt from the 2018 update of the North West Queensland Proterozoic Time-Space Chart (Hinman, 2017), with annotation highlighting additional datasets and/or interpretations relevant to this project.

Soldiers Cap Group

The structurally complex Soldiers Cap Group comprises a fine- to coarse-grained, marine clastic sequence which includes iron formation (mainly within Mount Norna Quartzite (MNQ)) and a distinct suite of Fe-rich mafic igneous sills that are found in all three units but are most abundant in the Toole Creek Volcanics (TCV; 20-30%; Hatton, 2004). The lowermost unit, Llewellyn Creek Formation (LCF), comprises schist, phyllite, and shale interpreted to have been deposited as turbidites in a deep water setting (Southgate et al., 2013; Withnall and Hutton, 2013). Hatton (2004) favoured a proximal to medial, narrow shelf, with high extrabasinal input, for deposition of the dominantly coarser-grained lower MNQ due to storm influenced debris flows (Table 1.1). The narrow shelf is interpreted to have persisted during deposition of the mid to upper MNQ and lower TCV tempestites due to density and turbidity currents, with evidence of increasing water depth and a more quiescent environment in the mid to upper TCV (Hatton, 2004). However, Southgate et al. (2013) favour a slope to basin floor setting for most of the SCG based on the contrast of the deeper water facies of the EFB with the shelfal facies of the WFB.

Soldiers Cap Group Iron Formation and Mafic Sills

Detailed mapping and analysis of the SCG, especially the iron formation units and distinct Fe-rich mafic igneous bodies, in the Snake Creek – Weatherly Creek area by Hatton (2004) and Hatton and Davidson (2004) provide key insights on the stratigraphy and development of the basin in which these units were deposited. The iron formation units mainly occur within the Mount Norna Quartzite (Mount Norna at the base; Weatherly Creek near the top) and rarely within the Toole Creek Volcanics (near base at Monakoff- Pumpkin Gully), and although the mafic sills are found in all three units they are most dominant in the Toole Creek Volcanics, which also includes some basalt, followed by the upper Mount Norna Quartzite (Table 1.1).

The iron formation units are interpreted as chemical sediments that formed due to exhalation of Fe-P-Mn rich fluids from basin-scale aquifers at the sediment-water interface in localised, relatively quiescent depressions (Hatton, 2004). Convection was driven by transfer of heat from emplacement of Fe tholeiite magma chambers at depth within the basin and expulsion was triggered by renewed extension resulting in extensional faults tapping the aquifer *prior to* the main stage of mafic sill emplacement (Hatton, 2004).

The laterally extensive Fe-rich mafic sills are syn-sedimentary to late diagenetic, with some emplaced into wet sediments at a maximum depth of ~1.6km (Hatton, 2004). The Fe-rich magmas are significantly higher density than the sediments explaining the predominance of sills; sill emplacement however, increases density of the sequence and the next sill is emplaced higher (Hatton, 2004). The thick, massive sills >150 m dominate in the upper MNQ and lower TCV, and are subordinate in rest of TCV. Basalts are volumetrically low, mainly sit above the large massive sills, and are interpreted as end products of the feeder system of underlying sills (Hatton, 2004). The Fe-rich tholeiite magma chambers are interpreted to drive fluid convection but the chemical sediments predate emplacement of the sills, and the sill emplacement represents the climatic stage of SCG extension (Hatton and Davidson, 2004). Prolonged fractionation and crystallisation suggest significant heat transfer into the basin and increased hydrothermal activity around the time of Mount Norna Quartzite deposition (Hatton, 2004).

In general, Fe-rich magmas are interpreted to form in continental or active oceanic rifts. They require a large closed magma chamber separated from its mantle source with a low magma resupply and slow cooling (Hatton, 2004 and references therein). Eruption of high-Fe basalts is rare worldwide due to their high density and they require renewed rifting and/or magma replenishment to trigger eruption (Brooks et al., 1991).

Soldiers Cap Group Extension and Basin Evolution

The iron formation and Fe-rich mafic igneous units combined with sedimentalogical and structural observations indicate a significant period of extension during SCG deposition. Renewed extension at base of MNQ is indicated by the abrupt change to a higher energy environment with debris flows and coarser extrabasinal input, increased hydrothermal activity (resulting in development of chemical sediments), thickening of lower MNQ units (and/or TCV units) into syn-sedimentary faults (20-30% increase), and the sequential sill emplacement (Hatton, 2004). Eruption of the high-density, Fe-rich basalts is consistent with other evidence for renewed rifting at the base of the MNQ (Hatton, 2004) and coincides with Calvert - Sybella extension of the Western Fold Belt (Figure 1.3). The mid to upper MNQ and lower TCV storm current tempestites were deposited in a slope to basin floor setting (Southgate et al., 2013) or on a narrow shelf within the fault-controlled, south to southeast-deepening SCG basin (Hatton, 2004). Gibson et al. (2018) favour a vast basin that extends ~400 km east to the Etheridge Province (Georgetown Inlier). The Etheridge Group comprises similar rock types and includes ca 1670-1660 Ma high-Fe tholeiites similar to those of the SCG (Baker et al., 2010 and references therein).

Property	Toole Creek Volcanics	Mount Norna Quartzite	Llewellyn Creek Formation
Thickness	2800m	1300-2700m (or 1600-3500m; Giles, 2000)	2200m
Rock types	20-30% mafic units (amphibolite, metadolerite, metabasalt), psammopelite, pelite, quartzite, black shale, graphitic schist, carbonate-rich sediment, chert, rare BIF	Quartzite, psammite, psammopelite, phyllite, pelitic schist, iron formation (Mt Norna, Weatherly Ck), thick sills (>150m) of amphibolite or metadolerite, rare metabasalt	Schist, phyllite, shale and minor amphibolite; thicker amphibolite near top in the Snake Creek area
Depositional environment (Hatton, 2004)	Lower – same as MNQ; mid to upper – black shales and IF suggest more quiescent environment, possibly deeper water	Storm current influenced debris flows on narrow shelf (proximal to medial), tempestites due to density and turbidity currents	Not mapped, deep water turbidites (e.g. Southgate et al., 2013)
Top boundary	Not exposed; magnetic and gravity data suggest the TCV comprise fewer mafic units to the east and south. This may represent the upper TCV or a lateral transition.	Marked by increase in mafics including the first metabasalt and/or a 50m amphibolite	Two amphibolite units just below contact in Snake Creek area
Lower boundary	Marked by first metabasalt and/or a 50m amphibolite; black shales or graphitic shales/schist	Defined by massive quartzite	Not exposed

Table 1.1 Summary of the Soldiers Cap Group units in the Snake Creek – Weatherly Creek area (modified after Hatton, 2004).

Isan Orogenic Events

The general scheme of tectonic events involving early ~N-S shortening, and a main phase of ductile E-W shortening and crustal thickening, followed by 1-2 events of brittle-ductile to brittle faulting, has persisted for three decades or more although the nomenclature has varied (Table 1.2). This project is consistent with recent studies, but emphasises an early extensional event during deposition of the Soldiers Cap Group units, broadly equivalent to Dbp of Rubenach et al. (2008) and d1 of Giles et al. (2006a; 2006b). An early layer-parallel fabric has been documented over a wide area by numerous workers. There has been significant debate whether this near horizontal fabric results from extension or compression but the absence of recumbent folds, and regional upward-facing (pre-D2) favours an extensional origin (e.g. Giles et al., 2006a; Rubenach et al., 2008). Likewise the "young over old" relationship on the low-angle faults localised within the Staveley Formation carbonates favours an extensional origin (Giles et al., 2006a). This layer parallel fabric and extensional detachment beneath the SCG are consistent with the evidence for significant extension during deposition of the SCG in the Soldiers Cap Domain (previous page) and are herein interpreted as part of a ca 1680-1650 Ma extensional event. Within the EFB, this event is focussed within the Soldiers Cap Domain (and Marimo-Staveley area) and may not be present in other areas therefore explaining questions regarding the significance of the widely recognised early layer parallel fabric (extension vs compression vs both), and/or the existence of a pre-D1event in adjacent areas to the west (e.g. Murphy et al., 2017). Further work is required to better document the potential extent.

Based on the geology of the project area and datasets available for interpretation, this study has focused on the extensional event that accommodated deposition of the Soldiers Cap Group (see previous page). Although most or all faults of a suitable orientation were active during D2 E-W shortening, a significant amount of time and effort was focussed on distinguishing the faults that initiated during the extensional event and therefore have the potential to control Broken Hill Type SEDEX mineralisation, from those that initiated later during E-W shortening or other events. In the accompanying GIS project, the faults are distinguished by their interpreted age of initiation.

- De – extensional faults are best developed within the SCD; many are NW- or NE-trending, but orientation ranges to N-S and E-W; the low-angle faults separating the Staveley Formation carbonates from overlying SCG units (including Cloncurry Thrust) are interpreted as extensional detachment faults and can be traced to the east in seismic data. The extension direction during SCG deposition is interpreted as ~NW-SE similar to ~NW-SE to E-W for the Calvert / Sybella extensional in the Western Fold Belt (e.g. Gordon, 2004 Gibson et al., 2008), differing from ~ENE-WSW extension of Austin and Blenkinsop (2008; 2010) based on interpretation of the NNW-trending Cloncurry Fault as a normal fault.
- D1 – E-W folds and reactivation of extensional faults during N-S (or NW-SE) shortening, including reactivation of the Staveley detachment faults which preserve "young over old" despite later thrust reactivation which should place older units over younger.
- D2 – N-S-trending folds and numerous N-S faults; dominant dip direction is controlled by underlying basement terranes; D2 faults commonly cut or disrupt D2 folds and are interpreted as late in D2 (e.g. Murphy et al., 2017; Hinman et al., 2018).
- D2b – local overturning of D2 structures (Rubenach et al., 2008) and emplacement of some intrusions (Murphy et al., 2017).
- D3 and D4 – younger faults and folds in the covered areas are interpreted as D3 or D4 based on their orientation and whether they affect Williams age intrusions; these structures typically have small offsets and are best distinguished at permit or mine scale.

Table 1.2 highlights the widespread recognition of D1-D4 events across much of the EFB, despite some variation. It has been more difficult however to accurately date the age of events. This generally relies on dating the metamorphic minerals related to a specific event, however, the overprinting events and the degree of alteration in many areas has led to uncertainty. Rubenach et al. (2008) highlight the timing of various phases of metamorphism in relation to the tectonic events in the AOI with the main metamorphic peak (M3) occurring late during D2a E-W shortening ca 1590-1580 Ma (or 1570 Ma; Giles and Nutman, 2002; Rubenach et al., 2008). M1 metamorphism involved the main stage of cordierite growth and was very low pressure implying there was no crustal thickening consistent with an extensional event, whereas significant crustal thickening occurred during the main M3 metamorphic peak (at D2 time) with growth of garnet, staurolite and kyanite at 500-600 Mpa; followed by 400 MPa andalusite and sillimanite growth implying decompression and consistent with D2b being extensional (Rubenach et al., 2008). Porteau et al. (2018) provide further constraints on the metamorphic evolution of the Soldiers Cap Domain using Lu-Hf geochronology and metamorphic P-T estimation from equilibrium phase diagrams on garnet-bearing assemblages. Garnet that formed at ca 520-530 °C and 200-300 MPa yielded age dates of 1606.5 +/-2.4 Ma and 1603.9 +/- 4.5 Ma (Porteau et al., 2018) whereas conditions of ca 580 °C and 500-600 MPa in this region and 670 °C and 400-500 MPa at Cannington-Osbourne were reached at ca 1590-1580 Ma (Giles and Nutman, 2002; Rubenach et al., 2008). These age dates show that prograde metamorphism reached 520-530 °C and 200-300 MPa at ca 1605 Ma (Porteau et al., 2018), likely during D1 N-S thin-skinned deformation and rapidly transitioned to E-W shortening and crustal thickening by 1590 Ma. The P-T path for this region shows a strongly decreasing thermal gradient which is typical of an inverted rift or backarc basin (Giles et al., 2006a), from ca 45°C/km at ca 1605 Ma (Porteau et al., 2018) to 25-30°C/km at 1590 Ma.

Note that some workers relate ca 1590-1580 Ma peak metamorphism to D1 thin-skinned deformation, however the moderate pressure of assemblages associated with the main N-S fabric is indicative of crustal thickening (Rubenach et al., 2008). In addition, the recognition of garnet-bearing assemblages that include both low pressure assemblages (M2) and moderate pressure assemblages (M3) in the Snake Creek area (e.g. Rubenach et al., 2008) partly explains this controversy as this level of detail may not be preserved in many areas due to overprinting and/or lack of suitable rock types.

Metamorphism (Snake Creek)	Stress direction	This study	Hinman et al., 2018	Murphy et al., 2017	Rubenach et al., 2008	Austin & Blenkinsop, 2008	Giles et al., 2006a,b	O'Dea et al., 2006	Rubenach and Lewthwaite, 2003	Laing, 1998	Adshead-Bell, 1998	Bell and Hickey, 1998	Bell, 1983; 1991
M1 very low P	Subvertical; layer parallel fabric, low-angle faults	**De** NNE-SSW extn			**Dbp** (extensional)	Basin faulting	**d1** pre 1600 Ma		**D1**		**D1**		
M2 high T – low P; **ca 1605 Ma**	~N-S to NW-SE (thin-skinned)	**D1**	**D1** (1600-1570 Ma)	**D1** (1600-1570 Ma)	**D1**		**d2** 1600 -1580 Ma	**D1** NNW-SSE	**D2**	**D1**		**D1**	**D1**
M3 high T – moderate P; ca **1590-1580 Ma**	~E-W thick-skinned with crustal thickening	**D2**	**D2** (1550-1540 Ma)	**D2** (1550-1540 Ma)	**D2a**	**D2**	**D3** post 1560 Ma	**D2** ESE-WNW	**D3**	**D2**	**D2**	**D2**	**D2**
M4 mod-low P	Sub-vertical; extensional relaxation	**D2b**	**D2b**	**D2b**	**D2b** top W				**D4**		**D3** top W	**D2.5** top E&W	
M5	Various (local); brittle-ductile	**D3**	**D3**	**D3**	**D3** ENE-WSW	**D3** ENE-WSW	**d4**	**D3** E-W	**D5** ENE-WSW		**D4**	**D3** variable	**D3** ENE-WSW
M6	~NW-SE - brittle	**D4**	**D4**	**D4**	**D4** NW-SE	**D4** NW-SE			**D6** NW-SE	**D3**	**D5**		
Rubenach et al., 2008; Porteau et al., 2018		*central EFB*	*southern EFB*	*southern EFB*	*Snake Creek*	*Cloncurry Fault Zone*	*Snake Ck, SE EFB- Pegmont*	*Mitakoodi Culmination*	*Snake Creek*	*southern EFB*	*Starra-Selwyn*	*Mt Isa, WFB*	*Mt Isa, WFB*

Table 1.2 Summary of nomenclature of the Isan Orogenic events modified after Murphy et al., 2017 (DMQ project).

Chapter 2

Datasets

Geological Maps

This project builds on a wide range of previous mapping in the region.

- 250K detailed mapping and air photo interpretation 1969-1984
  - Three main units distinguished (LCF, MNQ, TCV) north of 21°S
  - South of ~21°S the rocks are higher grade and the three units are more difficult to distinguish in outcrop and drilling. The SCG units are undivided.
- 100K maps – Cloncurry, Mount Angelay and Selwyn (Geological Survey of Queensland, 2015; 2016a; 2016b)
  - Geological revision by integrated image interpretation and extensive field checking 2006-2010
  - The higher grade undifferentiated SCG units south of ~21°S were separated into TCV, MNQ and LCF.
- Compilation and release of digital datasets including: detailed surface geology, solid geology and structural datasets (current version Geological Survey of Queensland, 2018).
- Detailed maps at mine or permit scale: Canteen (Kreuzer, 2012 in Austin et al., 2016b), Eloise (Baker, 1998; Hodkinson et al., 2003), Maronan (Valenta, 2019; CR23506; Doherty, 1992); Fairmile (CR22877; Komyshan, 1991); and Strathfield (CR39056; Konecny, 2005).

Figure 2.1 shows the solid geology interpretation that formed the starting point for this project comprising work of the Geological Survey of Queensland, the Deep Mining Queensland project (DMQ; Murphy et al., 2017), and the Southern Eastern Fold Belt (SEFB; Hinman et al., 2018). The aim during the interpretation process has been to remain largely consistent with the interpreted outcrop geology. Although the LCF, MNQ and TCV are distinctive in areas where the entire sequence is exposed (north of ~21°S), the main rock types overlap and a smaller outcrop or belt of outcrops may not be easy to distinguish. Distinction of the three main units south of ~21°S is further complicated by the higher metamorphic grade, significantly higher strain in the Maramungee region (M), and variable outcrop quality. Several questions have been outlined in the Introduction above and are discussed in Chapter 5 (Solid Geology Interpretation).

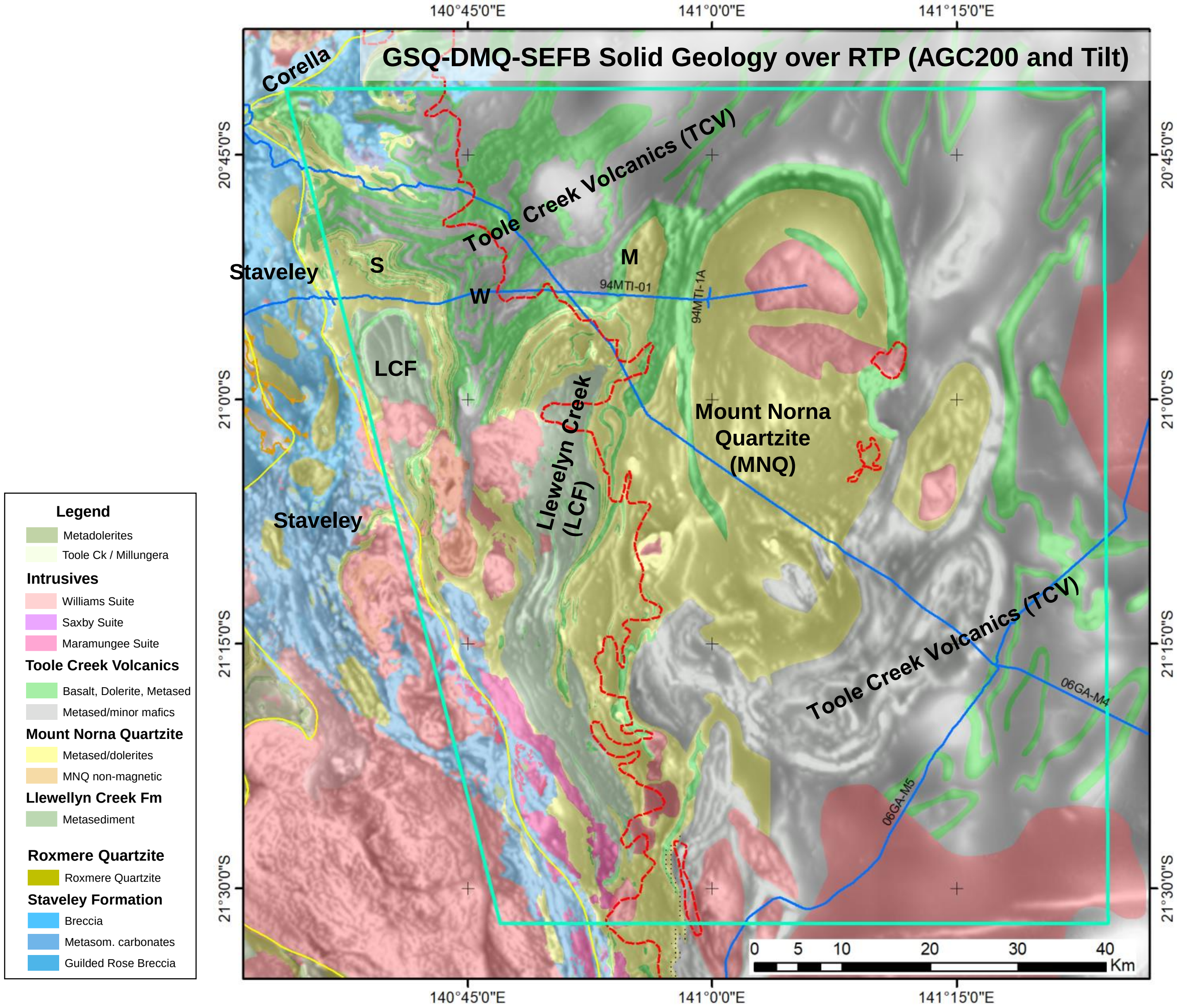


Figure 2.1. Solid geology interpretation prior to this project, from Geological Survey of Queensland, the Deep Mining Queensland project (DMQ; Murphy et al., 2017), and the Southern Eastern Fold Belt (SEFB; Hinman et al., 2018). Transparent, grey scale image of RTP in the background (AGC 200 and Tilt) from Frogtech's 2018 NWQ SEEBASE project. The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. The seismic lines are in blue.

Drilling data

The main drill dataset used for this project was compiled by Mark Hinman for the Solid Geology Interpretation of the southern Eastern Fold Belt project (Hinman et al., 2018) from data provided by South32-BHP and Minotaur Exploration. South32's exploration drillhole database contained data on drilling in the Eastern Fold Belt dating back to 1983; much drilled by BHP Exploration in its search for BHT deposits prior to the demerger of South32 in 2015. The South32 drillhole database provided to southern EFB Project contained 5,364 drillholes, the vast majority of which have a diamond drilling component. Minotaur Exploration also made available their drillhole database for the southern EFB Project, but this data did not extend into the AOI for this project. All collars in the databases were shifted to a SRTM Elevation Model so that all the drillhole data could be displayed and interrogated in a coherent Leapfrog™ model. Figure 2.2 shows the distribution of the drillhole database coloured by rock type. This dataset provided critical constraints on the solid geological interpretation.

Because information in the drillhole database spanned more than three decades of exploration, Mark Hinman rationalised and simplified over 170 lithology and altered lithology codes into simplified sets of:

- Cover sediment Codes,
- Proterozoic Metasediment Codes,
- Intrusive Magmatic Codes,
- Extrusive Magmatic Codes and
- 'Alteration' (Altered Lithology) Codes.

Mark Hinman also rationalized the Proterozoic Metasediment Codes into a simplified set of codes that attempted to reflect variations between psammite, through psammopelite to pelite and carbonaceous shale-dominated lithologies and encompassed all their schistose and gneissic, moderate to high metamorphic grade equivalents. The emphasis on original sediment type was aimed at aiding in package characterisation and ultimately depositional environment interpretation. In most cases metamorphic lithological descriptors can be re-cast in sedimentalogical terms; in some minor cases, ambiguity remains (Hinman et al., 2018).

Note that the drill hole lithology dataset shown in Figure 2.2 and included in the GIS project includes only the top basement sample. However, the full downhole dataset was used during interpretation.

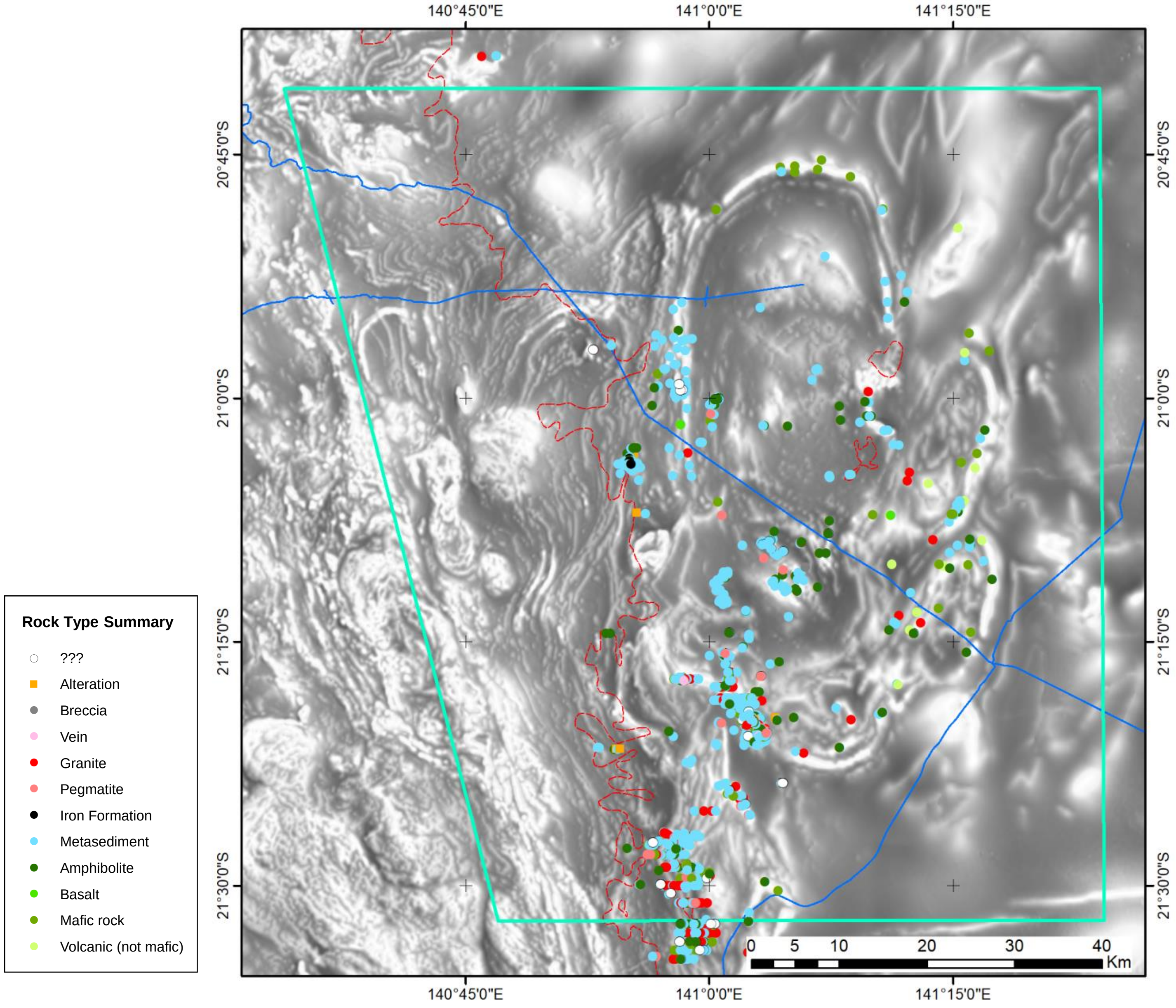


Figure 2.2. Distribution of drillhole data available within the project area (cyan outline) with transparent, grey scale image of RTP in the background (AGC 200 and Tilt). The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. The seismic lines are in blue.

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Magnetic Data

Magnetic data provided one of the key datasets for this project. Datasets from several different sources were used for this project.

- The South Cloncurry magnetic survey was acquired by Geological Survey of Queensland in 2017 at 100m line spacing and 50 m nominal terrain clearance. Gridded datasets used in this project have a 20m cell size.
- Magnetic datasets compiled for Solid Geology Interpretation of the southern Eastern Fold Belt project (Hinman et al., 2018). The data contributed by Sandfire Resources covers the eastern part of this project area (yellow outline). This dataset comprises surveys collected at 50-100m line spacing and 45 m nominal flight height. Gridded datasets used in this project have a 25m cell size.
- The North West Queensland SEEBASE project (Frogtech, 2018) used the 2015 TMI grid downloaded from Geoscience Australia, and included a wide range of filters in the accompanying GIS project. Refer to the original report and GIS for details. This large regional dataset was gridded with an 90m cell size.
- The higher resolution Cloncurry and Sandfire datasets were the main datasets used for interpretation during this project. The regional dataset compiled for the NWQ SEEBASE project provides a useful overview of the entire region and fills in a few gaps in the higher resolution datasets, but was not used for interpretation.

The main filters used during this project include 1VD, AGC, and Tilt filters of the Reduced to the Pole datasets. Figure 2.3 shows the 1VD of the Cloncurry dataset. Most of the images of magnetic data used in the report depict the lower resolution regional dataset as it is “less noisy” at this scale. The filters used are a combination of the AGC 200 (automatic gain control balances the strong and weak anomalies providing better continuity of anomalies) and the Tilt filter. The Tilt filter produces similar shapes to the 1VD, however the amplitudes are condensed to a small range, and therefore the anomalies appear sharper. Combination of the Tilt with the AGC 200 provides more information on the deeper longer wavelength anomalies and variation in amplitude. Refer to Geophysical Appendices of the NWQ SEEBASE project for further details (Frogtech, 2018).

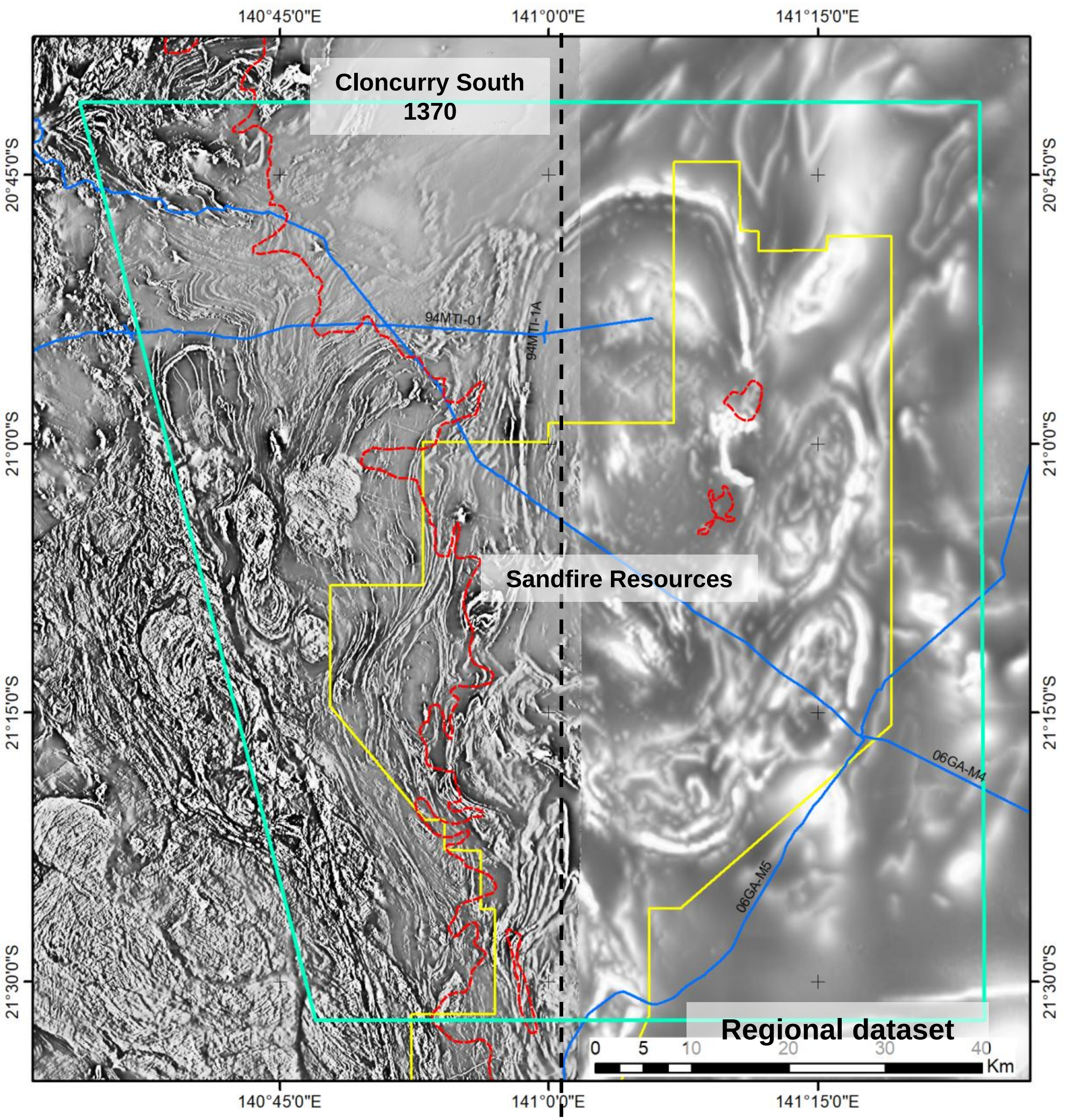


Figure 2.3. Distribution of magnetic datasets sued for this project (cyan outline). 1VD of RTP is shown for the Cloncurry South dataset and transparent, grey scale image of RTP in the background (AGC 200 and Tilt) from Frogtech’s 2018 NWQ SEEBASE project. The extent of the confidential Sandfire dataset is shown in yellow. The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. The seismic lines are in blue.

Gravity Data

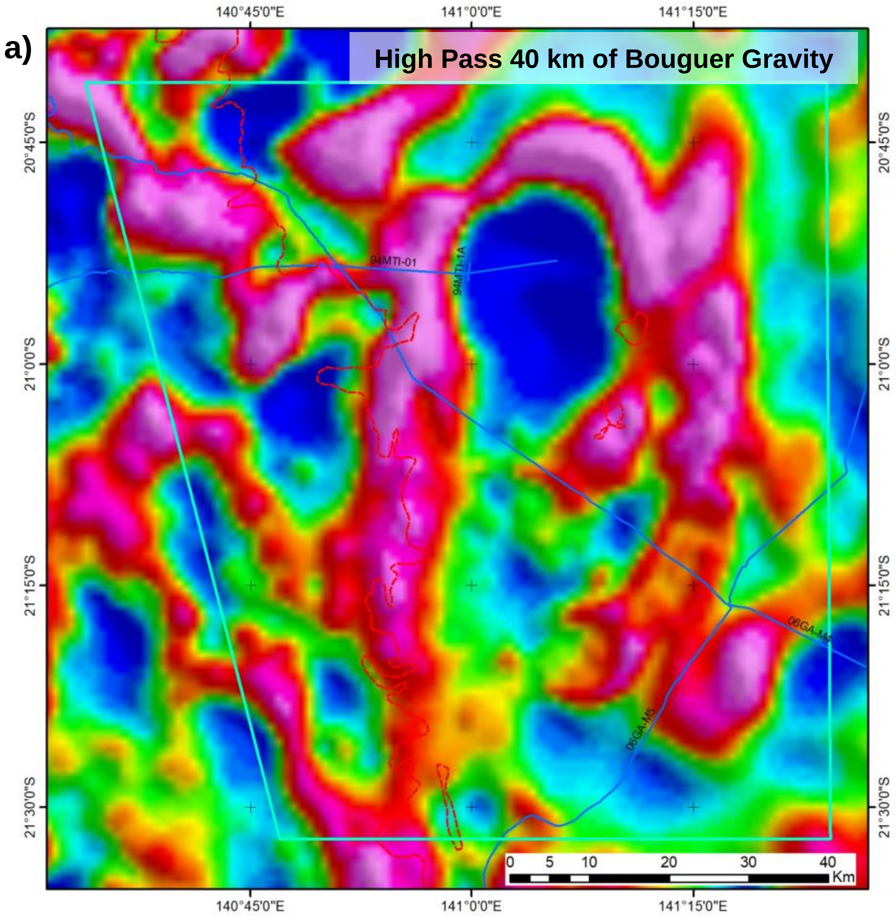
Gravity datasets were taken from the North West Queensland SEEBASE project (Frogtech, 2018) and the Deep Mining Queensland project (Murphy et al., 2017). The North West Queensland SEEBASE project (Frogtech, 2018) used the 2016 Onshore Gravity Grid downloaded from Geoscience Australia and stitched it with v 23.1 of the Satellite Free Air Gravity dataset to cover the offshore area. A wide range of filters were produced in the project. Refer to the original report and GIS for details. The High Pass 40 km filter shown in Figure 2.4. highlights the variations in density in the upper crust and matches well with the Apparent Density calculation shown at right.

