New constraints on the timing of metamorphism, deformation, and base metal mineralisation in the Aileron Province

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The Aileron Province is host to many small base metal deposits and prospects with a variety of metal assemblages and alteration styles (eg Warren *et al* 1974, Shaw 1990, Huston *et al* 2006, Scrimgeour 2013, McGloin *et al* 2016); however, the potential for world-class deposits remains uncertain. Uncovering this potential requires a more comprehensive understanding of the lithologies and geological events linked to mineralisation, including an understanding of the age of mineralisation events. Placing temporal constraints on mineralisation enables explorers to target geology that is favourable for new discoveries; this is challenged by the extensive history of metamorphism, deformation, and magmatism experienced by the Aileron Province. In many cases, the absolute age of mineralisation and host rock formation, deformation, and metamorphism is lacking, making it difficult to fully constrain the timing and mode of mineral deposit formation (eg syngenetic, epigenetic, or both). Here we highlight new chronologic results from several deposits and prospects (**Figure 1**) that have direct implications for exploration targeting of orthomagmatic nickel–copper–cobalt, granite-related tungsten and copper, and hydrothermal copper–lead–zinc and gold deposits in the Province. Highlights from this work at key deposits and prospects include:

1. new constraints on the timing of mineralisation
2. confirmation of several periods of mafic and felsic magmatism that are metallogenically favourable for mineral deposit formation
3. improved understanding of the relationship between mineralisation and host rocks
4. evidence for multiple metamorphic and hydrothermal events that may have allowed reworking and upgrading of pre-existing mineralisation to economic tenors.

Prospect D nickel–copper sulfide prospect

In the absence of more sophisticated data, prospectivity for orthomagmatic nickel–copper–cobalt deposits in greenfield areas is best indicated by evidence for base metal sulfide formation within (ultra-) mafic intrusions. The observation of these sulfides in mafic rocks, even in minor quantities, confirms that some of the same processes that form nickel deposits were active, and that intrusions in the region

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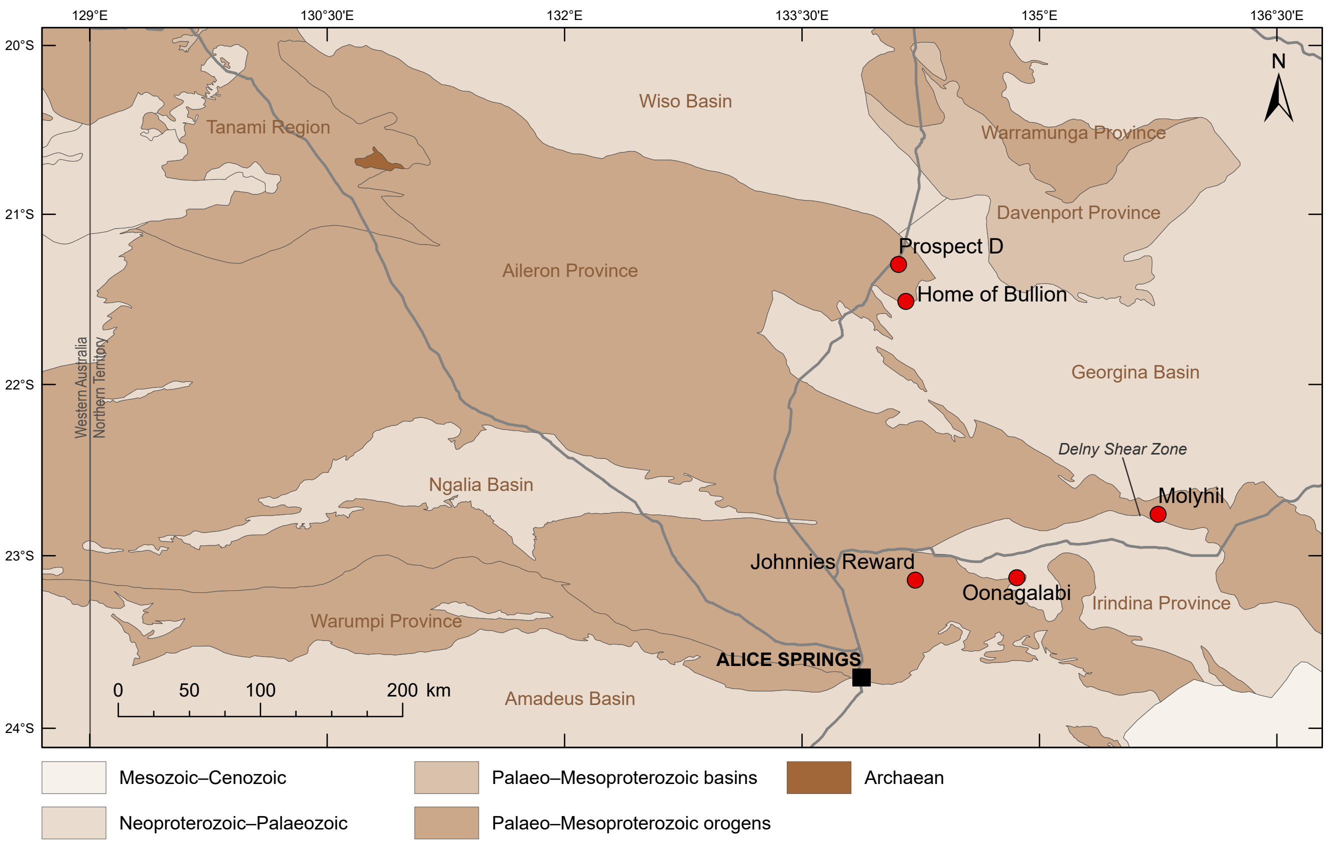

