

The greenfield Grapple and Bumblebee discoveries of the western Aileron Province: First constraints on sulfide mineralising processes

Matt V McGloin¹, Barry L Reno^{1,2}, Natalie Kositsin³, Simon Cornwell⁴, Doug Winzar⁴, Eloise E Beyer¹, David Huston³, David C Champion³ and Anthony Crawford⁵

Ore deposit discovery rates are in steady decline and forcing savvy explorers into underexplored terrains and more challenging environments. The long-term, regional-scale and systematic exploration strategies needed to buck this negative trend are emphasised by the successful greenfields discovery of polymetallic sulfide mineralisation at the Grapple and Bumblebee prospects in the western Aileron Province (**Figure 1**). The Aileron and Warumpi provinces of central Australia have not received the same attention as other apparently more mineral-rich provinces in Proterozoic Australia; these discoveries raise expectations that economic mineralisation may lie undercover (see Winzar 2016 and Whitford *et al* 2019, this volume).

Drilling and mapping of Grapple and Bumblebee provide a first opportunity to assess the nature of this mineralising system and collect valuable evidence that can be interpreted and applied directly to exploration. Using field observations integrated with petrographic, isotopic, geochemical, and chronological analyses, this abstract focuses on explaining our understanding of some of the processes and controls involved in mineralisation at these two prospects. The new data reported herein provide the first temporal constraints on sulfide mineralisation at Grapple and Bumblebee and help to constrain the nature of this mineralisation.

This study provides evidence that this hydrothermal base and precious metal mineralisation could have formed at or after ca 1.67 Ga; however, it is also possible that sulfide mineralisation was formed at ca 1.84 Ga and then reworked at ca 1.67 Ga. Analytical work is ongoing to test competing

models for mineralisation. Although syngenetic or diagenetic mineralisation cannot be precluded, the breccia-hosted pyrrhotite-dominant sulfide mineralisation at these prospects may be younger than other base and precious metal mineralisation previously reported in the Aileron Province; furthermore, it may be related to voluminous magmatism at ca 1.69–1.63 Ga in MOUNT RENNIE⁶.

Regional Geology

The Lake Mackay project of Independence Group NL is located at the southern margin of the Palaeoproterozoic North Australian Craton, straddling the Aileron Province to the north, and the Warumpi Province to the south (see MOUNT RENNIE 1:250 000-scale map). These provinces are separated by the Central Australian Suture (CAS), a major deep crustal-scale structure comprising a series of east–west-trending major faults and shear zones (Shaw *et al* 1992, Scrimgeour *et al* 2005a, Selway *et al* 2009, Morrissey *et al* 2011, Wong *et al* 2015).

The Warumpi Province records a ca 1.69–1.60 Ga history of voluminous, dominantly felsic magmatism, crustal thickening, and metamorphism along the southern margin of the Aileron Province (Close *et al* 2004, Scrimgeour *et al* 2005a, b). The Warumpi Province is divided into three main domains of which the most relevant to this study is the Yaya Domain. This domain comprises a sequence of metasedimentary rocks interpreted to have been deposited between ca 1.66 and 1.64 Ga (Close *et al* 2003, Scrimgeour 2005a,b) then subsequently metamorphosed and intruded by voluminous felsic and mafic magmatism during the ca 1.64–1.63 Ga Liebig Orogeny.

Felsic and mafic magmatism related to the Liebig Orogeny also occurred in the Aileron Province in MOUNT

¹ Northern Territory Geological Survey, GPO Box 4550, Darwin NT 0801, Australia

² Email: barry.reno@nt.gov.au

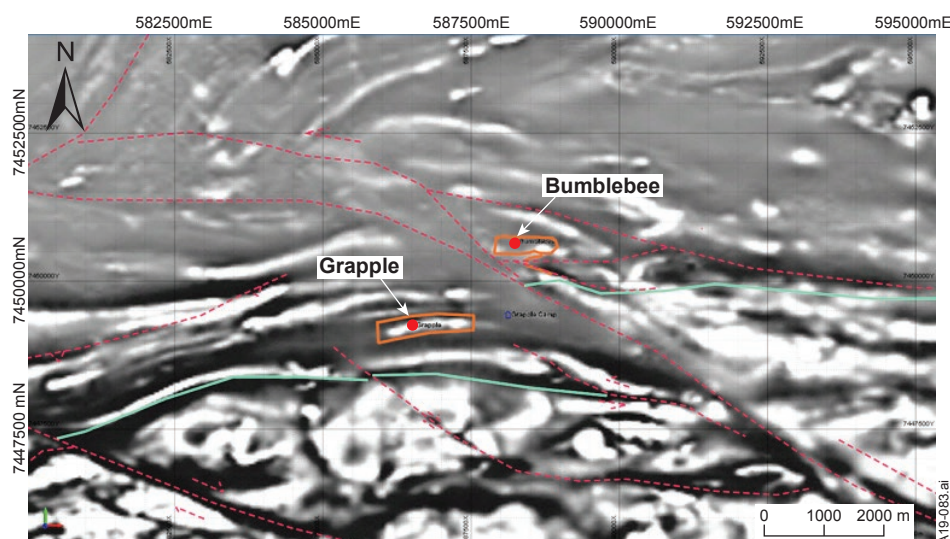
³ Geoscience Australia, GPO Box 378, Canberra ACT 2601, Australia

