Palaeoproterozoic copper mineralisation in the Aileron Province: New findings on temporal, spatial and genetic features

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The Palaeoproterozoic Aileron Province hosts many different examples of copper-related mineralisation (eg the Jervois mineral field, Home of Bullion, the Mount Hardy copper field, Perenti, and copper prospects in the Bonya Hills, Jinka Plain, Strangways Ranges, and ILLOGWA CREEK[9] areas; **Figure 1**, **Table 1**). There appears to be a spectrum of different copper-related mineralisation styles; however, scientific understanding of the geologic processes and the controls on the location and genesis of mineralisation has been poorly understood. Moreover, potential temporal and genetic links between each copper mineral system and larger regional tectonic processes and geologic events are not well constrained. Yet, the ability to recognise the fertility and potential of a particular terrain for copper and base metal mineralisation before commencing costly field work is critical to conducting efficient and successful mineral exploration programs.

This extended abstract reports new geochemical, petrological, isotopic, structural and geochronological results from selected copper-endowed mineral systems in the Aileron Province. The results demonstrate temporal and genetic differences between copper mineralisation in different areas and show that there are a range of syngenetic and epigenetic mineralisation styles. Broadly, this mineralisation can be related to an evolving active plate margin and associated basin formation, magmatism and high-*T*, low-*P* metamorphism between ca 1.82 and at least 1.7 Ga. Regional mafic and felsic intrusive bodies that formed from ca 1.82 Ga onwards were likely to have been critical in sourcing copper and driving hydrothermal fluid-related mineralisation. These intrusions also provided a potential passive source for metallogenic inheritance during subsequent periods of metamorphism, deformation and magmatism.

Summary of current knowledge and new observations and analyses

Syngenetic mineralisation in the Jervois mineral field

NTGS research on the Jervois deposits indicated that the massive sulfide mineralisation is syngenetic, sediment-hosted and volcanic-associated and formed at ca 1790 Ma (McGloin and Weisheit 2015, Reno *et al* 2015, Weisheit *et al* 2016). During 2015, NTGS research focused on some key unknown aspects of this mineralisation such as the

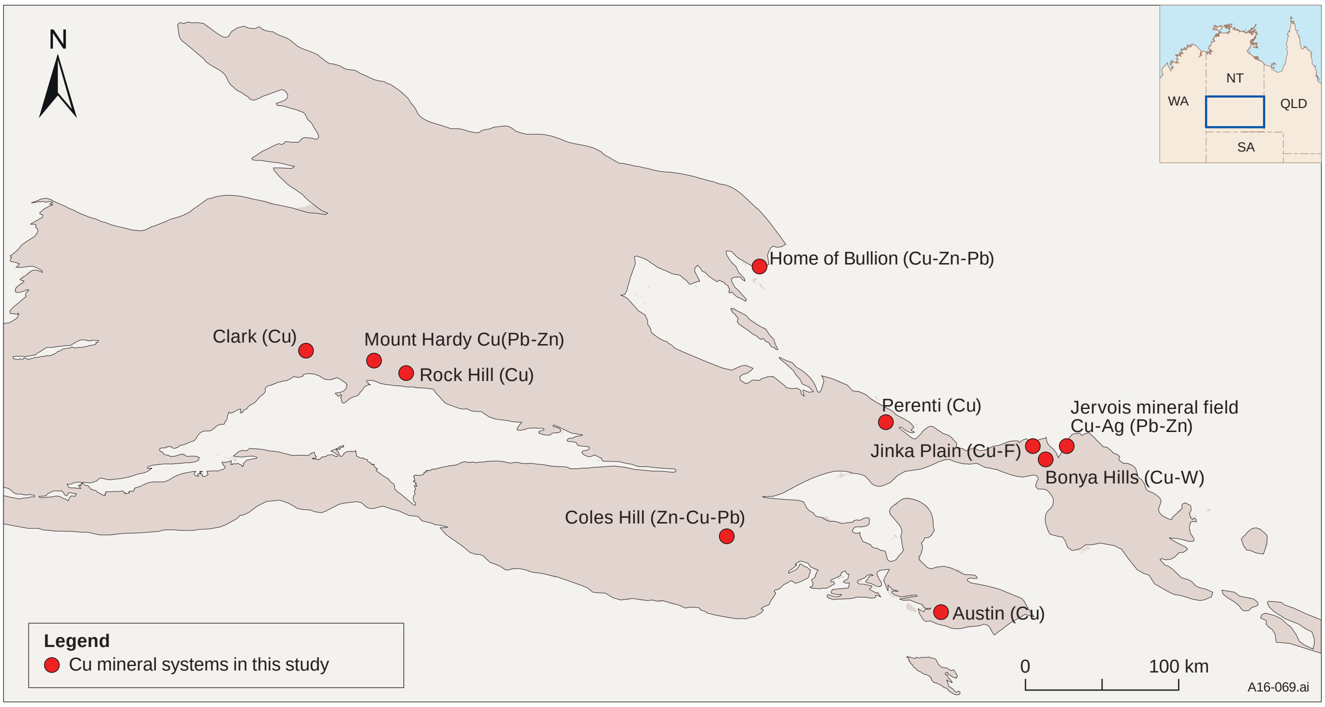

Figure 1. Location of selected Aileron Province copper-related mineralisation discussed in this abstract (adapted from Whelan *et al* 2013).

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9 Names of 1:250 000 and 1:100 000 mapsheets are shown in large and small capital letters, respectively, eg ILLOGWA CREEK, Jervois Range.

paleoenvironment, timing of mineralisation and potential applications for regional exploration. This research included:

- whole rock geochemistry and B isotope systematics of syngenetic tourmalinites associated with mineralisation
- the chemistry of mineralisation-related garnets
- an assessment of the potential existence and significance of metavolcanics in the lode rock stratigraphy
- robust determination of the crystallisation age for pegmatites that intrude base metal mineralisation.

Tourmalinite was sampled from two locations near the Reward deposit and a location near to both the Bellbird deposit and the Cox's Find prospect (**Figure 2a-b**). A quartz-tourmaline vein that cross-cuts earlier tourmalinite at the second locality was also analysed. Tourmaline was analysed for major elements by electron microprobe and for boron isotope chemistry by SIMS (secondary ion mass spectrometry). The preliminary results indicate all tourmaline sampled has Fe-rich chemistry (**Figure 2c**). Most significantly, this tourmaline yields extremely light $\partial^{11}B$ isotopic signatures indicating either continental evaporite or granite-derived fluid sources (**Figure 2d-e**).

Garnets from the lode sequence at the Reward deposit formed when syngenetic mineralisation and host rocks were metamorphosed. Regional metamorphism was recently Pb-Pb monazite dated at ca 1757 ± 9 Ma[10] (Reno *et al* in prep). These garnets were microprobed revealing elevated though variable Mn-rich chemistry (**Figure 3**) with some garnets also containing ≤ 500 ppm Zn.

Previous attempts at dating pegmatite crystallisation ages at the Reward and Green Parrot deposits yielded non-useable metamict zircon data and imprecise Pb-Pb apatite ages (eg McGloin and Weisheit 2015). New Pb-Pb columbite ages from the same Reward pegmatites suggest crystallisation ages of 1749 ± 6 and 1742 ± 6 Ma, post-dating peak-metamorphism in Jervois Range after ca 1755 Ma (Weisheit *et al* 2016).

Although felsic igneous rocks are known in the Bonya Metamorphics regionally (Reno *et al* 2015), there has been considerable debate as to the existence and significance of metavolcanics near and within the lode sequence at Jervois where quartz-sericite schists are interpreted as derived from volcanic rocks (see Thom 2004, McGloin and Weisheit 2015). The highly altered, deformed and metamorphosed nature of the Jervois lode sequence makes protolith discrimination extremely difficult. As such, qualitative observations alone are notoriously unreliable in determining the protolith of polydeformed and metamorphosed felsic rocks (Gower 1997). To unravel this problem, several outcrops of potential meta-volcanic rocks in the J-fold, as well as outcrops in the northeast of the Jervois mineral field and near

10 All geochronological ages were acquired employing the LA-ICPMS U-Pb zircon technique unless otherwise stated.

Table 1. Summary of selected areas of copper mineralisation in the Aileron Province.