Figure 1. Map of geological regions showing the location of the prospects and deposits discussed herein.

are capable of producing nickel–copper–cobalt sulfide mineralisation (see Dulfer *et al* 2016). One such example is Prospect D in the northern Aileron Province (**Figure 1**), a small and sub-economic nickel–copper sulfide prospect first explored in 1972. McBride (2006) reported an inferred (non-JORC compliant) resource of 1.63 Mt at 0.151% Ni and 0.521% Cu over an average width of 9.1 m for oxide ore, and 1.53 Mt at 0.247% Ni and 0.621% Cu over an average width of 8.5 m for sulfide ore.

Mineralisation at Prospect D is associated with the margins of an altered or metamorphosed mafic sill that intrudes the ca 1.82 Ga Hatches Creek Group (McKinnon-Matthews 2005). Primary mineralisation occurs as recrystallised, disseminated pentlandite and chalcopyrite (**Figure 2**), indicating formation prior to metamorphism, most plausibly during magmatic emplacement. The age of mafic magmatism (and mineralisation) at Prospect D is unknown, although it has previously been hypothesised to be a constituent of the ca 1.80 Ga continent-scale Hart Large Igneous Province (LIP; eg Pirajno and Hoatson 2012) based on the presence of voluminous ca 1.80 Ga mafic magmatic rocks throughout the Aileron Province (eg Attutra Metagabbro, Carmencita Metadolerite, Mount Hay Granulite, etc). However, it can be imprudent to build models on such assumptions as any good hypothesis can be disproven by collecting data. For example, the gabbro that hosts the Mount Peake iron–titanium–vanadium deposit was largely assumed to have a similar ca 1.80 Ga age before U–Pb zircon and baddeleyite dating indicated a ca 1.06 Ga age (Beyer *et al* 2016).

Voluminous LIPs are considered a key prospective target for orthomagmatic sulfide mineralisation (Pirajno and Hoatson 2012), and ca 1.80 Ga intrusions are a well-documented metallogenic epoch for intrusion-related nickel–copper sulfide mineralisation [NC-3 (eg Pechenga) and NC-5 (eg Jinchuan) type deposits of Naldrett 2010]. Confirmation of a ca 1.80 Ga age for mafic magmatism (and mineralisation) at Prospect D would provide further evidence for nickel and copper prospectivity in the Aileron Province associated with the Hart LIP.

