

MAPPING, MAGNETICS AND MICROSCOPES: UNDERSTAND THE SETTING OF VAMS MINERALISATION IN THE ORDOVICIAN GIRILAMBONE GROUP, WESTERN NSW

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Keywords

Girilambone Group, VAMS, copper, Lachlan Orogen, Trittton, Tottenham, Girilambone.

Abstract

The Girilambone Group in northwestern New South Wales hosts significant copper-rich deposits including Trittton, and those near Girilambone and Tottenham. The deposits are interpreted to be VAMS (volcanic-associated massive sulfide) in origin. They formed during Early Ordovician rifting, with basalts of mid-ocean ridge affinity driving hydrothermal cells into unconsolidated turbiditic sediments. This paper summarises key findings from mapping and research in the area at a variety of scales.

Introduction

Copper-rich ore has been mined intermittently in the Girilambone-Hermidale-Tottenham area of northwest New South Wales since the early-1880s. Current mining operations in the Girilambone-Hermidale district, including the Trittton deposit, have a resource of 50 Mt @ 2% Cu (Jones 2012), classifying the district as 'very large' on the global VAMS inventory of Galley et al. (2007). Despite this, the area remains underexplored by modern exploration, particularly away from the old workings in the Girilambone-Hermidale and the Tottenham-Albert districts in areas of colluvium and alluvium. In fact, the Trittton deposit was a 'blind' discovery by down hole EM techniques (Collins 2001).

In order to understand the geological setting, timing and style of mineralisation in the area, the Geological Survey of New South Wales (GSNSW) commenced regional mapping of the Coolabah 1:100 000 map sheet area in 2011 (Gilmore et al. in prep.). This followed previous work by GSNSW that focused on the Trittton deposit (Downes 2008, Burton 2011), 1:250 000 metallogenic mapping and study (Gilligan and Byrnes 1995), and mapping of the Sussex and Byrock 1:100 000 map sheet areas (Burton et al. 2012). Complementing the Coolabah regional mapping project, Gilmore (2015) completed a Masters of Economic Geology thesis with CODES (ARC Centre of Excellence in Ore Deposits) at the University of Tasmania to study mineralisation and associated exhalative rocks in the area. The understanding of local mineralisation has been furthered by observations and research by company geologists (e.g. Fogarty 1998, Collins 2001, Jones 2012 and Mincor 2012).

This abstract and presentation is an integration of geological observations that include microscopy, geochemistry, mapping of mine geology, regional mapping and regional geophysics, in order to present an overview of the copper-rich mineral systems, and to refine exploration vectors for future discovery.

Geological Setting

The Girilambone Group consists of a sequence of variably metamorphosed interbedded sandstone, siltstone and claystone with lesser chert and minor mafic rocks in northwestern NSW (Figure 1). The group is subdivided into the Early Ordovician (late Lancefieldian to Chewtonian) Narrama Formation, and the Middle Ordovician (Darriwilian) Lang and Ballast formations based on lithological and micropalaeontological (conodont) evidence, with an overall decrease in thick sandstone beds and an increase in cherty beds up-sequence (Burton et al. 2012).

The Girilambone Group was deposited as a series of turbiditic and pelagic sediments in a deep to very deep (slope to basin) marine environment (Burton et al. 2012). Chert horizons in the Girilambone Group indicate deep water and a quiet depositional environment. Primary sedimentary features such as graded bedding (common) and load casts (rare) have been observed. The Girilambone Group lacks strike extensive marker horizons, although the Budgery Sandstone Member is a key unit regionally. This member is a quartz-rich metasandstone to quartzite that may represent a feeder channel within a turbidite fan (Trigg, in prep. a). The unit has a similar provenance and maximum depositional age to other parts of the Narrama Formation, based on detrital zircon studies (Fraser et al. 2014). Jasper units have been noted at several locations in the Girilambone Group, including in direct contact with basalts at Mount Dijou (Burton et al. 2012).