⁴ Independence Group NL, PO Box 496, South Perth WA 6151

⁵ A&A Crawford Geological Consultants, 493 Tinderbox Rd, Hobart TAS 7054, Australia

⁶ Names of 1:250 000-scale mapsheets are shown in capital letters, eg MOUNT RENNIE.

Figure 1. Reduced to pole first derivative magnetic image showing location of Grapple and Bumblebee prospects and their similar stratigraphic position compared to the Nyirripi Beds (south of the teal coloured line). The prospects have been offset by a large sinistral strike slip fault (red dashed line).



RENNIE, MOUNT DOREEN, and WEBB (eg Andrew Young Igneous Complex; Wyborn *et al* 1998, Cross *et al* 2005, Scrimgeour *et al* 2005a, Hollis *et al* 2013).

Sulfide mineralisation at Grapple and Bumblebee occurs in the western Aileron Province, hosted in low hills of poorly-exposed rocks covered by sand plains and dunes (Close *et al* 2004). The oldest rocks are ca 1.84–1.81 Ga metasedimentary rocks of the Lander Rock Formation (Close *et al* 2005, Hollis *et al* 2013, Kositcin *et al* in prep). Between ca 1.81–1.70 Ga, this metasedimentary succession was intruded and metamorphosed by several phases of magmatism (Scrimgeour 2013, Hollis *et al* 2013), including the ca 1.80 Ga mafic Du Faur Suite and the loosely defined ca 1.77 Ga felsic Carrington Suite (Close *et al* 2004, Edgoose *et al* 2008, Kirkland *et al* 2009, Hollis *et al* 2013).

Local geology

Logging and mapping suggests the Grapple and Bumblebee prospects share a stratigraphic sequence with the prospects subsequently displaced to their current positions by a large sinistral strike slip fault (**Figure 1**). The stratigraphy is dominated by metasedimentary rocks of the Lander Rock Formation (metasandstone and schists; **Figure 2a**). An early lower amphibolite facies metamorphic assemblage is recorded by andalusite and biotite porphyroblasts that contain aligned biotite inclusions. A pervasive mylonitic S_2 foliation fabric, evidenced by aligned mica and elongate quartz in schistose metasedimentary rocks, strikes east–west and dips steeply- to near-vertically to the north. The S_2 fabric deforms and rotates the andalusite and biotite porphyroblasts (**Figure 2a**), which suggests at least two periods of deformation at the prospects. Structural analysis from drill core and surface mapping indicates that the entire stratigraphic package may be tightly folded.

At Grapple, vergence patterns in outcropping metasandstone and porphyroblastic schists are consistent with a south-dipping antiform centred where mineralisation is located. The mineralised lenses have an apparent plunge of approximately 30–40° to the west. This geometry correlates well with lineation measurements from surface mapping (L_2 on S_1). The Bumblebee prospect is hosted in a similar south-dipping antiform but additionally shows evidence for a D_3 fold set. The F_3 fold structures possess axial-planar S_3 disjunctive cleavage, crenulation, and kink-banding seen at surface; in the macroscale they give the Bumblebee prospect a distinctive U-shape.

The foliated metasedimentary rocks are locally intruded by mafic sills and dykes that vary from 1 m to 50 m thickness (**Figure 2b**). A majority of mafic sills and dykes predate S_2 ; however, one observed mafic intrusion at Bumblebee has an unusual porphyritic augite–actinolite–plagioclase mineralogy and overprints the mylonitic S_2 fabric of the host rock (**Figure 2c**). Minor felsic and syenite sills and dykes also occur at the prospects (Crawford 2017).

The vast majority of sulfide mineralisation at Grapple and Bumblebee generally occurs as two massive to semi-massive lenses of mineralised breccia ≤ 9 m thick, hosted by the Lander Rock Formation; they occur between and bounded by mafic sills (**Figure 2b, 3a, 3b**). Stringer

and quartz vein-hosted sulfides also overprint adjacent metamafic and metasedimentary rocks around the breccia zones (**Figure 4a**).