Cu mineralised region	Example deposit/ prospects	Metal assemblage and grade/ tonnage/ or best drill intercept	Earliest (or maximum) age and timing of mineralisation	Proposed classification
Jervois mineral field	*Reward, Bellbird*	Cu-Ag(Pb-Zn)Fe 26.7 Mt at 1.12% Cu, 16.6 g/t Ag; Pb-Zn resource of 3.8 Mt at 3.7% Pb, 1.2% Zn, 0.72% Cu, 67.5 g/t Ag.	ca 1790 Ma; syngenetic	metamorphosed, sediment-hosted, volcanic-associated massive sulfide mineralisation
Bonya Hills	*Bonya, Marrakesh, Molyhil Jericho*	Cu-W-Fe Bonya best intersection: 38 m @ 4.4% Cu Molyhil: 4.71 Mt at 0.28% WO_3 and 0.13% Mo, minor Cu Jericho: 600 t/vertical metre, up to 1% WO_3; 40 m x 5 m; small opencut mine	ca 1725 Ma; epigenetic	Granite and pegmatite-related secondary vein and skarn
Jinka Plain	*Oorabra Reefs Fluorite veins A-G*	F, Fe, Cu, Ba 375 920 t @ 39.6% CaF_2 ≤ 500 ppm Cu	< ca 1720 Ma; epigenetic	Granite-hosted, unknown vein and breccia related
West Huckitta	*Perenti*	Cu, Fe, F 7 m at 0.56 % Cu	< ca 1810 Ma; epigenetic	Granite-hosted, unknown vein and breccia related
Illogwa Creek	*Austin*	Cu, F Austin: 3 m @ 0.18% Cu	< ca 1750 Ma; epigenetic	Granite-hosted, unknown vein and breccia related
Barrow Creek	*Home of Bullion*	Cu-Zn-Pb-Ag-Au 2.5 Mt @ 1.8% Cu, 2% Zn, 36 g/t Ag, 1.2 % Pb, 0.14 g/t Au at 0.5% Cu cut-off	ca 1825 Ma; syngenetic	metamorphosed, volcanic-associated sediment-hosted massive sulfide mineralisation
Mount Hardy	*Mt Hardy, Browns, Clarke, Rock Hill*	Cu(Pb, Zn) Mount Hardy: 12 m @ 0.65% Cu, 0.39% Pb and 0.87% Zn	ca 1825–1800 Ma; epigenetic	metamorphosed, pegmatite and granite vein related
Strangways Ranges	*Coles Hills, Edwards Creek*	Zn-Pb-(Cu) Coles Hill :13.35 m @ 3.3% Zn, 0.5% Pb	ca 1800 Ma; syngenetic	metamorphosed volcanic-hosted massive sulfide mineralisation

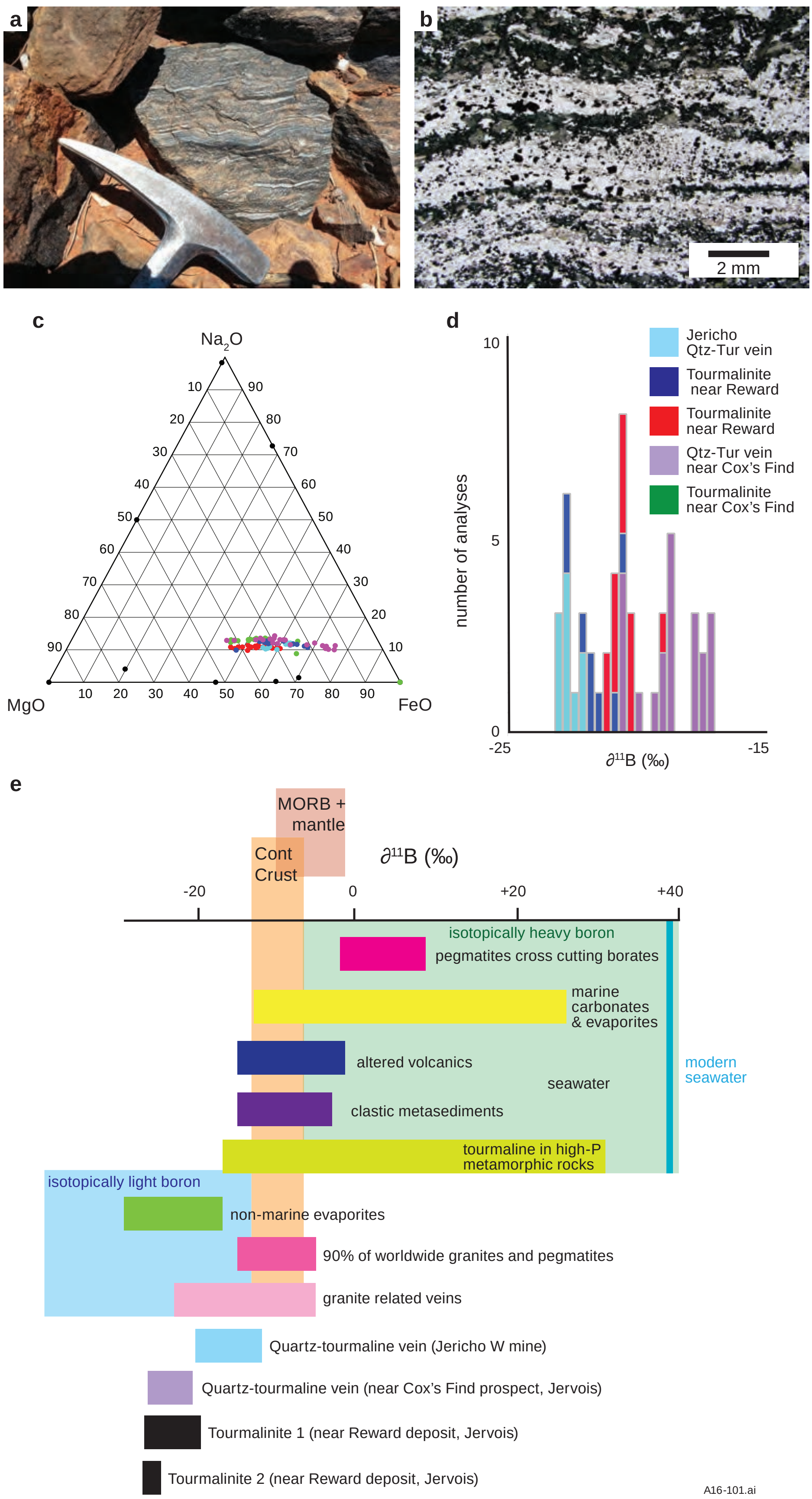

Figure 2. Tourmaline observations, geochemistry and boron isotope data from the Jervois mineral field and Bonya Hills. (**a**) typical stratiform though foliated tourmalinite near the Cox's Find prospect at Jervois. (**b**) photomicrograph of the same tourmalinite showing banded layers of tourmaline and quartz. (**c**) ternary Na_2O-MgO-FeO elemental oxide weight percentage plot for tourmalinite and quartz-tourmaline veins in the Jervois mineral field and Jericho W prospect. (**d**) histogram of boron isotope data for two tourmalinites from the Jervois J-fold: a quartz-tourmaline (Qtz-Tur) vein from near Cox's Find prospect and a quartz-tourmaline vein from the Jericho W prospect in the Bonya Hills. (**e**) measured boron isotope composition as a function of host rock type and inferred B sources plotted with 4 samples from this study. Maximum internal precision errors = 0.15 ‰. MORB = mid-ocean ridge basalt; adapted from Marschall and Jiang (2011).