Dating the timing of emplacement and metamorphism of metamafic rocks is difficult due to the paucity of ideal phases for geochronology such as zircon, baddeleyite, or monazite. Phases such as apatite can also be used; however, apatite's propensity to incorporate common lead during crystallisation can lead to large analytical or geological uncertainty. The metagabbro at Prospect D contains apatite that both overprints the chlorite fabric and occurs along grain boundaries in the calcite–quartz–chlorite±sulfide alteration assemblages in the rock, indicating that it likely dates or just post-dates alteration or metamorphism of the gabbro. New NTGS *in situ* LA–ICP–MS U–Pb dating of apatite in a sample metagabbro yielded an isochron with a lower intercept of 1776 ± 53[6] Ma, interpreted to record the timing of apatite growth (Reno *et al* in prep). Although the confidence interval on this lower incept age is large, it provides a minimum age on the timing of mineralisation at Prospect D. A maximum age is provided by a ca 1.82 Ga volcanic member of the Hatches Creek Group (Smith 2001), which hosts the mafic sills at Prospect D. This narrows the window for mafic magmatism and mineralisation at Prospect D to between ca 1.82 and ca 1.72 Ga. Although this is a large ca 100 million year window for mineralisation, 1) it is consistent with the hypothesis that mafic magmatism and mineralisation occurred as part of the ca 1.80 Ga Hart LIP, and 2) it disproves a possible younger Mesoproterozoic or Palaeozoic age for mineralisation at Prospect D. Confirmation of a ca 1.80 Ga age for mafic magmatism and mineralisation would indicate a previously unrecognised potential for economic orthomagmatic sulfide deposits in the Aileron Province.

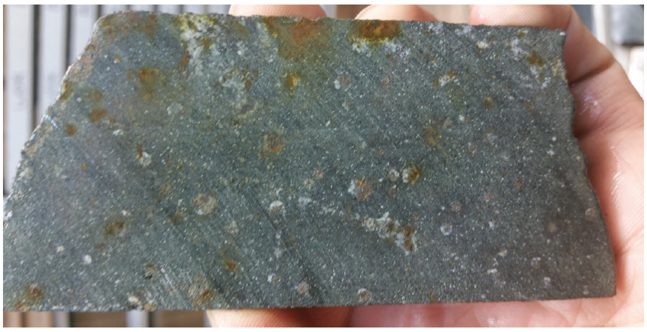

Figure 2. Disseminated sulfide assemblage of violarite–chalcopyrite–pentlandite overprinting altered metagabbro from Prospect D. Core is 63.5 mm wide.

Home of Bullion copper–lead–zinc deposit

The Home of Bullion copper–lead–zinc deposit in the north central Aileron Province (**Figure 1**) was mined intermittently during the early- to mid-1900s, producing 1370 t of copper (7115 t of ore graded 19–20% Cu; Blanchard 1936, Haines 1991). Home of Bullion has been interpreted as a metamorphosed volcanogenic massive sulfide (VMS) deposit; however, the origin and style of mineralisation remains uncertain due to the lack of clear evidence for volcanic rocks. New geochronology at the deposit aims to constrain the timing of mineralisation and better understand ore-forming processes.

The mineralisation consists of four sheared sulfide bodies (comprising pyrrhotite, sphalerite, chalcopyrite, galena and pyrite, with minor bornite and chalcocite; **Figure 3**).

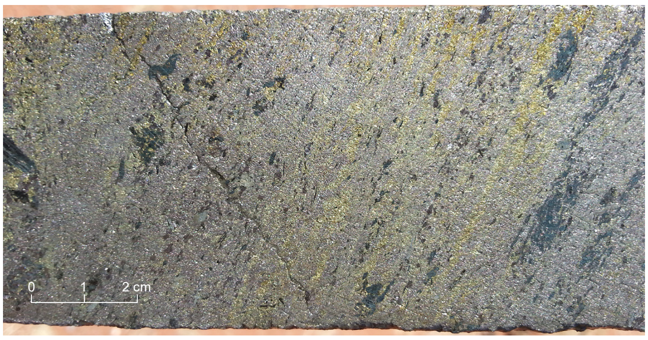

Figure 3. Garnet-bearing orthogneiss containing chalcopyrite and sphalerite, with minor pyrrhotite and galena and trace pyrite from Home of Bullion. Core is 63.5 mm wide.

[6] All uncertainties are presented as ~95% confidence intervals; see referenced publications for geological, analytical, and statistical detail

Sulfides occur within sericite-altered metasedimentary rocks of the Bullion Schist that are intruded by minor mafic amphibolite rock (Blanchard 1936, Reno *et al* 2019).