Note that integration with more detailed ground gravity stations, and/or gravity gradiometry, available from open file reports, or contributed by industry, would improve data resolution and help to refine the solid geology interpretation.

Apparent Density

The Apparent Density dataset used for this project was produced for the Deep Mining Queensland Project (Murphy et al., 2017) and does not cover the entire AOI. The description of the Apparent Density Model (Figure 2.4b) is taken from Murphy et al. (2017). The model was derived from a *Vpmg* 'Basement only' inversion of the GA 2011 Isostatic Residual Gravity Anomaly grid data. An apparent density model is constructed by establishing an input model of vertical prisms that extend from surface to a depth of 25 km. A single density value is assigned to each prism and the inversion process iteratively adjusts the density of each prism until a match between the model's gravitational response and the observed gravity data is achieved within some density range constraint. Prism dimensions were 900x900m. The apparent density model assumes no crustal architecture, but very usefully highlights density *deficits* and *surpluses* in relation to areas of known granite and Proterozoic outcrop. Because the density is allowed to vary freely in each prism within prescribed limits the apparent density model provides useful quantitative estimates for density contrasts throughout the model area. Refer to Murphy et al. (2017) for further details.

a)



b)

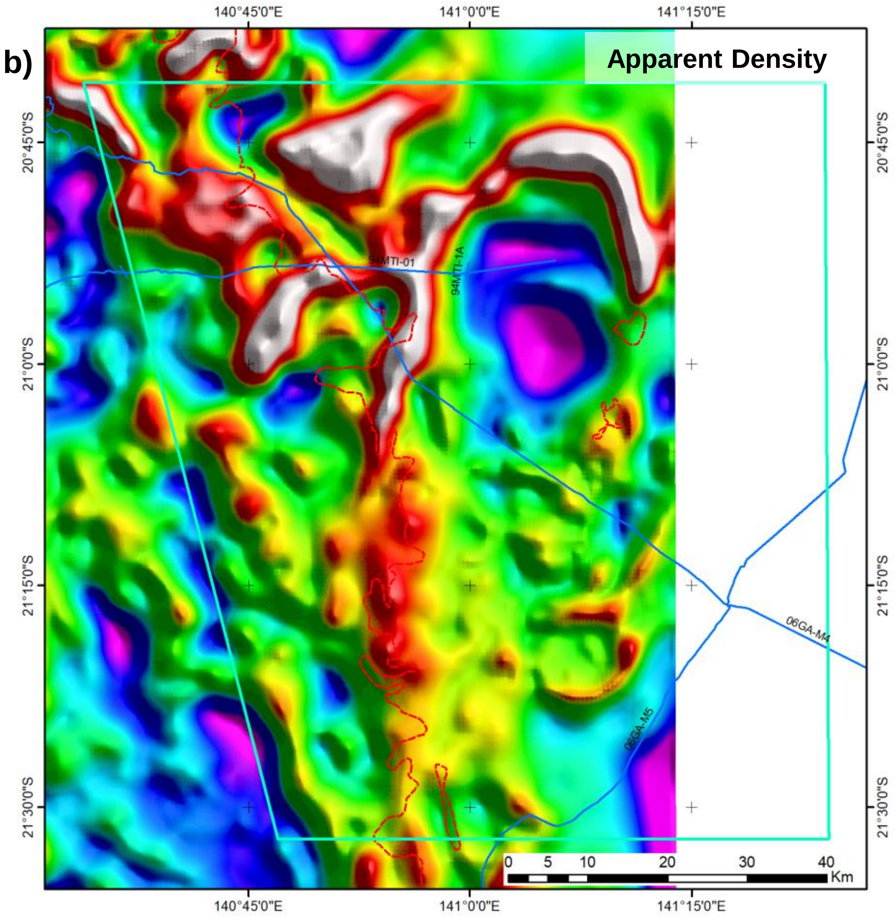


Figure 2.4. a) High Pass 40km of the Bouguer Gravity (left; from Frogtech, 2018) and b) Apparent Density (right; from Murphy et al., 2017).

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Radiometric Data

Radiometric data from the South Cloncurry magnetic survey acquired by Geological Survey of Queensland in 2017 at 100m line spacing and 50 m nominal terrain clearance provided the highest resolution data covering the outcrop within the study area. Gridded datasets used in this project have a 20m cell size.

ASTER v2 and Hyperspectral Data

Satellite multispectral ASTER v2 and HyMap hyperspectral mineral mapping products were developed in a collaborative CSIRO project including Geological Survey of Queensland, Geoscience Australia and James Cook University and are available for download from CSIRO and GSQ. Refer to Cudahy et al., 2008 for details. Detailed interpretation indicated that features in the false colour ASTER TIF appear to be offset relative to other datasets by ~80m. This dataset has therefore not been used to accurately map the location of features.

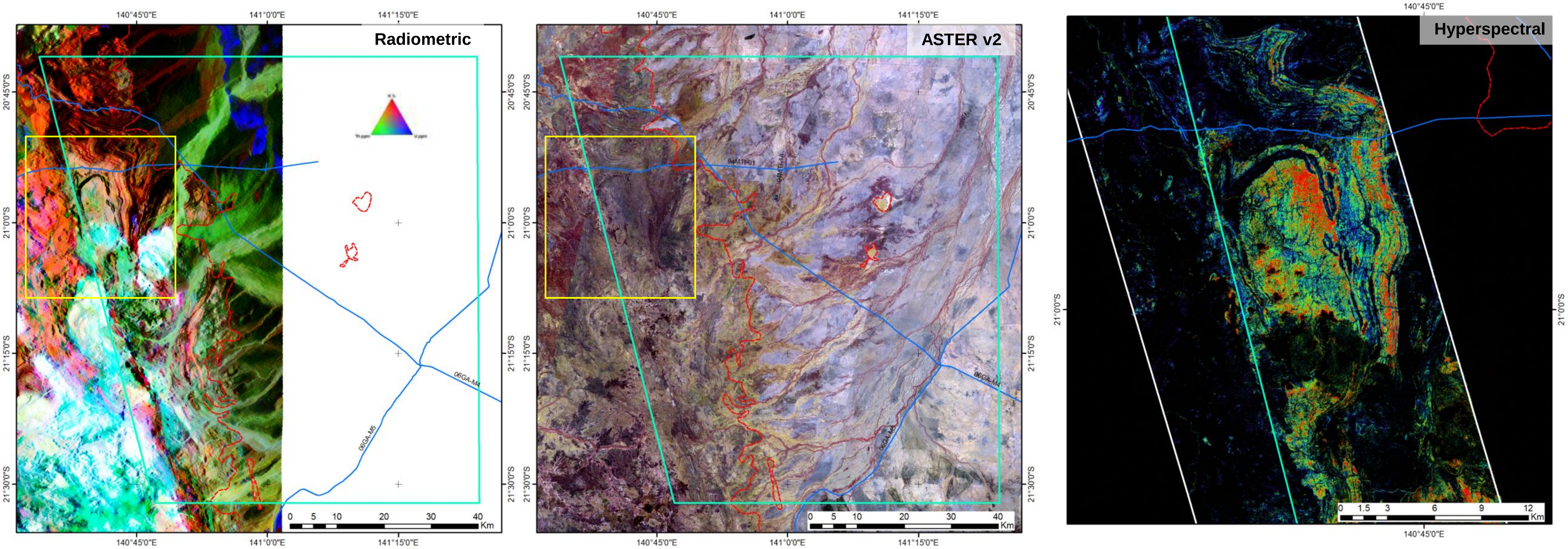


Figure 2.5. Coverage of the radiometric, Aster v2 and hyperspectral datasets used for this study. The yellow box shows the location of the image for the hyperspectral data.

Chapter 3

Regional Architecture

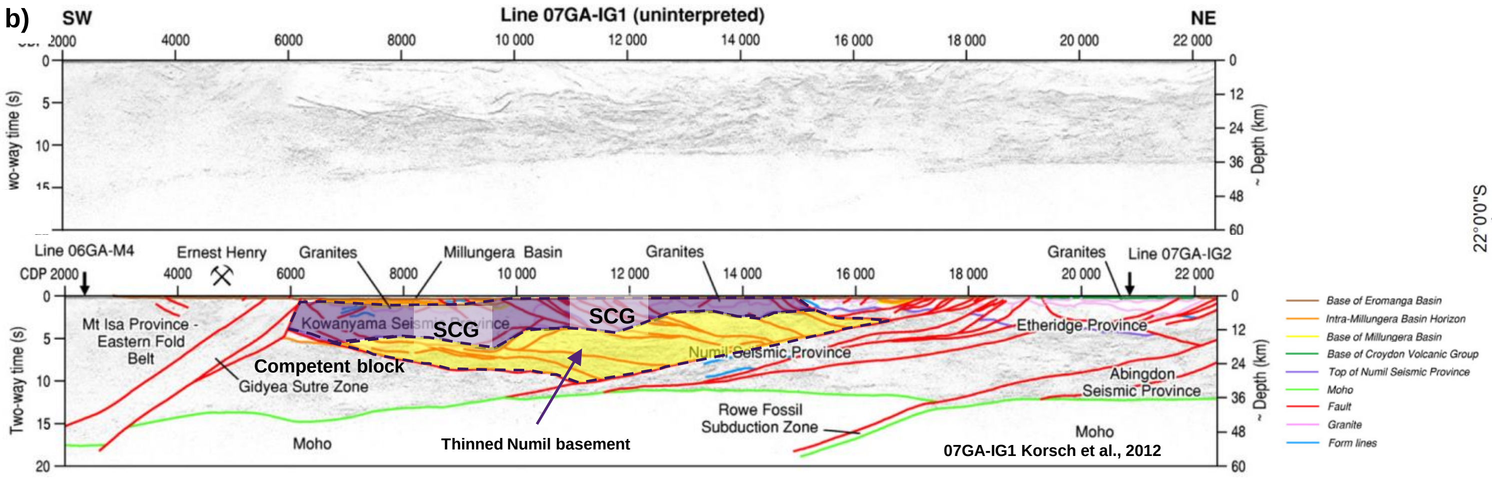
THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Regional seismic data

A series of deep crustal seismic lines were collected across the Mount Isa region from 1994 to 2015 by federal and state governments (Figure 3.1). The quality of the seismic imaging is variable due to a range of factors including the nature of the local geology (e.g. the presence of a strong velocity contrast near surface that reflects much of the seismic wave and limits transmission, or attenuation of seismic waves due to near surface absorption in a low velocity zone such as karst topography and caves). The seismic lines are largely E-W to NE-SW and cross the geological fabric at a high angle although changes in geology mean that collection at a high angle to the geology is not always possible and compromises data quality. As a result, little geological information can be extracted in some areas. Despite these limitations, the seismic data provides fundamental constraints on the underlying basement terranes as well as the geology and structure of the upper ~10 km within the Soldiers Cap Group basin.

The 3 seismic lines that cross the AOI, 06GA-M4, 06GA-M5 and 94MTI-01 (Figure 3.1) show some variation in the seismic response of the underlying crust, but this is difficult to interpret with confidence due to the limited extent of these lines and variations in data quality. Therefore the crustal architecture and extent of different basement terranes was assessed on a more regional scale using seismic lines 07GA-IG1, 06GA-M6 and 14-15GA-CF3 with a focus on the Soldiers Cap Domain and adjacent areas to the west. The nature of the basement terranes beneath the AOI were more readily interpreted based on the regional insights.

- Korsch et al. (2012) interpreted the west-dipping Gidyea "Suture" Zone of seismic line 07GA-IG1 as separating poorly reflective, thick crust of the Mount Isa Province from thinner two layered crust comprising highly reflective lower crust (Numil seismic province) and weakly reflective upper crust (Kowanyama seismic province). A distinct triangular block of moderately reflective crust lies between the Gidyea Suture and central Numil province (Figure 3.1). This block is essentially unfaulted in comparison to the highly faulted central Numil province indicating its a distinct rheological domain of more competent crust. The central Numil province (highlighted in yellow; Figure 3.1b) is dominated by a series of low-angle faults that dip 5-20° to NE on this line and dip 20-30° to the SE on 14GA-CF1 (Donchak and Clark, 2015) implying an overall south or southeast dip. On 07GA-IG1 these low-angle faults offset the boundary between Numil and Kowanyama provinces with both thrust and extensional offsets; these structures sole into a set of SW-dipping faults of the eastern Numil which comprises SW-dipping slivers of faulted crust beneath the Etheridge Province (Korsch et al., 2012). Nordsvan et al. (2018) interpret the Etheridge Province as a fragment of Laurentia based on paleocurrent and provenance data linking it to Laurentia ca 1700-1650 Ma, however Gibson et al. (2018) argue that the detrital zircon data is not conclusive and that Sm-Nd and Pb isotope data (Champion and Huston, 2016) indicate the presence of suitable age crust in North Australia. Korsch et al. (2012) interpret the Numil seismic province to have accreted to Mount Isa at ca 1865 Ma and the Kowanyama and Etheridge provinces as a 1700-1620 Ma sedimentary sequence. The Kowanyama province is intruded by numerous Williams age granites (Korsch et al., 2011).
- The sedimentary units of the 10-15 km thick Kowanyama seismic province are herein interpreted to correlate with the Soldiers Cap Group. Given the significant shortening and crustal thickening documented during the ca 1610-1500 Ma Isan Orogeny, preservation of extensional offsets on some low-angle faults within the SCG and Numil is consistent with this fault set originating in an extensional setting. In addition, the number and geometry of the low-angle fault blocks within the central and eastern Numil province is consistent with highly attenuated crust.



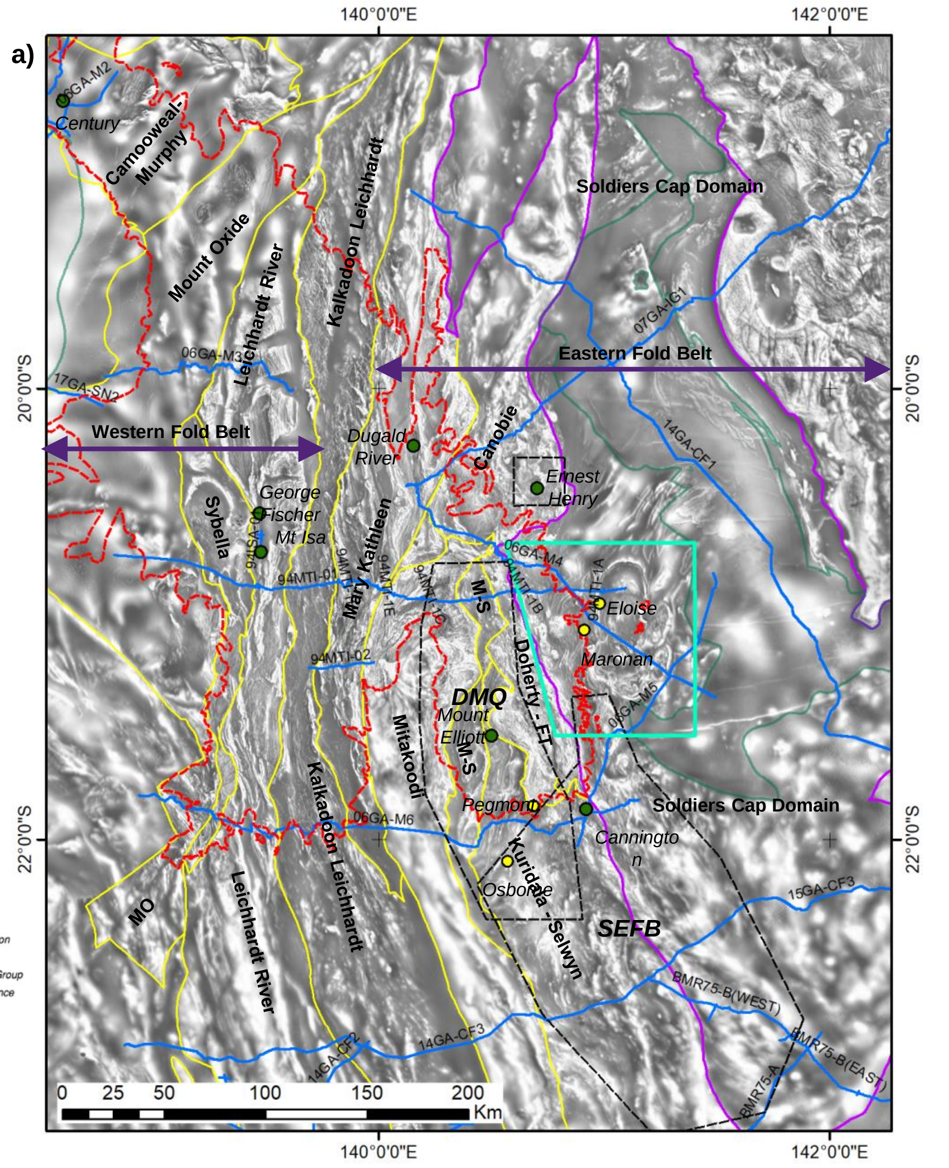


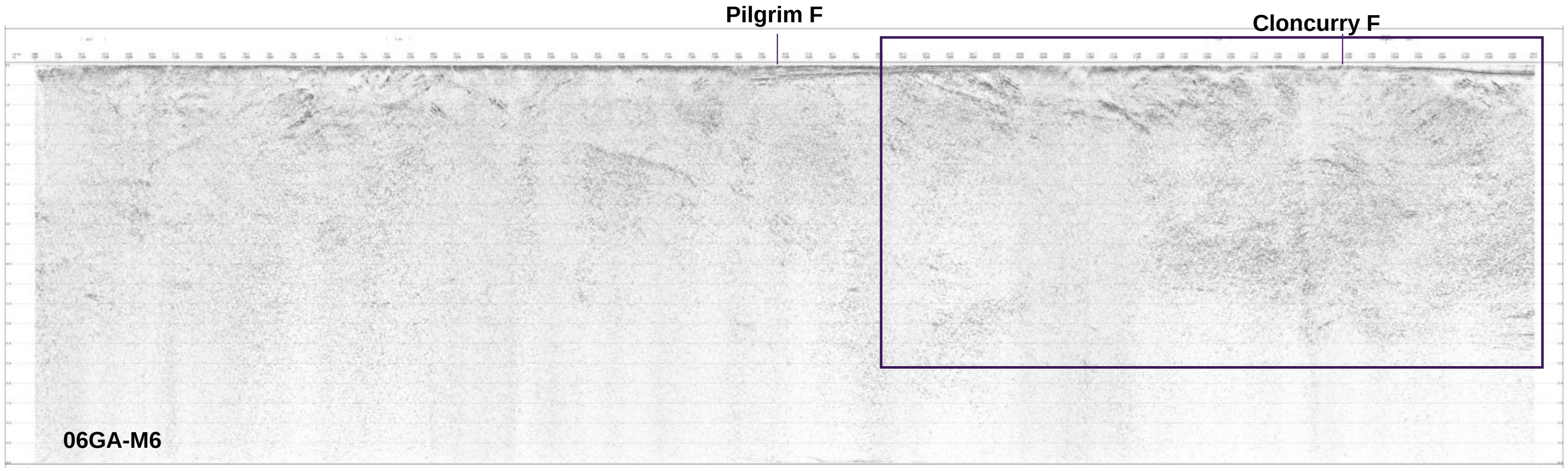
Figure 3.1a. Regional location map showing the seismic lines and Mount Isa domains over a grey scale image of RTP in the background (AGC 200 and Tilt). The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. Mount Isa Province domains are shown in yellow with Soldiers Cap Domain highlighted in purple. The previous projects are shown in black dashed lines. The seismic lines are in blue. Green dots = giant ore deposits and yellow dots = medium to large deposits mentioned in text. b) Uninterpreted and interpreted images of 07GA-IG1 modified from Korsch et al., 2012).

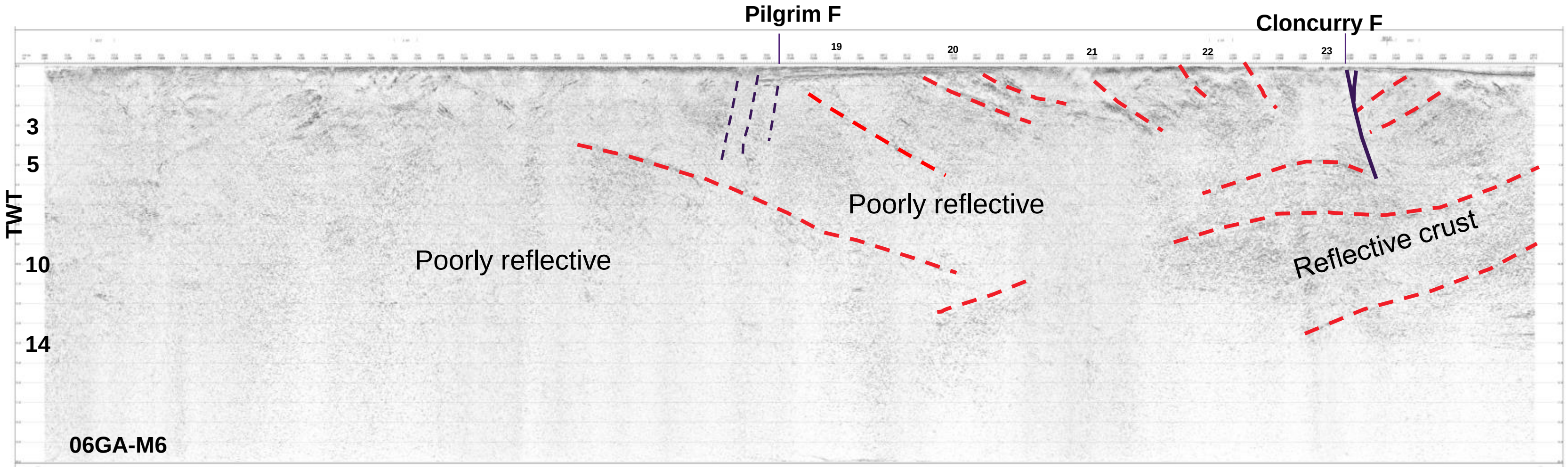
Seismic line 06GA-M6

Seismic line 06GA-M6 extends E-W across the Mount Isa Province to the south of the AOI. Figure 3.2 shows the entire line down to 20 sec TWT. The crust of the Mount Isa Province west of the Cloncurry Fault shows a few packages of strong reflections but overall is relatively poorly reflective as noted for 07GA-IG1 and other seismic lines (e.g. Korsch et al., 2012). The location of the Pilgrim Fault at surface is shown for reference. The Cloncurry Fault is evident as a steep east-dipping structure where reflections are disrupted and change dip. The upper ~3-4 sec TWT, ~9-12 km, between the Cloncurry and Pilgrim faults is dominated by east-dipping stratigraphy and faults. This section has been interpreted in detail by Murphy et al. (2017) as part of the DMQ project and is considered on the following page.

Reflective crust with a pervasive west dip is evident at the east end of the seismic line and it extends west beneath the Cloncurry Fault, almost to the Pilgrim Fault. The Moho is not well defined on this line, but the west-dipping reflections die out around 14-15 sec TWT. This reflective crust is distinct from the poorly reflective crust of the Mount Isa Province and is more consistent with that of the Numil province on 07GA-IG1. Seismic line 06GA-M5 intersects 06GA-M6 near its eastern end and shows this same highly reflective crust with a strong west dip (Figure 3.4).

Note that the interpreted surface position of the Pilgrim Fault roughly coincides with both a steep structure and a moderately east dipping structure in the seismic data. The steep structure is more consistent with the late, brittle timing and steep dip noted for the Pilgrim Fault in outcrop just to the north of the seismic line. Further south however the extrapolated position of the Pilgrim Fault in the GSQ structure dataset appears to be based on magnetic data and coincides with a moderately east-dipping structure on seismic line 14GA-CF3. The nature and location of the Pilgrim Fault requires review in the covered region south of 06GA-M6.





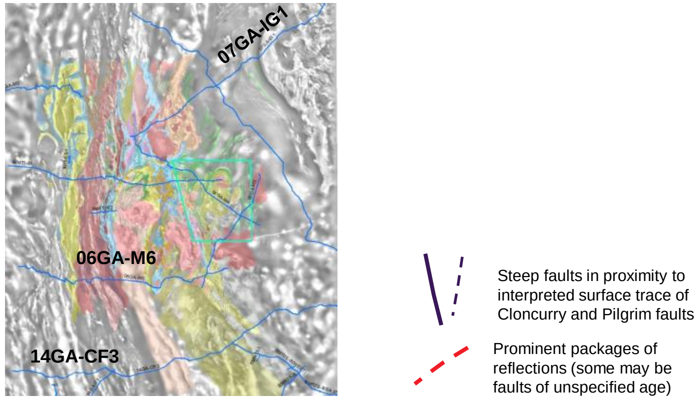


Figure 3.2. Uninterpreted (top) and interpreted (bottom) images of 06GA-M6. Inset shows location of seismic lines. Note that line work highlights a few main features for the purpose of this discussion and is not intended as a detailed interpretation.

Seismic line 06GA-M6

Figure 3.3a shows the eastern end of seismic line 06GA-M6. The DMQ interpretation is shown for the upper 6 sec TWT (Figure 3.3a; Murphy et al., 2017). This interpretation is integrated with detailed mapping and 3D modelling. The main faults from the DMQ interpretation are shown on the lower image. The seismic data shows a strong east dip throughout the upper crust west of the Cloncurry Fault. These reflections die out at ~5-6 sec in the west and 3-4 sec approaching the Cloncurry Fault. The strong west-dipping reflections of the mid to lower crust extend beneath the upper east-dipping reflections. The transition between these two sets of reflections is not well defined in the seismic but is likely to be obscured by large tabular granite bodies (likely Williams age) as indicated by the 3D modelling of the DMQ project (Murphy et al., 2017). The extent of granite bodies shown in Figure 3.3b is based on the 3D modelling and the seismic data.

The fundamental feature evident from 06GA-M6 is that a basement terrane comprising highly reflective crust underlies the Soldiers Cap Group units east of the Cloncurry Fault and extends west beneath the poorly reflective crust of the Mount Isa Province which is overlain by a highly faulted cover sequence comprising SCG equivalents (Kuridala, New Hope and Answer), ca 1725-1700 Ma Staveley and 1755-1770 Ma Mitakoodi, Marraba and Bulonga sequence. Review of all the seismic lines indicates that the highly reflective mid to lower crust at the east end of the line is part of the Numil seismic province. Seismic line 14-15GA-CF3, ~80 km to the south, shows remarkably similar geometry and crustal types supporting this interpretation and has been tested by gravity modelling (Simpson, 2019). The eastern limit of the Mount Isa Crust is not well defined, but it does not appear to extend as far as the Cloncurry Fault. The boundary between the Mount Isa and Numil basement is equivalent to the Gidyea "Suture" identified on 07GA-IG1 by Korsch et al. (2012), but it is not as sharply defined. Note that this structure projects to surface east of the Cloncurry Fault where it will lie within the SCG units (see Figure 4.7 below).

Note that interpretation of the segment east of the Cloncurry Fault differs to the DMQ. This interpretation is based on the better imaging on 06GA-M5 (see Figure 4.7 below). Note also that the Staveley and older package of Mitakoodi, Marraba and Bulonga are strongly reflective.

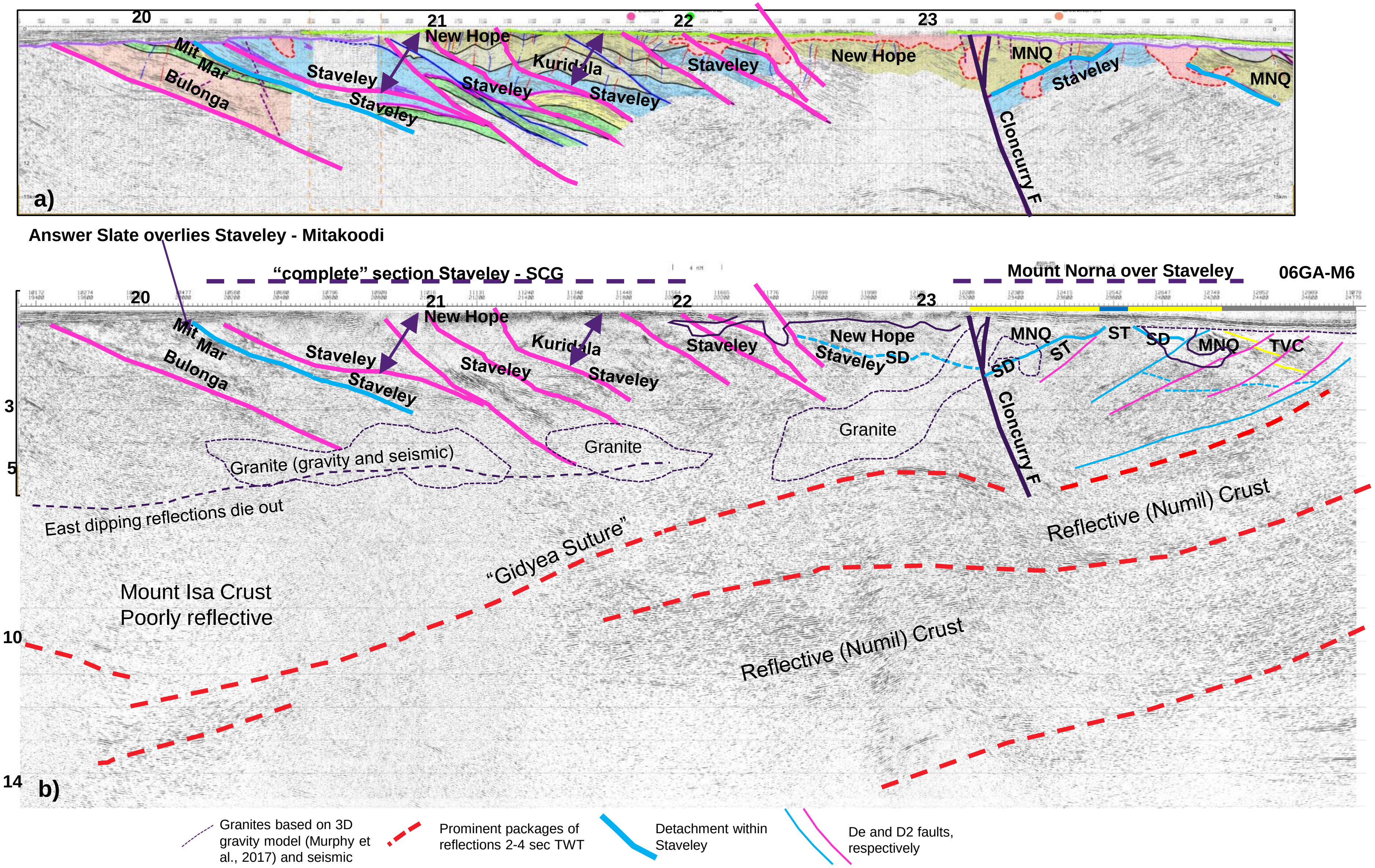


Figure 3.3. Detail of interpreted segment of 06GA-M6 from DMQ project (Murphy et al., 2017). 3.3b. Interpreted faults and main units from Murphy et al. (2017) are shown in the upper 5 sec TWT and the west dipping features in the highly reflective lower crust are highlighted at depth. Note that line work highlights a few main features for the purpose of this discussion and is not intended as a detailed interpretation.

Seismic line 06GA-M5

The critical feature evident from 06GA-M5 is that the underlying basement terrane comprises highly reflective crust with a pervasive west dip. This line intersects 06GA-M6 which shows that the strongly reflective crust extends west beneath the poorly reflective Mount Isa Province (Figure 3.3), similar to the west-dipping boundary on 07GA-IG1 (Figure 3.1). The subhorizontal detachment fault of 94MTI-01 is not evident (see also Figure 4.7 below). The west-dipping structures of the lower crust extend into the upper crust where they offset the SCG units. The boundary between the SCG and underlying basement is not well defined. Likewise, the steep Cloncurry Fault is not well defined, but appears to dip less steeply than on 06GA-M6. As discussed for 06GA-M6 the equivalent structure to the Gidyea “Suture” will project to surface east of the Cloncurry Fault where it will juxtapose units within the SCG. The prominent west-dipping structure that surfaces at ~12000 CDP may represent the near surface structure linked to the Gidyea “Suture” at depth to the west.

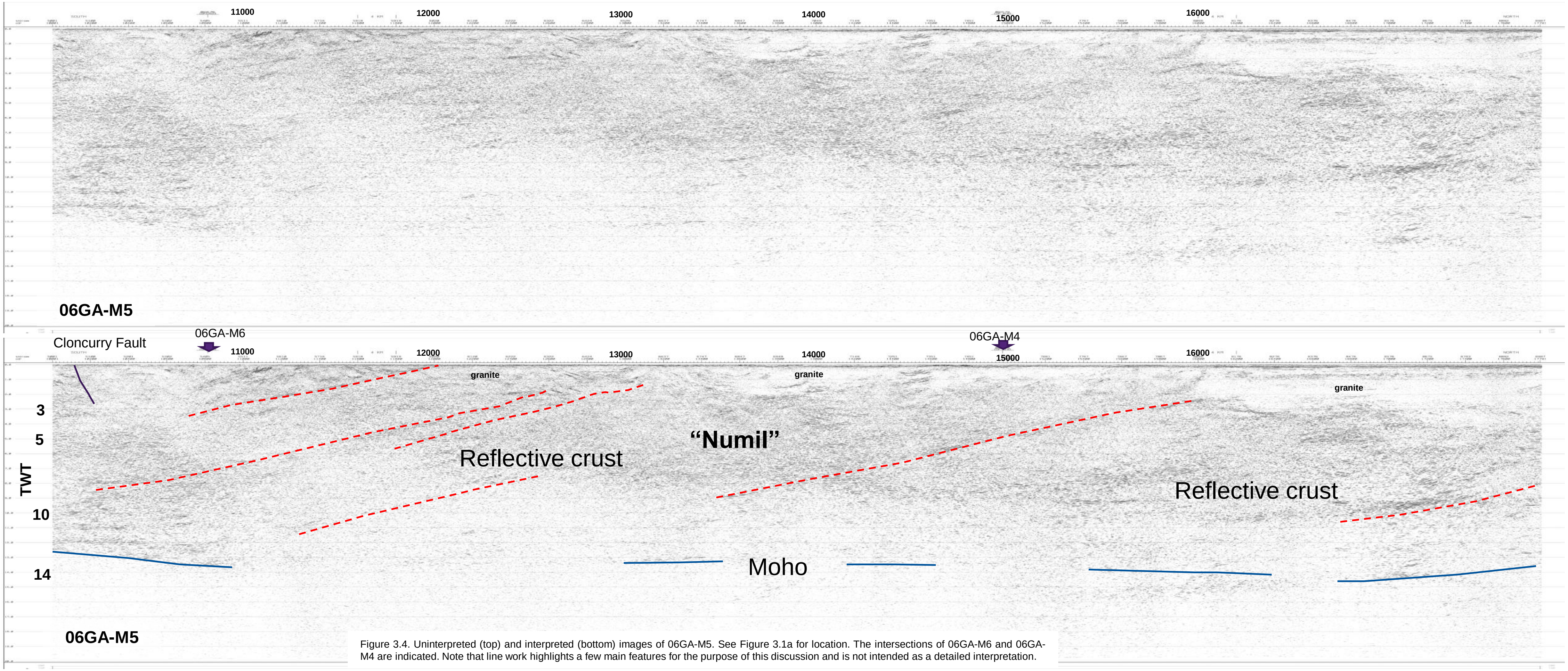


Figure 3.4. Uninterpreted (top) and interpreted (bottom) images of 06GA-M5. See Figure 3.1a for location. The intersections of 06GA-M6 and 06GA-M4 are indicated. Note that line work highlights a few main features for the purpose of this discussion and is not intended as a detailed interpretation.