Hamburger Hill prospect (3 km east of the Reward deposit) were visited. Zircon geochronology, whole rock petrology and geochemistry were performed on the new samples. Historical samples were re-assessed where necessary for felsic igneous protoliths. The following observations were made:

- Historical petrological observation of bi-pyramidal phenocrysts within quartz sericite schist have been interpreted as evidence for metavolcanics (Peters *et al* 1985). Generally this quartz-sericite schist is stratiform and cross-cuts (on the map-scale) the metasedimentary sequence of the Bonya Metamorphics (Reno *et al* 2015). The location of the outcrops described in Peters *et al* (1985) are not specified and could not be independently verified.
- Metamorphosed and deformed quartz-sericite schist was sampled from a fluorite-bearing pit in the south of the J-fold near Bellbird. This rock was previously interpreted as rhyolite (Thom 2004); however the protolith cannot be conclusively determined given that this deformed and re-crystallised sample has ambiguous chemistry and petrology, consistent with either a granite-derived volcaniclastic sediment or a felsic igneous rock. The highly metamict zircons are very discordant and show Pb loss and common Pb contamination; they could not provide any robust age constraints. If the zircons are detrital, the observation of some euhedral igneous zircon grains with concentric oscillatory zoning indicates that these zircons have undergone little transport from their original source. However, the majority of zircons are highly metamorphosed making this assessment uncertain.
- A quartz-rich outcrop near the Rockface prospect has granite chemistry and contained bi-pyramidal quartz confirming a (sub)volcanic protolith despite field interpretation as a quartzite. The analysed zircons contain common Pb and show Pb loss and fail to constrain a robust crystallisation age.
- A historic sample of quartzofeldspathic rock from north of Hamburger Hill previously interpreted as Bonya Schist (now named Bonya Metamorphics) yielded a SHRIMP zircon upper intercept discordia age of 1807 ± 17 Ma interpreted to record maximum deposition of a sedimentary protolith (Claoué-Long and Hoatson 2005). A reassessment of this sample in the context of field relationships, and new geochemical, petrologic, and chronologic data indicates the sample is instead a deformed meta-felsic igneous rock. Zircons from a new sample taken from the same locality yield a $^{207}Pb/^{206}Pb$ SHRIMP age of 1778 ± 6 Ma (2σ; Kositcin *et al* in prep) interpreted to record timing of crystallisation of the igneous protolith. It remains inconclusive whether the igneous protolith was intrusive or extrusive.
- A gneiss from Hamburger Hill, tentatively interpreted in the field as a metavolcanic rock, contains fine-grained garnet and mineralogy typical of a metapelite with no evidence for igneous textures or protolith; this suggests a metasedimentary origin. All zircons showed evidence for common Pb contamination and Pb loss. The resultant Pb-Pb isochron produced an upper intercept age of 1679 ± 100 Ma interpreted to represent metamorphic disturbance.
- Another gneissic sample from Hamburger Hill was dated after removing zircons with Pb loss and common Pb inheritance. The oldest undisturbed zircon population is unimodal and produced a Pb-Pb isochron upper intercept age of 1822 ± 9 Ma. The gneiss probably had a meta(sub)volcanic protolith although the protolith cannot be constrained beyond doubt.

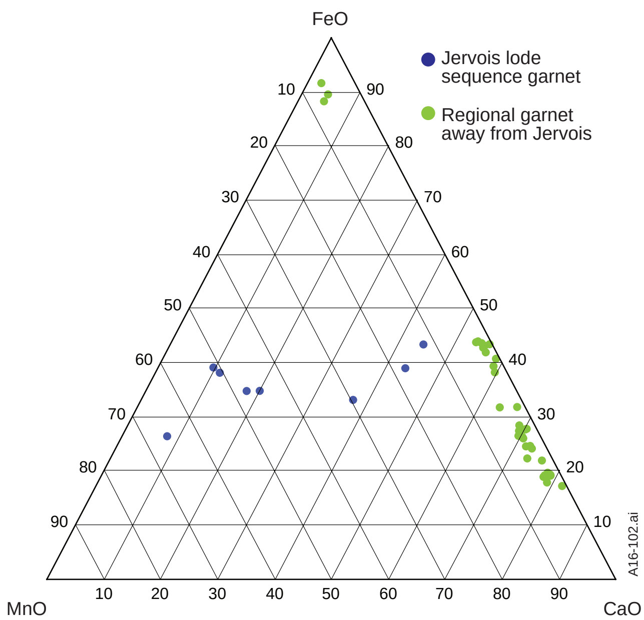

Figure 3. Ternary FeO-MnO-CaO elemental oxide weight percentage plot comparing garnets from the lode sequence at the Reward deposit (this study: blue) and regional garnets from the Bonya metamorphics (green). Data for regional garnets sourced from Peters *et al* 1985, Cartwright *et al* 1997, Riemer 2000, Reno 2016 (unpublished data).

In summary, these new observations and analyses confirm that there are some small bands of felsic igneous rocks hosted within the Bonya Metamorphics. The significance of these rocks is considered in the discussion.

Cu and W mineralisation in the Bonya Hills

Approximately 100 former Cu and W mines, prospects and occurrences exist in the Bonya Hills area, located approximately 30 km west of the Jervois mineral field. Tungsten and copper mineralisation was discovered in the early twentieth century, including the Bonya high-grade copper deposit and the Jericho and Samarkand W deposits (Nye and Sullivan, 1942; Morrison, 1960). Relatively little information is available on the genesis of this mineralisation however. This mineralisation is hosted in quartz veins or disseminated in calc-silicate rock. Although W mineralisation in the Bonya Hills area has been previously researched (Riemer 2000), no significant research into the Cu mineralisation, nor an assessment of the connection between local Cu and W mineralisation has been attempted. Preliminary research on both copper and tungsten mineralisation in the Bonya Hills suggested that this mineralisation was epigenetic, post-peak-metamorphic and vein and skarn-related, forming at ca 1730–1700 Ma (McGloin and Weisheit 2015). New results from the Bonya Hills support those observations and strongly suggest a genetic link between regional Cu and W mineralisation, skarn and vein formation and regional metasomatism related to post-tectonic granite and pegmatite intrusions.

Diamond drill core and reverse circulation chips were analysed from the historical Bonya mine after Rox Resource's 2014 drilling campaign. Drill core logging clearly identified that chalcopyrite-pyrite mineralisation is hosted in quartz veins and is spatially associated with pegmatites. Both the quartz veins and pegmatites overprint the regional S_{main} foliation. They also overprint and are spatially related to mafic sills of the Kings Legend Amphibolite that intruded the Bonya Metamorphics before regional deformation and metamorphism. Locally the S_{main} foliation has been independently Pb-Pb monazite dated at 1760 ± 4 Ma in an andalusite-biotite schist northwest of Bonya mine (Reno *et al* in prep). In the same study, Pb-Pb monazite dating of a contact metamorphosed metasedimentary rock was interpreted to represent a minimum age at 1770 ± 6 Ma for the intrusion of the Kings Legend Amphibolite into the Bonya Metamorphics near Bonya. Molybdenite associated with chalcopyrite and pyrite in a cross-cutting quartz vein sampled from RC chips yielded a new Re-Os age of 1726 ± 8 Ma confirming a post-peak metamorphic timing for this copper mineralisation.

There are currently no techniques that allow for the direct dating of W mineralisation. Pb-Pb dating of apatite from a pegmatite from Samarkand W prospect provided a best estimate of the timing of mineralisation with an intercept age of 1680 ± 59 Ma; this is interpreted to represent a maximum igneous crystallisation age. However, this age should be used cautiously because the apatite grains show complex mixing of common Pb. Nonetheless the pegmatite age is considered to be reasonably robust despite the large age errors. A tourmaline-bearing quartz vein associated with scheelite mineralisation at Jericho W-Cu mine has light $\delta^{11}B$ isotope values (-16.9 to -20.5 ‰) and a Fe-rich chemistry (≤ 10.9 % FeO). These results are consistent with either a granite-pegmatite or non-marine evaporite boron source (**Figure 2c-e**).

All regional Cu and W occurrences, prospects and deposits show similar vein or late skarn alteration. Copper mineralisation is spatially associated with metamorphosed mafic rocks at the contacts with cross-cutting veins, pegmatites or granite intrusions; mineralisation is also commonly associated with epidote and chlorite alteration. Scheelite mineralisation is consistently found in either calc-silicate rock or in nearby pegmatite and granitoid phases. All the Cu and W occurrences share common geochemical relationships including elevated Cu content in W occurrences and elevated W in Cu occurrences. Whole rock geochemistry from mineralised Cu and W samples have elevated Mo, Sn, U, Bi, Co, Fe and low concentrations of Pb, Zn and Au. **Figure 4** shows sulfide S isotope data from Cu and W deposits and prospects including Bonya, Marrakesh, Molyhil, Petra and Xanten. These values are most consistent with a magmatic sulfur source, and are further supported by the spatial association of this mineralisation with mafic rocks.