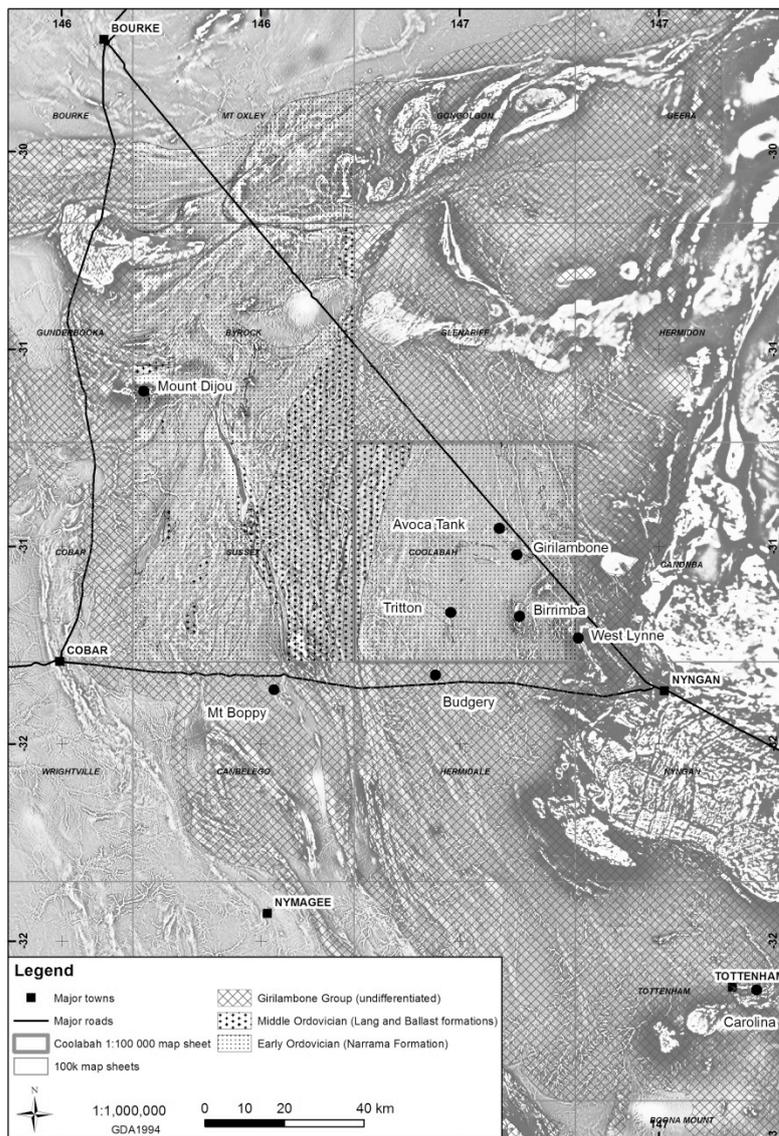


Figure 1. Location of the Girilambone Group in northwestern New South Wales. Background image is the first vertical derivative of total magnetic intensity. Geology from Hegarty (in prep.), Burton et al. (2012) and Gilmore et al. (in prep.)

Mafic rocks identified within the Girilambone Group can be distinguished by their geochemical affinity with either ocean island basalts (OIB) or mid-ocean ridge basalts (MORB) (Burton et al 2012, Burton 2011, Bruce 2013, Burton 2014). The Mount Dijou Volcanic Member comprises amygdaloidal basaltic pillow lavas with OIB geochemical affinities and is constrained to an Early Ordovician age by conodont fossils (Burton et al. 2012). Chlorite and actinolite schists from Tritton and Tottenham, interpreted to be altered basaltic lavas, have MORB geochemistry (Burton 2011). As these MORBs are associated with Early Ordovician metasedimentary rocks, an Early Ordovician age is inferred. Jones (2012) interpreted mafic rocks in the Tritton sequence to be bedding-parallel sills based on chilled margins on upper contacts of some mafic units, with some possible flows. Pb-isotope analysis by Downes (2008) and Huston et al. (2013) indicate a Late Cambrian to Early Ordovician Pb-reservoir respectively. Ultramafic rocks associated with the Girilambone Group include ‘alpine-style’ harzburgite of the West Lynne Serpentinite (Bruce 2013) – the age of this unit is unknown, but

its geometry suggests it is pre-Benambran Orogeny (Gilmore et al. 2015), and 'Alaskan-style' zoned ultramafic complexes, including the undeformed Honeybugle Complex, where a dioritic phase has been dated at 442.1 ± 2.1 Ma (Fraser et al. 2014).