Seismic line 06GA-M4

The highly reflective crust with a pervasive west dip that extends across 06GA-M5 (Figure 3.4) is evident on the southeast end of 06GA-M4 and extends northwest to ~11500-12000 CDP. The reflective crust appears to thin to the NW and is thrust over the central block. Poorly reflective, thick crust of the Mount Isa Province is evident at the NW end of this line which intersects 07GA-IG1. The crust in the middle section is generally non reflective and its boundaries are not well defined. It may represent a continuation of the poorly reflective Mount Isa crust or it may represent a distinct competent block similar to that imaged on 07GA-IG1 (Figure 3.1). Given that the reflective Numil crust is thrust over this poorly reflective central block, the later interpretation is preferred (Numil overthrusts the competent block on 07GA-IG1 and underthrusts Isa crust on other seismic lines that cross the boundary; e.g. 06GA-M6 Figure 3.3). The prominent NE-trending fault zone, associated with a large step in the EFB in map view, is not well imaged although some reflections are disrupted (CDP ~14800). This feature is generally interpreted as a steep transfer or normal fault formed during early evolution of the basement and/or extensional events during deposition of various cover sequences ca 1790-1600 Ma (Austin and Blenkinsop, 2010 and references therein). Displacement on the steep, late Cloncurry Fault decreases to the north and it is not well defined on this seismic line but the location of the Cloncurry Thrust (part of Staveley detachment fault system) is indicated (see Figure 4.6 and following section for further discussion).

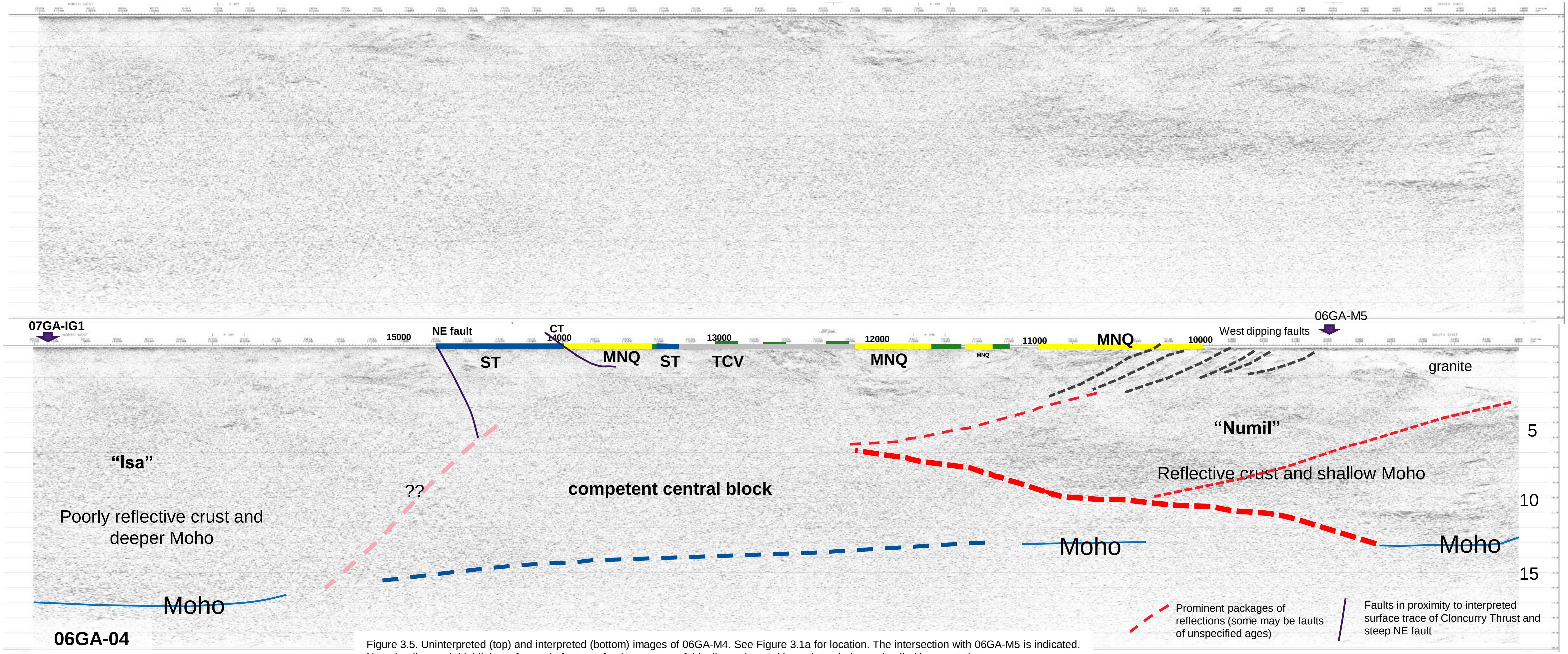


Figure 3.5. Uninterpreted (top) and interpreted (bottom) images of 06GA-M4. See Figure 3.1a for location. The intersection with 06GA-M5 is indicated. Note that line work highlights a few main features for the purpose of this discussion and is not intended as a detailed interpretation.

3.0 Regional Crustal Architecture

Evidence for extension during Soldiers Cap Group deposition

The detailed sedimentalogical and structural observations from the Snake Creek region indicate a significant period of extension during deposition of the 5-8 km thick SCG in a south to southeast-deepening SCG basin (Hatton, 2004; Giles et al., 2006a) as highlighted above (see stratigraphy discussion in Introduction). Renewed extension at the base of MNQ is indicated by the abrupt change to a higher energy environment with debris flows and coarser extrabasinal input, increased hydrothermal activity (resulting in development of chemical sediments), thickening of lower MNQ units (and younger TCV units) into syn-sedimentary faults (20-30% increase), and the sequential sill emplacement (Hatton, 2004). The distinctive high-Fe tholeiites are sourced from the mantle and have a chemistry consistent with an intracontinental rift (Williams, 1998), continental margin or propagating oceanic rift (Hatton, 2004 and references therein), and in addition, eruption of the high-density, Fe-rich basalts required renewed rifting and/or magma replenishment to trigger eruption (Brooks et al., 1991) both consistent with an increase in tectonothermal activity at the base of the MNQ (Hatton, 2004).

Additional support for a significant extensional event during SCG deposition includes:

- The SCG (or equivalents) range to 10-15 km thickness on seismic lines to the east (07GA-IG1 Korsch et al., 2012; 14GA-CF1 Donchak and Clark, 2015) indicating development of an extensive, deep basin.
- The aerially extensive detachment fault in the Staveley Formation carbonates is consistently at a low-angle to bedding and overlain by younger units of the SCG, or equivalent units, and the widespread, pervasive layer parallel fabric lacks recumbent folding and occurs within metasedimentary units that were regionally upward facing prior to D2 (Giles et al., 2006a; b).
- High-Fe tholeiites, ca 1665 Ma, ~400km to east (Etheridge Province) are typical of continental rift tholeiites (Baker et al., 2010) similar to those of the SCG (Williams, 1998; Hatton, 2004). Baker et al. (2010) favoured a volcanic passive margin setting for the Etheridge Province (i.e. supercontinent breakup) based on the geochemistry, however other data favours break-up in a back-arc setting (Gibson et al., 2018 and references therein). The 1690-1685 Ma arc related rocks of the Etheridge Province, as well as an unimodal population of 1655 Ma zircons and evidence for large quantities of juvenile material in upper Etheridge Group units (Nordsvan et al., 2018 and references therein) are indicative of an arc setting in the Etheridge Province at least from ca 1690 to 1610 Ma.
- Gibson et al. (2018) note that the high-Fe tholeiites of the SCG and Etheridge Province are more MORB-like than other mafic igneous units of the Mount Isa Province and suggest that they erupted through lithosphere that had breached or was close to breaching.
- Felsic igneous rocks such as the ca 1657 Ma Ernest Henry Diorite and 1654 Ma -1650 Ma Tommy Creek units (microgranite and volcanics, respectively; Figure 1.3) indicate bimodal magmatism during SCG time, typical of continental rifts.
- Seismic data shows the central Numil crust comprises 5-15 km thick slices bound by low-angle faults (Korsch et al., 2012) that preserve a geometry typical of an extensional fault system.
- The high geothermal gradient, 45°C / km, at ca 1605 Ma (Porteau et al., 2018) is interpreted to reflect crustal thinning given the lack of evidence of heat input form other sources (e.g. Giles et al., 2006a).
- Extension is coeval in Western Fold Belt (late Calvert and Sybella Batholith emplacement; e.g. Gordon, 2004; Southgate et al., 2013).

A widespread extensional event focused in the Soldiers Cap Domain initiated at ca 1680-1675 Ma resulting in emplacement of the Sybella Batholith in the west and deposition of Mount Norna Quartzite, and development of iron formation, followed by initial emplacement of high-Fe mafic sills in the Soldiers Cap Domain (Figure 1.3). Inversion ca 1640 Ma in the WFB (Bradshaw and Scott, 1999; Gibson et al., 2018) may have affected the EFB but is not well documented. Tommy Creek magmatism and evidence for a pulse of ca 1630-1625 Ma Toole Creek mafic magmatism (Griffin et al., 2006) coincide with renewed rifting in the WFB (Figure 1.3; e.g. Gibson et al. 2018).

Architecture of highly attenuated crust

Improved imaging of crustal architecture arising from advances in seismic acquisition and imaging over several decades has shown that evidence for hyperextension, extremely thinned continental crust and/or exhumed subcontinental mantle, is common on rifted continental margins (e.g. Iberian margin, Exmouth plateau, Australian-Antarctic margins, West Africa, and mid Norwegian margin), and that the remnants of hyperextended domains can also be found in collisional orogens (e.g. Alps, Pyrenees, and Caledonides; Tugend et al., 2014 and references therein). These hyperextended domains can provide insights into the crustal architecture of the highly attenuated crust during SCG deposition, and its influence on the localisation of compression during the 1610-1500 Ma Isan Orogeny.

Figure 3.7 shows the progression of hyperextension, serpentinisation and detachment faulting on an extended margin (Perez-Gussinye, et al., 2001): 1) As the stretching factor increases and the crust thins (to ~10 km), the upper and lower crust become coupled and embrittled; 2) the brittle faults extend through the entire crust allowing sea water to access mantle; and 3) partial hydration (serpentinisation) of the upper mantle produces a weak zone that forms a detachment, leading to mantle exhumation and crustal separation.

Key observations from rifted margins and remnants of hyperextended domains in collisional orogens include:

- Highly attenuated crust comprises low-angle fault blocks separated by low-angle faults that sole into a detachment and may include isolated extensional allochthons (e.g. Perez-Gussinye, et al., 2001; Peron-Pinvidic and Manatschal, 2010; Masini et al., 2013).
- The most highly attenuated crust is spatially related to the area where more stratigraphy is missing (e.g. the youngest units overlie the detachment fault; e.g. Clerc et al., 2016).
- Syn-rift units vary in areal extent, e.g. the older syn-rift units are less extensive than the youngest syn-rift units and the older syn-rift units can be cut by extensional faults during ongoing extension (e.g. Clerc et al., 2016).
- Although most examples are found on passive continental margins, hyperextension may also occur in an intracontinental rift, or back-arc basin. For example, hyperextension in the Cretaceous Pyrenean-Basque-Cantabrian rift did not progress into a mature oceanic domain (Tugend et al., 2014).
- Competent blocks (or continental ribbons in 3D) result from pre-existing rheological variations in the crust (Peron-Pinvidic and Mantschal, 2010) and strongly influence later collisional processes (Tugend et al., 2014; Cadenas et al., 2018).

Interpretation of SCG and underlying crust

The interpretation of seismic line 07GA-IG1 by Korsch et al. (2012; Figure 3.6) clearly shows the low-angle fault blocks within the Numil basement underlying the SCG. The system of low-angle faults locally preserve extensional offsets (Korsch et al., 2012) despite significant shortening, and sole into a low-angle SW-dipping detachment fault. The structural geometry of the Numil basement is herein interpreted to represent a series of low-angle extensional fault blocks formed (or reactivated) during the 1680-1650 Ma extensional event (compare the structural geometry with Figure 3.7). The present juxtaposition of basement terranes reflects 1610-1500 Ma Isan collisional processes, whereas the hyperextended crust represented by the thin to very thin Numil fault blocks would have been distributed over a wider area and are likely to have been separated, or nearly separated, from the western competent block (and eastern crustal fragments) prior to the Isan Orogeny starting ca 1610 Ma (cf. Cadenas et al., 2018).

The evidence for extension during SCG deposition, the crustal architecture evident from seismic, and insights from other hyperextended terranes have been used to provide the context for the detailed interpretation of the geology and structure of the upper ~10 km of crust in the AOI using integrated interpretation of the seismic and plan view datasets.

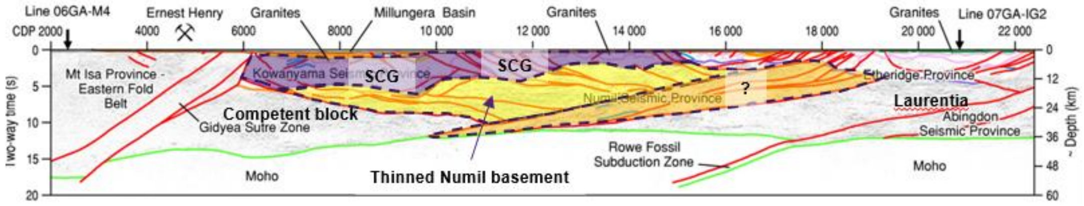
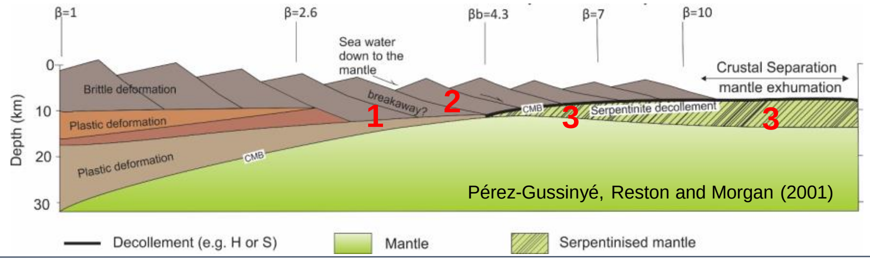


Figure 3.6 (left). Interpretation of 07GA-IG1 modified after Korsch et al., 2012).

Figure 3.7 (Right). Schematic crustal scale cross section depicting the progressive thinning of continental crust, hyperextension, serpentinisation of the mantle and development of a decollement leading to crustal separation.



Chapter 4

Geology and Structure of the Soldiers Cap Group

Introduction

The aim of the simplified seismic interpretations in this report is to provide a working model that is consistent with: 1) outcrop geology; 2) magnetic data; 3) gravity data; and 4) other datasets (radiometrics, ASTER and hyperspectral), and to demonstrate the constraints provided by this dataset. Detailed and accurate interpretation of the seismic data is beyond the scope and budget of this project. However, this dataset provides some fundamental constraints to the interpretation of the solid geology. Therefore a first-pass interpretation has been completed using tiff images of the seismic data. The quality of these images limits the accuracy of the interpretation. Further insights and improved accuracy of the location and geometry of faults and horizons can be achieved using a seismic interpretation software package, and by dedicating a suitable period for this work.

Dip of geological features - outcrop vs seismic

It has been noted that the moderate to gentle dips in the seismic data generally don't match the steeper dips mapped in outcrop. There are a range of factors that can account for this observation.

- Steep features generally do not reflect seismic energy and therefore are not well imaged.
- The upper 0.2-0.5 sec TWT of the seismic data is generally not well imaged making it difficult to directly link seismic features with outcrop.
- In some areas the anomalously shallow dips result from the apparent dip of geological reflectors that are subparallel to the seismic line. The apparent dip of reflections on a single seismic line is likely to differ from the true dip unless the line is perpendicular to the geological feature, e.g. dip of layering. The orientation and dip of features that intersect more than one line can be more confidently interpreted.
- In some outcrop it may be difficult to accurately distinguish bedding from pervasive cleavage, and in the case of the Soldiers Cap Group, the TCV mafic sills may dip more steeply than bedding providing anomalously steep dip information at surface.
- Given that the present outcrop surface is broadly around the brittle – ductile transition, the seismic data will consistently show the underlying ductile zone, whereas many outcrop areas (especially those west of the AOI) are dominated by the overprinting effects of the later Isan events that steepened earlier structures and preferentially developed steep, ductile-brittle and brittle faults.
- In addition, many of the faults appear to be listric in seismic data, and steepen toward the surface. Inversion of listric faults and wedge-shaped, growth packages commonly results in an anticline with an amplitude that decreases or dies out at depth. Both the faults and high amplitude segment of the fold can be further tightened and steepened during later events.

A combination of these factors is likely to be involved to some degree within the EFB, but the *present erosion level* and the effects related to *inversion of listric normal faults and growth packages* are considered two of the major factors in the AOI.

Detailed mapping and integrated interpretation is required to better evaluate and understand the relationships between the steep dips mapped at surface and moderately dipping seismic reflections. Regardless, the seismic data includes packages of well-developed seismic reflections that provide geological information on the subsurface. In general terms, the strong reflections represent well-developed layering with a contrast in acoustic impedance. Within the study area, these reflective packages are interpreted to represent: 1) sedimentary layering (i.e. bedding or modified bedding); 2) structural zones (e.g. low-angle detachment faults); and 3) sills or basalts (e.g. the abundant high-Fe tholeiites of the Toole Creek Volcanics).

Seismic line 94MTI-01

The eastern half of seismic line 94MTI-01 was interpreted by Murphy et al. (2017) as part of their 3D analysis during the DMQ project (Figure 4.1). The seismic data shows moderate dips within the Mitakoodi Culmination. Most faults dip moderately to the east and are not vertical at the scale of the upper crust as interpreted by other modelling (Murphy et al., 2017). The late, steep Cloncurry Fault (CF) is well defined by stratigraphic truncations and a change in dip on 06GA-M6 to the south (Figure 3.3) but dies out to the north as shown by the minimal offset on 94MTI-01 (Murphy et al. 2017). West of the Cloncurry Fault, the broadly sub-horizontal detachment faults between the Staveley and the Answer Slate in the Marimo-Staveley area (highlighted in white on the seismic line) has been folded by N-S D2 folds and cut by younger D2 faults. The New Hope and Kuridala formations, equivalent to the Mount Norna and Llewellyn Creek formations are both absent. These structures were interpreted as D1 thrusts but are interpreted here as a set of extensional detachment faults and referred to as the Staveley detachment fault system (refer to stratigraphy section in the Introduction). The Cloncurry Thrust (CT) is mapped just west of the Cloncurry Fault and is interpreted as a D1 thrust fault by Murphy et al. (2017) and as an extensional fault related to the Staveley detachment fault system in this project. The Staveley detachment (SD) is shown to dip to the east beneath the Soldiers Cap Domain where the complete SCG stratigraphic section is mapped in outcrop just south of the seismic line, although the base of the LCF is not exposed. The eastern segment of seismic line 94MTI-01 is interpreted in further detail on the following pages.

The area east of the Cloncurry Fault was largely outside the project area for the DMQ project, and the existing solid geology was used to constrain the seismic interpretation. Detailed integration of seismic and plan view datasets during this project has resulted in significant new insights on the geology and structure of the upper ~10km of the SCG in the Soldier Cap Domain. Most significantly the network of early extensional faults has been mapped for the first time.

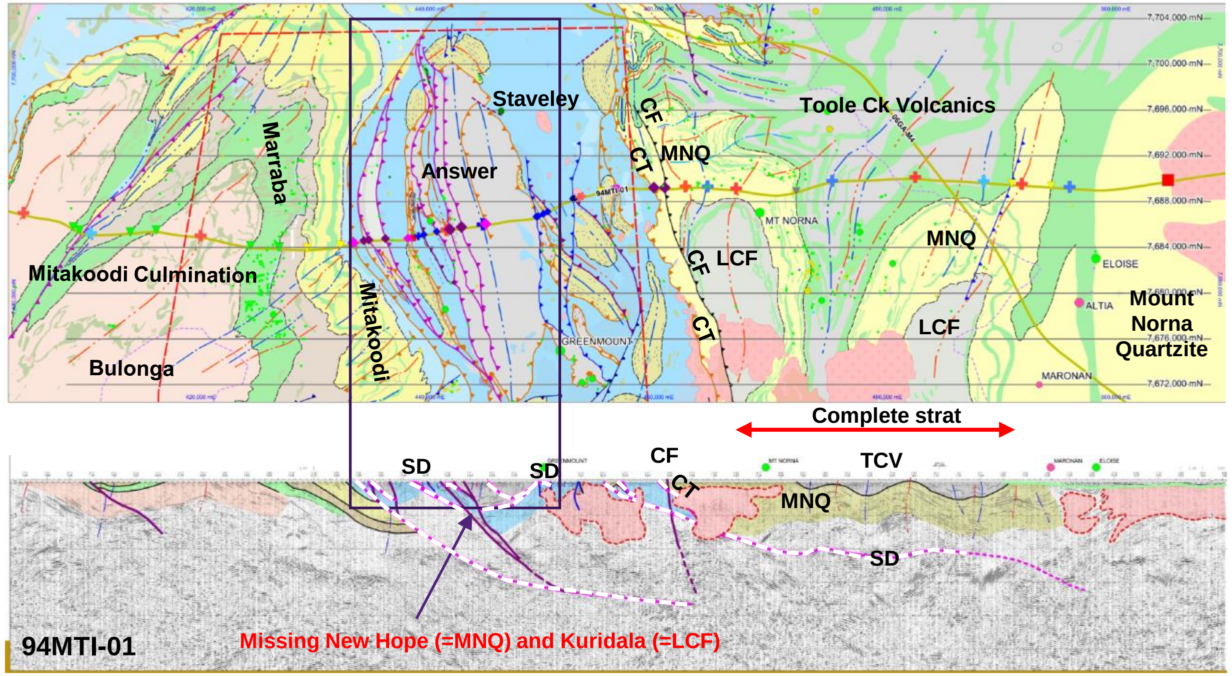


Figure 4.1. Detail of interpreted segment of 94MTI-01 and plan view geology from DMQ project (Murphy et al., 2017).

Seismic in the AOI

The assessment of the regional crustal architecture and nature of the SCG extensional event outlined in the previous section provide the context and setting for interpretation of the geology and structure of the SCG within the upper crust. Integrated interpretation of the 3 seismic lines with the large range of plan view datasets has been used to constrain the interpretation at depth and to better assess the 3D architecture of the SCG extensional fault system. Figure 4.2 shows the regional extent of the different basement terranes from the assessment of the regional seismic lines. The interpreted extent of each basement terrane along the seismic lines is shown by the different colours with the competent block in white, the highly reflective Numil crust in yellow, and the Mount Isa crust in purple. The approximate *surface location* of the Gidyea "Suture", or equivalent structure, is shown in pink. Note that the near surface continuation of the Gidyea "Suture" in the south lies within the SCG units. This structure marks the boundary between the Numil and Mount Isa at depth within the crust (e.g. see Figure 3.3).

Figure 4.3 shows the approximate location of the underlying basement terranes in the AOI. The extent of the competent block is not well defined so its limit is approximate on line 06GA-04. The wedge of Numil crust on 06GA-04 pinches out close to ~12000 CDP, whereas the Numil crust with its strong ~west dipping reflections extends along the full length of 06GA-05. It is thrust beneath the Mount Isa Crust to the west (Figure 3.3). These underlying basement terranes and their boundary zones provide one of the fundamental controls on upper crustal geology and structure of the SCG sediments.

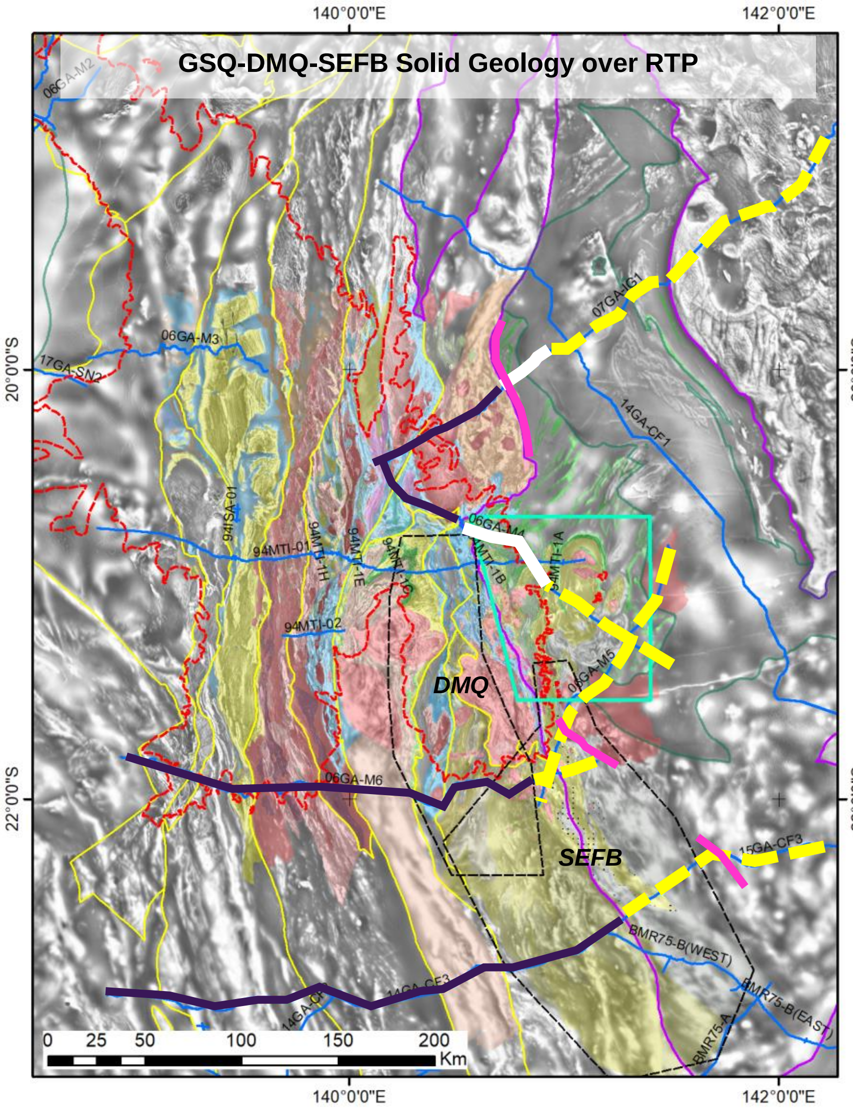


Figure 4.2. The regional scale extent of the highly reflective Numil crust, the competent block, and the location of the Gidyea Suture are highlighted in yellow, white and pink respectively. These features are overlain on the solid geology interpretation from the DMQ-SEFB projects (with partial coverage of GSQ solid geology to west and north) with RTP in the background (AGC 200 and Tilt). The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. Mount Isa Province domains are shown in yellow with Soldiers Cap Domain highlighted in purple (Australian Geological Provinces dataset). The seismic lines are in blue.

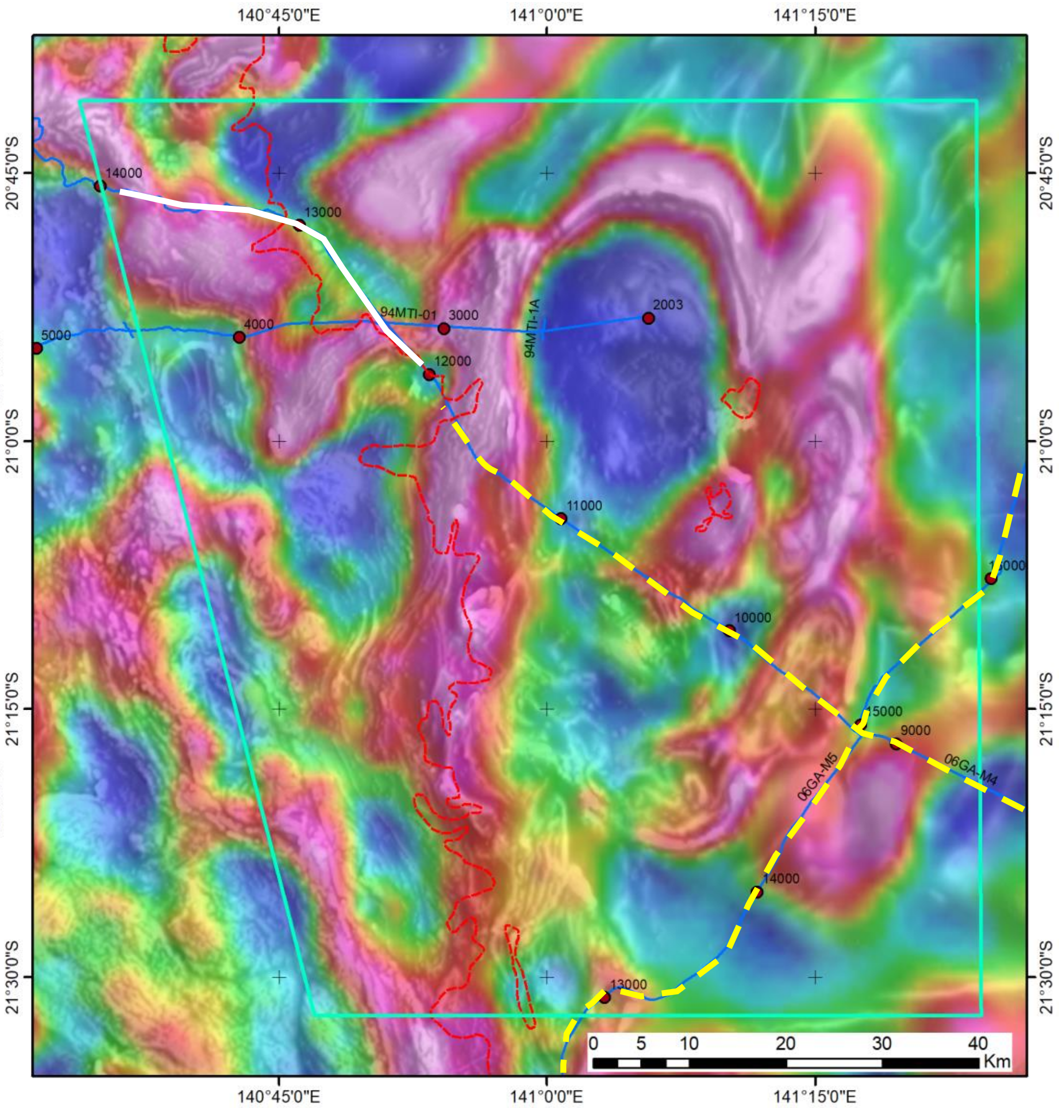


Figure 4.3. Approximate extent of the highly reflective Numil crust, the competent block overlain on an image combining the gravity (HP40 km of Bouguer) and magnetic data (RTP - AGC 200 and Tilt). The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. Mount Isa Province domains are shown in yellow with Soldiers Cap Domain highlighted in purple (Australian Geological Provinces dataset). The seismic lines are in blue with CDP points shown.

Seismic line 94MTI-01

Figure 4.4 shows the pre-2019 solid geology map in a band along seismic line 94MTI-01 and provides a simplified interpretation of the main features of the seismic line. Although outcrop mapping indicates fairly steep dips across the Snake Creek and Weatherly Creek folds, the seismic data is dominated by moderate dips from ~0.5-1 sec TWT or 1.5-3 km depth (as discussed in the introduction to this section). The main trends of packages of reflections are highlighted in purple for the upper 2 sec TWT (5-6 km) and red for deep packages.

- The reflective packages are folded and are cut by dominantly east-dipping faults. Antiformal folds are evident in the data roughly coinciding with the Snake Creek and Middle Creek anticlines, although the dips are shallow to moderate. The eastern limb of the Snake Creek anticline shows west-dipping reflections which imply the presence of significant faults. NNE-trending faults that control changes in unit thickness have been recognised in outcrop in this area (Hatton, 2004) and steep east dips are recorded east of CDP 4000 suggesting some complications to the anticline.
- The Weatherly Creek syncline which appears well defined in outcrop, magnetic and radiometric datasets, is not immediately obvious in the seismic data where it appears to be a relatively small, faulted syncline. More significantly the map view implies that the broad Weatherly Creek syncline should have thick limbs that dip towards its core, whereas the seismic data shows a faulted structure that is broadly antiformal (between ~3400 and 4000 CDP).
- The Cloncurry Thrust (CT) and other faults of the Staveley detachment fault system (shown in blue) dips east beneath the Snake Creek anticline. The strong reflective package beneath the detachment (SD) is interpreted as Staveley Formation (ST) and may include other older units such as the Mitakoodi, Marraba and Bulonga sequence (ST+). All of these units are strongly reflective on seismic line 06GA-M6 (Figure 3.3 above; Murphy et al., 2017). Folding in the upper 2 sec does not extend below ~2 sec indicating that the Staveley detachment continues beneath the Weatherly and Middle creek folds. The late, steep Cloncurry Fault (CF) dies out to the north and appears to merge into, or die out above, rather than offset the east-dipping CT (part of Staveley detachment).
- The granite in the core of the Kevin Downs anticline is defined by a ~0.8 sec TWT thick (~2-2.5 km) zone of poor reflectivity. Gravity modelling suggests the presence of granites in the core of the Snake Creek anticline and to the west of the Cloncurry Fault within the Staveley Formation (Murphy et al., 2017). Note that the two small intrusions in the Snake Creek anticline are smaller than the DMQ interpretation (Figure 4.2), and are limited by the strongly reflective packages interpreted as SCG sediments and mafic sills.

Interpretation: Although the seismic data does not show the steep dips mapped in outcrop, it does show clear packages of reflections that provide geological data. The seismic data shows a set of anticlines (3-4 km wavelength) separated by dominantly east-dipping faults (Figure 4.4) differs from the three large folds mapped at surface. In cross section view on the seismic line, these faulted anticlines are typical of a set of inverted normal faults. Shortening of a wedge-shaped growth package against a normal fault results in an anticline adjacent to the fault and a much smaller or no syncline. The extensional fault system is interpreted in more detail in Figure 4.5.