Regional copper-bearing fluorite-quartz veining and brecciation

Quartz-fluorite-iron oxide veins and vein-breccias outcrop in several areas including Jervois mineral field, the Oorabra reefs of Jinka Plain, Perenti and in the southeasternmost exposures of the Aileron Province in ILLOGWA CREEK. These veins and breccias contain copper mineralisation as chalcopyrite, associated with pyrite and iron oxide mineralisation, and in some cases, with carbonate and/or barite. These veins and breccia commonly cross-cut host granite. For the Cu prospects in ILLOGWA CREEK, Whelan *et al* (2013) suggested a possible link to IOCG-style alteration based on the iron-oxide-fluorite-silica-potassic alteration, brecciation and granite-host. These observations were subsequently interpreted as evidence for a regional IOCG belt (Lyons *et al*, 2013). However

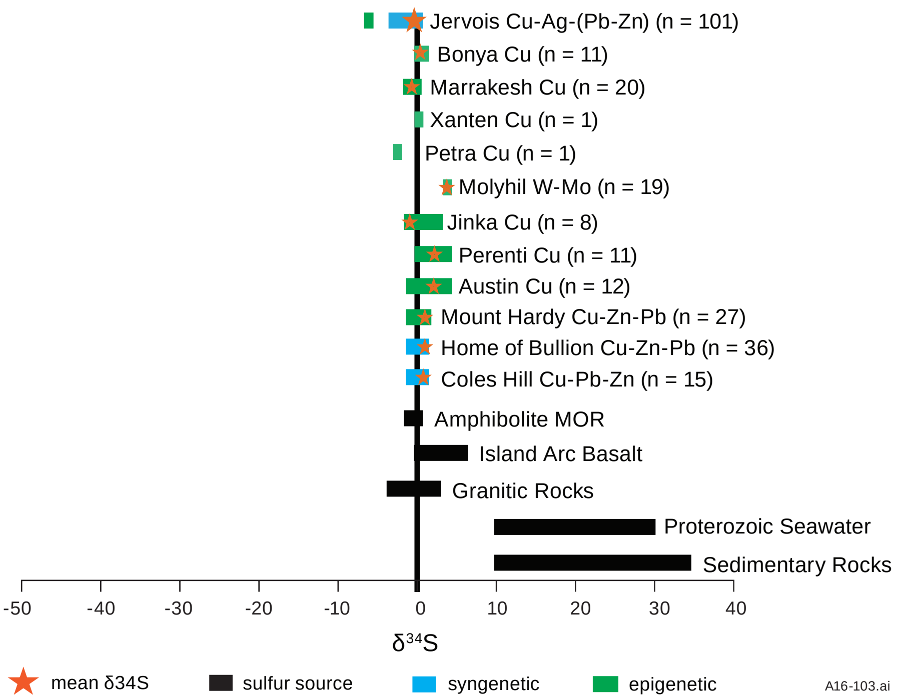

Figure 4. Regional $\delta^{34}S$ sulfide isotope data from 262 sulfide samples from various copper deposits and occurrences in the Aileron Province and a comparison with typical values from prospective S reservoirs from Hoefs (1980).

given that in most areas of the Aileron Province with such veins, including the Cu prospects at ILLOGWA CREEK, there is very limited data on fluid sources, timing and links to regional tectonic events, the genetic origins for this mineralisation remain poorly constrained. New results reported here involve sulfide S isotope data, some constraints on the timing of mineralisation and estimates on fluid flow volumes.

Sulfide $\delta^{34}S$ isotope data from Illogwa, Jinka Plain and Perenti show values between ca 0-5 ‰ (**Figure 4**). The slightly elevated $\delta^{34}S$ values compared to near-zero values are probably due to pH and fluid-rock interactions. Mineralisation is associated with mafic amphibolite at both the Austin and Perenti prospects. This suggests that meta-igneous rocks may be a suitable copper and sulfur source for these regional veins. No direct association between the quartz-fluorite veins and mafic meta-igneous rocks are known at Jinka; however, the Bonya Metamorphics that host these intrusive granite hosts contain voluminous mafic bodies and sills. Furthermore, there is evidence for large mafic xenoliths in granites that host these quartz-fluorite veins. Similar mafic enclaves are found in the granites hosting quartz-fluorite veins and breccias at Illogwa.

Direct Re-Os dating of pyrite and chalcopyrite from Jinka, Perenti and Austin failed due to low Re concentrations (< 0.5 ppb). As such, minimum age constraints are limited to cross-cutting relationships in host granites. At Jinka, km-long and several m-wide fluorite-quartz veins intrude metasomatised and sheared granites that have yielded weighted average Pb-Pb zircon ages of 1712 ± 30 Ma and an isochron Pb-Pb age of 1736 ± 36 Ma respectively; these age thus constrain a minimum timing for this veining. At Jervois where thin fluorite-quartz-carbonate-copper veins overprint polymetallic mineralisation, a minimum age for fluorite veining is provided indirectly by a Re-Os age of 1706 ± 7 Ma from molybdenite that overprints chalcopyrite (McGloin and Weisheit 2015). A maximum mineralisation age at Perenti is constrained by the deformed granite host that has a SHRIMP U-Pb zircon crystallisation age of 1809 ± 4 Ma (Kositicin *et al* 2014). At ILLOGWA CREEK, dating of the granite that hosts copper mineralisation yielded a SHRIMP U-Pb zircon crystallisation age of 1750 ± 4 Ma (Kositcin *et al* 2012). At Jinka Plain, using conservative estimates of quartz-fluorite veining dimensions and quartz and fluorite solubility at relatively low temperature and pressure conditions, an estimated total fluid volume of ≥ 1.92 km^3 was involved in vein formation. A lack of continuous outcrop limits estimations of vein and breccia dimensions at Perenti and southeastern ILLOGWA CREEK. However estimated conservative minimum total fluid volumes of ≥ 7 million m^3 for ILLOGWA CREEK and ≥ 2 million m^3 for Perenti are required to produce the observed quartz-fluorite-iron alteration, veining and brecciation.

Home of Bullion

The Home of Bullion deposit is located 30 km east of Barrow Creek, 300 km north of Alice Springs (**Figure 1**). The deposit has been mined several times since the 1920s with some of the highest ever Australian copper ore grades reported during this period (Brittingham, 1950). Despite this rich mining history, relatively little is known about the characteristics and genesis of this deposit. In 2014 and 2015, reconnaissance and structural mapping along with new drill core logging was completed at the Home of Bullion deposit by NTGS and PGN Geoscience. The results of this work together with new geochemical, petrological and geochronological data from the deposit and regional rocks help to constrain the timing and origins for this mineralisation.

Massive sulfide mineralisation at Home of Bullion is stratabound and hosted in the lower amphibolite-facies Bullion Schist, a package of metapelite-dominated metasedimentary rocks (**Figure 5a-b**). The mineralisation is spatially related to a mafic protolith now found as retrogressed chlorite and biotite schist; however the mineralisation may also be related to several less altered metagabbro bodies intruding near the deposit. The primary coarse-grained mineralisation is associated with magnetite and consists of pyrite, chalcopyrite, sphalerite, bornite, galena and minor chalcocite (**Figure 5c-d**). At surface, mineralisation is oxidised. Lode zones are enriched in Cu, Zn and Pb with minor Ag and trace Au.

Host rocks at Home of Bullion are intensely folded and sheared especially near mineralisation and where competency contrasts are found in host rocks (**Figure 5b, e**). Most shearing is related to F_1 tight isoclinal folds with strain localised into fold limbs. The geometry of the mineralisation is strongly controlled by F_1 folding where mineralisation thickens into hinge zones. Consequently mineralisation is thinned and boudinaged in the limbs of the shear folds. Three later deformations rework the F_1 structures and retrogress the host rocks. The D_2 event produced the intense S_{main} foliation that overprints F_1 structures but does not appear to be associated with folding. Later shearing and folding events localise some mineralisation into plunging shoots.