The visible sulfides are dominated by pyrrhotite with lesser chalcopyrite, stringer sphalerite, and coarse-grained arsenopyrite, with minor galena and pyrite occurring as inclusions within pyrrhotite. All main sulfide minerals also occur as inclusions within other sulfides, or on their grain boundaries (**Figure 4c, d**). The breccia also contains sub-angular, lithic clasts of altered country rock including metadolerite and metasedimentary rocks (**Figure 3a, b**). These clasts are sometimes poikiloblastic and/or contain smaller inclusions of sulfides (eg pyrrhotite, sphalerite, minor chalcopyrite, and galena) or other silicates. The breccia also includes monomineralic amphibole, clinopyroxene, and carbonate.

Stringers and quartz-vein related sulfides have similar mineralogy to the pyrrhotite breccias but typically contain higher concentrations of chalcopyrite, sphalerite, and galena (**Figure 3a, 4a**). In one drill core interval at Bumblebee, a different style of mineralisation occurs whereby minor S_2 -foliated and re-crystallised, net-textured pyrrhotite (lacking enrichment in economic metals) is found in mm- to cm-scale discrete layers within siliceous bands hosted in metasandstone (**Figure 4b**). This pyrrhotite probably represents minor diagenetic pyrite that was subsequently metamorphosed, as typical of metamorphosed sedimentary sequences.

Metasedimentary rocks on the margins of sulfide mineralisation are commonly bleached, silicified, and weakly micaceous. The metasedimentary host rocks to the main sulfide mineralisation, particularly where they are adjacent to mafic rocks, are typically altered to a series of amphibole–quartz–chlorite and calcic-skarn assemblages (**Figure 4f**). Typical alteration minerals identified include hornblende, fibrous actinolite, clinopyroxenes (cummingtonite, grunerite and augite), garnet, carbonate (calcite?), chlorite, clinozoisite, biotite, and quartz. Some intervals also contain significant tourmaline and fluorite.

The base of mineralisation at the Grapple prospect is associated with a tremolite schist of the Lander Rock Formation. This schist is of particular economic interest because it also contains the highest gold enrichment at the prospects; the gold occurs as non-visible electrum, distinct from mineralisation in the massive sulfide zones. Importantly, the highest-grade gold is not directly associated with massive, base metal-rich sulfide.

Both prospects appear to have similar element enrichments, sulfide assemblages, grade, and distribution of metals. Assay data from the main mineralised zones at Grapple indicate significant enrichment in ore-forming elements Fe, S, Cu, and Zn. There are also significant enrichments in Pb, As, Co, and Bi; and the precious metals Ag, Te, and Au. Compared to average upper crustal abundances, the highest enrichments are in Te, Bi, and S; with significant enrichments in Cu, Ag, Pb, As, Zn, Au, Co, and Sn. The net-textured S_2 -foliated pyrrhotite, which is found only at the Bumblebee prospect, lacks enrichment in economic metals compared to the breccia, stringer and vein sulfides (Crawford 2017).

Indirect constraints on timing of mineralisation

New chronologic data provide the first analytical constraints on the timing of mineralisation at the Grapple and Bumblebee prospects. Maximum age constraints are provided by a metasandstone sample that yielded a maximum depositional age of ca 1.86 Ga (Kositcin *et al* in prep). This age is within uncertainty of a maximum depositional zircon age of 1858 ± 5 Ma yielded from turbiditic Lander Rock Formation from the Dufaur Hills in MOUNT RENNIE (Cross *et al* 2005). The zircon inheritance spectra and interpreted maximum depositional age are consistent with numerous samples of the Lander

Rock Formation across the Aileron Province that yielded zircon maximum depositional ages of ca 1.86–1.84 Ga (Scrimgeour 2013 and references therein).

Monazite aligned in and overprinting the main mylonitic fabric in schist at Grapple yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1668 ± 7 Ma (Reno *et al* 2018). The internal morphology of most monazite grains is consistent with dissolution–reprecipitation during fluid interaction; the age is most likely related to fluid-flow during, or shortly after, mylonite formation. The timing of fabric formation also provides a maximum timing constraint on sulfide breccia formation because the sulfide breccia cross-cuts the main foliation of the host rock (**Figure 3a–b**). The timing of sulfide breccia formation may reflect the timing of