The seismic line is parallel to the strike of layering within the core of the Snake Creek Anticline; hence shallow dipping reflections are expected

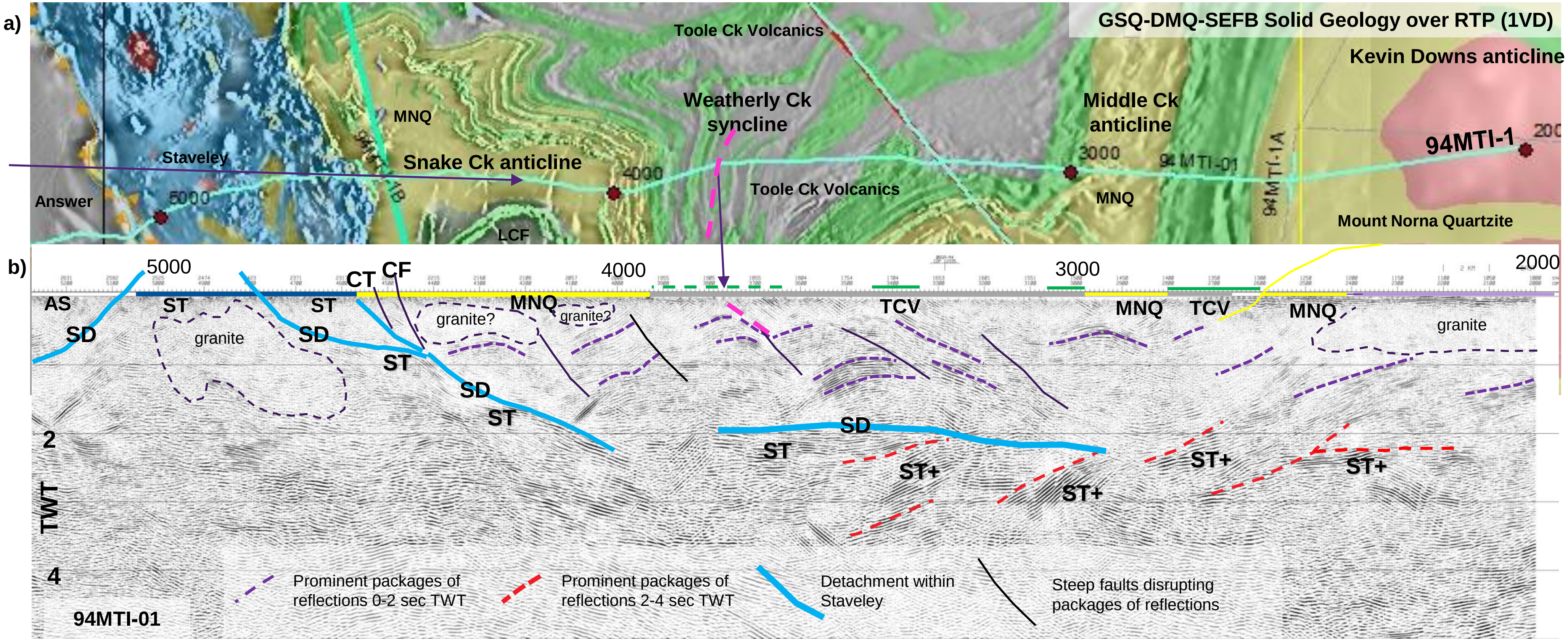


Figure 4.4. a) The strip map shows the solid geology interpretation prior to this project in order to highlight the large scale mapped folds. See Figure 2.1 for geological legend and details on sources of the data.
b) Simplified interpretation of seismic line 94MTI01.

Seismic line 94MTI-01 with extensional faults

Figure 4.5 shows the new solid geology map and a slightly more detailed interpretation of 94MTI-01 with the extensional faults in blue. The approximate position of the MNQ-TCV (yellow) contact is shown to highlight the fold geometry. Several zones where interpretation of the dip of the MNQ-TCV surface is not clear, or there is conflicting information, are highlighted by a "?".

- Faulting is required in order to account for the west-dipping reflections (stratigraphy?) on the east limb of the Snake Creek anticline (SCA; ~4000 CDP). The MNQ-TCV contact is reasonably well exposed and stratigraphy appears roughly parallel and consistent along its length precluding significant faulting on the contact. Therefore a NNE fault mapped in outcrop and another fault interpreted from seismic and magnetics can account for these changes in dip. West of CDP 4000, 75-80° west dip is documented for strata with unknown facing, indicating some variations from the expected east dips.
- The reflections within the TCV on the east limb of the Weatherly Creek syncline dip to the east. Therefore faulting is required in order to maintain the accepted stratigraphic relationship with TCV overlying MNQ within the Middle Creek anticline (MCA). The gravity data (Figure 4.3) shows distinct and sharp changes indicating significant variations in the thickness of the mafic units of the TCV in this region. Some of these faults strike NW and are interpreted as steep, transfer faults.
- Another tight faulted syncline is localised within the TCV (black oval) between the MCA and KDA, along strike of the Levuka trend and the Eloise deposit. Data from the Eloise mine indicate near vertical dips to ~1000m below surface (Baker, 1998; Hodkinson et al., 2003), whereas seismic data indicates moderate to shallow dips from ~0.6-0.8 sec TWT or 1.5-2.5 km depth.
- The MNQ and/or TCV are interpreted to thicken into several faults based on integrated interpretation of all the available data. These are indicated by "#".
- The interpreted MNQ-TCV boundary shown in yellow, broadly matches the major folds mapped in outcrop and interpreted by previous workers: Snake Creek anticline (SCA), Weatherly Creek syncline (WCS), Middle Creek anticline (MCA) and Kevin Downs anticline (KDA). Note however, that the geometry is dominated by anticlinal folds and the synclines are minor features controlled by faults. The broad WCS can be considered as a down-faulted zone of TCV controlled by early extensional faults. The gravity data (Figure 4.3) suggests the presence of a thicker sequence of mafic igneous units on the eastern limb of the WCS.
- Detailed outcrop mapping is required to test this interpretation and better understand the relationships between the seismic data and outcrop geology. In part the steep dips at surface are interpreted to result from disharmonic folding above detachment faults and inverted listric normal faults.

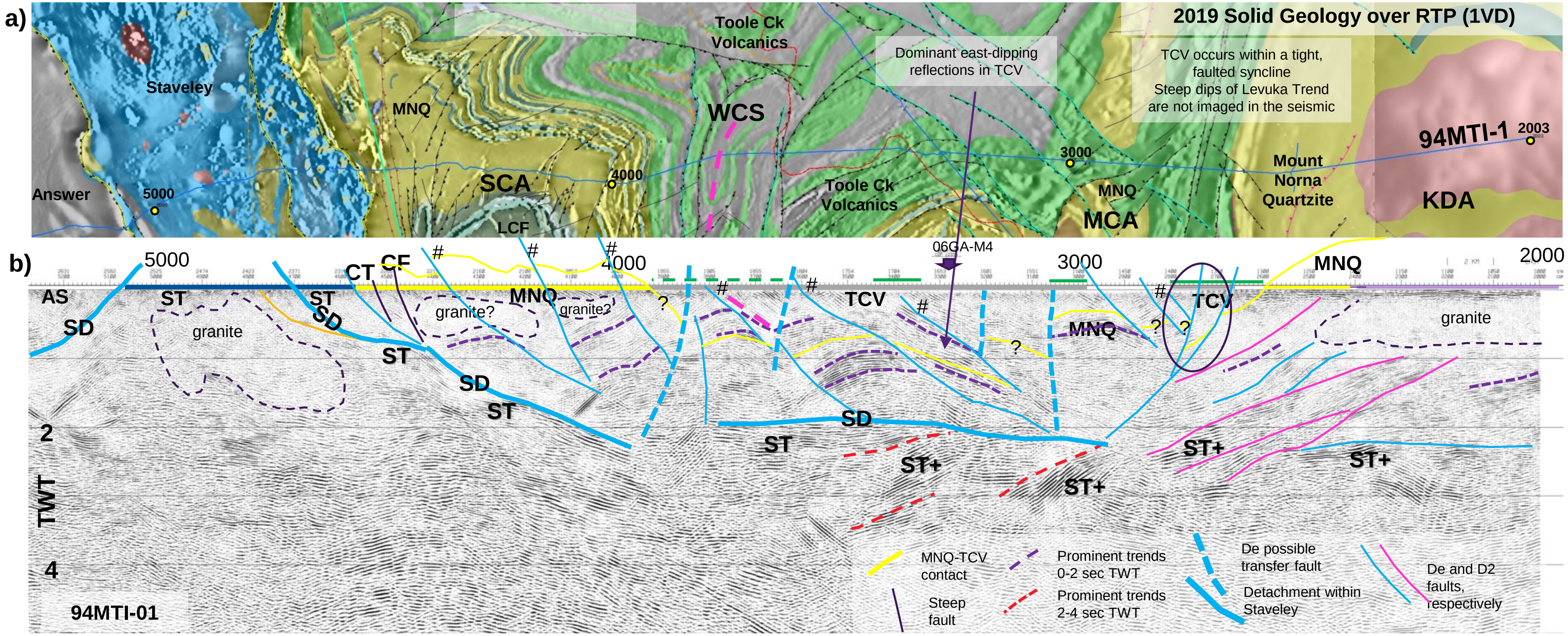


Figure 4.5. a) The strip map shows the updated solid geology interpretation from this project in order to highlight the modified interpretation of the large scale mapped folds. See Figure 5.1 for geological legend.
b) Simplified interpretation of seismic line 94MTI01 highlighting the location of the extensional fault system in blue. These faults are interpreted to have been active during SCG deposition, especially the MNQ and TCV. The approximate location of the boundary between the MNQ and TCV is shown in yellow. The aim of this interpretation is to provide a working model the fits with: 1) outcrop geology; 2) magnetic data; 3) gravity data; and 4) other datasets such as radiometrics, ASTER and hyperspectral data that map geological units in areas with sparse cover.

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Seismic line 06GA-M4

Figure 4.6 provides a simplified interpretation of seismic line 06GA-M4 and the inset map shows the extent of the seismic line depicted in the image. Seismic reflections are well developed in the southeast (Breena area) where the seismic line is at a high angle to the strike of the geologic units and structures. Strong reflections are also present on the northwest end of this segment. It is unclear why seismic reflections are not well developed in the central segment around Middle Creek.

- The Staveley detachment fault outcrops just to the west of the segment shown here, with TCV over Staveley Formation. The SE-dipping detachment is well defined by dipping reflections from surface to ~2 sec TWT. The detachment flattens at around 2 sec TWT time and continues beneath the Middle Creek anticline (MCA) as on 94MTI-01, although reflections are not as well developed. The detachment does not appear to extend beneath the Levuka Trend (or on 94MTI-01; Figure 4.5), but it is difficult to be certain due to the lack of strong reflections.
- The MNQ and/or TCV are interpreted to thicken into several faults based on integrated interpretation of all the available data. These are indicated by "#".
- The reflections within the TCV on the east limb of the Weatherly Creek syncline dip to the east or southeast, as confirmed on 94MTI-01. As discussed for 94MTI-01 faulting is required in order to maintain the accepted stratigraphic relationship with TCV overlying MNQ. Several geometries can be considered but thrust reactivation on early extensional faults is most consistent with all the available data. Other options include local overturned stratigraphy on a fold limb, regional overturned stratigraphy in a large nappe, or a range of fault orientations are possible as the geometry of the core of the MCA is not constrained by the seismic data. The steep faults affecting the MCA on 94MTI-01 are parallel to this line.
- The interpreted MNQ-TCV boundary shown in yellow, broadly matches the major folds mapped in outcrop and interpreted by previous workers: The Middle Creek anticline (MCA) appears as a "pop-up" bounded by reactivated normal faults. In both this line and 94MTI-01 this antiform marks a reversal of the dominant dip of stratigraphy and faults. The seismic line crosses the southern end of the Kevin Downs anticline (KDA) which is not as well developed at this location as it appears to be from magnetic data around its northern end. Two anticlines bounded by faults are evident at the SE end of the seismic image and in plan view data. Similar to 94MTI-01, the broad WCS can be considered as a down-faulted zone of TCV controlled by reactivation of extensional faults. The gravity data suggests the presence of a thicker sequence of mafic units in this later area.
- Figure 3.5 shows the full seismic line to 20 sec TWT and highlights the three basement terranes: the wedge of reflective Numil crust in the southeast, the central competent block, and the thicker Mount Isa Province crust (west of the segment shown below). The zone of west-dipping stratigraphy and faults east of the KDA marks a distinct change in structural style and is spatially related to the western limit of the wedge of Numil crust. The extent of the underlying Numil crust and its dominant west-dipping structures (Figure 3.6) have controlled the development of structures in the overlying crust during Isan shortening. The flat-lying Staveley detachment fault is well developed within the segment of 06GA-M4 which overlies the central competent block (Figure 3.5).

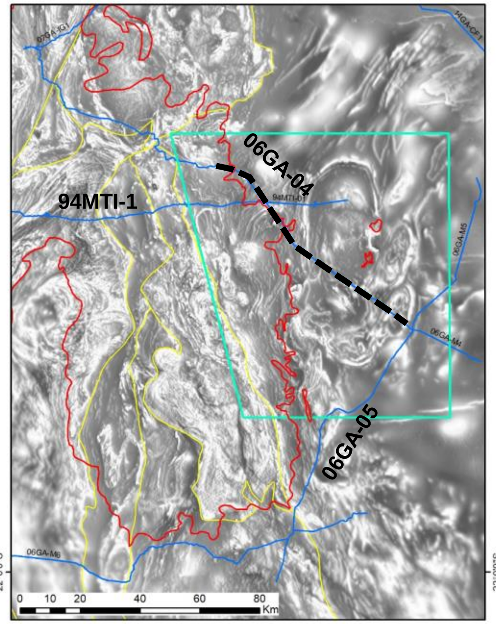
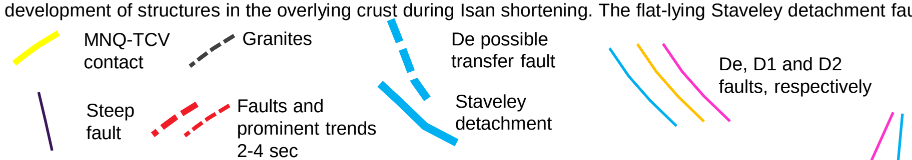
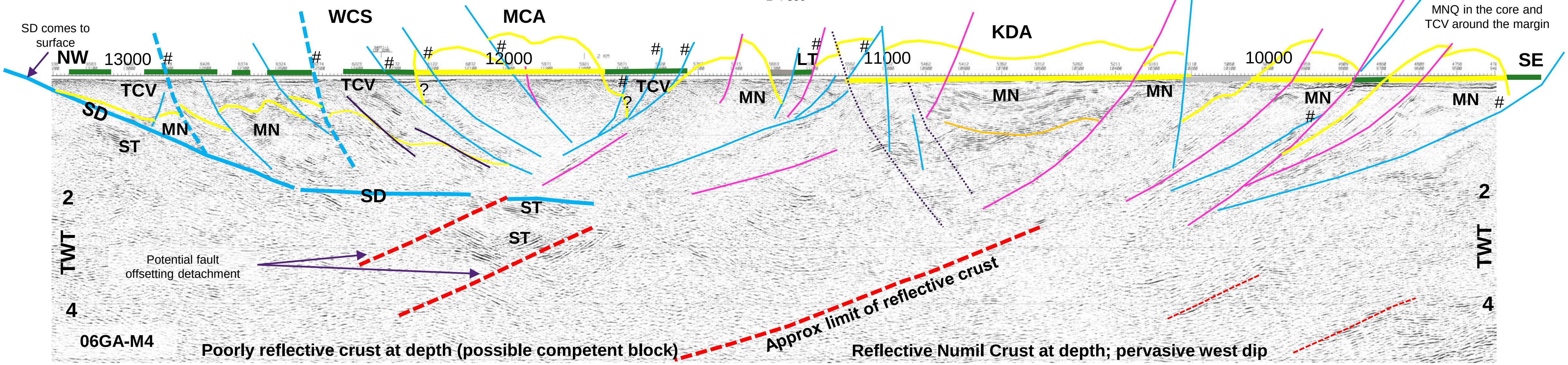


Figure 4.6. Simplified interpretation showing part of seismic line 06GA-M4 highlighting the location of the extensional fault system in blue. These faults are interpreted to have been active during SCG deposition, especially the MNQ and TCV. The approximate location of the boundary between the MNQ and TCV is shown in yellow. The aim of this interpretation is to provide a working model the fits with: 1) outcrop geology; 2) magnetic data; 3) gravity data; and 4) other datasets such as radiometrics, ASTER and hyperspectral data that map geological units in areas with sparse cover.





THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Seismic line 06GA-M5 southwest segment

Figure 4.7 shows a simplified, first-pass interpretation of the SW end of seismic line 06GA-M5 and the inset map shows this extent. Although this segment of the seismic is largely outside of the AOI, it provides key information on the geometry of units in a NNW-trending belt extending into the project area. Well developed seismic reflections in the upper ~4 sec TWT constrain the dip of the major structures and stratigraphy. Correlation between this line and 06GA-M6 improves interpretation of both lines.

- The Staveley Formation outcrops in an antiformal closure just north of the seismic line, and magnetic data suggests this structure continues south to intersect the seismic line (e.g. Hinman et al., 2018). The Staveley Formation and overlying MNQ are interpreted to be separated by a D1 thrust fault in the southern EFB solid geology project (Hinman et al., 2018), but this structure is herein interpreted as the Staveley detachment fault (SD). The folded units are well imaged in the seismic data. This anticline is interpreted as D2 (Hinman et al., 2018) and it sits in the hangingwall of a well-imaged, west-dipping fault zone. The east-dipping stratigraphy on the eastern limb of the D2 anticline is disrupted by a set of W-dipping faults interpreted as splays on the main fault. Given that this west dipping fault system disrupts this D2 fold, it should nominally be late D2 or younger. However, this main west-dipping fault system is interpreted to have initiated during extension given that it represents the limit of the Numil Province that was highly attenuated during SCG extension. It also may represent the near surface projection of the “Gidyea Suture”.
- Seismic reflections are not well-developed in the upper few km around the Cannington orebodies and their altered halo, 1.5 km to the west of the seismic line. The orebodies dip 50° toward 105° (down-dip extent of up to 750m) and 35° towards 150° (down-dip extent of up to 900m; Hinman et al., 2018), at a high angle to the very well-developed, west-dipping reflections (CDP 11000) that lie to the east and below Cannington. This implies a structural discontinuity between the orebodies and this package of reflections within the Mount Norna Quartzite (MNQ).
- The outcrop geology and seismic line indicate that the MNQ is thicker than >2 sec TWT, or ~6 km, at ~CDP10500, and may be up to ~3-4 sec TWT if the units continue at a similar dip. The estimated MNQ thickness from outcrop in the Snake Creek area is 2.7-3.5 km (Hatton, 2004; Giles et al., 2006a). Seismic line 06GA-M6 (Figure 3.3) similarly shows MNQ to over ~2 sec TWT adjacent to the Cloncurry Fault. The marked thickness of the MNQ along its southern extent, suggests that the Cloncurry Fault was active during SCG deposition in agreement with other workers (e.g. Queensland Dept Mines and Energy et al., 2000; Austin and Blenkinsop, 2008; 2010; Donchak and Clark, 2015). The fault is likely to have been reactivated several times and late movement is indicated by offset of the ca 1520-1500 Ma Williams suite intrusions (e.g. Austin and Blenkinsop, 2010).
- Although late faulting is evident at CDP 13100-13200 (minor changes in depth of magnetic units), the significant changes in geology to the north of the seismic line indicate the presence of an older more significant fault, interpreted here as a transfer fault during SCG extension. For example, many units and structures cannot be correlated, or are difficult to correlate, across this fault zone in the area between 06GA-M5 and 06GA-M4.

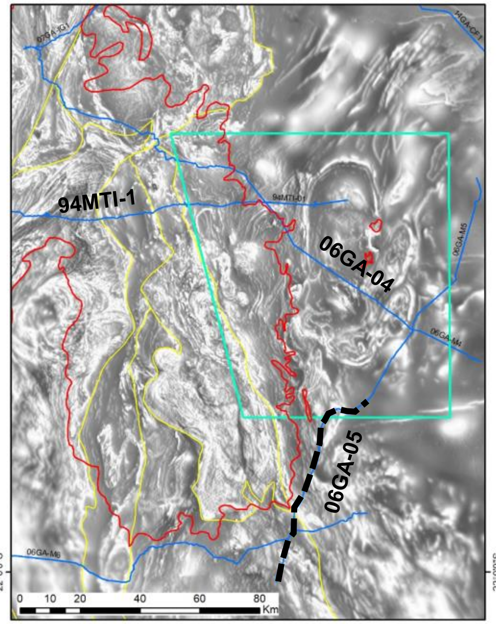
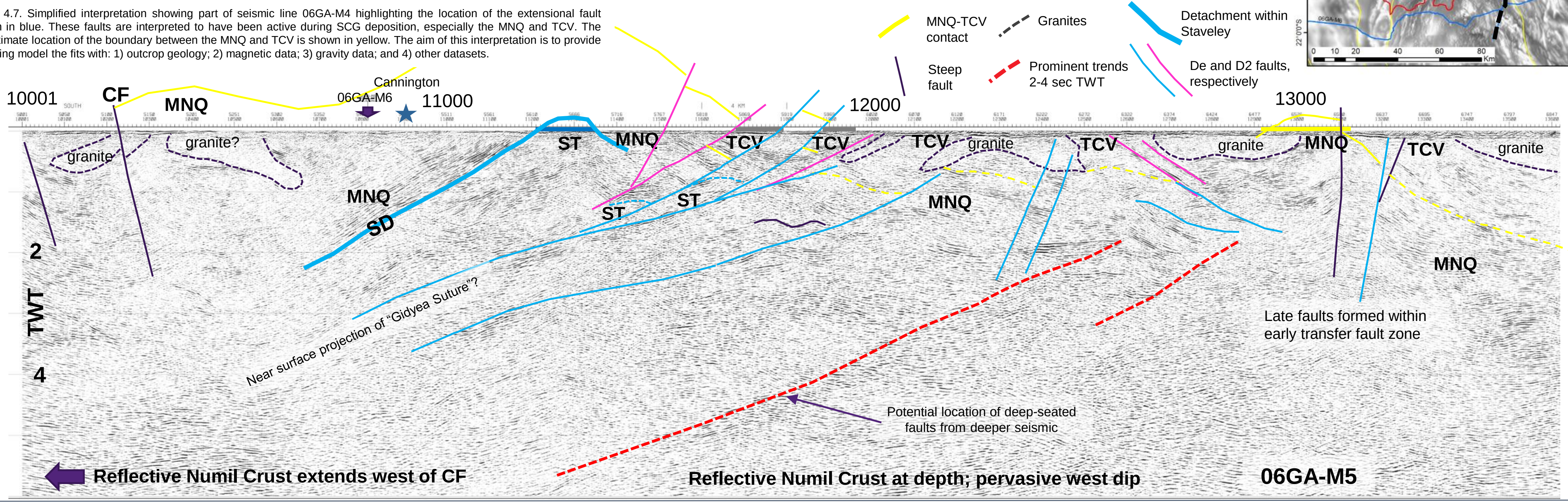


Figure 4.7. Simplified interpretation showing part of seismic line 06GA-M4 highlighting the location of the extensional fault system in blue. These faults are interpreted to have been active during SCG deposition, especially the MNQ and TCV. The approximate location of the boundary between the MNQ and TCV is shown in yellow. The aim of this interpretation is to provide a working model the fits with: 1) outcrop geology; 2) magnetic data; 3) gravity data; and 4) other datasets.



Chapter 5

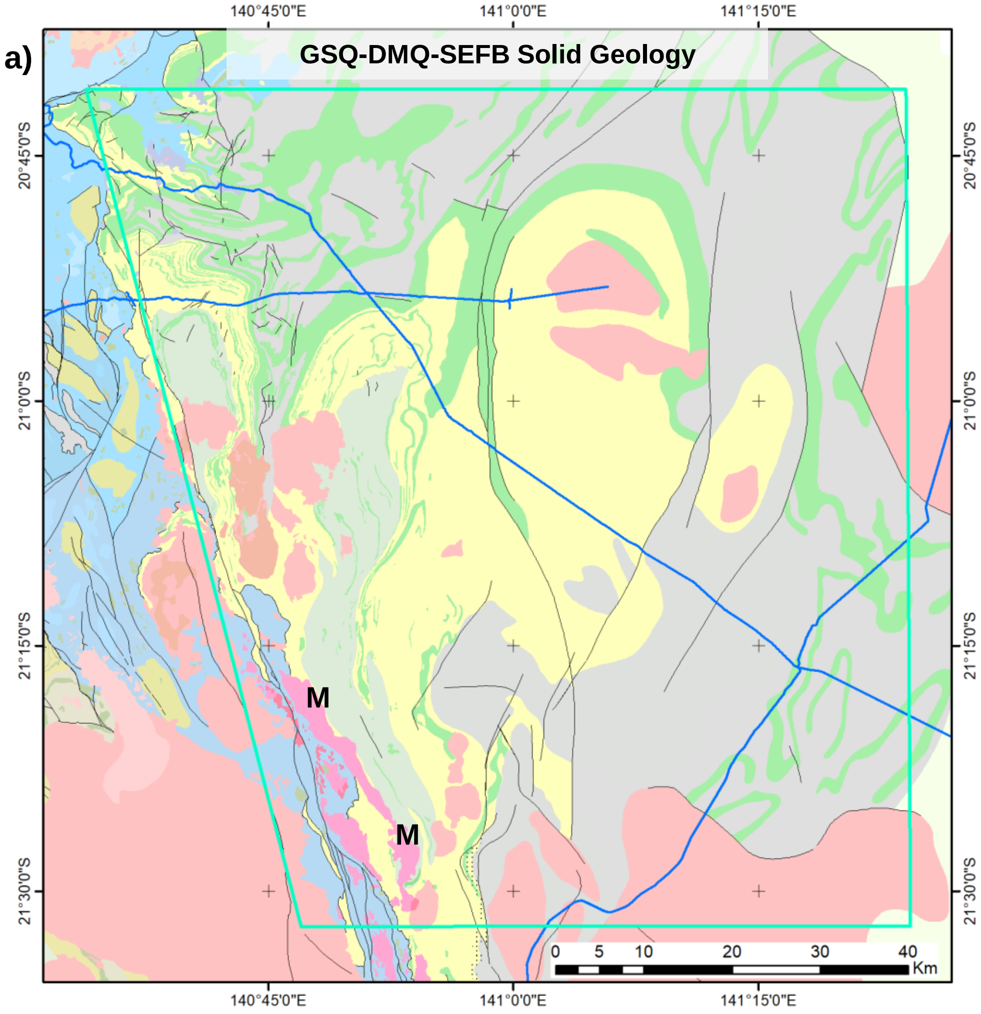
Solid Geology Interpretation

5.0 Solid Geology Interpretation

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

Introduction

Figure 5.1a shows the GSQ-DMQ-SEFB solid geology interpretation that formed the starting point for this project. It comprises work of the Geological Survey of Queensland, the Deep Mining Queensland project (DMQ; Murphy et al., 2017), and the Southern Eastern Fold Belt (SEFB; Hinman et al., 2018). The aim during the interpretation process has been to remain largely consistent with the interpreted outcrop geology. Although the LCF, MNQ and TCV are distinctive in areas where the entire sequence is exposed (north of ~21°S), the main rock types overlap and a smaller outcrop or belt of outcrops may not be easy to distinguish. Distinction of the three main units south of ~21°S is further complicated by the higher metamorphic grade, significantly higher strain in the Maramungee region (M), and variable outcrop quality. Several questions have been outlined in the Introduction above and are discussed in this section. Figure 5.1b shows the 2019 solid geology interpretation for comparison.



Legend

- Metadolerites
- Toole Ck / Millungera

Intrusives
- Williams Suite
- Saxby Suite
- Maramungee Suite

Toole Creek Volcanics
- Dolerite sills
- Basalt, Dolerite, Metased
- Metased/minor mafics

Mount Norna Quartzite
- Metased/dolerites
- MNQ non-magnetic

Llewellyn Creek Fm
- Metasediment

Roxmere Quartzite
- Roxmere Quartzite

Staveley Formation
- Breccia
- Metasom. carbonates
- Guilded Rose Breccia

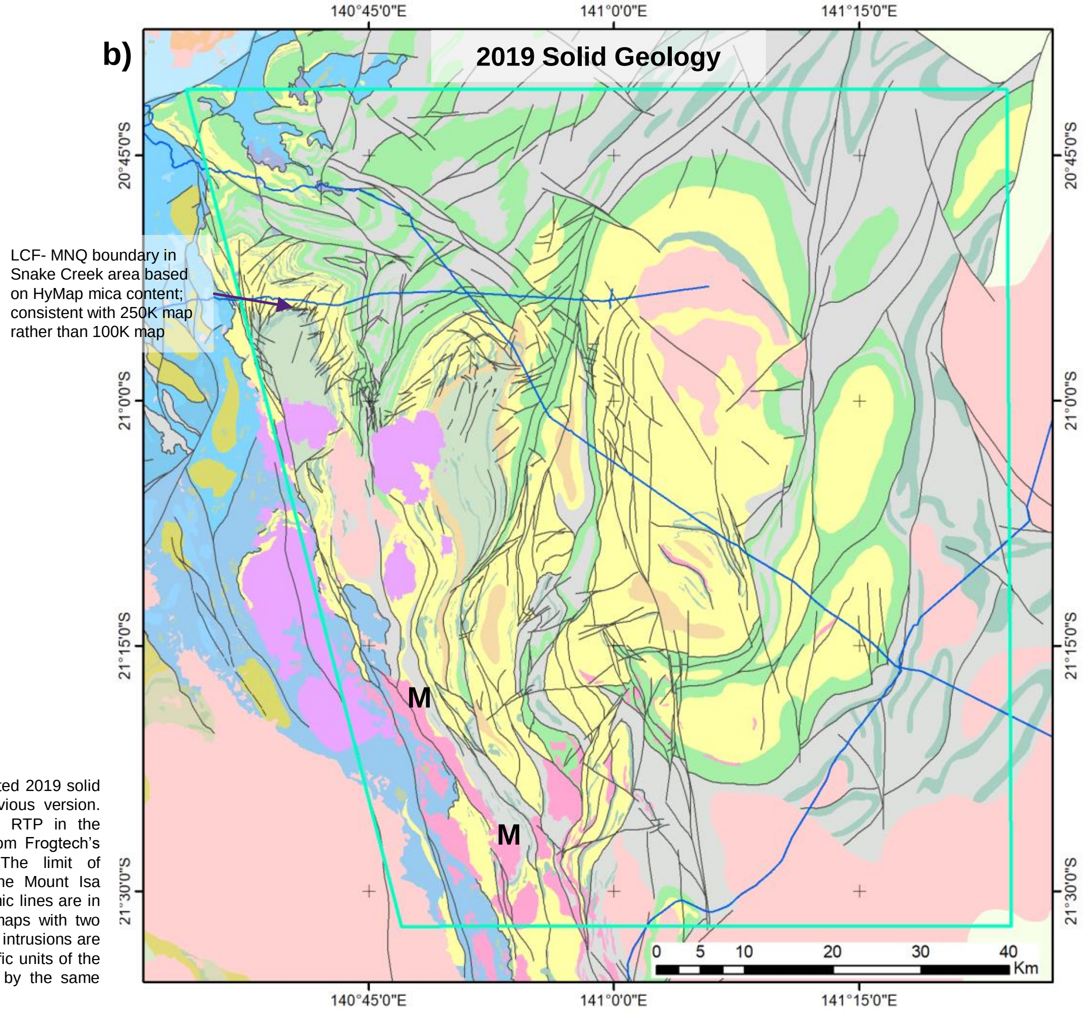


Figure 5.1. Comparison of the updated 2019 solid geology interpretation and the previous version. Transparent, grey scale image of RTP in the background (AGC 200 and Tilt) from Frogtech's 2018 NWQ SEEBASE project. The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. The seismic lines are in blue. The legend applies to both maps with two exceptions. The Williams and Saxby intrusions are coloured by composition and all mafic units of the Toole Creek Volcanics are shown by the same colour in "a".

5.0 Solid Geology Interpretation

Questions in areas of outcropping geology

It is recommended that several outcrop areas be assessed in further detail to confirm the stratigraphic units if possible. Numbers on Figure 5.2 correspond to the following features:

1. The gravity data (Figure 5.3) suggests that the ~N-S band of TCV that crosses the 94MTI-01 and 06GA-M4 seismic lines east of the outcrop limit, continues to the south as a very narrow band within units previously mapped as MNQ. This area is discussed further on the following page.
2. The gravity data also indicates the presence of higher density units in a N-S band in the Garnet Creek – Bluff Creek permit area on the edge of outcrop and just under cover. These units were previously interpreted as MNQ, rather than TCV.
3. LCF south of 21°15’S – the GSQ solid geology map interprets an elongate unit of LCF extending south to ~21°30’S based on the outcropping units that are dominantly pelitic (Figure 5.1a). Correlation of units across the Saxby granite (S) and structural geometry (from seismic data to the south and north) has lead to questions on this interpretation.
4. The TCV may be present along the western and eastern margins of the Foxes Creek intrusion (FC) and continue to the south based on the hyperspectral and radiometric data.

These areas and a few additional ones are discussed on the following pages.

Features of interest undercover

Several features interpreted in the covered areas are highlighted here and discussed below.

a. The folds in the Breena permit area are well defined by both the magnetic and gravity datasets, and seismic data shows that they are antiformal. The drill data indicate that MNQ forms the cores of the folds and is overlain by the mafic-dominated basal unit of the lower TCV (including basalt and graphite-bearing metasediments).

b. The basal TCV is also interpreted to be at the top of basement in the Box Creek area (BC) based on the gravity and magnetic response. The one available drillhole in this anomaly confirms the presence of volcanic rocks (presumably mafic but not specified). The structural geometry and magnetic data indicate that the basal TCV and upper MNQ may come to top basement again to the NE of Box Creek (BC2 on Figure 5.2). Although this folded magnetic anomaly lies on the edge of a positive gravity anomaly, the overall gravity is distinctly lower than that of the Box Creek and Breena areas (see Figure 5.3). This may indicate that an upper stratigraphic level of the TCV is at the top of basement, that the mafic units of the basal TCV are thinner here, and/or that adjacent granite bodies extend into this area. Note that the high resolution magnetic datasets do not cover the northeast corner of the AOI (Figure 2.3). The Mesoproterozoic Millungera Basin (green dashed line; Figure 5.2) obscures the magnetic response of the SCG northeast of Box Creek, but the Toole Creek Volcanics (and local MNQ) are interpreted to continue to the east beneath the basin edge.

c. The near surface geology across the north and the east of the AOI, is interpreted to comprise TCV similar to the GSQ solid geology. The magnetic data shows distinct folded magnetic units that are interpreted as sills within the metasediments. The magnetic pattern gives the impression that the mafic units are less abundant in this region. This may in part reflect the fact that the stratigraphy appears subhorizontal or shallowly dipping in contrast to steeper dips in the outcrop area.

d. The older SCG units are exposed or near surface in the west of the AOI and the eastern region appears to be dominated by TCV with a shallow dip as discussed in the previous point. The exposure of older units in the west results from localisation of strain and uplift along the boundary between the Mount Isa and Numil basement terranes. But may also reflect a greater thickness of the Toole Creek Volcanics to the east of the AOI where seismic data suggest the SCG is up to 15km thick (e.g. Korsch et al., 2012; Donchak and Clark, 2015).

e. Seismic data and gravity modelling indicate that the large intrusions of the Williams-Naraku suite form thick, subhorizontal bodies (Korsch et al., 2011; Murphy et al., 2017); e.g. intrusions to the east and within the Kevin Downs anticline (KDA).