New galena Pb model ages calculated for samples from Home of Bullion using the regional model of Warren *et al* (1995) indicate earliest mineralisation at ca 1825 Ma. These ages are reasonably consistent with new zircon geochronology that suggests local mafic intrusions crystallised at 1822 ± 27 Ma and granite intrusions at 1823 ± 9 Ma. Dating of detrital zircon from a sample of Bullion Schist yielded a maximum depositional age of 1870 ± 6 Ma. Further work is needed to constrain the timing and to determine the relationship between mineralisation and host rocks. However it is possible that some of the host metasedimentary rocks were deposited at a similar time to mineralisation and were contemporaneous with nearby magmatism. Further evidence for such a link may come from sulfide $\delta^{34}S$ isotope values from the deposit. These values plot consistently near zero (mean = 1.27 ‰, range -0.74 to 1.65 ‰; **Figure 4**) suggesting a magmatic sulfur source.

Mount Hardy copper field

Several Cu and W prospects and occurrences are found in the Mount Hardy region. Cu occurrences including

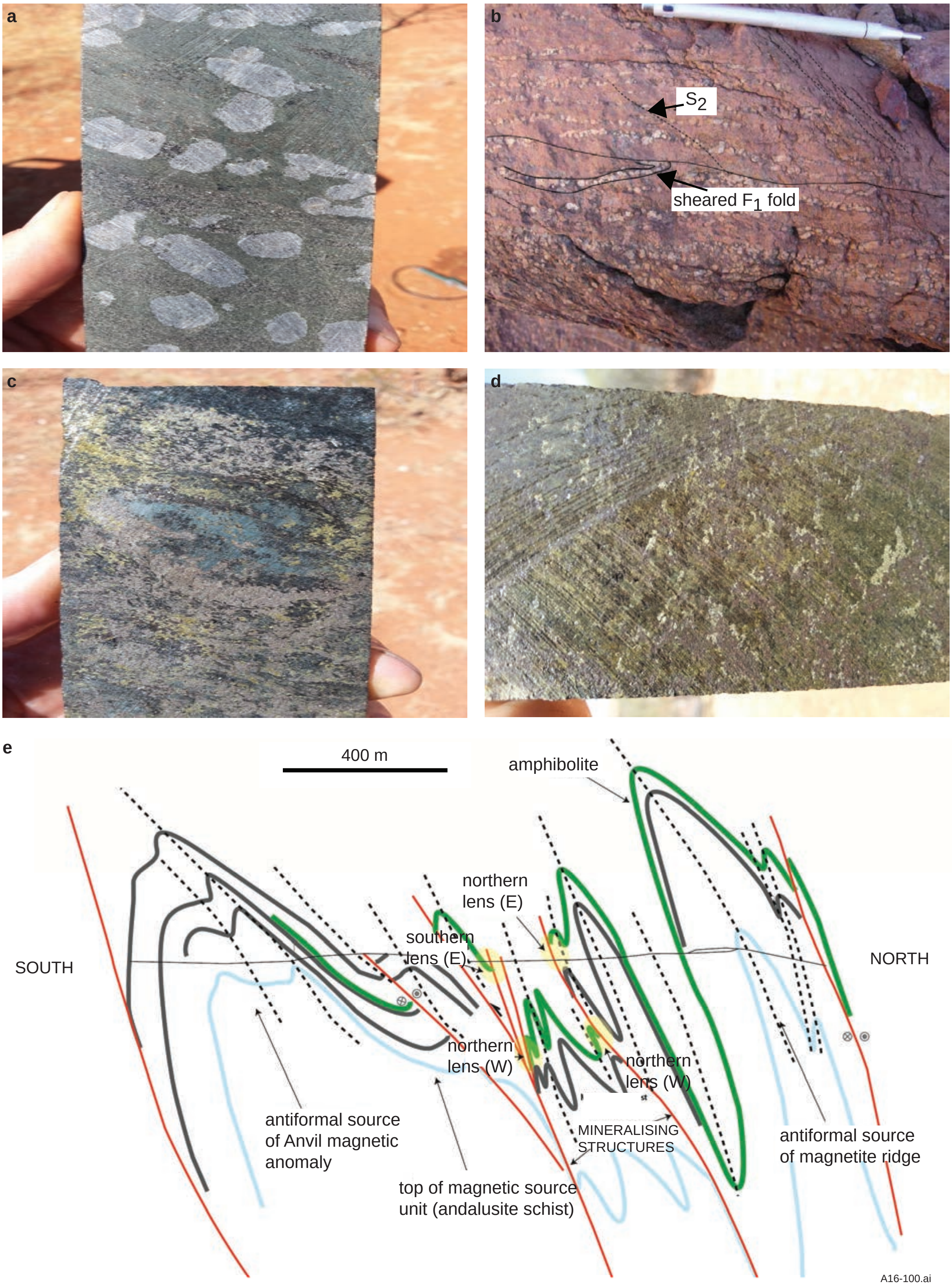

Figure 5. Mineralisation, host rock and structural interpretation from Home of Bullion deposit. (**a**) andalusite-chlorite schist from drill core (**b**) banded andalusite-rich horizons in andalusite-chlorite schist from the hangingwall to the northern lens of mineralisation. Note the sheared F1 fold. (**c**) massive sulfide mineralisation in drill core showing chalcopyrite, pyrite and sphalerite associated with magnetite. (**d**) foliated, banded chalcopyrite-pyrite-sphalerite mineralisation associated with chlorite, biotite and magnetite. All drill core is 5 cm width. (**e**) schematic cross section incorporating drilling, surface observations and interpolation through the Home of Bullion deposit. The green layer represents the mafic sill that can be structurally repeated throughout the area. The two yellow zones at surface indicate outcropping gossans and the eastern extents of the northern and southern lenses. The two yellow zones at depth are inferred based on coincidence of mineralised faults and intersecting mafic sill. These two inferred occurrences at depth would correlate with the western extents of the northern and southern lenses assuming a moderate to steep NE plunge. Diagram reproduced with permission from Kidman Resources Limited.

Mount Hardy deposit have been intermittently mined since the 1930s (Grainger, 1968) but the origins and characteristics of this mineralisation is not well understood. New fieldwork and subsequent analyses identifies previously unmapped granite intrusions and reports new local granite and pegmatite geochronology. This work also characterises the petrology, whole rock and isotopic geochemistry and mineralisation ages for several of the Mount Hardy Cu deposits and prospects.

Copper mineralisation at Mount Hardy is hosted predominantly within deformed quartz veins and stringers that show evidence for serrated grain boundaries, brecciation and foliated mica minerals (**Figure 6c-d**). Some quartz shows evidence for later annealing. A number of the prospects contain Cu-only mineralisation whereas other prospects such as Brown's are enriched in Zn with minor Pb. Secondary mineralisation near surface is oxidised to malachite and chrysocolla. At depth, primary mineralisation consists of chalcopyrite, pyrite, minor native copper, and less commonly, sphalerite, pyrrhotite and minor galena (**Figure 6c-d**). The mineralised quartz veins are spatially associated with pegmatite intrusions showing graphic quartz-feldspar intergrowths (**Figure 6a-b**).

Host rocks are biotite-muscovite-quartz gneiss, metapsammite and metapelite of the Lander Rock Formation. Although no depositional ages are reported near Mount Hardy deposit, a psammitic gneiss from the Lander Formation on ALCOOTA is interpreted to have a maximum depositional Pb-Pb zircon age of 1835 ± 6 Ma (Beyer *et al* 2013). Mineralised quartz veins predominantly host chalcopyrite and pyrite with variable proportions of pyrrhotite, galena and sphalerite associated with chlorite and biotite. The mineralisation and host rocks are recrystallised and altered by subsequent lower-amphibolite to upper-greenschist facies metamorphic and hydrothermal events. The exact timing of mineralisation relative to pegmatite intrusions and quartz veining is complicated by at least two phases of pegmatite intrusion, and both early and late quartz veining. Some pegmatites are foliated and deformed, whereas others cross-cut the S_{main} foliation in the host rocks. The youngest quartz veins are not mineralised.

New galena Pb model ages calculated using the regional Pb model (Warren *et al* 1995) suggest mineralisation formed at ca 1825 Ma. Although this age is reasonably accurate, the high µ values in Pb isotope values suggest this age may be slightly imprecise. Sulfide $\delta^{34}S$ isotopes from the Mount Hardy mineralisation yield homogenous values (mean = 1 ‰; range = -0.74 to 1.65 ‰; **Figure 4**) most consistent with a magmatic sulfur source.