An extensional geodynamic setting in the Early to Middle Ordovician has been interpreted for deposition of the Girilambone Group by numerous workers (e.g. Scheibner & Basden 1998, Gray & Foster 2004, Fergusson et al. 2005, including a back arc basin setting (e.g. Collins & Richards 2008, Glen & Meffre 2009). The association of mafic and ultramafic rocks in the older Narrama Formation, and the fining upward trend for the sediments in the group with time, may be correlated with rift and sag phases of the 'Girilambone basin' – though further work is required.

The sequence was variably metamorphosed to generally lower greenschist facies. Development of tectonic fabrics is strongly dependant on the composition of the protolith sedimentary unit and the thickness of beds. For example, only weakly-defined fabrics have developed in the quartz-rich sandstones of the Budgery Sandstone Member (Trigg, in prep. a). Following other GSNSW mapping in the region, Burton et al. (2012) correlated S_{1-3} fabrics with the widespread Benambran Orogeny (e.g. Glen et al. 2007), and a later S_4 fabric with Devonian inversion of the Cobar Basin that may correlate with the Tabberabberan Orogeny. Deformation of the Girilambone Group is domainal, with areas of low and high strain. Understanding the geometry of the multiple deformations is critical to mapping ore body geometry.

VAMS mineralisation in the Girilambone Group

Previous workers interpreted mineralisation to be syngenetic with stratiform, banded and massive sulfide bodies hosted by metasedimentary rocks of the Girilambone Group, which was subsequently deformed (e.g. Smith 1971, Suppel 1974, Suppel 1977, Gilligan & Byrnes 1995, Jones 2012a). Smith (1973) and Suppel (1974) suggested that the deposits were similar to Cyprus-style deposits. Gilligan (1978), Burton (2011) and Jones (2012a,b) compared the VAMS-style in the Girilambone-Hermidale district to Besshi-style deposits. In contrast, some authors consider the ore to be epigenetic, for example Fogarty (1998) interpreted mineralisation to be structurally controlled related to mafic intrusive bodies, and Downes (2008) proposed a metamorphic genesis for Tritton based on mineral paragenesis and Pb isotopes values. Further Pb isotope work by Huston et al. (2013) found evidence for syngenetic and syndeformational Pb.

Several key characteristics of the Cu-rich deposits (including Tritton, Bonnie Dundee, Murrawombie and pits to the north, Budgery and Carolina at Tottenham) in the Girilambone Group are apparent:

- Mineralisation is hosted within metasedimentary rocks. Mafic rocks occur in the footwall. Overlying the mineralisation are metasedimentary rocks, and quartzite of the Budgery Sandstone Member. A soft-sediment breccia with massive sulfide clasts overlies mineralisation at Tritton (Jones 2012).
- Silica–iron horizons immediately overlie the ore zones and may be laterally extensive and mineralised.
- Mineralisation consists of pyrite-rich banded, and massive sulfide (chalcopyrite–pyrite) zones, with sub-economic stringer and discontinuous veins in the footwall sequence (Jones 2012). Although these deposits are copper-rich, zones of elevated gold, zinc and silver are common.
- Alteration zoning includes proximal Fe-chlorite to distal Mg-chlorite in the footwall, silicification of the ore zone, and carbonate-altered hangingwall assemblages (Jones 2012).
- Mineralisation, including massive sulfide lenses, has been deformed in the same geometry as metasedimentary sequences, indicating a pre-deformation origin.

However, there has been remobilisation of copper during deformation, e.g. Suppel (1974) describes mineralisation as transgressing cleavage in the Albert field.