The Bullion Schist has maximum depositional U–Pb zircon ages of 1833 ± 11 Ma regionally (Claoué-Long *et al* 2008), and 1833 ± 15 Ma and 1821 ± 19 Ma at the Home of Bullion deposit (Yang *et al* in prep). $^{207}Pb/^{206}Pb$ zircon crystallisation ages for the Ooralingie and Bean Tree granites of the Barrow Creek Granite Complex, which intrude the Bullion Schist, provide minimum absolute depositional ages for the Bullion Schist of 1809 ± 5 Ma and 1806 ± 6 Ma respectively (Smith 2001). The Bullion Schist is also unconformably overlain by the 1805 ± 6 Ma Strzeleckie Volcanics (Claoué-Long *et al* 2008). These data constrain the timing of deposition of the Bullion Schist protolith and the maximum timing of mineralisation to ca 1.82–1.81 Ga.

Previous Pb isotope analyses of Pb-rich sulfides from Home of Bullion have equated to model mineralisation ages of ca 700 Ma (Warren *et al* 1995); however, new unpublished NTGS Pb isotope data imply Palaeoproterozoic Pb model ages instead (McGloin *et al* in prep). $^{207}Pb/^{206}Pb$ ages for monazite included in andalusite constrains the timing of metamorphism and fluid infiltration to between 1813 ± 30 Ma and 1762 ± 14 Ma (Reno *et al* 2019); monazite included in recrystallised and deformed chalcopyrite–sphalerite constrains the timing of sulfide deformation to 1778 ± 10 Ma (Reno *et al* 2019).

These new data indicate that sulfide mineralisation formed between ca 1.81–1.78 Ga, which is consistent (but not conclusively) with a syngenetic origin. Nonetheless, more widely across the Aileron Province, a number of interpreted syngenetic (synsedimentary or volcanic-related) basin-hosted base metal deposits, spatially associated with mafic magmatism of the same age, appear to share a broadly similar timing with Home of Bullion: eg deposits and prospects in the Jervois mineral field (McGloin and Weisheit 2015, McGloin 2017, Weisheit *et al* 2019), and the Strangways Range (Hussey *et al* 2006). This suggests a fertile basin across the Province for base metal mineralisation, although debate remains as to where and how a world-class deposit of these styles might form.

Molyhil tungsten–molybdenum deposit

The Molyhil tungsten–molybdenum deposit (**Figure 1**), the Pinnacle Hill tungsten prospect, and several minor tungsten occurrences, all occur at the northern margin of the Delny Shear Zone in the northeastern Aileron Province. The Molyhil deposit has an estimated resource of 13 300 t at 0.28% WO_3, 6800 t at 0.14% Mo, and 2200 t at 0.05% Cu (Thor Mining PLC 2019). The Molyhil deposit represents a rare example of a Palaeoproterozoic-aged magmatogenic skarn deposit in Australia; its connection with other deposits in the Aileron Province was not clear until recently. Mineralisation in the Molyhil area occurs in skarns at the contact zone between altered Palaeoproterozoic metacarbonate rocks of the Deep Bore Metamorphics (exoskarn) and Marshall Granite (endoskarn; Barraclough 1979, Shaw *et al* 1984, Freeman 1986, 1990; McGloin and Bradey 2017, McGloin and Weisheit in prep; **Figure 4**).

Chronologic constraints for rocks from the Molyhil deposit, and from elsewhere in the Molyhil area, indicate a protracted metamorphic history. U–Pb zircon dating of the Deep Bore Metamorphics revealed a metavolcaniclastic component with $^{207}Pb/^{206}Pb$ zircon maximum depositional ages of 1822 ± 9 Ma, 1819 ± 9 Ma (Reno *et al* 2018), 1806 ± 6 Ma (Kositcin *et al* 2018a), and 1805 ± 5 Ma (Scrimgeour and Raith 2001). The succession was intruded by widespread felsic and minor mafic magmas starting at 1797 ± 7 Ma (Reno *et al* 2017, Beyer *et al* in prep). The rocks were metamorphosed at up-to-granulite facies and deformed during a long-lived Palaeoproterozoic tectonothermal cycle (Reno *et al* 2017). Scrimgeour *et al* (2001), Reno *et al* (2018), and Kositcin *et al* (2018a, b) recorded multiple phases of metamorphic zircon growth in the Deep Bore Metamorphics between 1787 ± 11 Ma and 1717 ± 7 Ma.