The nearest exposed granite outcrops to Mount Hardy were previously mapped as part of the ca 1570–1530 Ma Southwark Suite. However new field mapping combined

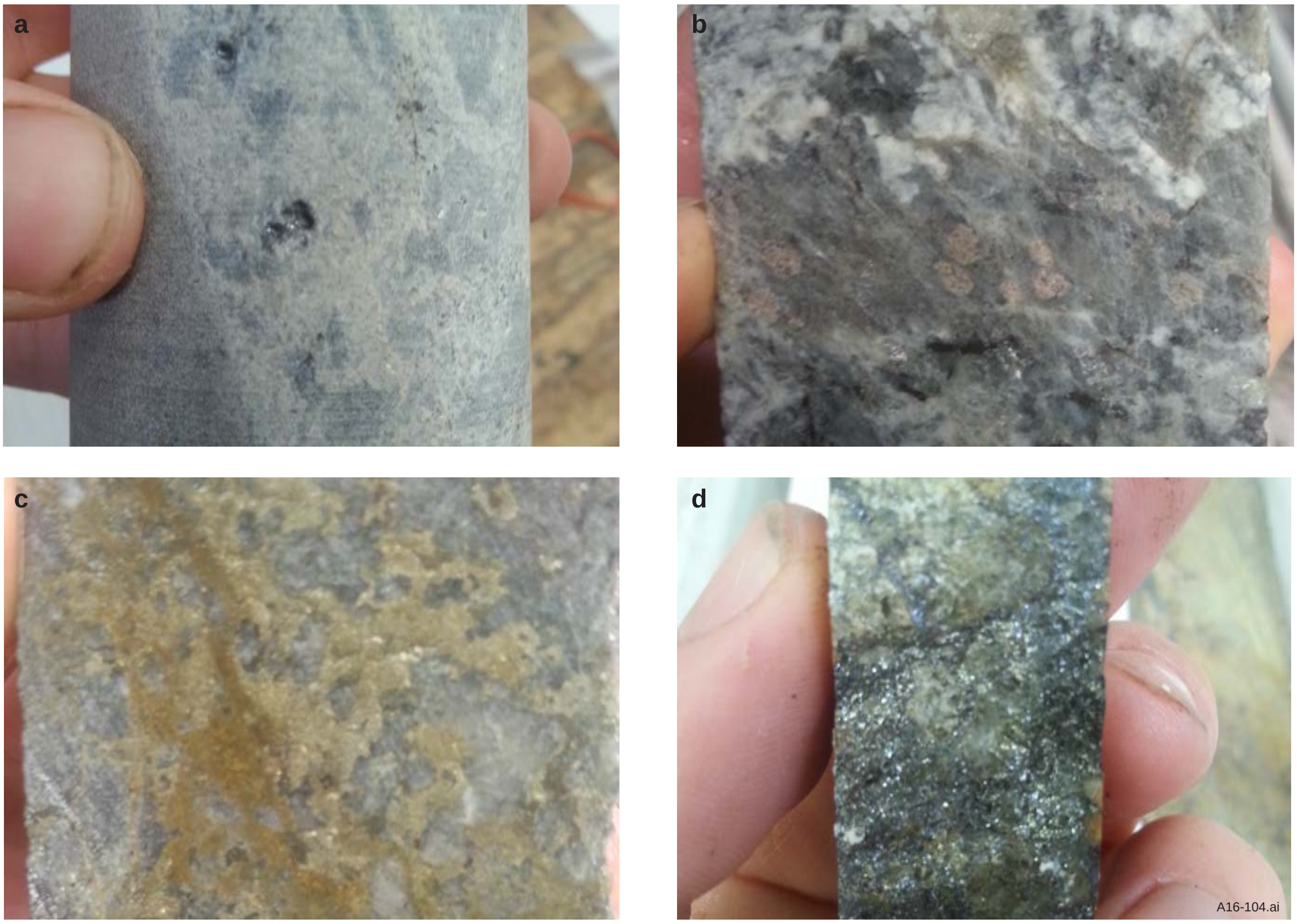

Figure 6. Pegmatites and quartz-vein hosted mineralisation in drill core from the Mount Hardy copper field. (**a**) deformed chalcopyrite-galena-bearing pegmatite. (**b**) foliated garnet-bearing quartz-feldspar-muscovite pegmatite. (**c**) typical chalcopyrite-pyrite quartz vein mineralisation showing evidence for deformation; width of all drill core in a-c = 5 cm. (**d**) ¼ drill core (2.5cm width) showing galena-chalcopyrite-pyrite mineralisation hosted in a quartz vein.

with preliminary zircon geochronology demonstrates a more complex history of granite intrusions in the area. Previously unmapped granite and granodiorite intrusions to the southwest and north of Mount Hardy yield magmatic crystallisation zircon ages of 1808 ± 7 Ma and 1823 ± 25 Ma respectively. The closest outcropping granite to Mount Hardy had been previously mapped but not dated. This rapakivi megacrystic granite yielded a U-Pb zircon magmatic crystallisation age of 1577 ± 9 Ma.

Local pegmatite ages remain less well constrained than the granites. Nonetheless preliminary LA-ICPMS Pb-Pb monazite and U-Pb zircon data from two pegmatites in the Mount Hardy deposits yield crystallisation ages of ca 1820 Ma followed isotopic disturbance at ca 1750 and ca 1550 Ma. Similarly Re-Os dating of molybdenite from a pegmatite intruding near mineralisation at Mount Hardy yields an 1800 ± 8 Ma mineralisation age. A pegmatite at a Rock Hill Cu prospect yielded a magmatic crystallisation age of 1789 ± 25 Ma. Other granitoids south of Mount Hardy in MOUNT DOREEN yielded zircon and monazite crystallisation ages of 1559 ± 9 Ma and 1561 ± 8 Ma. Near the Clarke Cu prospects, biotite granite yielded a zircon crystallisation age of 1778 ± 4 Ma and a foliated granite produced a Pb-Pb monazite age of 1580 ± 4 Ma.

Discussion

The new data from the Palaeoproterozoic copper mineralisation in the Aileron Province provide evidence and new constraints for mineralisation processes, regional and local paleotectonic settings, geochemical vectors to mineralisation, and temporal links between different copper-mineralised regions. **Table 1** briefly summarises these findings and interpretations.

At Jervois, the boron isotope and geochemical analyses of tourmaline in stratiform tourmalinite has potential implications for the paleoenvironment and mineralisation processes. Tourmalinites are generally thought to form by the metasomatism of aluminous sediments by B-rich fluids (Slack 1996) thus tourmaline chemistry is partly dependent on the bulk composition of the original sediments. The high Fe^{2+} content of the Jervois tourmalinites is unusual for tourmalinites in volcanogenic massive sulfide (VMS) and SEDEX[11] settings that typically have enrichment in Mg or Na. Their Fe-rich nature may be related to Fe-rich sediments (chemical sediments; see McGloin and Weisheit, 2015) or Fe-rich hydrothermal fluids.

The extremely light $\delta^{11}B$ isotopic tourmalinite signature at Jervois can be derived from only two sources: continental (non-marine) evaporites or granite-derived fluids (**Figure 2e**). Despite the possibility of some replacement of tourmaline in the tourmalinite beds (currently being investigated by tourmaline Pb step-leaching dating), it is most likely that this isotopic signature represents boron sources at a similar time to syngenetic mineralisation at Jervois. Although there could be both marine and non-marine facies in the palaeobasin at Jervois, borate minerals are rare in marine facies (Palmer *et al* 2004). The similar isotopic signature of both granites and non-marine evaporites may suggest a link to hydrothermal fluids from a restricted basin setting (Slack *et al* 1989). This is particularly pertinent as one source for B in modern isolated freshwater basin settings is the inflow of hot springs of saline brines enriched in Na, SO_4 and B (Vengosh *et al* 1995).

The identification of voluminous zones of Mn-rich garnets adjacent to syngenetic mineralisation in the Jervois lode sequence appears to be a unique characteristic distinct from all other reported garnet chemistries in the Bonya Metamorphics (**Figure 3**). Some garnets also show elevated Zn-concentrations. The Mn-enrichment is most likely related to the abundance of Fe- and Mn-rich chemical sediments in the mineralised sequence (McGloin and Weisheit, 2015). Metamorphic minerals (eg garnets, staurolite, gahnite) with high metal concentrations can indicate the metamorphism of pre-existing sulfides and the potential existence of nearby metamorphosed sulfide deposits (Spry *et al* 2000). Thus the anomalous Mn chemistry in these garnets highlights the potential for using metamorphic indicator minerals in regional exploration. As such, regional mapping, soil and creek sampling programmes may benefit from an assessment of these metamorphic minerals in prospective terrains, particularly as they are relatively more resistant to weathering than sulfide minerals.