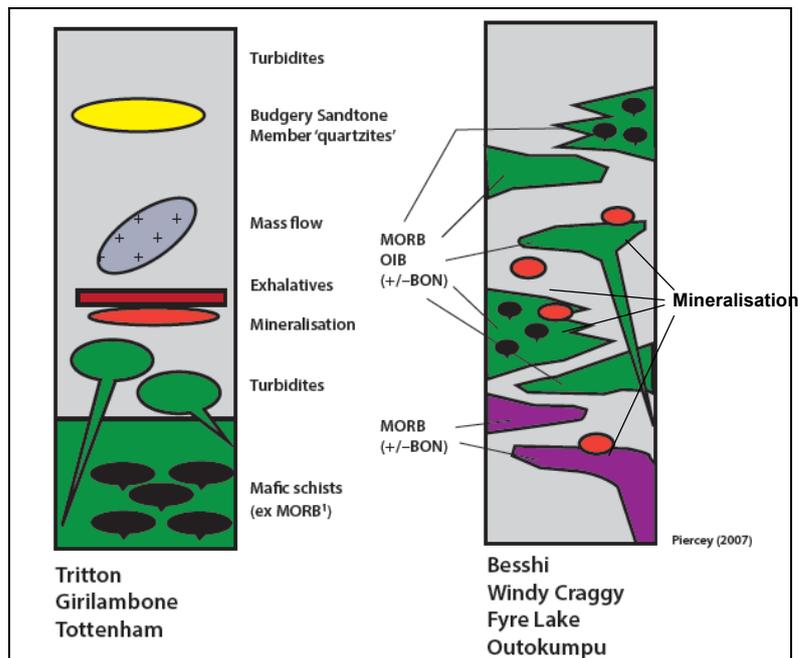


Figure 2. Schematic of VAMS mineralisation in the Girilambone Group compared to mafic-siliciclastic systems (Piercey 2007).

New research

Highlights from mapping of the Coolabah 1:100 000 map sheet area (Gilmore et al. in prep.) include:

- Identification of packages of Narrama Formation (to the east) and Lang Formation (to the west) based on conodont identification in cherts and siliceous metasiliciclastics, supported by detrital zircon studies (Campbell in prep.). Therefore the host metasedimentary sequences at Tritton and Girilambone are interpreted to be Narrama Formation (i.e. Early Ordovician).
- Interpretation of the northern continuation of the Gilmore Fault from magnetic data. The Gilmore Fault is the boundary between the Narrama and Lang formations.
- Mapping of the quartz-rich metasandstone of the Budgery Sandstone Member. The geometry of the unit is key to understanding folding through the region, particularly regional D₃ folds (Trigg, in prep. b).
- Mapping of extensive horizons of silica-iron (or quartz-magnetite-hematite [QMH]) units, named the Birrimba Member, near Birrimba and Narringa.

The similarity of the silica-iron units of the Birrimba Member with those overlying Cu-rich lodes at Tritton, Girilambone and Tottenham, and the lack of detailed studies of the ore systems, led to a detailed study of their genesis by Gilmore (2015). The aim of this research was to study the silica-iron horizons through the Girilambone Group, the formation and relationship of the silica-iron horizons relative to mineralisation, and the usefulness of the silica-iron horizons as an exploration vector for further VAMS deposits.

Key points from Gilmore (2015) are:

- Silica-iron horizons in the Girilambone Group are restricted to the Early Ordovician Narrama Formation. Age control is limited in the Tottenham area, with a Narrama

Formation (or equivalent) host in this area interpreted by extrapolation along strike from known biozonation to the north. The silica–iron rocks are interpreted to be horizons within metasedimentary rocks of the Narrama Formation, though contacts are rare outside of the mine sequence. The exception is at Mount Dijou, where jasper units are in direct contact with basalts, and within enclosing sedimentary rocks exposed around the volcanic pile.