The metasedimentary–meta-igneous lithologic package in this area experienced extensive partial melting during this metamorphic cycle resulting in the emplacement of widespread plutons of Marshall Granite throughout the Molyhil area. The Marshall Granite has a $^{207}Pb/^{206}Pb$ zircon age of 1720 ± 18 Ma (Kositcin *et al* 2018b) and a $^{207}Pb/^{206}Pb$ apatite age of 1732 ± 4 Ma (Reno *et al* in prep), both interpreted to record crystallisation of the Marshall Granite at the end of the supersolidus portion of the metamorphic cycle and cooling of this domain below solidus temperatures (Reno *et al* 2017). The timing of mineralisation at Molyhil is constrained directly by a Re–Os model age for molybdenite of 1721 ± 8 Ma (Cross 2009) and indirectly by a xenotime $^{207}Pb/^{206}Pb$ age of 1714 ± 26 Ma (Cross 2009) from an intensely-altered rock in the deposit; both phases are interpreted to have grown contemporaneous with the intrusion of the Marshall Granite.

Monazite U–Pb and hornblende and biotite argon data from Molyhil area samples indicate the area was at elevated temperatures for an extended period of time, and experienced periodic phases of heating, deformation, and fluid influx until the Mesoproterozoic. $^{40}Ar/^{39}Ar$ data for hornblende from the deposit indicate it cooled below 520–480°C at 1702 ± 5 Ma and experienced a phase of late

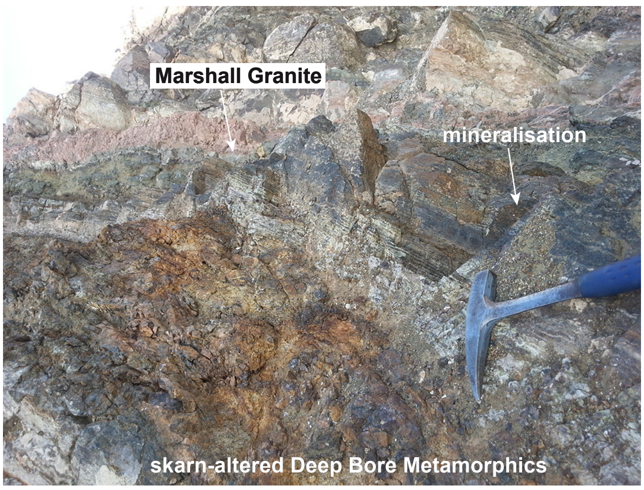

Figure 4. Marshall Granite dyke intruding layered and foliated calc-silicate rock of the Deep Bore Metamorphics and producing minor magnetite–scheelite–molybdenite mineralisation below the contact zone at Molyhil. Hammer is 30 cm long.

fluid infiltration unrelated to mineralisation at 1660 ± 4 Ma (Reno and Fraser 2021). Rocks from other units in the Molyhil area record $^{40}Ar/^{39}Ar$ cooling ages of ca 1.60 Ga for hornblende and ca 1.55 Ga for biotite (Scrimgeour and Raith 2001), which indicates the area experienced slow cooling until the Mesoproterozoic.

Rocks in the Molyhil area, including in the Molyhil deposit, are locally overprinted by mylonites related to the Delny Shear Zone, which has an extensive history of Palaeoproterozoic and minor Mesoproterozoic deformation. Reno *et al* (2020a, b) presented *in situ* monazite ages for mylonites of the Delny Shear Zone that indicate multiple phases of deformation between ca 1.72 Ga and 1.68 Ga, and minor ductile deformation and fluid flow at ca 1.63 Ga and between 1.59 Ga and 1.56 Ga.