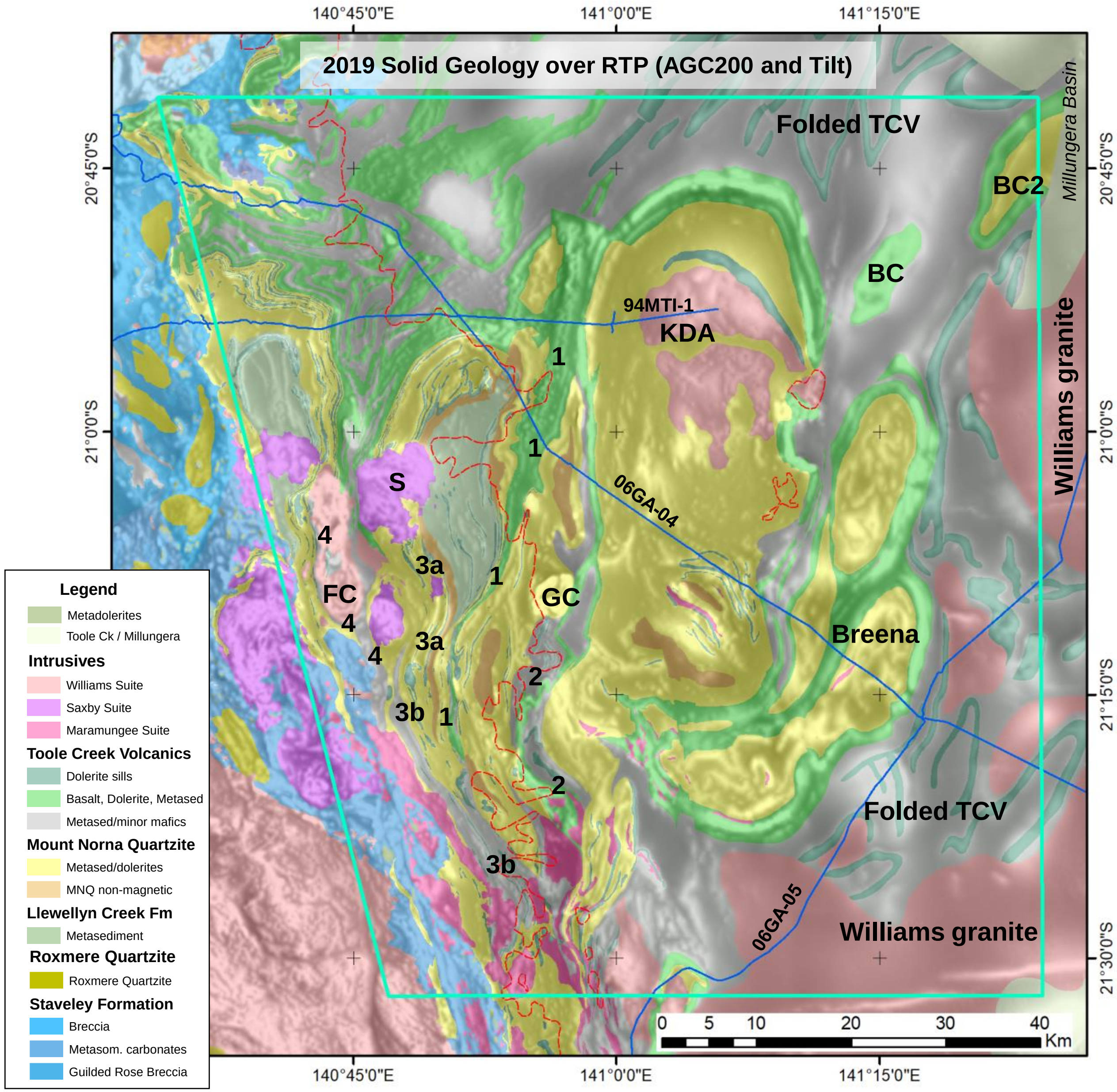


Figure 5.2. 2019 solid geology interpretation overlain on transparent, grey scale image of RTP (AGC 200 and Tilt) from Frogtech’s 2018 NWQ SEEBASE project. The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. The boundary of the Soldiers Cap Domain is shown in purple, and the overlying Millungera Basin is in dashed green (Australian Geological Provinces dataset). The seismic lines are in blue. Numbers indicate areas referred to in text. FC = Foxes Creek granite, GC = Gold Creek magnetic anomaly; BC = Boxes Creek; KDA = Kevin Downs anticline; S = Saxby granite.

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Gravity data

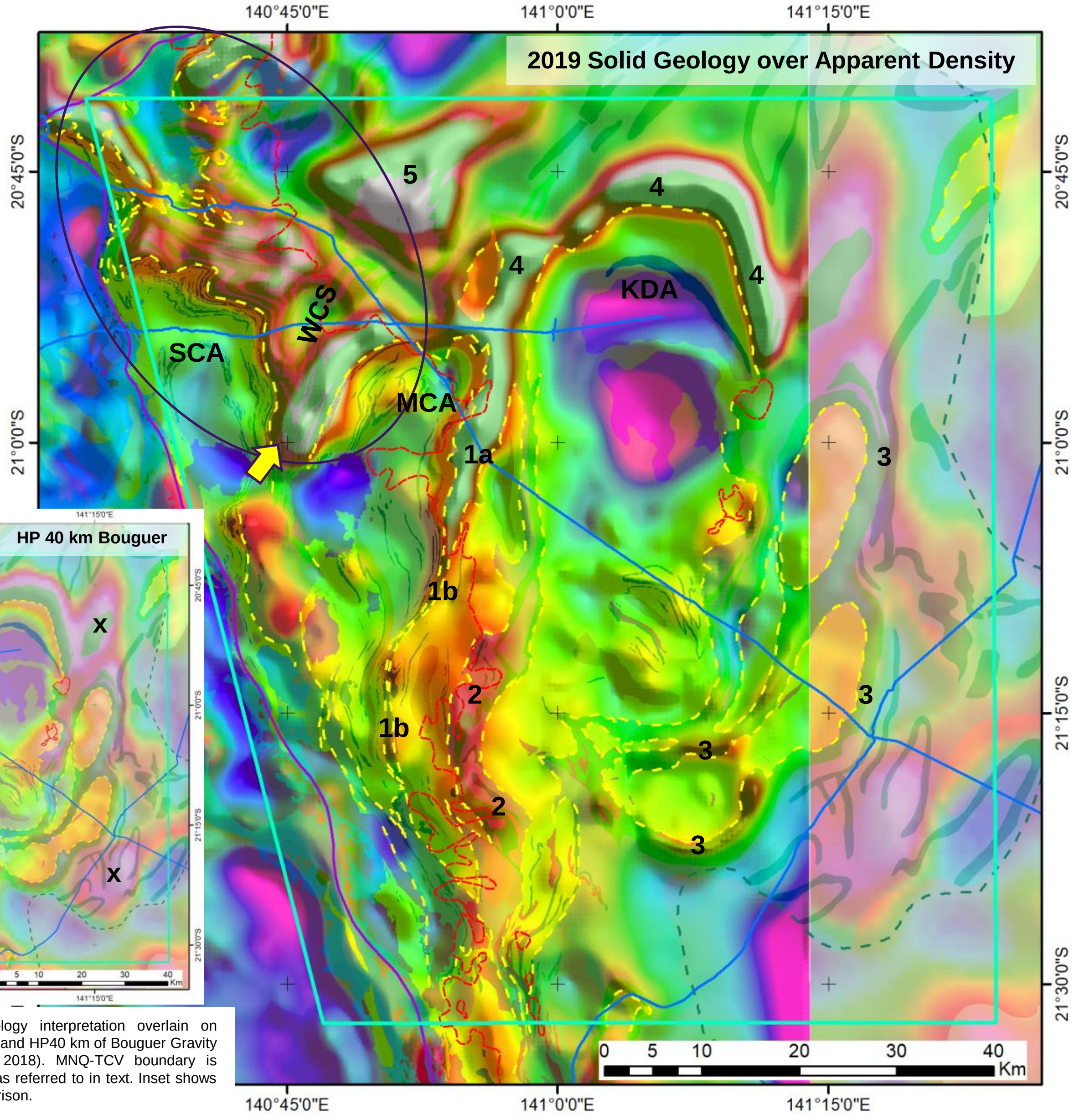
The gravity data is useful for interpretation of granite bodies (see below) but it is also very useful in this area for mapping the lower part of the TCV which is higher density due to the large proportion of mafic igneous units. Outcropping TCV in the northwest corner of the AOI (oval on Figure 5.3) shows a strong correlation with the higher gravity response as indicated by the higher apparent density (red to white colours). Although the upper MNQ includes a number of thick mafic sills, the gravity response changes very close to its upper contact with the TCV (yellow dashed line; Figure 5.3) rather than within the upper MNQ. The gravity can therefore be used as a first pass guide to indicate the presence of the TCV in the covered areas, and also to reassess the outcropping belts.

A prominent, NE-trending, positive gravity anomaly (yellow arrow) correlates with abundant mafic sills on the east limb of the Weatherly Creek syncline (WCS). Given that this anomaly is distinctly stronger in comparison to that of the west limb, the mafic component must be significantly thicker on the east limb. This may result from the presence of a mafic intrusive body at depth (i.e. the magma chamber responsible for the sills and flows, cf. Hatton, 2004), localisation of more sills due to syn-emplacement faulting, thickening of sills into syn-depositional faults, and/or repetition or thickening of mafic units due to inversion.

The gravity data has been key to interpretation of units in several areas.

1. The northern segment of anomaly 1 (1a) coincides with curvilinear magnetic anomalies. Correlation across the Middle Creek anticline (MCA) and local drilling supports interpretation as the lower TCV. This prominent gravity anomaly continues south (1b) along the eastern edge of outcrop previously interpreted as MNQ, and corresponds with abundant mafic igneous units (supported by magnetic and radiometric data where outcrop is scattered). A narrow band of TCV is interpreted to continue to the south based on the gravity. The radiometric data is consistent with MNQ to either side and limits the potential width of outcropping TCV.
2. This north-trending gravity anomaly (Garnet Creek – Bluff Creek permit area) suggests that a band of lower TCV is present in this area. Distinction between the TCV and MNQ is not possible in this region using the magnetics alone therefore the gravity is used to indicate the main unit present and the magnetics provide higher resolution details on trends and boundaries.
3. Prominent curvilinear gravity anomalies in the southeast of the AOI (Breena permit area), correspond with magnetic anomalies. Drill data from several locations indicate the presence of basalt and graphitic schist both characteristic of the basal TCV.
4. The coincident gravity and magnetic anomalies around the north of the Kevin Downs anticline (KDA) are interpreted as the lower mafic unit of TCV in the GSQ solid geology, and this is supported by scattered drill holes intersecting mafic igneous rocks.
5. This area shows the largest positive gravity anomaly in the AOI; it is a high amplitude anomaly similar to that on the east limb of the WCS (yellow arrow). Magnetic data shows small scale folding of a broadly subhorizontal unit in the near surface, and a long wavelength magnetic anomaly at depth (Figure 5.2). The broad, deep gravity and magnetic anomalies are interpreted as a greater volume of high-density, high susceptibility mafic igneous units, either thick mafic sills within the stratigraphy and/or an intrusive complex at depth.

Given that the highest amplitude gravity anomalies occur in the north of the AOI (north of ~21°S) it is considered likely that magma chambers that sourced the mafic sills will be found in the this same area. The two largest gravity anomalies, on the east limb of the WCS (yellow arrow) and area 5, are interpreted to include a mafic igneous complex at depth, although the east limb of the WCS does not coincide with a long wavelength magnetic anomaly. Hatton (2004) interpreted at least two magma chambers based on variations in geochemistry of the high-Fe tholeiites. These intrusive centres are likely to be located around the base of the SCG (Hatton, 2004). Additional intrusive centres may be present in the east and south, although the Williams suite intrusions make interpretation more difficult. Two areas are flagged by an "x" (on inset map) to indicate positive gravity anomalies that are not readily explained by the near surface geology. The northern one coincides with a long wavelength magnetic anomaly and the southern anomaly is located east of a long wavelength magnetic anomaly. These four areas (inset map) represent the most likely locations of a mafic igneous complex at depth based on the gravity and magnetic data, however the potential field response may instead reflect thick, near surface mafic units within the TCV.



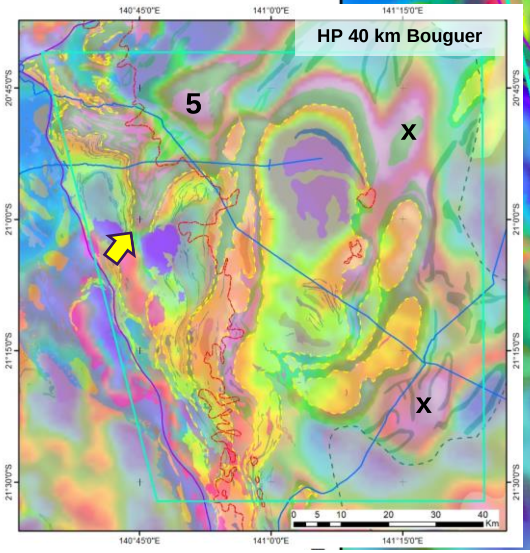


Figure 5.3. Transparent 2019 solid geology interpretation overlain on Apparent Density (from Murphy et al., 2017) and HP40 km of Bouguer Gravity along eastern boundary (from Frogtech, 2018). MNQ-TCV boundary is highlighted in yellow. Numbers indicate areas referred to in text. Inset shows HP40 km image for the entire AOI for comparison.

Magnetic data

The magnetic data shows widespread and distinct anomalies across the AOI (Figure 2.3). Most of the outcropping intrusions are variably magnetic and the Soldiers Cap Group shows distinct curvilinear magnetic anomalies Figure 5.4). Magnetic units within the SCG include:

1. Local iron formation and more widespread quartz-magnetite units;
2. Fe-rich mafic igneous sills that are found in all three units but are most abundant in the Toole Creek Volcanics (TCV; 20-30%; Hatton, 2004), followed by the upper Mount Norna Quartzite (MNQ); and
3. Low to high susceptibility stratigraphic units that may result from detrital magnetic minerals, growth of magnetite adjacent to mafic sills, and/or alteration localised along layering / foliation or layer-parallel shear zones.

Given the range of interpretations for the curvilinear magnetic anomalies, it is not possible to confidently interpret the source of any given anomaly in the absence of additional supporting data, e.g. HyMap or radiometrics in areas of outcrop or little cover and drilling in covered areas. In addition, in areas where there is sufficient data, it appears that some mafic sills are magnetic and some are not. Therefore only magnetic anomalies with additional supporting data have been interpreted as mafic sills, basalt or magnetite iron formation. Other magnetic anomalies are highlighted by trend lines.

Figure 5.4 shows a comparison of the magnetic data with the HyMap and radiometric data. The HyMap image shows that the mafic igneous units within the LCF, MNQ and TCV are generally high in Mg and Fe and the radiometric image shows that they are low in K and have little or no U and Th (dark shades). The sills within both the LCF and MNQ are generally magnetic with a moderate to high susceptibility. The MNQ along the eastern limb of the Snake Creek anticline (red arrows) has a prominent fairly continuous sill near the top of the unit and another in the middle – lower section and a few shorter segments of sills in between. In contrast the MNQ within the northern hinge zone has up to 9-10 sills.

Many of the linear magnetic anomalies on the eastern limb of the Snake Creek anticline, do not coincide with bands of high Mg and Fe (Figure 5.4 a), and do not correspond with dark bands in the radiometric data. Instead the radiometric response is similar to the non-magnetic units of the MNQ (Figure 5.4c) indicating that magnetic metasediments are common within the SCG units. This is evident in many areas throughout the AOI, including the Gold Creek permit area (see Figure 5.2 for location) where drilling failed to intersect any significant mafic units within the highly magnetic folded sediments.

A set of prominent ridges comprising anomalous quartz-rich rocks outcrop around the Snake Creek hinge within the MNQ (pink lines). They occur along strike of the Mount Norna iron formation (indicated by red X). The dark response of the radiometric data shows that this unit is low or very low in K, U and Th, and HyMap shows sporadic Fe and Mg (inset image). The anomalous quartzites are interpreted as Tertiary on the 100K map (Geological Survey of Queensland, 2016), however, this interpretation seems unlikely. Although the unit is white, massive, very thick, unbedded, unfoliated, well-sorted, very quartz-rich and is not typical of MNQ quartzites, and locally appears to be at a low angle to layering in adjacent pelites (Ian Withnall, pers. comm. 2019), it is broadly parallel to stratigraphy suggesting that it represents a preferentially altered unit within the MNQ. The weak Fe and Mg anomalism indicates that this unit could be related to the syn-depositional fluids responsible for the Mount Norna iron formation.

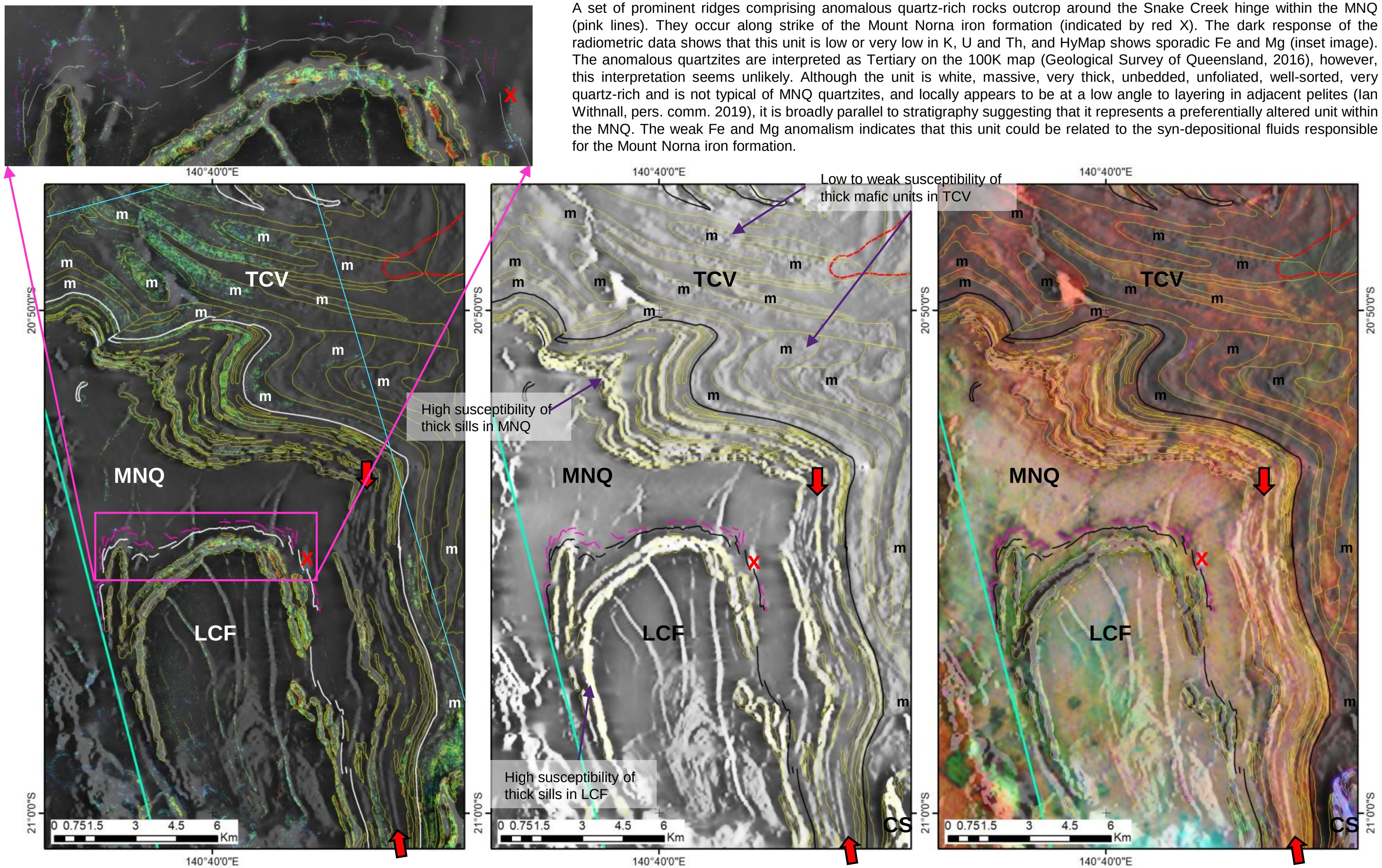


Figure 5.4. a) Transparent HyMap (ferrous iron and MgOH) image overlain on 1VD of RTP; b) 1VD of RTP and c) transparent ternary radiometrics overlain on 1VD of RTP. Outline of mafic units are shown in yellow and unit boundaries are in black (or white in a). The anomalous quartzite unit in the lower MNQ is shown in pink. The mafic units within the TCV are labelled "m". Mount Norna iron formation is indicated by red x. CS = Canteen South.

5.0 Solid Geology Interpretation

The University Of Queensland
AUSTRALIA

MNQ vs TCV in Garnet Creek – Bluff Creek area

The **Garnet Creek – Bluff Creek** permit areas (Figure 5.5) overlap the eastern limit of Proterozoic outcrop (red outline) and extend east under cover. Outcropping units along the margin have previously been interpreted as mainly MNQ (yellow) with the exception of LCF (pale green) in the south (Figure 5.5e). However, several lines of evidence suggest revision is required.

- Gravity data – a prominent N-S positive gravity anomaly occurs along the limit of Proterozoic outcrop (area 2 Figures 5.2 and 5.3) and a region of low to moderate gravity response extends to the east under cover.
- Magnetic data - In other areas the magnetic data can be used to help distinguish between TCV and MNQ, e.g. where both units and their contact are present and/or sufficient drill data confirms the presence of some key rock types which distinguish the TCV. However, the juxtaposition of several faulted packages in this zone means the magnetic data does not help to distinguish between the main rock units.
- Drill data - The available drill database only has a few drill holes along the prominent gravity high, but has good coverage within the area of low to moderate gravity response to the east (pink oval). The drill data has been used to map out some of the mafic units and granite intrusions (Figure 5.5d). The sedimentary units intersected in these drill holes are dominated by psammite / gneiss with only ~20% finer grained units (e.g. pelite / schist).

Interpretation - The MNQ is consistently lower density than the TCV in the well exposed Snake Creek –Weatherly Creek area (Figure 5.3) therefore the N-S positive gravity anomaly favours the presence of lower TCV along this N-S belt (black oval). Figure 5.5d shows TCV mafic (green) and TCV sediments (grey), whereas the drill data indicates that the area to the east is dominated by coarser grained psammite/gneiss typical of the MNQ (pink oval). The low to moderate gravity response supports this interpretation. In addition, outcropping geology and the seismic lines have been used to constrain the interpretation.

Note the E-W structures in the N-S belt dominated by MNQ (pink oval Figure 5.5d) that are interpreted from the magnetic data (Figure 5.5b). The variation in the geology and structure is too significant for these faults to be have formed during late deformation; they are therefore interpreted as syn-depositional with late Isan reactivation (e.g. D4) and local development of new D4 faults.

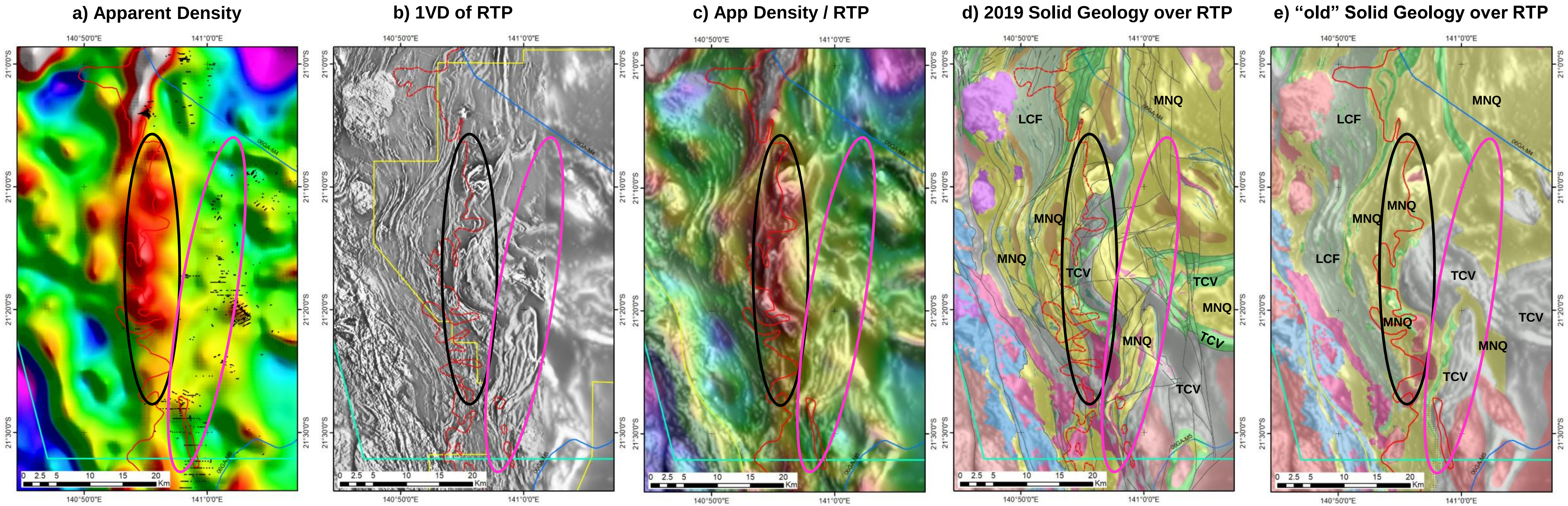


Figure 5.5. a) Apparent density (from Murphy et al., 2017) overlain by drillhole locations; b) 1VD of the RTP (South Cloncurry 1370) with outline of Sandfire dataset in yellow; c) RTP (AGC 200 and Tilt) over the Apparent Density); d) Transparent 2019 solid geology interpretation overlain on RTP (AGC 200 and Tilt).; and e) Transparent pre-2019 solid geology overlain on RTP (AGC 200 and Tilt). The limit of outcrop of the Mount Isa Province is shown in red. The black and pink ovals highlight the two areas discussed in the text. Figure b, c, d and e show the regional RTP data from Frogtech, 2018.

MNQ – LCF boundary south of Saxby Granite

The GSQ solid geology map shows the LCF-MNQ boundary stepping west south of the Saxby Granite and an elongate unit of LCF extending south to ~21°30'S (Figure 5.1b). Correlation of units across the Saxby granite (S) and the structural geometry (from seismic data to the south and north) has lead to questions regarding the location of this boundary. An alternative is presented here as an option to consider and investigate. It is difficult to question the rock units interpreted from outcrop solely on the basis of the datasets available for this project, and field checking is strongly recommended. The MNQ is generally distinguished on the dominance of coarser-grained, quartz-rich units (originally sandstones) over fine-grained pelitic units, however the original 250K mapping did not distinguish between LCF, MNQ and TCV south of the Saxby Granite suggesting that the rock types in this higher grade and higher strain belt may not be as distinctive as they are in the Snake Creek area. MNQ includes intervals that are more pelitic, however, interpretation of LCF in the area of question presumably reflects the presence of dominantly pelitic schists in outcrop.

- The 2016 interpretation on the Cloncurry 100K map sheet shows the MNQ-LCF boundary stepping further west as it crosses the Saxby Granite as highlighted by the pink dashed line (Figure 5.6a). Whilst the upper most LCF has 1-2 prominent sills in the Snake Creek area, this interpretation results in several large mafic sills over a much larger section (2 km surface width compared to less than 1 km in the Snake Creek area). In addition, although the MNQ includes some non-magnetic packages, it is dominated by bedding parallel magnetic anomalies some of which do not coincide with mafic sills. These are interpreted as stratigraphic beds that are richer in magnetite. Some magnetite-rich units are directly related to the syn-sedimentary iron formations (e.g. Hatton, 2004), but others may result from detrital magnetite or magnetite growth adjacent to sills. Later alteration has also played a role but cannot account for the widespread magnetic beds within the MNQ.
- The abundance of mafic sills and high-magnetite sedimentary beds (indicated from the magnetic and radiometric data) south of the Saxby granite in the band between the pink and black dashed lines are more consistent with the number of sills and magnetic units in the MNQ north of the Saxby Granite.
- Interpretation of the MNQ-LCF boundary lying further to the east as shown in the 2019 interpretation (Figure 5.6b) results in a boundary that projects through the Saxby Granite in an orientation that is more consistent with geological trends to the east and west. This MNQ-LCF boundary also allows for the continuation of the magnetically quiet MNQ (orange unit) which is evident to the north of the granite.
- This alternative interpretation results in pinching out of the LCF along a NE-trending high strain zone (interpreted as an extensional fault).

A review of the outcrop geology and variations within the three units of the SCG is recommended.

Continuity of TCV south of Foxes and Saxby intrusions

The 2019 interpretation shows the possible continuity of the TCV sediments between the Foxes and Saxby intrusions and continuing to the south to overlie the Staveley carbonates and detachment (Figure 5.6b). This interpretation is based on continuity of units in the radiometric data and hyperspectral data. The hyperspectral data and the SW trend of the MNQ stratigraphy around the north end of the Foxes Creek granite suggests the lower TCV may be present along the west margin. The radiometric and hyperspectral data suggest the sediments along the eastern margin of the Foxes Creek granite may be the TCV instead of the MNQ. North of the FC intrusion this band of sediments lies above the basal mafic unit of the TCV and this correlation implies that the basal mafic unit either pinches out to the south or is faulted out along the Staveley detachment.

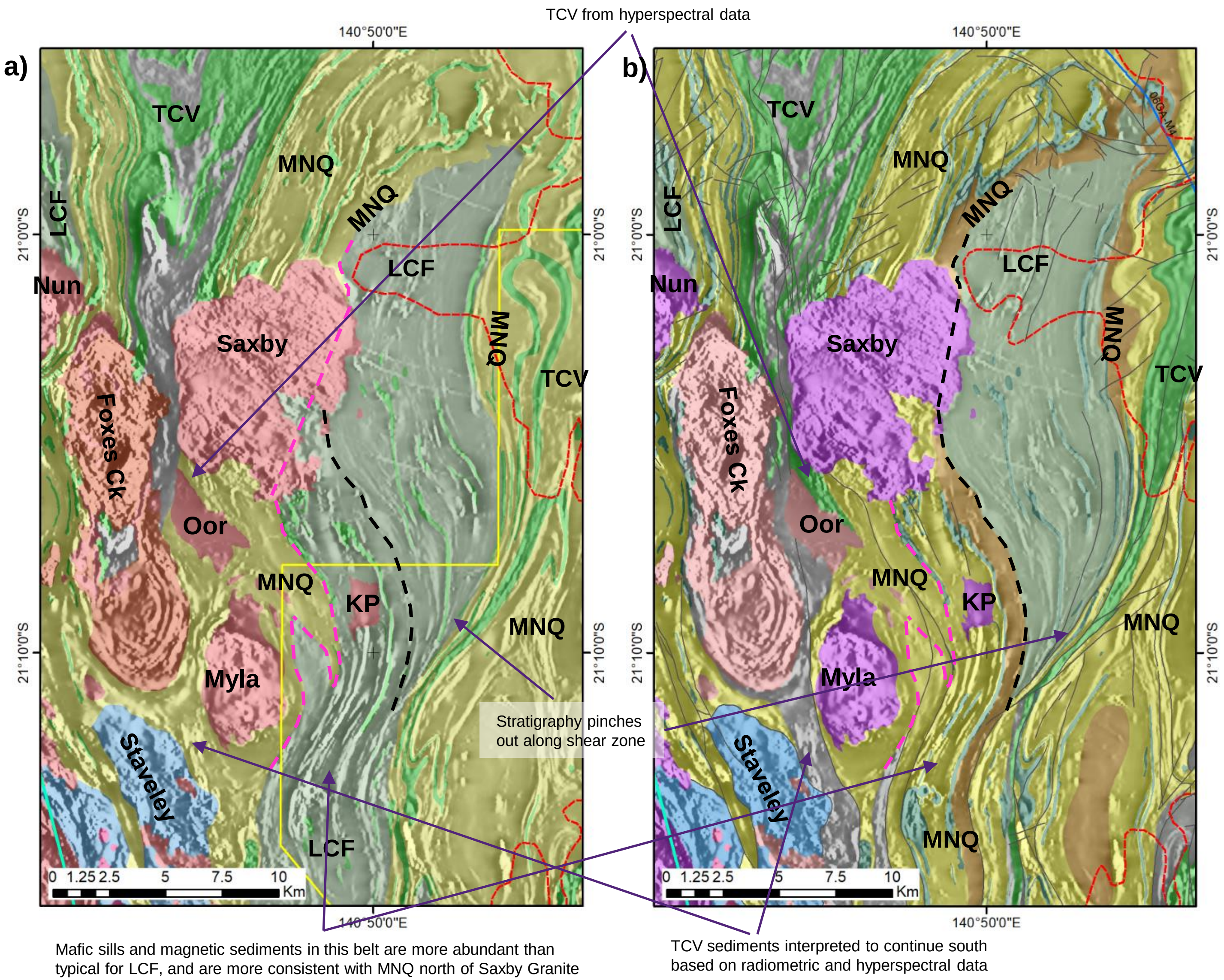


Figure 5.6. a) Transparent pre-2019 solid geology overlain on RTP (1VD); and b) Transparent 2019 solid geology interpretation overlain on RTP (1VD). Red dashed line shows limit of Mount Isa Province outcrop. Yellow outline shows extent of Sandfire magnetic survey used for interpretation. KP = Kays Peak Granite; LCF = Llewellyn Creek Formation; MNQ = Mount Norna Quartzite; Nun = Nundata Granite; Oor = Oorindimindi Gneiss; TCV = Toole Creek Volcanics.

MNQ – LCF boundary in Maramungee area

The alternative interpretation for the LCF-MNQ boundary south of the Saxby Granite (Figure 5.6) combined with the structural geometry (from seismic data to the south and north) has lead to questions on the continuation of the narrow belt of LCF to the east of the Maramungee zone.

The elongate NW belt of LCF is flagged for review based on:

- The alternative interpretation of the MNQ-LCF boundary south of the Saxby Granite (previous page) results in pinching out of the LCF along a NE-trending high strain zone (Figure 5.6b).
- Early 250K mapping did not distinguish between MNQ, LCF and TCV in this region. Given the interpretation of LCF in this NNW trending belt in the 100K map sheet and digital geology, it is assumed that the outcropping units are dominated by pelites.
- The rocks are higher metamorphic grade including gneiss and locally granulite (Giles et al., 2006b; Rubenach et al., 2008), and are generally higher strain especially in the highly faulted zone to the east of the Maramungee Suite. The Maramungee Suite, Boorama Tank Gneiss, Minya Pegmatite, and Dingo Prospect Skarn, comprise a high strain zone that dips moderately to the east based on the regional gravity modelling of the Deep Mining Queensland project (Murphy et al., 2017), and alteration extends up to 2 km into the SCG sediments to the east (Giles et al., 2006a).
- Seismic lines 06GA-M5 and 06GA-M6 cross the folded Staveley detachment to the south of the AOI (Figures 3.3 and 4.7). The detachment is overlain by an anomalously thick upward-facing sequence of MNQ, which is in turn overlain by TCV, and LCF is absent. If this belt of pelitic rocks is LCF (Figure 5.7a) then it represents the core of an overturned anticline with a highly thinned west limb comprising *downward-facing* MNQ structurally overlain by LCF, and underlain by the Staveley Formation carbonates and detachment fault. This geometry is possible and in fact is similar to that of the Snake Creek anticline to the north. However, it is not consistent with that to the south from outcrop and seismic data (Figures 3.3 and 4.7). In addition, although the geometry is possible, there is little “room” for a large scale LCF cored fold between the east-dipping limb of the folded detachment and the dominant west-dipping structures (highlighted as black lines; Figure 5.7).
- Moderate east dip of the Maramungee intrusive complex and related structures is supported by seismic lines 06GA-M5 and 06GA-M6 which show a similar east dip within the MNQ stratigraphy on the eastern limb of the folded Staveley detachment (Figures 3.3 and 4.7).
- Figure 5.7b shows that much of the LCF has been reinterpreted as MNQ in areas with less outcrop and where the magnetic and radiometric data supports this interpretation. The MNQ does include pelitic rocks but should also include interbedded quartz-rich sandstones. Assuming that the outcropping units are dominated by pelitic rocks, then it is possible that the TCV is present as well.
- The geology map and satellite images indicate that the 1-1.5 km wide belt of east of the Maramungee Suite has a large percentage of outcrop, although the radiometric data suggests thin cover and scattered small intrusives. This belt is tentatively interpreted as TCV as this unit presumably has a higher percentage of pelitic units than the MNQ (Figure 5.7b). The radiometric outcrop response is partly obscured by Cenozoic alluvium but in some “windows” the radiometric data shows a similar response to the TCV in the Snake Creek area.