- Silica-iron rocks are generally strongly laminated with layered quartz and iron oxides, though some are massive.
- Geochemically the silica–iron rocks are 57 - 94% SiO₂ and 2 - 10% Fe₂O₃. The rocks with the highest Fe₂O₃ values reflect hematite content, and these rocks are typically brick-red to maroon.
- The silica–iron rocks are magnetic, due to the presence of magnetite, and have an average magnetic susceptibility of 1452 x 10⁻⁵ SI and a high of 52 100 x 10⁻⁵ SI. These are the highest values for all rocks regionally.
- The silica–iron rocks associated with economic mineralisation at Tritton and Tottenham are distinguished geochemically from those associated with barren systems by a positive Eu anomaly when normalised to chondrite, relative enrichment in REE, and elevated Cu and Ag.
- Sulfur isotopes from silica-iron rocks at Tritton and Tottenham had a narrow range of values between 10.2 and 12.8‰. Sulphur isotope values from within the ore zone at Tritton ranged from 6 to 12.2‰. These values suggest the source of sulfur in sulfides within the silica–iron and ore horizons was reduced sea water sulfate. In contrast, sulphur isotope values from silica-iron horizons away from known mineralisation (e.g. Mount Dijou) indicate a biogenic source for sulfur.
- Interpretation of pyrite geochemistry (by Laser Ablation-Inductively Coupled Plasma Mass Spectrometry of pyrite grains) indicates that:
 - The hottest condition for pyrite formation in any of the silica–iron horizons was at Tritton. In contrast, lower temperatures existed for pyrite formation in silica-iron (jasper) rocks at Mount Dijou, where jasper units directly overlie pillow basalt and the influence of direct seawater cooling would have been stronger.
 - Ni/Co ratios in pyrite in samples from Tottenham, Tritton and Birrimba show distinctive variations – that may indicate a sedimentary or mafic rock source. The Tritton samples were formed in reducing conditions, in contrast to the oxidised conditions at Mount Dijou, where the single Tottenham sample plots just into the oxidised field. At Tritton, distinct variations in the Ni/Co ratios in pyrite may indicate that the increased sedimentary input into the hydrothermal fluid occurred in the upper part of the sequence, i.e. magmatic fluids may have played a bigger role in pyrite within the ore zone compared to pyrite in the silica–iron horizon which has more sedimentary input.
 - Pyrite geochemistry at Tritton and Tottenham indicates that the hottest part of the system is the basal banded-pyrite zone, indicating that hydrothermal fluids cooled as they travelled up sequence. The ore zone formed in hotter conditions than the silica–iron horizons

Formation of VAMS in the Girilambone Group

Building on the ideas of previous workers (e.g. Smith 1971, Suppel 1974 and 1977, Gilligan 1978, Gilligan & Byrnes 1995, Burton 2011, Jones 2012 and Huston et al. 2013), Gilmore et al. (in prep.), Gilmore (2014) and Gilmore (2015) used the new mapping and research highlighted above to further develop the model for VAMS formation in the Girilambone Group, from

In this new model, as extension occurred in the Early Ordovician, hot, oxidised hydrothermal fluids sourced from MORB-affinity mafic sills and lava flows mixed with seawater in a pile of unconsolidated turbiditic sediments.

Although not directly dated, an Early Ordovician age for the mineralisation is constrained by three independent means:

- Conodont biozonation (late Lancefieldian to early Castlemanian) in the surrounding Narrama Formation (Campbell, in Gilmore et al. in prep.);
- An interpreted age of ~480 Ma for the Tritton and Avoca Tank deposits from Pb-isotope data (Huston et al. (2013));
- Maximum depositional age of a feldspathic sandstone unit within the Narrama Formation (Fraser et al. 2015).

As seawater cooled these fluids, temperature- and redox-controlled precipitation of cupriferous pyrite and other metals into preferential host rocks occurred. This process is supported by pyrite geochemistry at Tritton and Tottenham that indicates that the hottest part of the system is the basal banded-pyrite zone, indicating that hydrothermal fluids cooled as they travelled up sequence, i.e. the ore zone formed in hotter conditions than the silica-iron horizons. This is consistent with the zone refining model of Eldridge et al. (1983).

The early presence of copper is supported by pyrite geochemistry and petrology that shows chalcopyrite inclusions within early-stage pyrite. Zonation of metals from hotter parts of the system (e.g. Cu) to cooler parts of the system (e.g. Zn) occurred. Overlying exhalative silica-iron horizons formed by precipitation of spent-fluids upon further cooling. The presence of these silica-iron exhalites are characteristic of VAMS camps in oxidised marine basins (Galley et al. 2007), with composition (sulfide, oxide or carbonate exhalites) dependant on local conditions (Doyle and Allen 2003). They typically occur at the same stratigraphic level as the mineralisation, in proximal settings above sulfide deposits, as marginal aprons and as strike-extensive distal horizons (Slack 2010), or may overlie their own feeder structure, as seen in the Mount Windsor volcanic Belt (Davidson and Stolz 2001).