The new assessment of potential metavolcanics in the J-fold area of the Jervois mineral field indicates that there are small bands of felsic igneous rocks hosted within the Bonya Metamorphics. However any field interpretation for metavolcanics must be treated with scepticism until additional evidence can be produced from further petrological, geochronological or geochemical analyses. Despite the metamorphosed, deformed and altered nature of these quartz-sericite schists, the presence of both unimodal zircon populations and bi-pyramidal quartz in three samples are consistent with felsic igneous sources. Unfortunately, zircon dating could not determine the crystallisation ages of some of the samples due to zircon metamictisation. Discrimination of extrusive (eg rhyolite or volcanic) versus sub-volcanic (felsic sills or dykes) protolith is not possible. It must be emphasised that any such felsic igneous rocks in the lode sequence appear to be volumetrically minor compared to the abundant metasedimentary rocks. Most importantly, although metafelsic igneous rocks exist in the host sequence, the timing of their formation and thus their significance with respect to syngenetic mineralisation remains poorly constrained. Given that local deformation began with the intrusion of the Attutra metagabbro, it is likely that the quartz-sericite schist protolith rocks experienced the same deformation history as local metasedimentary rocks and metamorphosed mafic sills and bodies.

A thorough assessment of Cu and W occurrences in the Bonya Hills indicate that all these epigenetic skarn and vein occurrences formed between ca 1730–1700 Ma (Cartwright *et al* 1997, Riemer 2000, McGloin and Weisheit 2015; this study). These occurrences are also temporally related to the nearby *Molyhil* W-Mo skarn deposit on Jinka Plain. Cross (2007) dated this deposit at 1721 ± 8 Ma and ca 1710 Ma

[11] Note that the SEDEX term (sedimentary exhalative) is now considered inadequate because deposits from this class do not necessarily form by hydrothermal fluids vented directly into a water column. The term 'clastic-dominated sediment-hosted' is preferred (see Leach *et al* 2010; Wilkinson 2014).

using Re-Os molybdenite and Pb-Pb SHRIMP xenotime ages respectively. A regional epigenetic Cu and W mineralisation event therefore is suggested within the timeframe related to granite magmatism. Similarly some overprinting late Cu and W mineralisation and metasomatism is recorded in the Jervois mineral field (McGloin and Weisheit, 2015).

This regional Cu and W mineralisation shares similar petrological, geochemical and S isotope features. The close proximity of Cu occurrences to sulfide-bearing mafic sills, pegmatites and quartz-tourmaline veins suggests that mafic rock probably provided a passive source for Cu and S. The evidence for chloritic and propylitic alteration (epidote, chlorite, quartz) associated on such contacts probably relates to interaction of metasomatic fluids derived from granite and pegmatite intrusions with the host rock assemblage. These granite and pegmatite intrusions have similar ca 1730–1700 Ma crystallisation ages suggesting a genetic link (Reno *et al* 2015). New B isotope data from Jericho mine also suggests a granite-derived link for W mineralisation.

Copper-mineralised quartz-fluorite-iron oxide veins throughout the Aileron Province have poorly constrained timing and genetic origins. However results from 2015 indicate that in most regional occurrences, sulfur was likely derived locally from metagabbros found close to mineralisation. Similarly, sulfide $\delta^{34}S$ signatures in the veins are consistent with a magmatic sulfur source (**Figure 4**). More work is necessary to constrain the source and characteristics of the mineralising fluids. Although oldest possible formation ages of ca 1.7 Ga are suggested, it is likely that these vein and breccia systems were repeatedly sealed and re-opened over time. Other unknowns are the source of the required large volumes of fluids necessary for the vein systems considering the waning stages of known magmatism in these post-orogenic regions at 1.7 Ga, and the lack of known Palaeoproterozoic basin stratigraphy younger than ca 1.7 Ga in the region.

The preliminary results from Home of Bullion suggest a syngenetic origin for this metamorphosed and deformed polymetallic massive sulfide mineralisation (**Figure 5**). The mineralisation is hosted in Bullion Schist, but is intimately associated with orthoamphibolite. This model is supported by a similar ca 1825 Ma timing for the mineralisation and for both felsic and mafic intrusions locally. A magmatic association is also supported by a magmatic S isotope signature and Cu-rich mineral chemistry. As such, this deposit has many similarities to the Jervois deposits, but is hosted in an older basin sequence that formed ~35 my prior and was deformed and metamorphosed by a different metamorphic event (the Stafford Event at ca 1810–1790 Ma). The Bullion Schist is overlain by the Strzeleckie Volcanics; a SHRIMP U-Pb zircon age of 1805 ± 6 Ma (Claoue-Long *et al* 2008; Haines *et al* 1991) constrains a minimum age for mineralisation. Further work is proposed to determine the relationship of metamorphism and deformation to the geometry of the mineralisation at Home of Bullion.

Based on field reconnaissance and drill core logging, the initial results from Mount Hardy indicate an epigenetic copper mineral system hosted in quartz veins and related to pegmatite emplacement at ca 1800 Ma (**Figure 6**); however, mineralisation is complicated by several phases of pegmatite and granite intrusion, and the onset of regional metamorphism. Further pegmatite intrusions at ca 1780 Ma were probably near-contemporaneous with the formation of the regional S_{main} foliation; some quartz and pegmatite veins at Mount Hardy were probably deformed during this time. Given that some pegmatites and quartz veins cross-cut the S_{main} foliation, a period of syn to post-tectonic magmatism and retrograde alteration must also have occurred. The additional intrusion of undeformed granites at ca 1570 Ma does not appear to be related to copper mineralisation at Mount Hardy. Nonetheless this event may have deformed or altered pre-existing mineralisation. Ongoing work is required to fully understand the timing of mineralisation compared to metamorphism, deformation and granite emplacement.

Temporal and characteristic variation in copper mineralisation styles within a broad active-plate margin setting

The results from research of various Palaeoproterozoic copper-related mineral systems in the Aileron Province demonstrate clear temporal and genetic differences between copper systems in different settings. This new data provide evidence for both syngenetic and epigenetic copper mineralisation. In very broad terms, mineralisation can be related to an interpreted active convergent plate margin (eg Betts *et al* 2015; Giles *et al* 2002) with associated basin formation, high-*T*, low-*P* metamorphism and magmatism between ca 1.82–1.7 Ga (Weisheit *et al* 2016). However there are temporal and spatial distinctions between the oldest known syngenetic basin mineralisation at Home of Bullion (ca 1.82 Ma) in the central Aileron Province and the youngest at Jervois (ca 1.79 Ma) in the east. Similarly, epigenetic copper and tungsten mineralisation related to felsic magmatism has occurred between ca 1.82 Ga and at least 1.70 Ga in different parts of the Aileron Province (eg Mount Hardy, Bonya Hills). Large regional mafic and felsic intrusive bodies that formed from ca 1.82 Ga onwards were most likely critical to sourcing copper and driving hydrothermal-related mineralisation for these systems. The remarkably consistent regional sulfide $\delta^{34}S$ data from the various copper systems are interpreted to represent a dominant regional magmatic sulfur source. These intrusions, particularly mafic bodies, also likely provided a passive source for metallogenic inheritance through leaching by hydrothermal fluids during subsequent periods of metamorphism, deformation and magmatism.

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References

Betts PG, Armit RJ, Stewart J, Aitken ARA, Ailleres L, Donchak P, Hutton L, Withnall I and Giles D, 2015. Australia and Nuna: in Li ZX, Evans DAD and Murphy JB (editors). '*Supercontinent Cycles Through Earth History*'. *Geological Society, London, Special Publications* 424.

Beyer EE, Hollis JA, Whelan JA, Glass LM, Donnellan N, Yaxley G, Armstrong R, Allen CM and Schersten A, 2013. Summary of results. NTGS laser ablation ICPMS and SHRIMP U-Pb, Hf and O geochronology project: Pine Creek Orogen, Arunta Region, Georgina Basin and McArthur Basin, July 2008–May 2011. *Northern Territory Geological Survey Record* 2012-007.