A review of the outcrop geology in the NNW trending belt of pelitic rocks east of the Maramungee Suite is recommended, although it may be difficult to confidently interpret the rocks of this belt due to the high metamorphic grade, high strain and alteration.

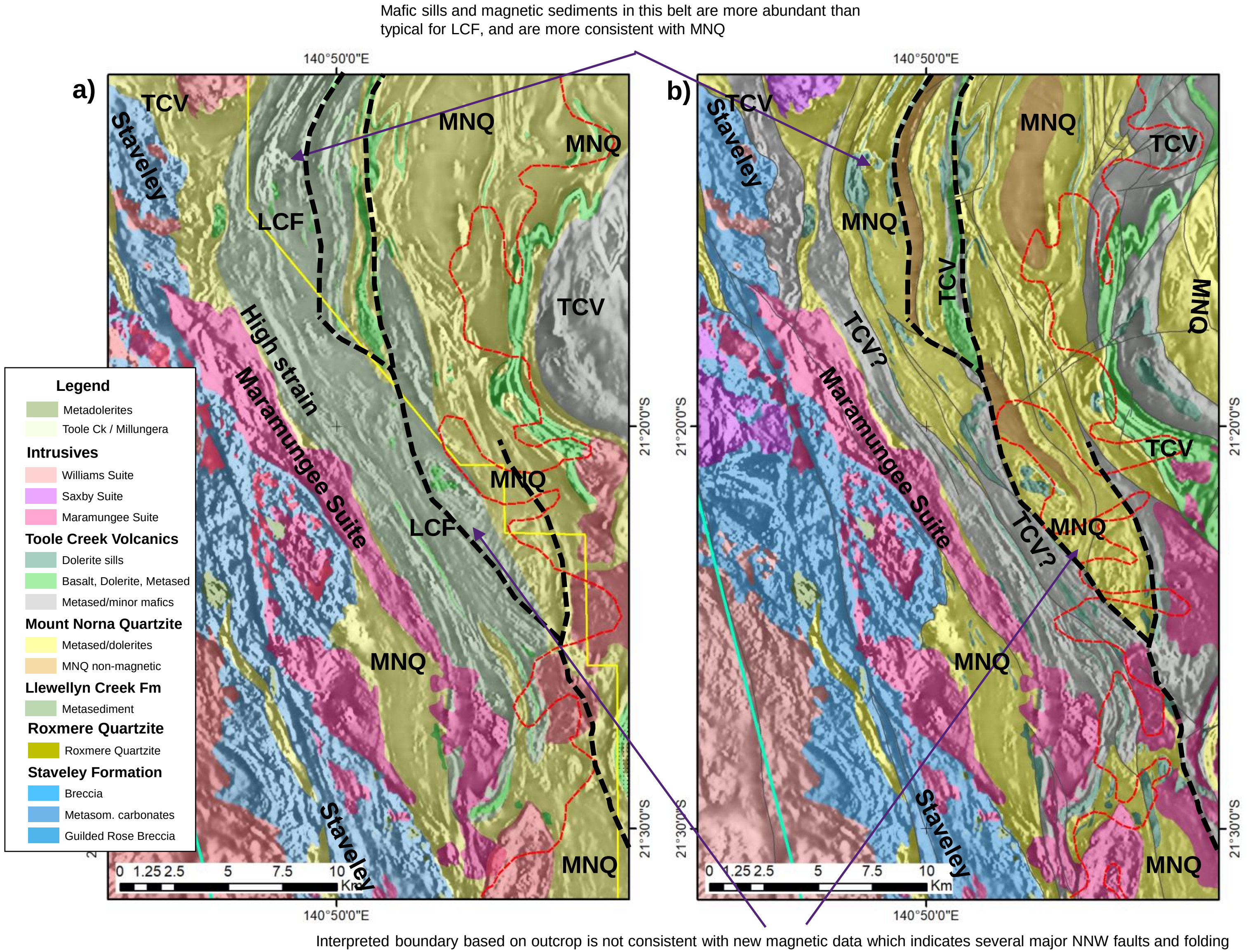


Figure 5.7. a) Transparent pre-2019 solid geology overlain on RTP (AGC 200 and Tilt); and b) Transparent 2019 solid geology interpretation overlain on RTP (AGC 200 and Tilt). Red dashed line shows limit of Mount Isa Province outcrop. Yellow outline shows extent of Sandfire magnetic survey used for interpretation. . LCF = Llewellyn Creek Formation; MNQ = Mount Norna Quartzite; TCV = Toole Creek Volcanics.

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

Maramungee Suite Age

Age dates for the Maramungee suite include 1545 +/-11 and 1547 +/- 5 Ma (Page and Sun, 1998). However, zircon populations documented by Griffin et al. (2006) from drainages in the study area that sample the Maramungee suite, document a distinct older population of magmatic zircons with oscillatory zoning ranging in age from ca 1569 to 1554 Ma. These zircons form a large population in several drainages consistent with a significant igneous event, and indicate that the age of the poorly dated Maramungee Suite ranges from 1569 Ma to 1545 Ma (cf. Griffin et al., 2006). The Maramungee Suite therefore initiated soon after the metamorphic peak and crustal thickening from ca 1590-1570 and intruded during continued ~E-W shortening Ma (e.g. Rubenach et al., 2008). Gravity modelling indicates that the large Maramungee Suite bodies (labelled MS at west edge of this image ; see also Figure 5.7) dip moderately to the east (Murphy et al., 2017) similar to the stratigraphy east of the Staveley detachment (SD) on seismic lines (06GA-M5 and M6; Figures 3.3 and 4.7) south of the AOI. Names of the various intrusions included in the Maramungee Suite are labelled on Figure 5.8a.

Maramungee Suite granites from drill data

The drill data available for the project provides good coverage of rock types in the Sugarbag permit area (Figure 5.8a). The main lithologies include metasediment (~80% psammite / quartz-feldspar gneiss, ~20% pelitic schist), amphibolite/mafic, and felsic intrusives. These are shown as blue, green and red, respectively, in Figure 5.8b. Integrated interpretation of the magnetic and drill data shows that the felsic intrusives (granite (dark red) to pegmatite (medium red)) occur parallel to the layering indicated by the magnetic data and the drill data. Figure 5.8a shows the interpreted extent of intrusions in this area. Many of the granites correspond to linear lows in the magnetic data, and only a few correspond to positive magnetic anomalies. The elongate, narrow granites are interpreted as part of the 1569-1545 Ma Maramungee Suite (MS) based on their geometric relationship to the stratigraphy, in contrast to the younger 1536-1523 Ma Saxby suite (not shown in this map), and main 1520-1500 Ma Williams-Naraku Suite (WN) intrusions which form broad, relatively flat intrusions that cross cut stratigraphy in 3D based on the gravity modelling of Murphy et al. (2017; see Figure 5.9).

The outcropping Lowman Tank Granite has been included as part of the Williams-Naraku suite in the 100K geological map (Geological Survey of Queensland, 2016a). No age data is available and interpretation as part of the Maramungee Suite is preferred here based on the well developed fabric and the elongate shape as constrained by the drill data. Note that the larger body of granite to the east, interpreted from drilling and magnetics, has been included as part of a large Lowman Tank granite in the 100K map (Geological Survey of Queensland, 2016a). However, integrated interpretation of the outcrop (red dashed outline), drill data and magnetics suggests that the Lowman Tank granite outcrop is separated from the larger body to the east. It is unclear whether the larger "Lowman Tank?" granite is part of the Williams or Maramungee suites.

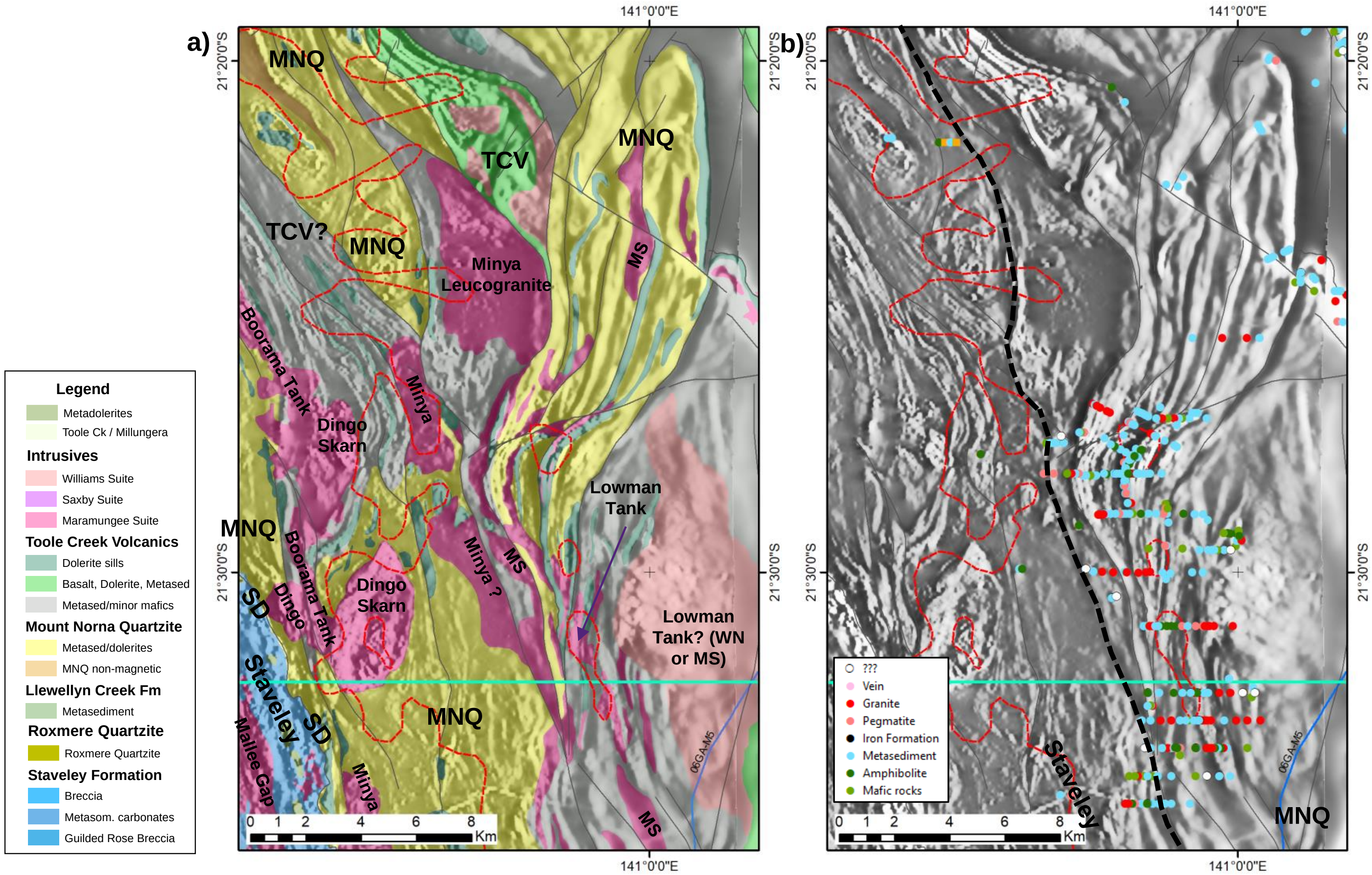


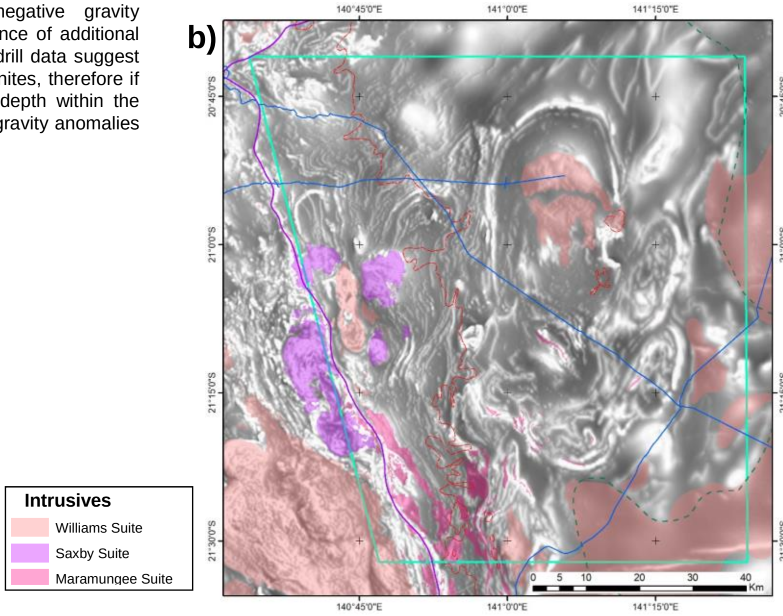
Figure 5.8. a) Transparent 2019 solid geology interpretation with drill colours, overlain on RTP (AGC 200 and Tilt). b) Drillholes coloured by lithology (red = granite, blue = sediment, and green = mafic) overlain on 1VD of RTP (Cloncurry South survey). Red dashed line shows limit of Mount Isa Province outcrop. Yellow outline shows extent of Sandfire magnetic survey used for interpretation. . LCF = Llewellyn Creek Formation; MNQ = Mount Norna Quartzite; MS = Maramungee Suite; SD = Staveley detachment; TCV = Toole Creek Volcanics; WN = granites of the Williams-Naraku Suite.

Williams – Naraku Suite

Several prominent negative gravity anomalies are interpreted as large intrusions of the Williams-Naraku Suite (Figure 5.9). These large granitic bodies have been recognised and interpreted by numerous workers, and have been included in the published GSQ solid geology (Figure 5.1a above) and most are included in the 3D gravity model of the DMQ project (Murphy et al., 2017). The updated interpretation during this project has resulted in slightly modified boundaries based on the magnetic data, seismic and in part on the drill database available for this project. Note that the ground gravity data is lower resolution than the other datasets but it highlights the areal extent of intrusions at depth. The DMQ detailed gravity modelling tested a wide range of options in an effort to ameliorate the inherent ambiguity and produce a geologically-reasonable 3D model of the granites (Murphy et al., 2017). The modelling results show that many of these Williams-Naraku granitic intrusions are more extensive at depth than near surface and are generally discordant relative to the Isan controlled Proterozoic trends. As a result, the outlines of the granitic bodies (Figure 5.9) do not directly match the gravity anomalies. Instead the near surface extent is defined by magnetic data, locally supported by the drill data and seismic. For example, the near surface outline of the intrusions in the core of the Kevin Downs anticline (KDA) are based largely on the magnetic data, and in the SE corner of the AOI, the magnetic data indicates the presence of thin rafts of TCV overlying the granites that appear more extensive from both gravity and seismic.

In the outcropping area around the Mount Angelay (MA), Nundata (N) and Saxby (S) granites and west of the AOI, the apparent density shows a good match to the intrusions mapped in outcrop, but also suggests that either the bodies extend further at depth and/or there are additional small bodies at depth along the Snake Creek – Maramungee corridor (e.g. Murphy et al., 2017). For example, the apparent density north of the Nundata and Saxby granites within the core of the Snake Creek and Middle Creek anticlines, is anomalously low and suggests the presence of granites at depth.

A few circular or semi-circular negative gravity anomalies suggest the possible presence of additional granite bodies. Magnetic data and/or drill data suggest that the near surface units are not granites, therefore if intrusions are present they occur at depth within the SCG units. Several of these negative gravity anomalies are indicated by "G?".



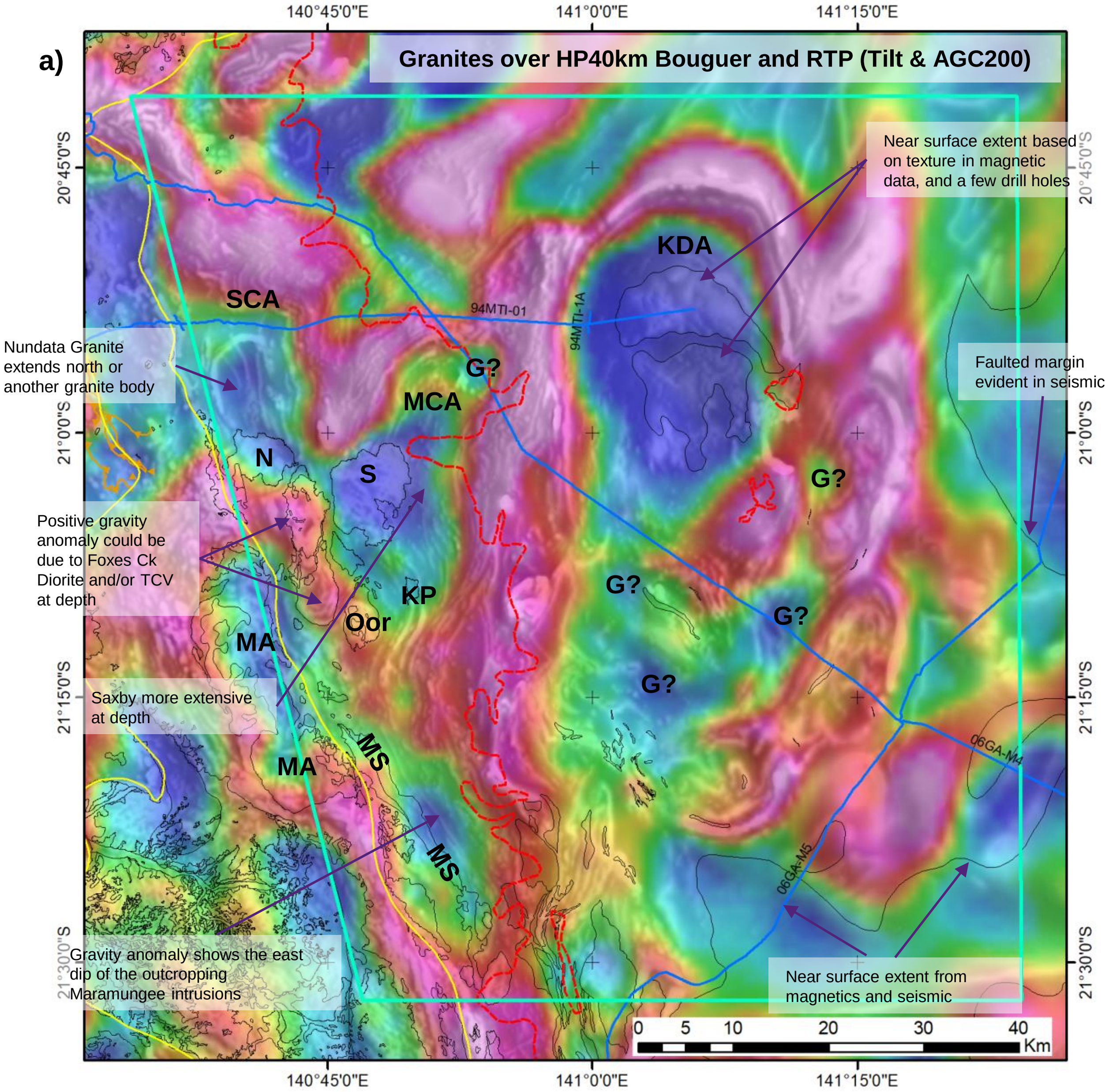


Figure 5.9. a) Outlines of intrusive bodies overlain on a combined gravity and magnetic image (transparent RTP (AGC 200 and Tilt) overlain on high Pass 40km of Bouguer Gravity). B) granite bodies coloured by age group. KDA = Kevin Downs anticline; KP= Kays Peak Granite; MA = Mount Angelay granite; MCA = Middle Creek anticline; MS = Maramungee Suite; N = Nundata Granite; Oor = Oorindimindi gneiss; S = Saxby Granite; SCA = Snake Creek anticline; WN = granites of the Williams-Naraku Suite.

De – SCG extensional fault system

Figure 5.10 shows the interpreted network of De faults formed during the ca 1680-1650 Ma Sybella – Soldiers Cap extensional event that accommodated deposition of the Soldiers Cap Group. Many of the NW-trending faults are interpreted as transfer structures. However, later overprinting by large Williams Suite intrusions, e.g. eastern half of AOI, and compressional deformation especially in the high strain zone between the Saxby and Maramungee suites (black outline), has reoriented and partly obscured the extensional fault system. Note that some of the offsets along the interpreted transfer faults may result from later reactivation during D3 and D4 (see Figure 5.13). Chemical sediments and emplacement of high-Fe mafic sills are both associated with this event (Hatton, 2004; see Introduction for details on stratigraphy). Alteration associated with extension is dated by monazite ages of 1680-1640 Ma from albitites spatially related to high-Fe mafic sills, and albite inclusions in porphyroblasts (Rubenach et al., 2008).

A summary of some of the key areas and evidence for extensional faulting is discussed below (numbers on map refer to text).

1. The Cloncurry Thrust (or "Overthrust") is a sheared, mylonitic zone at a low-angle to bedding along the boundary of the SCG and Staveley Formation (Giles et al., 2006a), exposed along the west of the AOI. The LCF and lower MNQ are consistently missing, and the entire MNQ is locally absent in the NW (labelled 1a; and west of AOI in the Marimo-Staveley area). While Austin and Blenkinsop (2008) argued for a broadly defined Cloncurry Fault zone (including both thrust and steep faults) that may have initiated as a basin fault, but was mainly active during D3 prior to D4 reactivation and alteration, Murphy et al. (2017) recognised an early low-angle fault that was reactivated during D2 and/or D3, and a distinct set of brittle faults that cut fully solidified Williams Suite intrusions. Whilst this study agrees with the interpretation of late brittle faults, it also recognises syn-sedimentary activity on the southern end of the steep Cloncurry Fault (as discussed in 4.0). In agreement with Giles and McCready (1997), the Cloncurry "thrust" is interpreted to have originated during deposition of SCG, and forms part of the Staveley detachment fault system (highlighted in yellow).
2. Outcrop mapping on the east limb of the Snake Creek anticline (S) shows variations in thickness of units (e.g. Hatton, 2004); Giles et al. (2006a) noted a northward thickening of MNQ from 1600 to 3500 m.
3. On the east limb of the Middle Creek anticline (M), the magnetic anomalies within the TCV and upper MNQ show localised folding of small scale thickened packages indicating inversion of a set of normal faults. These normal faults dip SSE and are antithetic to the main W-dipping extensional fault that controls the narrow syncline east of the Middle Creek anticline.
4. Truncation of magnetic units indicates the presence of this NW-trending fault zone and the gravity data indicates significant variations in thickness of the TCV mafic units (Figure 5.3). As discussed above, this thickness variation is interpreted as syn-depositional control on sill emplacement and thickness, and/or syn-emplacement control on the underlying magma chamber. Thickening or repetition during inversion may also have played a role.
5. The listric, N- to NE-trending faults dip moderately to W or NW with large scale NE-trending antiforms in their hangingwall (partly refolded by D2 folds) but no obvious synforms. These faults are interpreted to have initiated during SCG deposition and extension. Although the relationships are not as clear in comparison to other areas, there is evidence for thickening of the lower TCV and MNQ into these faults from seismic and magnetic data. These faults are linked at depth to the crustal scale ~ west-dipping faults evident in 06GA-05 suggesting the original orientation was N- to NNW-trending.
6. There is a distinct change in structural style (white oval) from ~NE- folds and faults to strong N-S structures. This zone is interpreted as a transfer zone with several NNW faults active during deposition. The magnetic data shows truncations and changes in stratigraphy suggestive of E-W normal faults as well. Sharp changes in geometry across both fault sets suggest syn-depositional activity.
7. Faulting around the Weatherly Creek syncline (W) is associated with thickness variations in mafic igneous units of the TCV (Figure 5.3; based on gravity, magnetics, radiometrics and seismic) consistent with reactivated normal faults.
8. South of the AOI, the main west-dipping fault zone from 06GA-M5 is interpreted as an extensional fault that was reactivated (Figure 4.7). This fault system extends north into the AOI.
9. The seismic data shows major zones of west-dipping faults either side of the Kevin Downs anticline (KDA) – these zones originated as part of the extensional system based on their link to deeper crustal structures but they also include faults formed during D2 shortening (Figures 4.5 and 4.6). On the west side of the anticline, these structures are well imaged at depth and most appear to be truncated by the Kevin Downs intrusion but at least one appears to extend to the near surface (Figure 4.5).

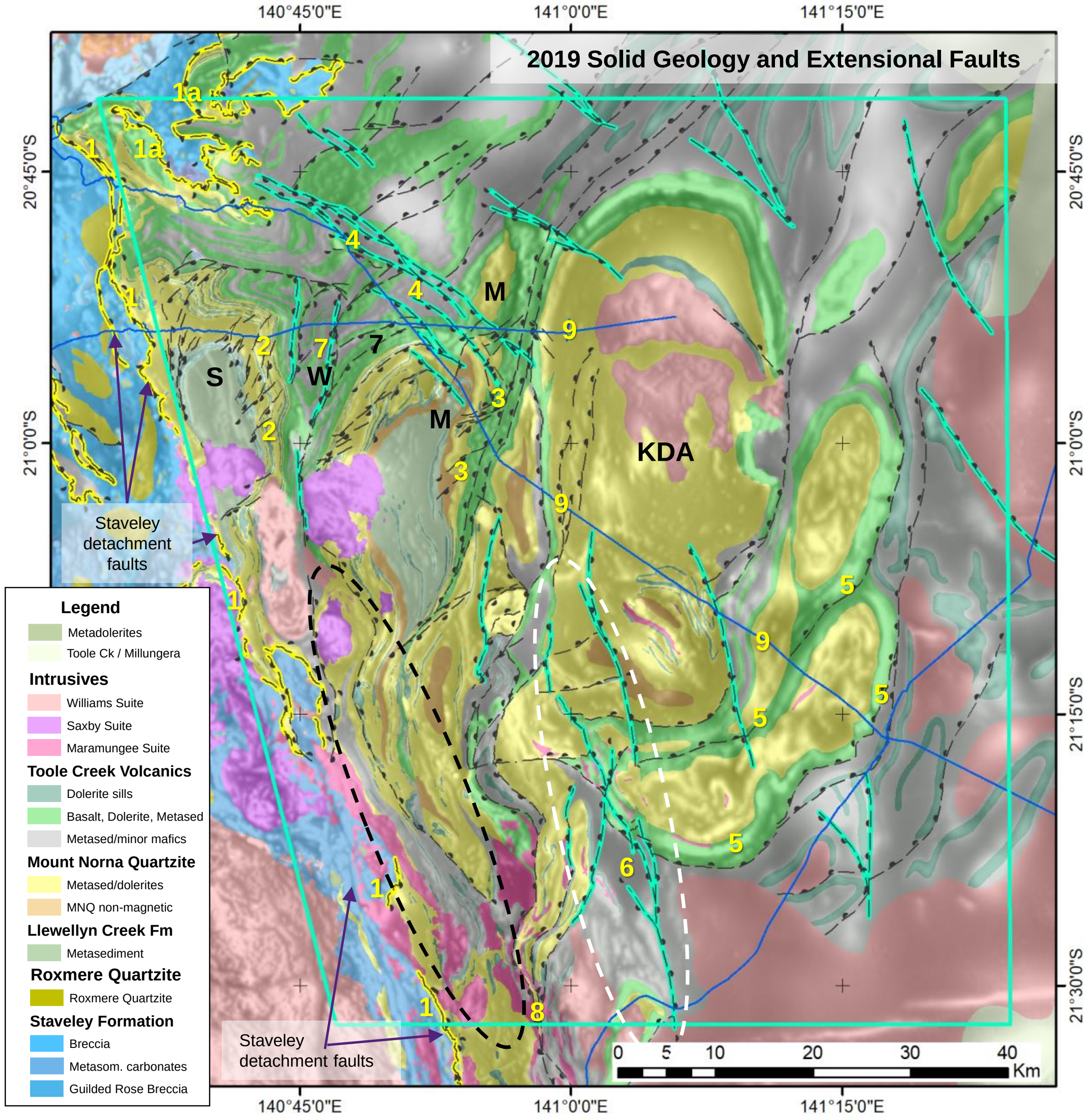


Figure 5.10. Extensional fault network overlain on a transparent 2019 solid geology interpretation with RTP in the background (AGC200 and Tilt). De faults are in black, the Staveley detachment is in yellow, and the main transfer faults are cyan. Red dashed line shows the limit of Mount Isa Province outcrop. Seismic lines are shown in blue. Numbers refer to text. S= Snake Creek anticline, M = Middle Creek anticline; W = Weatherly Creek syncline, KDA = Kevin Downs anticline.

D1 structures

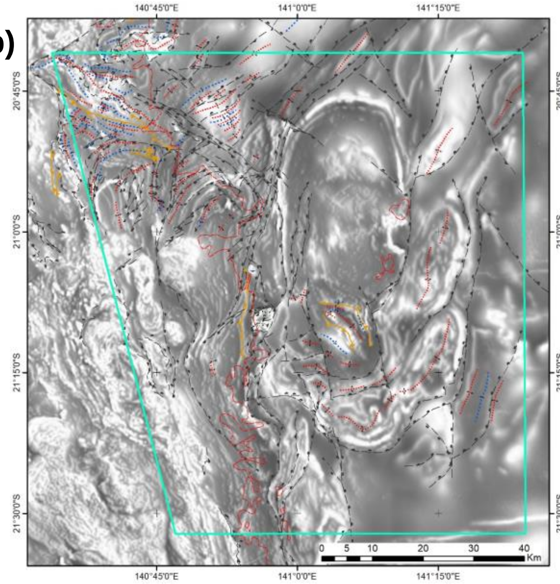
D1 folds and faults (Figure 5.11) have been interpreted by previous workers, and there is general agreement on which faults were active during D1 in this study. However the origin of many low-angle faults as extensional structures during SCG deposition is emphasised here. In most cases these faults are subhorizontal and preserve a “young over old” relationship with missing stratigraphy in contrast to thrust faults which typically juxtapose older units over younger units. In addition, a few are folded by the D1 E-W folds in the Toole Creek - Pumpkin Gully region in the NW of the AOI (e.g. Giles et al., 2006a; Murphy et al., 2017 report and GIS) indicating an earlier development (Figure 5.10).

D1 shortening was at a high or moderate angle to the De normal faults resulting in anticlinal folds in the hangingwall of the set of extensional faults (Figure 5.10). In addition, the elevated geothermal gradient during early Isan Orogeny (~45°C/km Porteau et al., 2018) and the rheological weakness of the Staveley detachment, both promoted reactivation of the normal fault system during shortening possibly at relatively low strain. It is considered likely that the main N-S folds of the western part of the AOI, Snake Creek, Middle Creek and other smaller folds, initiated during D1 inversion but were significantly tightened and locally overturned during D2. Folds in the Breena permit area (B; Figure 5.11) are interpreted to have formed during D1 shortening, and to have been locally refolded or more commonly tightened and reoriented during D2 (compare Figure 5.12).

Only a few faults have been interpreted to have originated during D1, whereas a large number of low-angle extensional faults are interpreted to have been reactivated during D1 thin-skinned deformation. The faults that are interpreted herein to have initiated during D1 shortening are those which can be interpreted to have formed in association with the D1 folds and/or are folded by ~N-S-trending D2 folds and are not likely to be related to early SCG extension. For example, D1 faults in the NW of the AOI are interpreted to have formed to accommodate space issues during progressive tightening in some folds.

The orientation of the folds in the north of the AOI is interpreted to strongly reflect the extensional architecture. In general terms, many D1 folds represent structures that formed in the thickened hangingwall sequences of normal faults related to initial inversion (Figure 5.11b). Therefore the orientation of D1 structures cannot be used to directly asses the D1 shortening direction. However, detailed work in this area and further south at Pegmont favours north and west thrusting (Giles et al., 2006a; b) consistent with evidence for ~N-S shortening in the Lawn Hill Platform of the Western Fold Belt (Bradshaw and Scott, 1999) and NNW-SSE shortening in the Mitakoodi Culmination (e.g. O’Dea et al., 2006). D1 shortening in this area is considered to have been NNW-SSE to ~N-S consistent with other workers (e.g. Table 1.2).

b)



a)

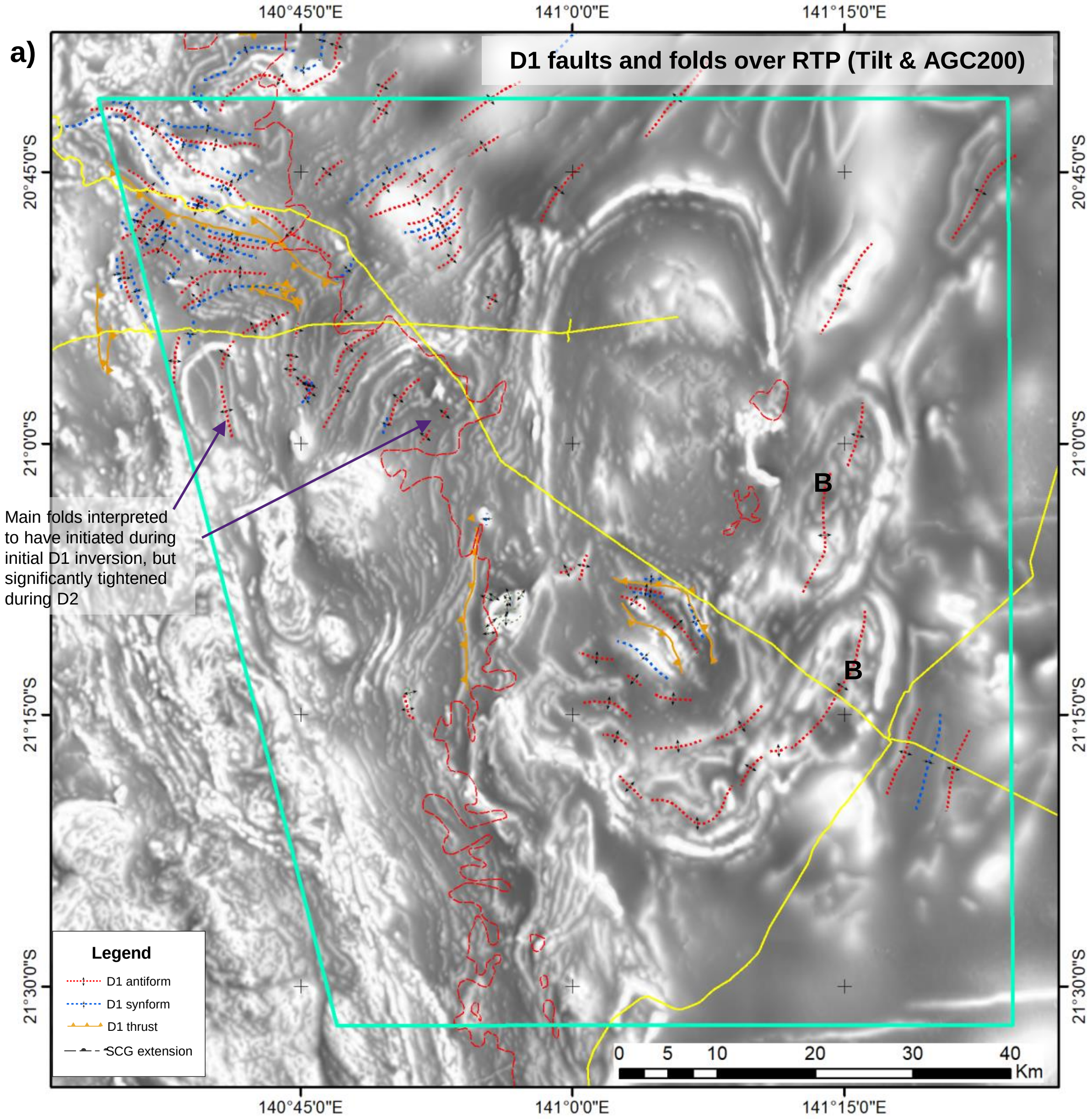


Figure 5.11. a) D1 faults and folds in relation to the SCG extensional fault system. RTP (AGC 200 and Tilt) in background. Red dashed line shows the limit of Mount Isa Province outcrop. Seismic lines are shown in yellow. b) Location of D1 folds relative to the SCG extensional faults.