At Tritton, the mixing of magmatic fluids or fluids with sulphur leached from mafic rocks and reduced seawater sulphate is supported by several datasets: (a) sulfur isotope analysis from the ore zone and exhalative horizons, (b) elevated Ni and Co values within early-stage pyrite indicating mafic-derived fluids, and (c) Ni/Co ratios that suggest an increase in sedimentary input into the hydrothermal fluid occurred in the upper part of the sequence. The increasing input of seawater at the end of sulfide deposition is also supported by spectacular U-Th-rich rims around pyrite.

A seafloor replacement model is preferred for the ore, due to the lack of barium and manganese in the system, although the lack of barium may reflect low barium in the mafic rocks. The presence of hematite-bearing and jasper-like rocks indicates oxidised conditions. The presence of sulfide clasts in conglomerates overlying the ore horizon at Tritton either indicates massive sulfide formation on the seafloor surface, or localised disruption of the seafloor (Jones 2012).

Preservation of VAMS was aided by seafloor replacement and continued deposition of turbiditic sedimentary rocks. Subsequent deformation of the Narrama Formation in the Early Silurian and the Devonian folded the sequence. Regional metamorphic grade reached lower greenschist facies. Tectonic foliations are strongly developed in the footwall and hangingwall metasedimentary sequences. Little foliation developed in the ore zones and the silica-iron horizons due to the competency of these units, and regional metamorphism temperatures lower than those required to deform pyrite in a ductile way. In contrast, chalcopyrite was remobilised during metamorphism and deformation. There is evidence for remobilisation of ore from Pb-isotopes (Downes 2008, Huston et al. [2013]). The overlying resistive silica-iron rocks protected the ore body from deformation and from erosion in recent time.

Therefore, VAMS mineralisation in the Girilambone Group is interpreted to be mafic-siliclastic, using the naming convention of Piercey (2007) (Figure 2), and pelitic-mafic-hosted (Besshi-type) Cu-Ag-(Au-Zn) VAMS using the naming convention of Downes et al. (2011).

Exploration Vectors

The exploration model proposed by Gilmore et al. (in prep.) includes exploration vectors at different scales. In summary these are:

- Known mineralisation is hosted by Early Ordovician Narrama Formation.
- Mineralisation is associated with basalts with MORB affinity (not OIB). These basaltic rocks occur in the footwall.
- The Budgery Sandstone Member overlies the known ore horizon.
- Silica-iron horizons:
 - Are the most magnetic unit in the sequence by an order of magnitude (Gilmore 2015);
 - Are geochemically distinct above the ore horizons at Tritton and Tottenham, with sulphur isotope values between 10.2 and 12.8‰, elevated Cu and Ag, a relative REE enrichment, and a positive Eu anomaly when normalised to chondrite (Gilmore 2015).
- Electrical geophysical surveys have been successful in the discovery of mineralisation in the field (e.g. Collins 2001, Wilson 2015).

The presence of massive sulfide clasts in a mass flow deposit overlying Tritton (Jones 2012) suggests that mineralisation above the known horizon may have been eroded, and the source of the clasts in the mass flow unknown. The region remains underexplored particularly away from old workings, as evidenced by Helix Resources' recent discovery at Collierina between Tritton and Tottenham (Wilson 2015). Further exploration opportunities may lie north of Tritton, and in the package of Narrama Formation rocks between Cobar and Mount Boppy.

Acknowledgements

Thanks to Phil Jones and Straits Resources Limited for access to core and mines, Peter Muccilli and John Thevissen (Mincor) for access to core, and landowners in the study area, and to GSNSW colleagues Rosemary Hegarty and John Greenfield for their geophysical and geological input respectively, and Kate Bull for reviewing the manuscript. Cameron Quinn (ex-GSNSW) is also acknowledged for his contribution to the mapping project.

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