Brittingham GJ, 1950. Proposed concentration of Home of Bullion ore, Barrow Creek, Northern Territory, Electrolytic Refining and Smelting. *Northern Territory Geological Survey, Open File Company Report* CR1950-001.

Cartwright I, Buick IS and Maas R, 1997. Fluid flow in marbles at Jervois, central Australia: oxygen isotope disequilibrium and zoning produced by decoupling of mineralogical and isotopic resetting. *Contributions to Mineralogy and Petrology* 128, 335–351.

Claoué-Long JC and Hoatson DM, 2005. Proterozoic mafic-ultramafic intrusions in the Arunta Region, central Australia. Part 2: Event chronology and regional correlations. *Precambrian Research* 142, 134–158.

Claoue-Long J, Maidment D and Donnellan N, 2008. Stratigraphic timing constraints in the Davenport Province, central Australia: a basis for Palaeoproterozoic correlations. *Precambrian Research* 166(1–4).

Cross A, 2007. SHRIMP U-Pb xenotime and Re-Os molybdenite dating of the Molyhil scheelite-molybdenite skarn, northeastern Arunta Region, central Australia. *Research School of Earth Sciences, Annual Report* 2007, Australian National University, Canberra.

Giles D, Betts P and Lister G, 2002, Far-field continental back-arc setting for the 1.80-1.67 Ga basins of northeastern Australia. *Geology* 30, 823–826.

Gower CF, 1997. Protolith recognition of metamorphosed felsic volcanic/volcaniclastic rocks, with special reference to the Grenville Province in southeast Labrador. Current Research 2007. *Newfoundland and Labrador Department of Natural Resources Geological Survey, Report* 07-1, 11–23.

Grainger DJ, 1968. The Mount Hardy Copper Mine, Northern Australia. *Bureau of Mineral Resources, Geology and Geophyscics, Record* 1968/100.

Haines PW, Bagas L, Wyche S, Simons B and Morris DG, 1991. *Barrow Creek, Northern Territory. 1:250 000 geological map series explanatory notes, SF 53-06*. Northern Territory Geological Survey, Darwin.

Hoefs J, 1980. *Stable Isotope Geochemistry. Second edition*. Springer-Verlag, Berlin, Heidelberg, New York.

Hussey KJ, Huston DL and Claoué-Long JC, 2005. Geology and origin of some Cu-Pb-Zn (-Au-Ag) deposits in the Strangways Metamorphic Complex, Arunta Region, Northern Territory. *Northern Territory Geological Survey, Report* 17.

Kositcin N, Reno BL and Beyer EE, in prep. Summary of results. Joint NTGS-GA geochronology project: Arunta Region July 2015–June 2016. *Northern Territory Geological Survey, Record*.

Kositcin N, Whelan JA, Beyer EE, Close DF, Wygralak AS and Dunkley DJ, 2012. Summary of results. Joint NTGS-GA geochronology project: Arunta Region, Murphy Province, Tanami Region, Ngalia Basin, 20112012. *Northern Territory Geological Survey, Record* 2013-004.

Kositcin N, Whelan JA, Hallett L and Beyer EE, 2014. Summary of results. Joint NTGS–GA geochronology project: Amadeus Basin, Arunta Region and Murphy Province, July 2012–June 2013. *Northern Territory Geological Survey, Record* 2014-005.

Leach DL, Bradley, DC, Huston D, Pisarevsky SA, Taylor RD and Gardoll SJ, 2010. Sediment-hosted lead-zinc deposits in earth history. *Economic Geology* 105, 593 – 625.

Lyons P, Mizow D, Lockheed A, Goldman M, McKinnon-Matthews J and Hutton D, 2013, Discovery of the Illogwa IOCG belt: Mithril opens new exploration space in the east Arunta Region: in '*Annual Geoscience Exploration Seminar (AGES) 2013. Record of abstracts*'. *Northern Territory Geological Survey, Record* 2013-001.

Marschall HR and Jiang S-Y, 2011. Tourmaline Isotopes: No Element Left Behind. *Elements* 7, 313 –319.

Morrison ME, 1968. Jervois Range reconnaissance trip, July 1968. *Northern Territory Geological Survey, Open File Company Report* CR1968-0026.

McGloin M and Weisheit A, 2015. Base metal and tungsten mineralisation in the Jervois Ranges and Bonya Hills: Characterisation, potential genetic models and exploration implications: in '*Annual Geoscience Exploration Seminar (AGES) 2015. Record of abstracts*'. *Northern Territory Geological Survey, Record* 2015-002.

Nye PB and Sullivan CJ, 1942. The tungsten deposits of the Northern Territory and possibilities of obtaining further supplies from them. *Aerial, Geological and Geophysical Survey of Northern Australia AGGSNA Report* 1942.

Palmer MR, Helvacı C and Fallick AE, 2004. Sulphur, sulphate oxygen and strontium isotopic composition of Cenozoic Turkish evaporites. *Chemical Geology* 209, 341–356.

Peters M, Kehrens P and van Gils H, 1985. *Geology and mineralization of the Jervois Range, NT, Australia*. MSc Thesis, State University of Utrecht, The Netherlands.

Reno B, Beyer EE, Weisheit A, Whelan JA, Kositcin N and Kraus S, 2015. Geological evolution of the Jervois Range area: 1:100 000 special mapsheet: in '*Annual Geoscience Exploration Seminar (AGES) 2015. Record of abstracts*'. *Northern Territory Geological Survey, Record* 2015-002.

Reno BL, Whelan JA, Weisheit A, Kraus S, Beyer EE, Meffre S and Thompson J, in prep. Summary of results. NTGS laser ablation ICP-MS in situ monazite geochronology project: Arunta Region, July 2013–June 2014. *Northern Territory Geological Survey Record*.

Riemer S, 2000. *Petrology and geochemistry of scheelite-bearing calc-silicate rocks, Bonya Block, Arunta Inlier, central Australia*. MSc Thesis, University of Leoben, Austria.

Slack JF, Palmer MR and Stevens BPJ, 1989. Boron isotope evidence for the involvement of non-marine evaporites in the origin of Broken Hill ore deposits. *Nature* 342, 913–916.

Slack JF, 1996. Tourmaline associations with hydrothermal ore deposits. *Reviews in Mineralogy* 33, 558–643.

Spry PG, Peter JM and Slack JF, 2000. Meta-exhalites as exploration guides to ore. *Reviews in Economic Geology* 11, 163–202.

Thom R, 2004. EL 9518 Jervois annual report for the year ending 2 October 2004. Reward Minerals Limited. *Northern Territory Geological Survey, Open File Company Report* CR2004-0547.

Vengosh A, Chivas AR, Starinsky A, Kolodny Y, Zhang B and Zhang P, 1995. Chemical and boron isotope compositions of non-marine brines from the Qaidam Bain, Qinghai, China. *Chemical Geology* 120, 135–154.

Warren RG, Thorpe RI, Dean JA and Mortensen JK, 1995. Pb-isotope data from base-metal deposits in central Australia: implications for Proterozoic stratigraphic correlations. *AGSO Journal of Australian Geology and Geophysics* 15, 501–509.

Weisheit A, Reno BL, Beyer EE, Whelan JA and McGloin M, 2016. Tectonothermal evolution of the eastern Arunta Region, Central Australia: in '*Annual Geoscience Exploration Seminar (AGES) Proceedings, Alice Springs, Northern Territory 15–16 March 2016*'. Northern Territory Geological Survey, Darwin (this volume).

Whelan JA, Close DF, Scrimgeour IR, Beyer EE, Kositcin N and Armstrong RA, 2013. The Cu ± Au potential of the Arunta Region: links between magmatism, tectonism, regional-scale alteration and mineralisation: in '*Annual Geoscience Exploration Seminar (AGES) 2013. Record of abstracts*'. *Northern Territory Geological Survey, Record* 2013-001.

Wilkinson JJ, 2014. Volume 13.9: Sediment-hosted zinc-lead mineralization: processes and perspectives: in Holland HD and Turekian KK (editors). '*Treatise on Geochemistry (Second Edition)*'. Elsevier Ltd, Oxford.