D2 folds and faults

D2 folds are N-S to NE in comparison to the D1 folds which are E-W to NE; many folds of both generations formed during inversion on extensional faults. D1 folds in the hangingwall of inverted normal faults such as those in the Breena (B) area in the SE (Figure 5.12) are likely to have been further tightened and possibly reoriented to a more NNE trending orientation during D2 ~E-W shortening. This set of folds and faults swings to the NNE in the NE of the AOI. This may reflect a number of controls from early extensional architecture of the basement to influence of the competent batholiths during late shortening after the Williams-Naraku event. The overlap in orientation of D1 and D2 folds in this area combined with potential reorientation and tightening of D1 folds during D2 (i.e. those D1 folds that trend NE rather than E-W), means that it can be difficult to confidently distinguish the origin of some folds. The Snake Creek anticline is one example for which both a D1 and D2 age has been published (e.g. Giles et al., 2006a; Rubenach et al., 2008, respectively).

As discussed for the D1 event, it is considered likely that the main N-S folds of the western part of the AOI, Snake Creek (SCA), Middle Creek (MCA) and other smaller anticlines may have initiated during D1 inversion but were significantly tightened during D2. These folds are tight to very tight, and locally overturned, and contrast with the open D2 folds that overprint E-W to NE-trending D1 folds in the northwest of the AOI.

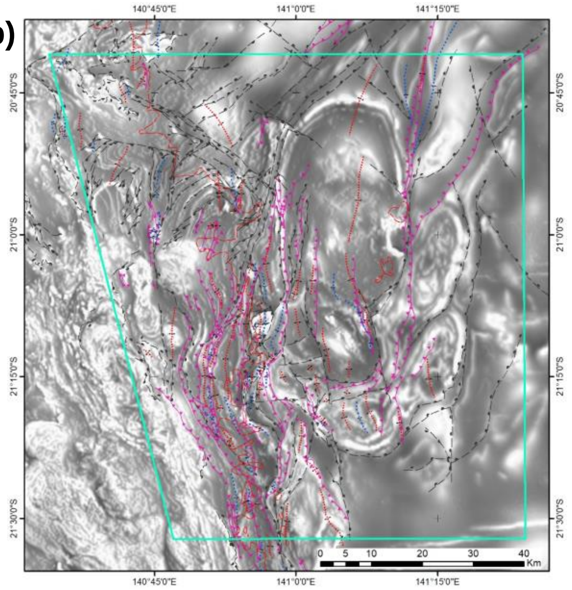
This distinct overprinting of E-W D1 folds *by broad, open* N-S D2 folds has been documented by numerous authors in the NW of the AOI (e.g. Giles et al., 2006a; Rubenach et al., 2008; Figure 5.12). These D2 folds are open and contrast with the tight, upright D2 folds mapped across the EFB. This is interpreted to reflect two factors: 1) the locally well developed E-W to ENE-WSW trend of the extensional and D1 structures which has locally resulted in a steep ~E-W layering with abundant, strong mafic units; and 2) strain partitioning related to the underlying basement terranes. The orientation and style of structures in the upper crust has been controlled by the rheology, boundaries and structures of the basement terranes.

A ~N-S curvilinear zone of higher strain extends from the southern boundary of the AOI north to Maronan (M) and Eloise (E). This zone includes a large number of ~N-S D2 folds and D2 thrust faults. The western boundary of this zone includes the deformed Maramungee Suite (MS) bodies within the Maramungee shear. This high strain zone lies along the western boundary of the Numil basement terrane.

.

The Kevin Downs anticline (KDA) has a wavelength of >20km and is distinctly larger than other folds in the area (Figure 5.12). It is associated with a negative gravity anomaly related a large intrusion considered to be part of the Williams - Naraku suite (e.g. Murphy et al., 2017). Seismic line 94MTI-01 shows that the intrusion is subhorizontal and cuts the dominantly west-dipping reflections (stratigraphy and faults), but is subparallel to layering toward the core of the fold at the end of the seismic line. To the south on seismic line 06GA-M4, the dominant west dip is evident but the large scale antiform is not. 06GA-M4 instead shows a couple smaller wavelength open folds. Note that the negative gravity anomaly related to the granite does not extend to 06GA-M4. Given that the wavelength of the fold in the north is roughly matched by the negative gravity anomaly, the northern end of the fold may largely reflect doming related to emplacement of the granite into the gently to moderately west-dipping zone evident on both seismic lines. If this is the case then the fold may be mainly formed during D4, although initiation of folding during D2 is likely.

b)



a)

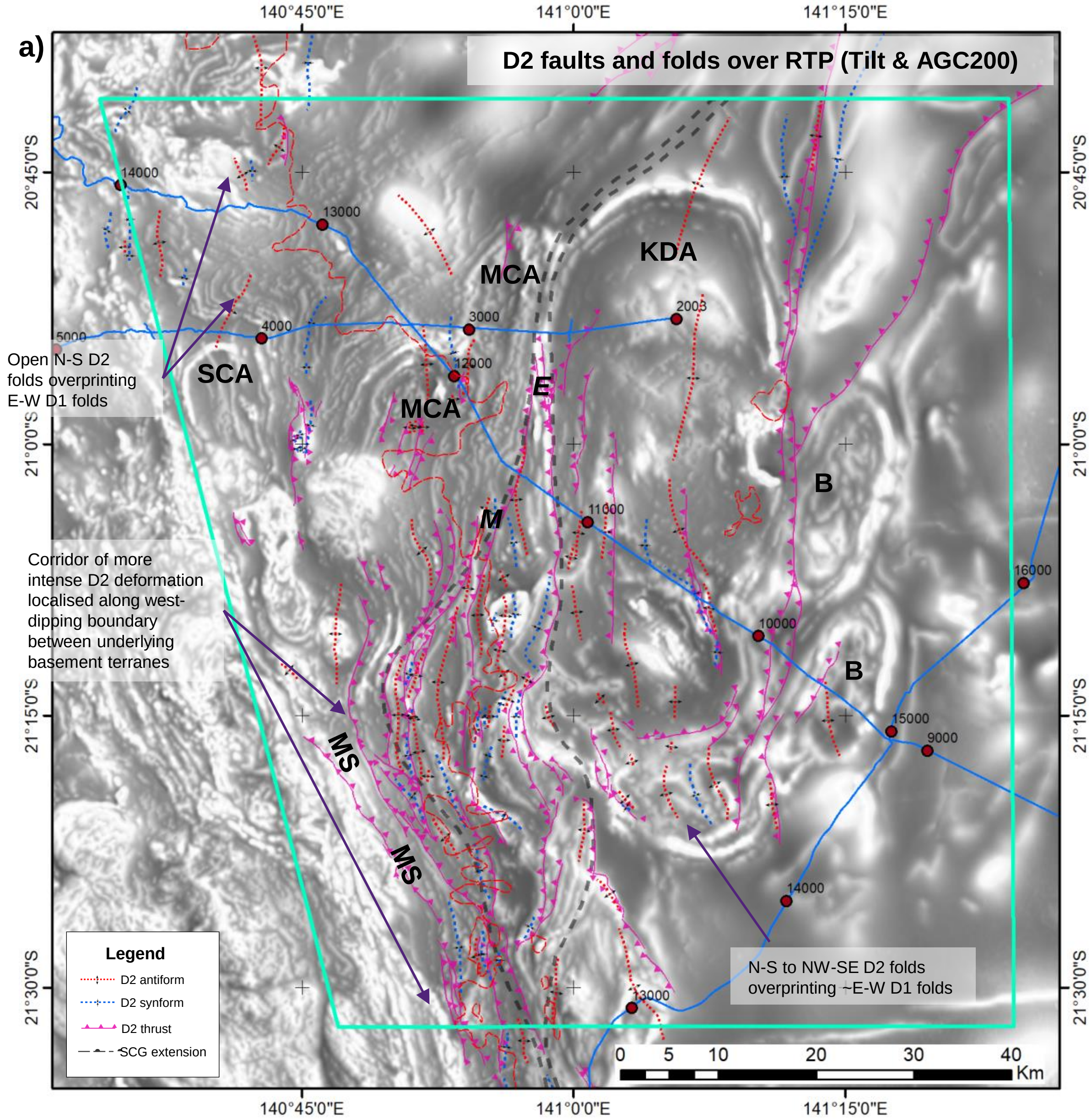


Figure 5.12. a) D2 faults and folds overlain on RTP (AGC 200 and Tilt). Green dashed line highlights the D2 high strain zone related to underlying terrane boundaries. Red dashed line shows the limit of Mount Isa Province outcrop. Seismic lines are shown in yellow. b) Small map shows location of D2 faults relative to the extensional fault system, which was largely reactivated during D2.

5.0 Solid Geology Interpretation

D3 and D4 structures

As discussed above, the emphasis during this project has been on the extensional fault system and separating it from D1 and D2 structures. The available data and the geology of the region facilitated this interpretation. Further detailed mapping at mine scale and/or integration of detail work from mines and prospects is required in order to better understand the post D2 events and the structures related to 1520-1500 Ma "D4" age mineralising events. D4 structures are generally smaller scale than earlier formed structures and are only mapped at mine and prospect scale.

D3 ~E-W to ENE-WSW shortening

- Post D2 faults that trend NNW are interpreted to have initiated during D3 (Figure 5.13) consistent with the CSIRO Uncover Cloncurry (Austin et al., 2016a), Deep Mining Queensland (Murphy et al., 2017), Southern Eastern Fold Belt projects (Hinman et al., 2018).

D4 ~NW-SE shortening (subvertical sigma 3)

- Murphy et al. (2107) summarised the stages of D4: ~1515-1500 early D4 shortening is associated with emplacement of thick, sill-like Williams-Naraku granites into the mid and upper crust; structures vary from brittle to ductile depending on lithologies and pre-existing fabrics (e.g. strongly foliated high grade units accommodate D4 by slip on appropriately oriented pre-existing fabrics); then as shortening continues strain partitioning around granites results in fracturing and brecciation providing conduits for high T oxidised brines associated with granites; this is followed by ~1500-1495 Ma (syn-) to late magmatism faulting that cuts IOCG mineralisation and granites.
- Late WNW-trending faults in Eloise area are referred to as D4 (Figure 5.13) based on detailed mapping at the mine (e.g. Baker, 1998; Hodkinson et al., 2003). Although their orientation is not consistent with NW-SE shortening, they do occur along strike of a corridor of NW-trending De faults and may therefore represent reactivation of pre-existing faults.
- In the Sugarbag – Strathfield permit area (yellow oval), NE- to ENE-trending D4 faults and folds overprint D2 structures consistent with ~NW-SE shortening direction (cf. Murphy et al., 2017) and reactivate earlier formed De faults. In addition, reactivation of De extensional faults and D2 thrust faults (shown in yellow) resulted in northward displacement of the Sugarbag area and reorientation of pre-existing structures (e.g. the ~E-W trends either side of the N-S late D4 fault were originally oriented NE to NNE). This deformation was influenced by emplacement of the large Williams-age intrusions to the south ("granite X") and north (Kevin Downs granite; KD).

Late D4

The best documented examples of structures that clearly cut fully solidified Williams-Naraku granites are the Cloncurry Fault and the fault cutting "granite Y" in the east of the AOI. The ~N-S fault zone in the centre of the AOI is interpreted to have been active at this time as well given the change in depth indicated by the magnetic data. Note that later Mesoproterozoic and younger movement has been documented on the Cloncurry Fault and structure cutting granite Y (Austin and Blenkinsop, 2008; Korsch et al., 2011, respectively).

- The Cloncurry Fault (as opposed to the Cloncurry Thrust) is a steep E-dipping reverse fault. It is not well imaged in the seismic data but disruption of reflections defines a steep, east-dipping fault on 06GA-M6 and 06GA-M5 to the south of the AOI where the movement is greater. This brittle transpressive fault system has minor displacement in the north but greater reverse displacement in the south (Murphy et al., 2017). Thickening of the MNQ to 6km or greater on seismic lines 06GA-M5 and M6 indicates syn-depositional activity on this fault in the region south of the AOI. But activity within the AOI may be dominantly D4.
- 06GA-M5 shows reactivation of a west-dipping fault zone that thrusts SCG over the large Williams-Naraku intrusion (Granite Y) and the overlying Millungera Basin at the east end of the seismic line (e.g. Korsch et al., 2011; Gibson et al., 2016).

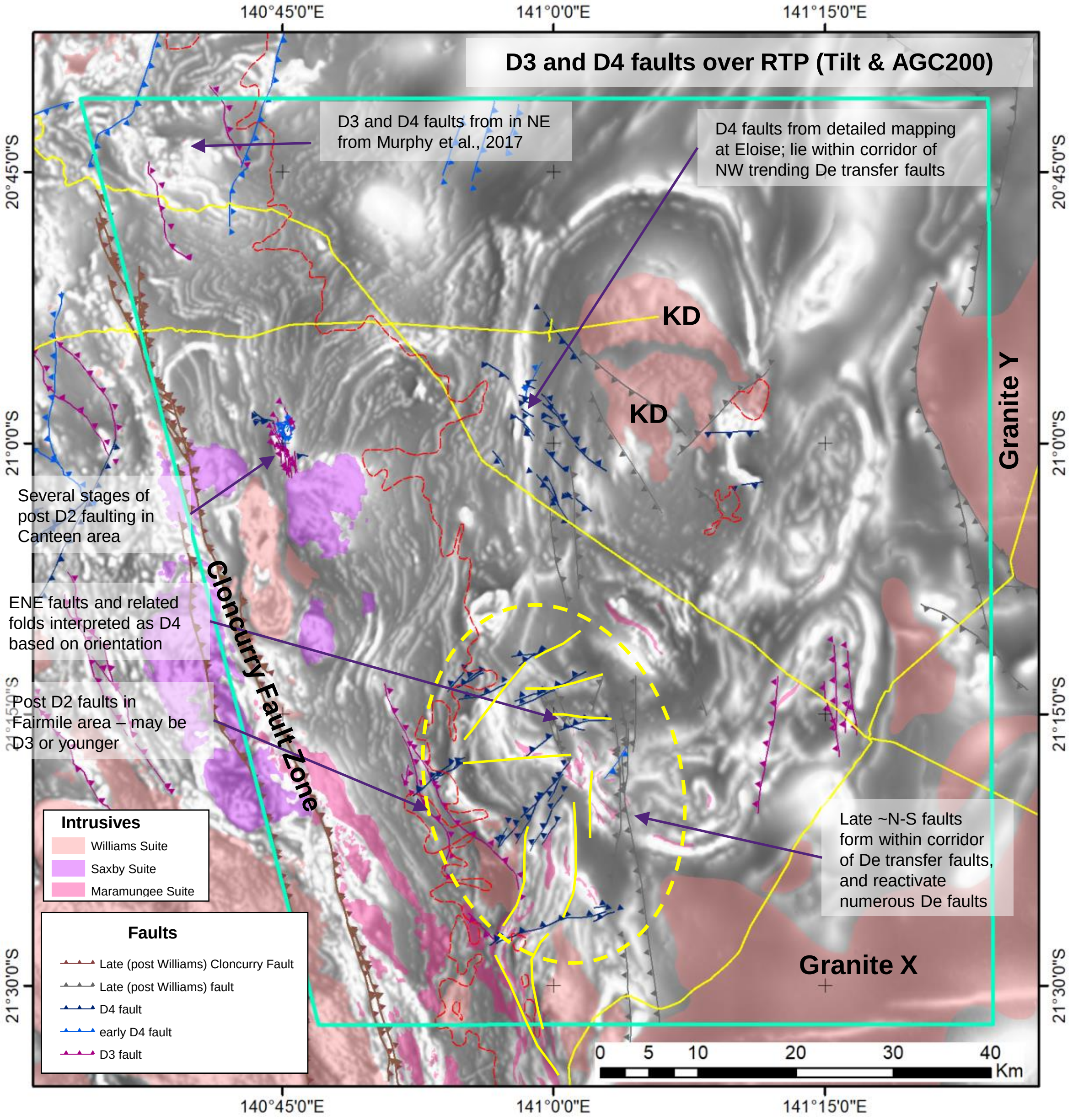


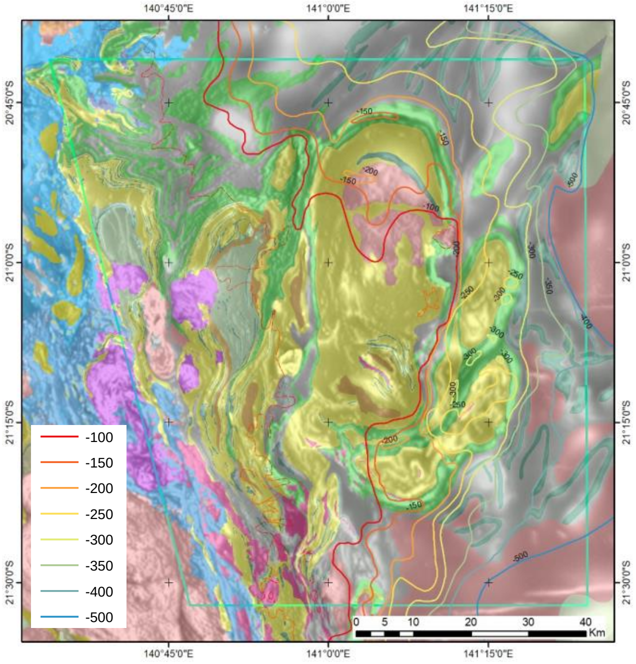
Figure 5.13. D3 and D4 faults overlain on RTP (AGC 200 and Tilt). Red dashed line shows the limit of Mount Isa Province outcrop. Seismic lines are shown in blue. Numbers refer to text. Intrusives of the syn-D4, 1520-1500 Ma Williams-Naraku suite are shown in pale pink; the older 1534 to 1523 Ma Saxby granites are in purple, and the 1569-1545 Ma Maramungee suite are in red. Yellow lines indicate reactivated faults discussed in text.

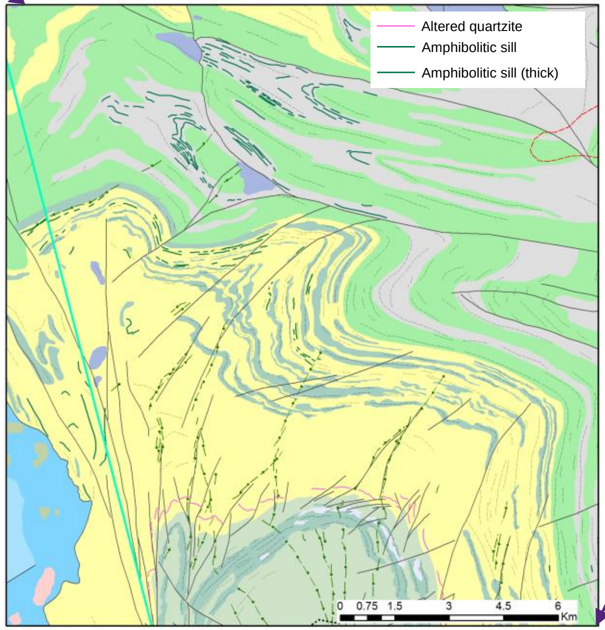
THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

Additional maps

Figure 5.14 shows a few additional datasets included in the GIS. The two dykes sets, one axial planar to the Snake Creek and Middle Creek anticlines (green dotted line) and a later cross cutting set (purple dotted line; possibly equivalent to the Lakeview Dolerite ca 1116 Ma), are shown on Figure 5.14a along with the interpreted buried intrusions (black dashed outline), faults (medium black lines) and trend lines (thin grey dashed lines). Figure 5.14b shows the updated depth to basement contours for the project area overlain on the solid geology with the RTP in the background. The contours are in metres below the surface. The geological units dataset includes thin units of iron formation, amphibolite, basalt, graphitic schist and a few ore zones. These features are shown in an enlarged area in Figure 5.14c, as they have been mainly interpreted at a high resolution based on a range of datasets including HyMap, mine or prospect scale maps, and drill data. The green lines in Figure 5.14c show the amphibolite sills mapped from HyMap data and the pink lines near the base of the MNQ show the altered quartzite unit mapped from HyMap and radiometric data, as well as Google Earth images (see also Figure 5.4).

Legend
Axial planar dyke
Late dyke
Faults
Trend_lines
Intrusion_within_basement





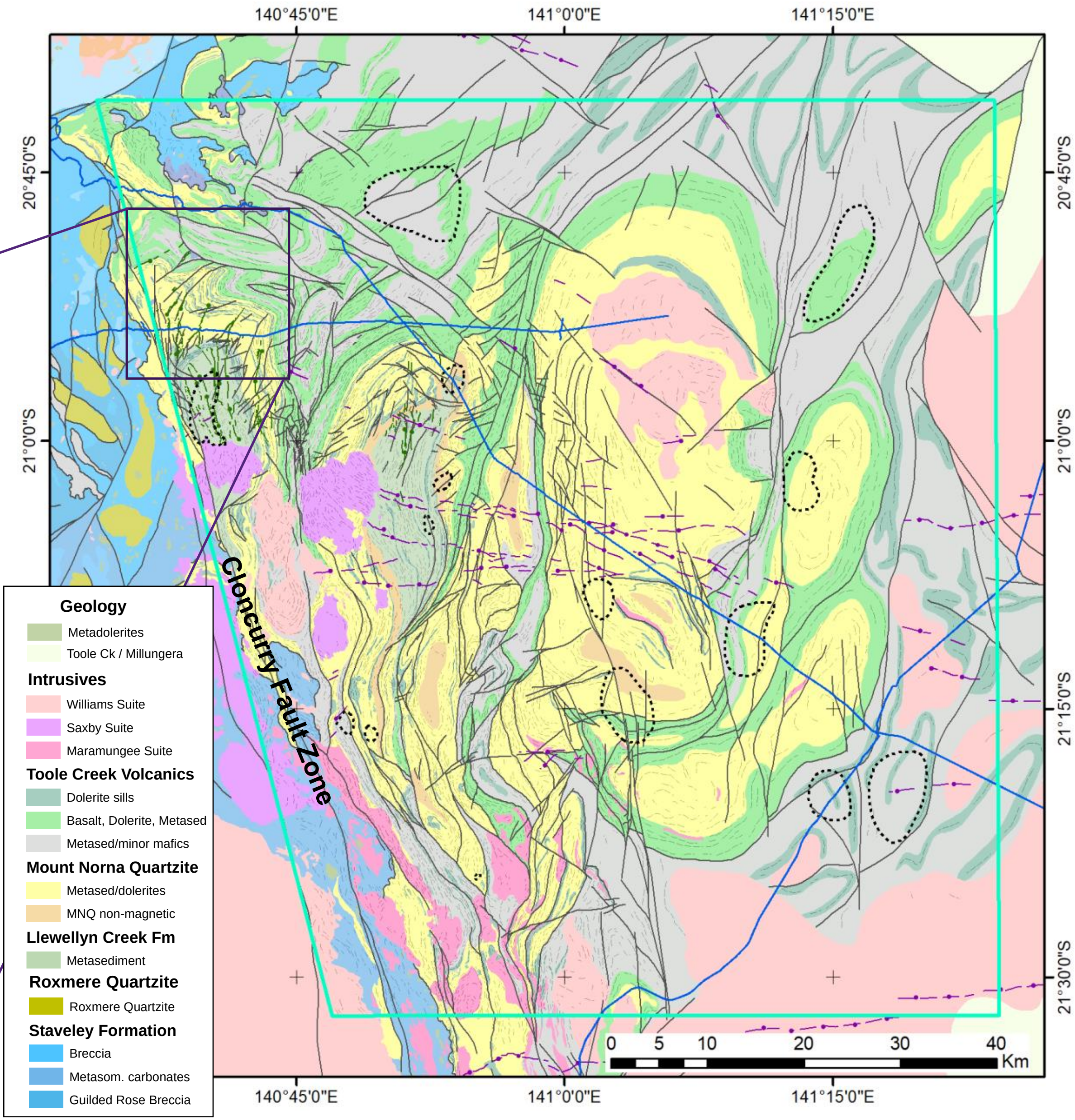


Figure 5.14. a) Solid geology map with faults, trend lines, dykes and interpreted location of intrusions within the basement. b) Solid geology map overlain with depth to basement contours (metres below the surface). c) detailed map of the hinge zone of the Snake Creek anticline showing the interpreted sills and altered quartzite.

Chapter 6

Summary and Conclusions

6.0 Summary of Key Results

Crustal architecture

The present structural geometry of the Soldiers Cap Group (SCG) and the juxtaposition of the underlying basement blocks reflects Isan collisional processes ca 1610-1500 Ma. The geometry and spatial relationships were very different during extension and deposition of the SCG ca 1680-1650 Ma. In addition, the ca 1780-1730 Ma period is marked by several periods of extension and deposition across the Mount Isa Province, however the extent and effects of these events in the Eastern Fold Belt are unclear as rocks of this age are not exposed. See Figure 6.1 for a map showing the approximate extent of the three basement terranes.

Numil

- The thin to very thin, low-angle fault blocks of the Numil crust (07GA-IG1; Figure 3.1) represent previously hyperextended crust. The fault blocks would have been distributed over a wider area and are likely to have been separated or nearly separated from the "central" competent block, Mount Isa crust and/or Etheridge Province crust prior to the Isan Orogeny.
- The observed dip of the Numil fault blocks, and bounding faults, varies between seismic lines and has been influenced by the more competent basement terranes adjacent. The W to NW dip on the eastern end of both 06GA-M5 and M4 (Figures 3.4; 3.5) is furthest from the influence of adjacent blocks and therefore probably is the least reoriented. Therefore the Numil faults blocks are tentatively interpreted to have originally dipped west to NW during extension but more gently than the present dip.

Central competent block

- The competent block is well defined to the north of the AOI on 07GA-IG1 where it has a steep, west-dipping boundary with Mount Isa crust (Gidyea Suture of Korsch et al., 2012), and low-angle eastern boundary where it is overthrust by the highly thinned fault blocks of the central Numil terrane. It may have formed part of either Mount Isa or Numil crust prior to 1680-1650 Ma (and earlier) extension; alternatively it may represent an exotic fragment caught up in Numil accretion to Mount Isa Province pre 1850 Ma.

Mount Isa

- Poorly reflective crust of the Mount Isa Province is thickest where it is juxtaposed against the "central" competent block (07GA-IG1, 06GA-M4; Figures 3.1; 3.3), in contrast the eastern edge of the Mount Isa crust has a wedge shape where it is thrust over the Numil crust in the south (06GA-M6 (Figure 3.5), 14-15GA-CF3).

These three distinct basement blocks were distributed over a wider area prior to initial Isan shortening from ca 1610 Ma. Stress during extension would have been localised along rheological contrasts such as the boundaries of competent blocks. The thinnest crust and deepest basins would therefore have been present adjacent to the competent basement blocks, i.e. Mount Isa and the central competent block. The effects of shortening would initially have been focussed in the basins overlying the thinnest crust, involving inversion of extensional faults (e.g. during D1; ca 1610 Ma), prior to increased interaction between the underlying basement terranes as the Isan Orogeny progressed during D2 crustal thickening by ca 1590 Ma.

Gidyea Suture

- The present-day Gidyea "Suture" (Korsch et al., 2012) represents juxtaposition of crustal blocks "separated" during SCG extension. This recognition allows for interpretation of the Numil crust as highly attenuated crust of the Mount Isa Province. However, given the pervasive fabric of the Numil terrane evident in seismic, it is considered likely to represent a distinct terrane, mostly likely an orogenic belt or a ribbon terrane, that accreted earlier in the evolution of the Mount Isa Province (e.g. pre 1850 Ma Korsch et al., 2012) prior to localising extension during SCG time.

Hyperextension, serpentinisation and mantle exhumation

- Whilst it is not possible to accurately assess the amount of extension and crustal thinning, the thin to very thin, low-angle fault blocks of the Numil crust (07GA-IG1; Figure 3.1) with locally preserved extensional offsets (Korsch et al., 2012) are interpreted to represent previously hyperextended crust. The central competent block would have been "separated" from the hyperextended Numil crust by a SCG depocentre floored by highly thinned continental crust, or exhumed mantle, or possibly even a narrow ocean basin. The central competent block and Mount Isa Province would have been similarly separated.
- Gravity modelling on 07GA-IG1 indicates the presence of higher density bodies along both margins of the central competent block (i.e. within the west-dipping Gidyea "Suture" and the eastern boundary with the Numil crust; Korsch et al., 2012). These higher density zones are consistent with incorporation of serpentinised mantle, or even slivers of ocean crust, in the "suture" zones bounding the central competent block. However, other explanations are possible and further work is required to assess this hypothesis.

Structure of the Soldiers Cap Group

The Soldiers Cap Domain represents a large extensional basin(s) inverted during the Isan Orogeny (cf. Giles et al., 2006a). The present-day geology and structure of the Soldiers Cap Group (SCG) has been strongly influenced by its extensional architecture and the underlying basement terranes.

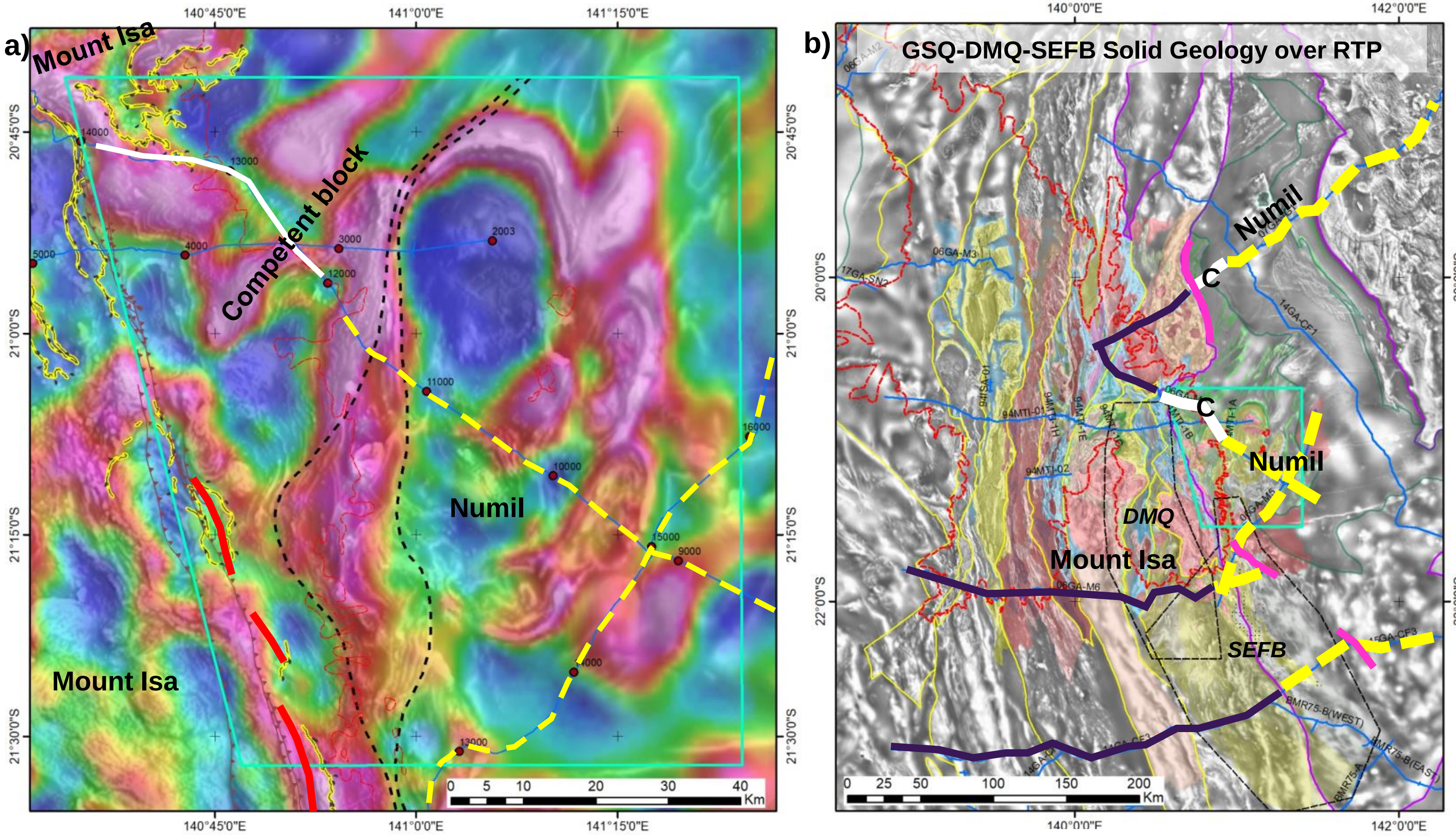
- Within the AOI, the Staveley detachment fault system, and associated set of inverted normal faults (Figure 4.5), is best preserved where it overlies the central competent block (Figure 4.6). It is most likely, however, that this spatial association results from translation during Isan shortening and that the overlying SCG package was deposited in a basin on the margin of the central competent block which formed a relative high during basin development.
- Along the SW of the AOI, the Staveley detachment is folded in an elongate NNW-trending fold cored by the Staveley Formation carbonates (Figure 6.1a). This feature is overprinted in part by intrusion of the 1569-1545 Ma Maramungee Suite but it can be traced in outcrop and magnetic data for >80km and is imaged on 06GA-M6 and M5.
- Austin and Blenkinsop (2008; 2010) suggest the Cloncurry Fault initiated during SCG basin development; the thickening of the MNQ to >6 km along the southern Cloncurry Fault (06GA-M6 and M5) supports their interpretation and indicates that the fault was active during MNQ deposition. It is unclear how much extension was localised along the southern fault zone. The underlying Mount Isa and Numil basement terranes both have a highly thinned margin that could be related to extension during SCG deposition, but could equally reflect earlier events.
- The strong E-W trend of D1 folds in the northwest of the AOI is interpreted to reflect the WNW- and ENE-trending extensional faults and the underlying ENE-trending faulted boundary between the Mount Isa crust to the north and the competent block to the south. D2 folds in this area are very broad, and open, contrasting with the tight upright D2 folds mapped across the EFB. This is interpreted to reflect the locally steep ~E-W layering with abundant, strong mafic units (controlled by extensional and D1 structures) and strain partitioning related to the underlying basement terranes.
- The structural geometry of the SCG differs in the south and east of the AOI where the Numil basement terrane underlies these units. The moderate, west dipping structures of the underlying crust extend into the upper crust and SCG units (Figure 4.6). The boundary between the SCG and underlying basement (and/or older cover units) is not obvious in the seismic data. But it is expected to be offset by reactivation of these structures. The west-dipping structures are interpreted to have been active during extension as well as later shortening (Figures 4.6 and 4.7).
- Variations in the thickness of the syn-extensional mafic igneous units of the TCV are evident from the gravity data. These thickness variations may result from the presence of a mafic intrusive body at depth (i.e. the magma chamber responsible for the sills and flows, e.g. Hatton, 2004), localisation of sills due to syn-emplacement faulting, thickening of sills into syn-depositional faults, and/or repetition or thickening of mafic units due to inversion. Two potential locations for mafic intrusive complexes are highlighted in the north of the area. Large granite bodies in the east and south of the AOI result in large negative gravity anomalies making it difficult to assess the extent and thickness variations of the TCV mafic igneous units, but a few smaller anomalies are evident and possibly indicative of a zone of greater mafic magmatism during extension.
- Hatton (2004) and Hatton and Davidson (2004) suggest that syn-depositional circulation of the basin fluids responsible for development of iron formations and BHT mineralisation was driven at least in part by the heat from the mafic magma chambers in the deeper levels of the SCG basin. The new understanding of the extensional architecture and potential location of magma chambers therefore provides insights for further detailed assessment and key information for future exploration.