There is rare evidence for new mineral growth after the Mesoproterozoic. Cross (2009) records two phases of Neoproterozoic xenotime at 755 ± 20 Ma and 648 ± 29 Ma, as well as evidence for lead loss during the Palaeozoic. Such ages are rarely observed in this portion of the Aileron Province, with the most well-known example being the 731.0 ± 0.2 Ma Mud Tank Carbonatite (Gain *et al* 2019), related to the rifting that led to formation of the Irindina Province (Hussey 2003). Such ages point to a cryptic effect of the global tectonics occurring at this time, including the rifting and breakup of Rodinia, initiation of Snowball Earth, and eventual assembly of Gondwana. Minor Palaeozoic monazite (Reno *et al* 2020a, b) and ca 364–362 Ma $^{40}Ar/^{39}Ar$ muscovite ages (Scrimgeour and Raith 2001) are associated with fluid flux or reheating during the Larapinta Event and Alice Springs Orogeny.

The ca 1.72 Ga age for tungsten–molybdenum mineralisation is consistent with ages obtained from nearby epigenetic copper and tungsten mineralisation in the Jervois mineral field and in the Bonya Hills area to the east of the Molyhil area (McGloin and Weisheit 2021, McGloin and Weisheit in prep). Further afield, McGloin *et al* (2020 and references therein) obtained Re–Os model ages for molybdenite that record timing of tungsten and copper mineralisation associated with emplacement of evolved felsic rocks at ca 1.72–1.71 Ga in the Tennant Creek mineral field and the Hatches Creek and Mosquito Creek tungsten fields. There now appears to be strong evidence for a regional copper and tungsten mineralising episode across wide parts of central Australia at this time. Other similar deposits may have formed at locations where hydrothermal fluids exsolved from similar ca 1.72 Ga granites and reacted with lithologies such as metacarbonates or metaexhalites.

Johnnies Reward prospect

The Johnnies Reward prospect (**Figure 1**) is one of several polymetallic prospects in the Strangways Range in the south-central portion of the Aileron Province. These prospects host a variety of metal assemblages and associated alteration styles (**Figure 5**). Davenport Resources (2018) report an inferred resource for Johnnies Reward containing 52 000 oz of gold at 0.7 g/t Au and 9000 t of copper at 0.4% Cu. In most cases, the prospects were metamorphosed to granulite-facies conditions during the Palaeoproterozoic (Hussey *et al* 2006). The apparent syngenetic and epigenetic mineralisation styles have previously been interpreted to represent a spectrum of mineralisation styles: metamorphosed volcanic-associated massive sulfide (VAMS), iron oxide copper gold (IOCG), and carbonate-replacement (eg Warren *et al* 1974, Warren and Shaw 1985, Skidmore 1996, Hussey *et al* 2006, Scrimgeour 2013). The different mineralisation styles have been interpreted by these authors to have a variety of mineralisation ages ranging from the Palaeoproterozoic into the Palaeozoic. Determining the precise genetic model for mineralisation in these prospects has been complicated by the lack of reliable absolute ages for mineralisation, and exacerbated by the lack of constraints on the timing of deposition of the host rocks and the age and nature of deformation and regional magmatism. Recent dating at the deposit aimed to clarify some of these interpretations by confirming the age of host rocks, and where possible, mineralisation.

Mineralisation at Johnnies Reward is hosted within altered metafelsic, metamafic, and metasedimentary granulite and marble of the lower Cadney Metamorphics (Shaw *et al* 1979, Warren 1980, Hussey *et al* 2006). The protoliths to the host succession are interpreted as dominantly sedimentary mudstone and carbonate rocks, and possibly (but unconfirmed) bimodal volcanic rocks, which are all intruded by bimodal igneous rocks represented locally by unnamed mafic sills (Hussey *et al* 2006).

New and legacy NTGS chronologic studies of rocks in the Johnnies Reward area provide some constraints on timing of mineralisation. An *in situ* LA–ICP–MS zircon $^{207}Pb/^{206}Pb$ age of 1791 ± 4 Ma for the Cadney Metamorphics is interpreted to place a maximum constraint for timing of deposition of the Cadney Metamorphics (Yang *et al* in prep). A $^{207}Pb/^{206}Pb$ zircon age of 1776 ± 5 Ma records emplacement of an orthogneiss that intrudes the Cadney Metamorphics, and provides a minimum timing for deposition (Yang *et al* in prep). Yang *et al* (in prep) interpret high-grade metamorphism and related igneous activity in the Johnnies Reward area between 1.75 Ga and 1.69 Ga; *in situ* LA–ICP–MS monazite dating of a sample of Cadney Metamorphics collected from the hanging wall of the Johnnies Reward prospect constrains a complex history of monazite growth associated with high-grade metamorphism and deformation to between ca 1.72 Ga

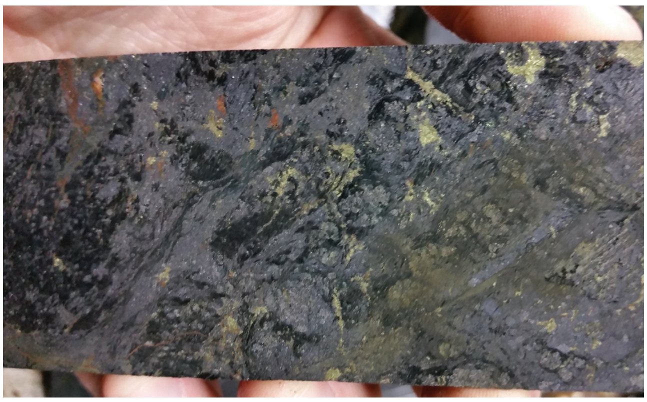

Figure 5. Garnet–magnetite rock from Johnnies Reward with chalcopyrite-bearing veins that overprint magnetite. Core is 63.5 mm wide.

and 1.67 Ga (Reno *et al* 2019). Reno *et al* (2019) and Yang *et al* (in prep) interpret zircon and monazite to record either heating or fluid flow events between ca 1.61 Ga and 1.50 Ga. A major fluid infiltration event is recorded at Johnnies Reward by ca 1.00 Ga monazite (Reno *et al* 2019); this may be related to igneous activity observed regionally at the time, including the 1001 ± 7 Ma Gumtree Granite (Kositcin *et al* 2018a) located ~20 km southwest of Johnnies Reward. $^{40}Ar/^{36}Ar$ dating of hornblende extracted from a quartz vein cross-cutting mineralisation yielded an inverse isochron age of 428 ± 31 Ma (McGloin *et al* 2017).

Attempts to directly date mineralisation at Johnnies Reward have yielded ambiguous results. Pb–Pb dating of galena yielded model ages between ca 1.8–1.7 Ga (Hussey *et al* 2006), and Re–Os molybdenite dating yielded model ages between ca 1.4 Ga and ca 0.9 Ga (McGloin and Creaser 2017). These ages span the range of igneous emplacement, metamorphism, and fluid flow observed at Johnnies Reward.

Although the timing of mineralisation remains ambiguous, it is possible that the various metamorphic and fluid flow events recorded at Johnnies Reward have led to a hybrid deposit, with early syngenetic mineralisation subject to later overprint (eg McGloin 2017), and possibly even upgrading of economic metals. Aseismic refinement of metal systems has been demonstrated as a potentially powerful mechanism to upgrade deposits in areas with long histories of tectonism, metamorphism, and multiple pulses of fluid flow (eg Wagner *et al* 2007, Voisey *et al* 2020) such as observed at the Johnnies Reward prospect.

Oonagalabi copper–zinc–(silver–lead) deposit

The Oonagalabi copper–zinc–(silver–lead) deposit (**Figure 1**) comprises about 4 km strike length of mineralised metacarbonate lenses hosted within the Bungatina Metamorphics (Skidmore 1996, Hussey *et al* 2006). The highest reported grades are from a gossanous rock with 31.25% Cu, 915 ppm Pb, 4.75% Zn, 2.7 ppm Au, 750 ppm W, and 220 ppm Ag (Nielsen 1973). The age and genesis of the Oonagalabi deposit remains contentious with volcanogenic (Warren and Shaw 1985, Hussey *et al* 2006), carbonate-replacement, and skarn (Skidmore 1996, Hussey *et al* 2006) mineralisation models proposed. Understanding the style of mineralisation has been hampered by the previous lack of robust chronologic data available for the Bungatina Metamorphics to constrain the timing of deposition of host rocks, emplacement of mafic sills and dykes, copper and zinc mineralisation, and deformation events that affect the Oonagalabi deposit.

Mineralisation includes malachite and limonite in marble and diopside-bearing schist, as well as sulfides associated with recrystallised quartz veins. Minor chrysocolla, smithsonite, azurite, chalcocite, chalcopyrite, sphalerite, pyrrhotite, and pyrite have been reported (Skidmore 1996, Hussey *et al* 2006; **Figure 6**). Most mineralisation occurs in the quartz–diopside schist that underlies forsterite marble. In mineralised metacarbonate zones, host marble is replaced by diopside-rich calc-silicate rocks and massive anthophyllite.