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Influence of the basement terranes

Figure 6.1 shows the extent of the different basement terranes from the assessment of the regional seismic lines for the AOI (Figure 6.1a) and the surrounding region (Figure 6.1b) with the competent block (C) in white, the highly reflective Numil crust in yellow and the approximate surface location of the Gidyea Suture in pink. The extent of the central competent block is not well defined so its limit is approximate on line 06GA-04. The wedge of Numil crust on 06GA-04 pinches out close to ~12000 CDP, whereas the Numil crust with its strong W-dipping reflections extends along the full length of 06GA-05 (Figure 6.1c). It is thrust beneath the Mount Isa Crust to the west (Figure 3.3). These underlying basement terranes and their boundary zones provide one of the fundamental controls on upper crustal geology and structure of the SCG sediments.

1. The flat-lying Staveley detachment fault system is well developed within the northwest part of the AOI where it overlies the central competent block (e.g. 06GA-M4 Figure 3.5; 4.6). The middle and lower crust is not well imaged on 94MTI-01, however given its position relative to 06GA-M4, the competent block must underlie the well-imaged Staveley detachment on the eastern part of line 94MTI-01 (e.g. Figure 4.5).
2. In contrast, the Staveley detachment is not evident above the Numil crust and the SCG of the upper crust shows the same dominantly west-dipping structures as the underlying basement. In addition, a prominent zone of west-dipping structures is developed along the western limit of Numil crust (dashed outline Figure 6.1a). This is evident on 94MTI-01, 06GA-M4 and 06GA-M5 (Figure 4.5; 4.6; 4.7). This zone is also evident on 14-15GA-CF3 and 06GA-M6 but is not as clear on 06GA-M6 as the line does not extend far enough to the east.
3. D2 folds and faults are abundant within this ~N-S high strain zone along the western boundary of the Numil basement terrane (Figure 6.1a) indicating localisation of deformation during D2 shortening. This zone has a moderate west dip similar to the pervasive fabric of the Numil basement terrane. The approximate surface location of this zone is outlined in black (Figure 6.1a). It trends NNW in the south of the AOI where the Numil is thrust under the Mount Isa Province and NNE to NE in the north where Numil is thrust over the central competent block.
4. The Staveley detachment fault system is exposed at surface along the western boundary of the Numil and central competent terranes with the Mount Isa Province basement to the west (Figure 6.1a). Its exposure reflects localisation of deformation along this boundary between underlying basement terranes largely during D2 ~E-W shortening, but some late uplift results from reactivation of the Cloncurry Fault post D2. The Staveley detachment is folded (thick red line Figure 6.1a) and these folds are cut by the late Cloncurry Fault. Seismic line 06GA-M5 shows the folded detachment (SD) sits in the hangingwall of a west-dipping fault zone (which comes to surface at CDP 1200; Figure 6.1c). This fault zone links at depth to the west with the equivalent of the Gidyea "Suture" which forms the boundary between the Mount Isa and Numil basement terranes (Figure 3.3). The Cannington deposit sits above this detachment fault (Figure 4.7; 6.1c). Note that the near surface continuation of the Gidyea "Suture", or equivalent structure, *lies within the SCG* units and the boundary between the Numil or Mount Isa crust occurs further west at depth (e.g. Figure 3.3) as indicated by the gap between the extent of the Mount Isa crust and the location of the Gidyea Suture on Figure 6.1b.



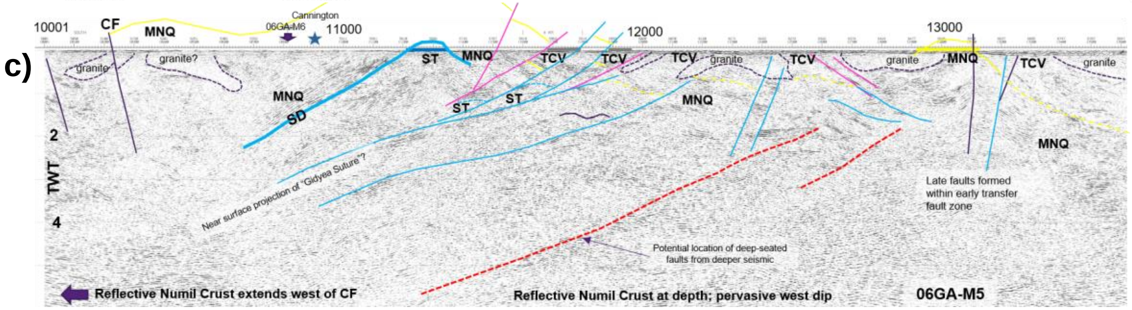


Figure 6.1. a) Approximate extent of the Numil crust (yellow) and the competent block (white) overlain on an image combining the gravity (HP40 km of Bouguer) and magnetic data (RTP - AGC 200 and Tilt) in the AOI. b) The regional extent of the distinctive Numil crust, the competent block, and the location of the Gidyea Suture are highlighted in yellow, white and pink respectively. These features are overlain on the solid geology interpretation from the DMQ-SEFB projects (with partial coverage of GSQ solid geology to west and north) with RTP in the background (AGC 200 and Tilt). The limit of outcropping Proterozoic units of the Mount Isa Province is shown in red. Mount Isa Province domains are shown in yellow with Soldiers Cap Domain highlighted in purple on b (Australian Geological Provinces dataset). The seismic lines are in blue. c) western end of 06GA-M5 showing the folded Staveley detachment fault (see Figure 4.7 for location).

6.0 Answers and Recommendations

Answers to key questions

A set of questions are outlined in the Introduction section:

- Basement beneath the SCG of the Soldiers Cap Domain comprises three basement terranes or blocks: Mount Isa Province, a central competent block and the Numil terrane.
- The Staveley Formation and its associated detachment fault system extends beneath the SCG in the north west of the AOI and along the western margin. It is unclear whether the carbonates and/or the detachment extended across the Numil basement in the east and south of the AOI. The pervasive, moderate to low-angle, west-dipping fabric and faults of the Numil crust would have readily accommodated extension and the detachment may not have developed in this area even if the carbonates were deposited.
- The Llewellyn Creek Formation is tentatively interpreted to be less extensive than currently shown on published GSQ geology maps, however, this requires at least field checking and possible additional analysis to evaluate. The LCF is interpreted to have been deposited prior to the 1680-1650 Ma SCG extensional event (e.g. Hinman, 2017; Figure 1.3), therefore its distribution may be more limited than the syn-extensional MNQ and TCV units and it may have been thinned and/or partly dismembered by extensional faulting during extension (cf. Clerc et al., 2016). It is considered unlikely that the NNW-trending belt of pelitic units east of the Maramungee Suite between ~21°15’S and ~21°30’S, comprises LCF. The regional geometry and stratigraphy from seismic and plan view datasets favours the presence of TCV and MNQ in this area.
- Several additional areas have been recommended for review of the geological units of the SCG including assessment of the potential for overturned stratigraphy on a local or regional scale.

Implications for mineralisation

This study provides a range of interpreted datasets and ideas to support exploration in Eastern Fold Belt and to provide the context for interpretation of permit and mine scale exploration datasets.

- The updated 2019 solid geology map provides a significantly improved understanding of the region as it is the first interpretation incorporating proprietary industry data to help constrain the rock types and distribution of units.
- Although numerous workers have interpreted the Soldiers Cap Domain as a large extensional basin (e.g. Giles et al., 2006a; Southgate et al., 2013; Gibson et al., 2018), this study provides the first interpretation of the SCG extensional fault system.
- The extensional fault system represents the main set of structures within the SCG and it has controlled all subsequent deformation to some degree. D1 thin skinned thrusting inverted many of the normal faults; D2 ~E-W shortening tightened D1 folds in some areas and developed new folds in other areas depending on the orientation of extensional structures and the location relative to the main terrane boundaries which localised deformation during the later stages of D2. More detailed mapping is required to assess the importance of the extensional faults during D3 and D4 shortening, however these events are typically more dependent on local variations in rock type (i.e. competency, cf. Murphy et al., 2017).
- This project defines the extent of underlying basement terranes which is a key step in understanding the crustal architecture.
    - The boundaries of the three terranes provide crustal scale zones of weakness that readily reactivate.
    - Differences in the nature of the three basement terranes influenced the upper crustal structural evolution (during extension and compression) and internal variation within each terrane controlled the location of crustal scale structural zones providing deep-seated conduits for magmas and fluids.
- The crustal architecture can be combined with the assessment of variations in thickness of the mafic igneous rocks and the controls on mafic magmatism to better understand the distribution of the potential heat sources driving syn-depositional circulation of basin fluids responsible for development of iron formations and BHT mineralisation (cf. Hatton;2004; Hatton and Davidson; 2004).

The combined interpretation of the surface geology, structure of the SCG and the architecture of the underlying crust provide the context required for a mineral systems approach as well as interpretation of permit to mine scale exploration datasets.

Recommendations

Further work is recommended in order to test the interpretation presented here and to further progress our understanding of the region. Additional improvement of the currently available data is possible, but time consuming.

1. Compilation and integration of additional ground gravity stations or gravity gradiometry data available from open file reports, or contributed by industry, would improve the resolution of the gravity data in some areas and would therefore help to refine the solid geology interpretation.
2. A vast amount of data is available from the company reports in the QDEX system. However, most heritage data is held as pdf and pgn documents, and requires manual handling to extract the relevant data. Useful data includes geological maps, geophysical data and drill hole data.
3. Drillhole database – compilation of additional drillhole data from QDEX or companies would provide further constraints on the solid geology interpretation.

Any project is limited by the time and budget available to complete the work. More detailed interpretation and/or compilation and integration of data would benefit the project.

1. More detailed interpretation of the seismic data using a seismic interpretation package would help to refine and test our understanding of the structure and stratigraphy.
2. Detailed field mapping in key areas to assess the outcrop geometry and its relationship to the seismic data.
3. Compilation and integration of detailed mapping and analysis from mine and prospect scale, would help to test and improve the geological model presented in this report.

Notes on the GIS datasets

In order to facilitate use of the project results for those working in the Eastern Fold Belt, the interpreted solid geology and structure datasets produced for this project have been largely integrated with the previous interpretation from the Deep Mining Queensland (DMQ; Murphy et al., 2017) and southern Eastern Fold Belt (SEFB; Hinman et al., 2018) projects, which in turn were integrated with the GSQ solid geology dataset available to those projects. The combined coverage included in this project is shown in Figure 6.1b. The symbology for units and structures has been largely maintained from the previous projects.

Datasets:

- The **solid geology** covering the AOI comprises a single dataset including all “timeslice” units that intersect the AOI and/or were modified during this project. This includes: Staveley Formation, Llewellyn Creek Formation, Mount Norna Quartzite, Toole Creek Volcanics (and dolerite sills within other Soldiers Cap Group units), Maramungee Suite, Saxby Suite and Williams Suite granites, and metadolerites. All other “timeslice”” units have not been edited, and are included in the GIS project as the individual datasets created during the DMQ and SEFB projects.
- The **fault, fold, trend line**, **dyke,** and linear **geological unit** datasets build on those from the SEFB project and provide a largely seamless interpretation. However, the D1 faults interpreted between the Staveley and SCG units have been left in the original dataset; they are duplicated in this project and interpreted as De extensional faults. The contacts dataset for this project is restricted to those within the Soldiers Cap Group. An additional dataset highlights the interpreted location of a few buried intrusions.
- The limit of Mount Isa outcrop has been updated for the project area, and the depth to basement contours have been updated based on the data available for this project.

Conclusions

The need to explore in areas of deeper cover and/or further from outcrop is currently driving a range of research initiatives and data acquisition programs across Australia. The resulting knowledge advancement and growing wealth of precompetitive data acquired by state and federal governments, provide new opportunities to industry but also require detailed interpretation and integration with existing datasets in order to continue to progress our understanding of the fundamental geology of the covered regions. This study of the central Eastern Fold Belt has been prompted by recent data acquisition. The new and older datasets such as the magnetic, gravity, radiometric, and drilling data highlight the folded patterns of the near surface geology in plan view, but integration with the seismic data has made the difference in providing a clearer picture of the 3D geometry and history of the major structures in the upper crust as well as the architecture of the inherently heterogeneous underlying crust (Figures 6.1 and 6.2).

Three distinct crustal blocks (basement terranes) are present in the mid to lower crust of the project area: 1) Mount Isa Province (thick, poorly reflective crust); 2) Numil Province (thinner highly reflective crust), and 3) an intervening competent block of moderately reflective crust (referred to here as the central competent block). These three distinct basement terranes would have been distributed over a wider area prior to 1610-1500 Ma Isan shortening. The effects of shortening would initially have been focussed in the basins overlying the thinnest crust, involving inversion of extensional faults (e.g. during D1), prior to increased interaction between the underlying basement terranes as the Isan Orogeny progressed during D2 crustal thickening.

The structural geology the upper crust in the NW area of the AOI comprises a network of extensional faults developed during the ca 1680-1650 Ma SCG extensional event (Figure 6.2a). The Staveley “detachment” outcrops just west of the AOI and it can be traced at depth in the seismic where it forms a detachment surface at ~2 sec TWT below the set of anticlines (3-4 km wavelength) separated by dominantly east-dipping faults in line 94MTI-01 (Figure 6.2b). These structures differ from the three large folds previously mapped at surface. In cross section view on the seismic line, these faulted anticlines are typical of a set of inverted normal faults. Shortening of a wedge-shaped growth package against a normal fault results in an anticline adjacent to the fault and a much smaller or no syncline.

Integrated interpretation of the seismic with the plan view datasets provides the first interpretation of the network of extensional faults in this region (Figure 6.2). The faults mapped in this study are broadly NE trending and NW trending faults consistent with the regional ~NW-SE to E-W extension direction for the Calvert / Sybella extensional event in the Western Fold Belt (e.g. Gordon, 2004 Gibson et al., 2008). Variations in the fault trends reflect both syn-extensional control by the underlying basement and reactivation during Isan Orogeny compression. The network of extensional faults has been interpreted based on thickness variations in plan view (outcrop or magnetics, radiometric), cross section geometry in seismic (and correlation along strike), and variations in gravity data indicative of a thicker mafic section in TCV.

The structural style within the SCG units of the upper ~ 10 km of crust differs in relation to the underlying basement terranes. For example, the Staveley detachment is well developed over the competent block, as well as to the west of the AOI overlying the Mount Isa Province. In contrast, the detachment fault is not developed over the Numil basement terrane. Instead the upper crust is dominated by west-dipping faults many of which extend into the lower crust or directly link with west-dipping fault zones of the underlying basement terrane.

The main aim of this project was to produce a new solid geology interpretation extending the highly prospective Eastern Fold Belt undercover to the east and south (Figure 6.2a) and resulting in an improved understanding of the structural complexity, as well as the context and controls on mineralisation, and to provide a basis for interpretation of new exploration datasets in the area. These objectives have been achieved by providing an understanding of the upper crustal geology and structure as well as the underlying crustal architecture of the central Eastern Fold Belt, both of which are critical to a minerals system approach to exploration for Broken Hill Type Ag-Pb-Zn massive sulphide as well as IOCG-style Cu-Au deposits in this region. Although previous workers have interpreted the Soldiers Cap Domain as a large extensional basin that was inverted during the Isan Orogeny (e.g. Giles et al., 2006a), this study provides the first interpretation of the early extensional fault system of the Soldiers Cap Domain and its control on subsequent shortening during the Isan Orogeny, and hence provides significant support for exploration in this highly-prospective covered region. This project also defines the extent of underlying basement terranes, their control on upper crustal structural evolution and the location of crustal scale structural zones that provide deep-seated conduits for magmas and fluids. This information can be combined with the assessment of controls on mafic magmatism to better understand the distribution of the potential heat sources driving syn-depositional circulation of basin fluids responsible for development of iron formations and BHT mineralisation (cf. Hatton;2004; Hatton and Davidson; 2004).

Follow-up work is recommended in order to test this interpretation, including more detailed mapping and integration with prospect and mine scale data. Reassessment of the Soldiers Cap Group stratigraphy and distribution of the three main units is also recommended in several areas.

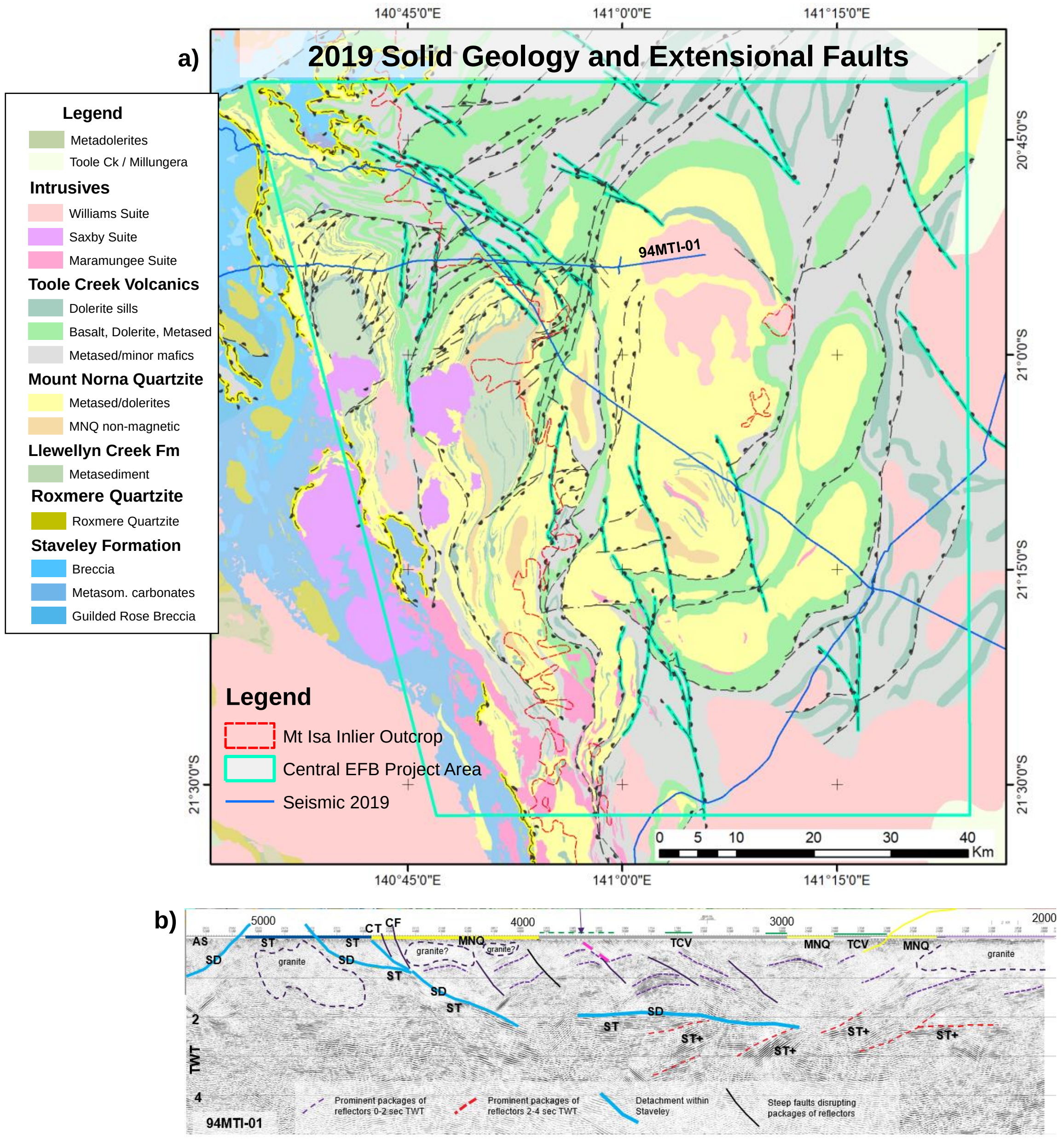


Figure 6.2. a) 2019 solid geology map and the extensional fault system. Detachment faults are highlighted in yellow and the main transfer faults in cyan. b) Simplified interpretation of seismic line 94MTI01 (location shown on map). CF = Cloncurry Fault; CT = Cloncurry Thrust; MNQ = Mount Norna Quartzite; SD = Staveley detachment; ST = Staveley Formation; ST+ = Staveley Formation plus older units; TCV = Toole Creek Volcanics.

References

References

Adshead-Bell, N. S. 1998. Evolution of the Starra and Selwyn high strain zones, Eastern Fold Belt, Mount Isa Inlier: Implications for Au-Cu mineralization: Economic Geology, 93, p. 1450-1462.

Austin, J.R., Gazley, M.F., Walshe, J.L. and Patterson B.O., 2016a. Uncover Cloncurry – Summary: Integrated structural, metasomatic and metallogenic history of the Cloncurry District. CSIRO report EP166451, Australia, pp. 45.

Austin, J., Walshe, J., Gazley, M., Sisson, M., leGras, M., Godel, B. 2016b. Canteen Cu-Au prospect: Integrated petrophysical and geochemical analyses. In: Gazley, M., editors. Uncover Cloncurry. North Ryde: CSIRO; 2016.

Austin, J.R., Blenkinsop, T.G., 2008. The Cloncurry Lineament: geophysical and geological evidence for a deep crustal structure in the Eastern Succession of the Mount Isa Inlier. Precambrian Research 163, 50–68.

Austin, J.R., Blenkinsop, T.G., 2010. Cloncurry Fault Zone: strain partitioning and reactivation in a crustal-scale deformation zone, Mt Isa Inlier, Australian Journal of Earth Sciences, 57, 1-21.

Baker, T., 1998. Alteration, mineralisation and fluid evolution at the Eloise Cu–Au deposit, Cloncurry district, NW Queensland. Economic Geology, 93, 1213–1236.

Baker, M.J., Crawford, A.J., Withnall, I.W., 2010. Geochemical, Sm-Nd isotopic characteristics and petrogenesis of Paleoproterozoic mafic rocks from the Georgetown Inlier, north Queensland: implications for relationship with the Broken Hill and Mount Isa eastern succession. Precambrian Research, 177, 39–54.

Bell, T. H. 1983. Thrusting and duplex formation at Mount Isa, Queensland, Australia. Nature, 304, 493-497.

Bell, T.H., 1991. The role of thrusting in the structural development of Mount Isa mine and its relevance to exploration in the surrounding region. Economic Geology, 86, 1602–1625.

Bell, T. H. and Hickey, K. A. 1998. Multiple deformations with successive subvertical and subhorizontal axial planes in the Mount Isa Region: Their impact on geometric development and significance for mineralisation and exploration. Economic Geology, 93, pp. 1369-1389.

Bradshaw B.E. and Scott D.L. 1999. Integrated basin analysis of the Isa Superbasin using seismic, well log and geopotential data: An evaluation of the economic potential of the Northern Lawn Hill Platform. AGSO Record 1999-19, p. 28.

Brooks C. K., Larsen L. M. and Nielsen T. F. D. 1991. Importance of iron-rich tholeiitic magmas at divergent plate margins. Geology, 19, 269–272.

Cadenas, P., Fernández-Viejo, G., Pulgar, J. A., Tugend, J., Manatschal, G., and Minshull, T. A. 2018. Constraints imposed by rift inheritance on the compressional reactivation of a hyperextended margin: Mapping rift domains in the North Iberian margin and in the Cantabrian Mountains. Tectonics, 37, 758–785.

Champion, D.C., and Huston, D.L. 2016. Radiogenic isotopes, ore deposits and metallogenic terranes: Novel approaches based on regional isotopic maps and the mineral systems concept. Ore Geology Reviews, 76, 229–256.

Clerc, C., Lagabrielle, Y., Labaume, P., Ringenbach, J-C., Vauchez, A., Nalpas, T., Bousquet, R., Ballard, J-F., Lahfid, A., and Fourcade, S. 2016. Basement – cover decoupling and progressive exhumation of metamorphic sediments at hot rifted margin. Insights from the Northeastern Pyrenean analog. Tectonophysics, 686, 82-97.

Cudahy, T., Jones, M., Thomas, M., Laukamp, C., Caccetta, M., Hewson, R., Rodger, A. and Verrall, M. 2008. Next Generation Mineral Mapping: Queensland airborne HyMap and satellite ASTER surveys 2006–2008. CSIRO report P2007/364.

Doherty, G. 1992. Exploration Permit 6982 Soldiers Cap, Second Annual Report submitted by Billiton Australia, February 1992, CR23506.

Donchak, P.J.T. and Clark, D. 2015. Structural architecture of deformed subsurface basins flanking the Mount Isa Inlier interpreted from recent deep crustal seismic transects. Conference abstract and presentation. Specialist Group in Tectonics and Structural Geology, Caloundra, Queensland.

Frogtech Geoscience 2018. North West Queensland SEEBASE® Study and GIS. Queensland Geological Record 2018/03, 161p.

Geological Survey of Queensland. 2015. Cloncurry 1:100,000 Geological Series Sheet 7056. Queensland Government, Department of Natural Resources, Mines and Energy.

Geological Survey of Queensland. 2016a. Mount Angelay 1:100,000 Geological Series Sheet 7055. Queensland Government, Department of Natural Resources, Mines and Energy.

Geological Survey of Queensland. 2016b. Selwyn 1:100,000 Geological Series Sheet 7054. Queensland Government, Department of Natural Resources, Mines and Energy.

Gibson, G.M., Rubenach, M.J., Neumann, N.L., Southgate, P.N., Hutton, L.J., 2008. Syn- and post-extensional tectonic activity in the Paleoproterozoic sequences of Broken Hill and Mount Isa and its bearing on reconstructions of Rodinia. Precambrian Research, 166, 350–369.

Gibson G.M., Meixner A.J., Withnall I.W., Korsch R.J., Hutton L.J., Jones L.E.A., Holzschuha J., Costelloe R.D., Henson P.A. and Saygin E. 2016. Basin Architecture and Evolution in the Mount Isa Mineral Province, Northern Australia: Constraints from Deep Seismic Reflection Profiling and Implications for Ore Genesis. Ore Geology Reviews, 76, 414-441.

Gibson, G.M., Champion, D.C., Withnall, I.W., Neumann, N.L., and Hutton, L.J. 2018. Assembly and breakup of the Nuna supercontinent: Geodynamic constraints from 1800 to 1600 Ma sedimentary basins and basaltic magmatism in northern Australia. Precambrian Research, 313, 148-169.

Giles, D. 2000. Tectonic setting of Broken Hill-type mineralisation: the Cannington perspective. PhD thesis, Monash University, Melbourne, Victoria.

Giles, D., Ailleres, L., Jefferies, D., Betts, P.G., Lister, G.S., 2006a. Crustal architecture of basin inversion during the Proterozoic Isan Orogeny, Eastern Mount Isa Inlier, Australia, Precambrian Research, 148, 67-84.

Giles, D., Betts, P.G., Ailleres, L., Hulscher, B., Hough, M., Lister, G.S., 2006b. Evolution of the Isan Orogeny at the south eastern margin of the Mount Isa Inlier. Australian Journal of Earth Science, 53, 91–108.

Giles, D. and MacCready, T. 1997. The structural and stratigraphic position of the Soldiers Cap Group in the Mount Isa lnlier. In Ailleres L. and Betts, P. eds Structural Elements of the Eastern Successions, Australian Geodynamics Research Centre Technical Publication, 63, p61-74.

Giles, D. and Nutman, A. P. 2002. SHRIMP U– Pb monazite dating of 1600 – 1580 Ma amphibolite facies metamorphism in the southeastern Mt Isa Block, Australia. Australian Journal of Earth Sciences, 49, 455 – 465.

Griffin, W. L., Belousova, E. A., Walters, S. G. and O'Reilly, S. Y. 2006. Archaean and Proterozoic crustal evolution in the Eastern Succession of the Mt Isa district, Australia: U – Pb and Hf-isotope studies of detrital zircons, Australian Journal of Earth Sciences, 53, 125-149.

Gordon R. 2004. Isan deformation, magmatism and extensional kinematics in the Western Fold Belt of the Mount Isa Inlier, PhD thesis, University of Queensland, St Lucia, Queensland.

Hatton, O.J. 2004. Sedimentology, geochemistry, Volcanology, and basin evolution of the Soldiers Cap Group Eastern Succession, Mt Isa Inlier, Northwest Queensland, Australia. PhD Thesis, University of Tasmania, Hobart, Tasmania.

Hatton, O.J. and Davidson, G.J., 2004. Soldiers Cap Group iron formations, Mt Isa Inlier, Australia, as windows into the hydrothermal evolution of a base-metal-bearing Proterozoic rift basin. Australian Journal of Earth Sciences 51, 85–106.

Hinman, M. 2017. North West Queensland Proterozoic Time-Space Chart, DNRME-GSQ-SREP Funded Industry Study, Geological Survey of Queensland, Department of Natural Resources, Mines and Energy, Brisbane.

Hinman, M., Huisman, D., Little, G. and Porter, M., 2018. Solid Geological Interpretation of the southern Eastern Fold Belt, Mount Isa, Northwest Queensland. DNRME-GSQ-SREP Funded Industry Study, Geological Survey of Queensland, Department of Natural Resources, Mines and Energy, Brisbane, 15 pages.

Hodkinson, I., Grimsley, E., and Baensch, A. 2003. Eloise Copper Mine Geology - Back to Basics. 5th International Mining Geology Conference, Bendigo, Australia. 17-19 November 2003. p. 1-8.

Komyshan, P. 1991. Mt Tracey JV, Exploration Permits M5734, M5735, M 5827, Combined Annual Report submitted by Aberfoyle Resources Ltd, February 1991, CR22877.

References

Konecny, S. 2005. Exploration Permits 6788, 11169, 11867, 12023, 12285, 12290, Annual Report submitted by Exco Resources NL, August, 2005, CR39056.

Korsch, R.J., Struckmeyer, H.I.M., Kirkby, A., Hutton, L.J., Carr, L.K., Hoffmann, K.L., Chopping, R., Roy, I.G., Fitzell, M., Totterdell, J.M., Nicoll, M.G., Talebi, B., 2011. Energy potential of the Millungera Basin: a newly discovered basin in north Queensland. The APPEA Journal, 51, 295–332.

Korsch R.J., Huston D.L., Henderson R.A., Blewett R.S. and Withnall I.W. 2012. Crustal Architecture and Geodynamics of North Queensland, Australia: Insights from Deep Seismic Reflection Profiling. Tectonophysics, 572-573, 76-99.

Laing, W. P. 1993. Structural/metamorphic controls on ore deposits in the east Mount Isa Block: the key to tonnes and grade: AIG Bulletin 14.

Masini, E., Manatschal, G., and Mohn, G. 2013. The Alpine Tethys rifted margins: Reconciling old and new ideas to understand the stratigraphic architecture of magma-poor rifted margins. Sedimentology, 60, 174–196.

Murphy, T., Hinman, M., Donohue, J., Pirlo, M., Valenta, R., Jones, M. and Pratt, A. 2017. Deep Mining Queensland: Prospectivity Analysis in the Southern Cloncurry Belt, Queensland, Australia. DNRM-GSQ Commissioned Industry Study, Geological Survey of Queensland, Department of Natural Resources, Mines and Energy, Brisbane.

Nordsvan, A.R., Collins, W.C., Li, Z.-X., Spencer, C.J., Pourteau, A., Withnall, I.W., Betts, P.G., and Volante, S. 2018. Laurentian crust in northeast Australia: Implications for the assembly of the supercontinent Nuna. Geology, 46, 251–254.

O’Dea, M. G., Betts, P. G., MacCready, T., and Ailleres, L. 2006. Sequential development of a mid-crustal fold-thrust complex: evidence from the Mitakoodi Culmination in the eastern Mt Isa Inlier, Australia. Australian Journal of Earth Sciences, 53, 69-90.

Page R. W. and Sun S-S. 1998. Aspects of geochronology and crustal evolution in the Eastern Fold Belt, Mt Isa Inlier. Australian Journal of Earth Sciences 45, 343 – 362.

Perez-Gussinye, M., Reston, T. J. and Phipps-Morgan, J. 2001. Serpentinization and magmatism during extension at non-volcanic margins – the effect of initial lithospheric structure. In: Wilson, R. C. L., Whitmarsh, R. B., Taylor, B. and Froitzheim, N. (eds) Non-Volcanic Rifting of Continental Margins: A Comparison of Evidence from Land and Sea. Geological Society, London, Special Publications, 187, 551–567.

Peron-Pinvidic, G. and Manatschal, G. 2010. From microcontinents to extensional allochthons: witnesses of how continents break apart? Petroleum Geoscience, 16, 189–197.

Pourteau, A.., Smit, M.A., Li, Z-X., Collins, W.J., Nordsvan, A.R., Volante, S., and Li, J. 2018, 1.6 Ga crustal thickening along the final Nuna suture. Geology, 46, 959–962.

Queensland Department of Mines and Energy, Taylor Wall and Assoc., SRK Consulting, ESRI Australia. 2000. North West Queensland Mineral Province Report.

Rubenach, M. J., Foster, D. R. W., Evins, P. M., Blake, C. M., and Fanning, C. M. 2008. Age constraints on the tectonothermal evolution of the Selwyn Zone, Eastern Fold Belt, Mount Isa Inlier. Precambrian Research, 163, 81-107

Rubenach, M.J., Lewthwaite, K.J., 2002. Metasomatic albitites and related biotite-rich schists from a low-pressure polymetamorphic terrane, Snake Creek Anticline, Mount Isa Inlier, north-eastern Australia: microstructures and P–T–d paths. Journal of Metamorphic Geology, 20, 191–202.

Simpson, J. 2019. Interpretation of seismic, gravity and MT in the southern Mount Isa Province. New Discovery Program, Technical Workshop for Industry. Mount Isa September 18-19, 2019. Geological Survey of Queensland, Department of Natural Resources, Mines and Energy, Brisbane. https://smi.uq.edu.au/files/48832/IsaSepD2_04_Simpson_Isa%20Geophysics%20Interp.pdf

Southgate, P.N., Neumann, N.L. and Gibson, G.M. 2013. Depositional systems in the Mt Isa Inlier from 1800 Ma to 1640 Ma: Implications for Zn–Pb–Ag mineralisation. Australian Journal of Earth Sciences, 60, 157–173.

Tugend, J., Manatschal, G., Kusznir, N. J., Masini, E., Mohn, G. and Thinon, I. 2014. Formation and deformation of hyperextended rift systems: Insights from rift domain mapping in the Bay of Biscay-Pyrenees. Tectonics, 33, 1239–1276.

Valenta, R., 2018. NW Queensland Mineral Province Deposit Atlas Prototype Report – the Mount Isa and Ernest Henry Deposits. DNRME-GSQ commissioned study and report.

Valenta, R., 2019. NW Queensland Mineral Province Deposit Atlas Report – Chapter 5 Cannington, Pegmont, and Maronan. DNRME-GSQ commissioned study and report.

Williams, P.J., 1998. Magmatic iron enrichment in high-iron metatholeiites associated with "Broken Hill-type" Pb-Zn-Ag deposits, Mt Isa Eastern Succession. Australian Journal of Earth Sciences, 45, 389-396.

Withnall, I.W. and Hutton, L.J. 2013. North Australian Craton. In: Jell, P.A. (ed.) Geology of Queensland. Geological Survey of Queensland, Brisbane, 23–112.

Assoc Prof Karen Connors| Principal Research Fellow
WH Bryan Mining and Geology Research Centre
The Sustainable Minerals Institute
k.connors@uq.edu.au

www.smi.uq.edu.au

facebook.com/uqsmi

twitter.com/smi_uq

linkedin/school/sustainable-minerals-institute