New chronologic data from the Oonagalabi deposit has sought to clarify understanding of this deposit. Kositcin *et al* (2018a) presented magmatic crystallisation SHRIMP $^{207}Pb/^{206}Pb$ ages of 1770 ± 4 Ma and 1770 ± 5 Ma from rocks of the Bungatina Metamorphics interpreted to have a probable shallow intrusive or sub-volcanic igneous origin; this provides a minimum timing for deposition of this unit. LA–ICP–MS $^{207}Pb/^{206}Pb$ monazite and SHRIMP $^{207}Pb/^{206}Pb$ ages indicate granulite-facies metamorphism of the Bungatina Metamorphics occurred between 1772 ± 17 Ma and 1724 ± 12 Ma (Kositcin *et al* 2018a, Reno *et al* 2019). Reno *et al* (2019) interpret the unit to have experienced multiple pulses of fluid infiltration at 1669 ± 15 Ma, 1020 ± 20 Ma, and 450 ± 5 Ma. The absolute age of the mafic sills and dykes interpreted to intrude the succession remains unknown.

Galena Pb model ages estimate mineralisation occurred between ca 1.79–1.77 Ga (Hussey *et al* 2006), which is consistent with the ca 1.77 Ga magmatic crystallisation age and metamorphic ages; these ages plausibly support either a syngenetic or carbonate-replacement origin for the prospect. However, it is unresolved whether some mineralisation at the Oonagalabi deposit is related to shallow felsic magmatism, syngenetic processes, or even epigenetic processes. More robust constraints on the timing of deposition of the protolith of the metasedimentary rocks are required. It is also unclear if the evidence for multiple episodes of later hydrothermal fluid flow, including an episode at ca 1.00 Ga similar to that observed at Johnnies Reward, affected the deposit.

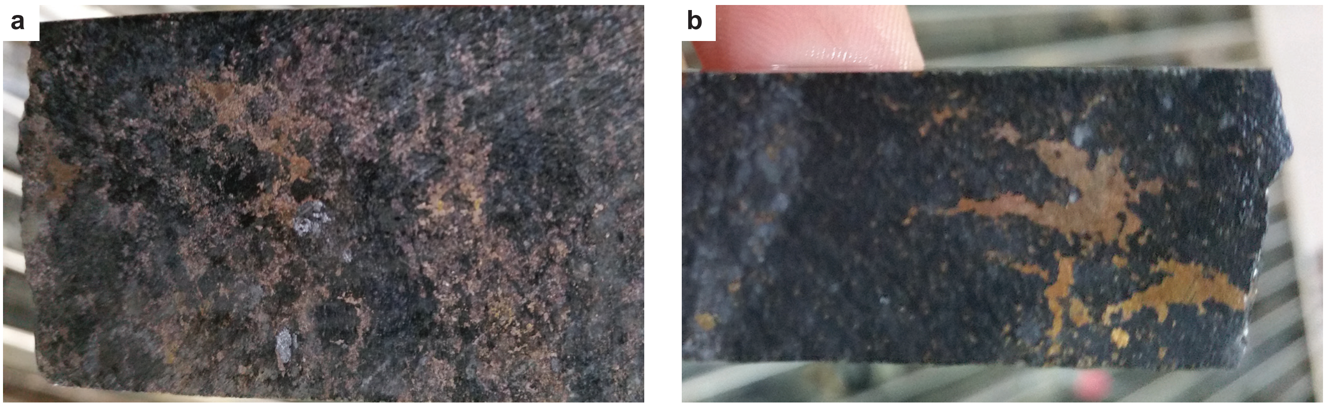

Figure 6. Core photos from Oonagalabi. (**a**) Chalcopyrite, pyrite, and pyrrhotite in garnet-rich zones associated with recrystallised quartz veins in a metamafic rock. Core is 63.5 mm wide. (**b**) Disseminated veinlets and interstitial sulfides, including sphalerite, pyrite, pyrrhotite, and chalcopyrite within a diopside-rich zone. Core is 32 mm wide.

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