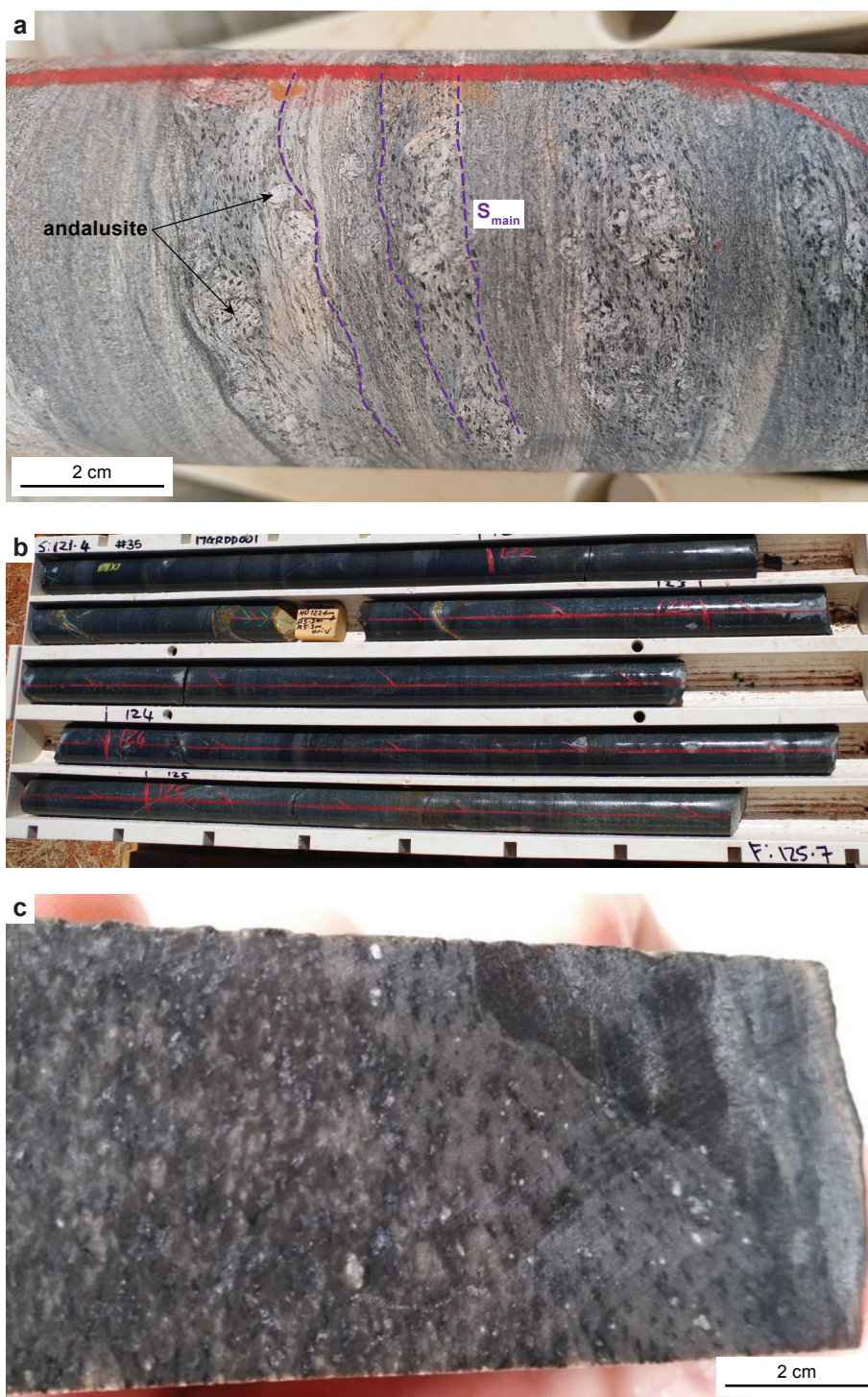


Figure 2. Photographs of country rocks and associated intrusive rocks at the prospects: (a) S_2 -foliated andalusite–biotite–muscovite schist of the Lander Rock Formation. (b) Mafic sill inferred to be part of the mafic Du Faur Suite. (c) Mafic of intermediate composition that overprints the S_2 -foliation fabric of the host metasedimentary schist of the Lander Rock Formation.

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mineralisation (eg formation of a breccia) or, alternatively the timing of remobilisation or deformation of pre-existing massive sulfide (eg formation of 'durchbewegung' textures). In the former case, the ca 1.67 Ga age represents the maximum age of mineralisation; in the latter case, this age is a minimum age of mineralisation.

An unnamed porphyritic dacite intrusion from the Warumpi Province, ~80 km southwest of the prospects and containing trace chalcopyrite and pyrite, yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ zircon magmatic crystallisation age of ca 1.63 Ga (Kositcin *et al* in prep). Four mafic intrusions at the prospects (including one cross-cutting foliated schist) all yielded lower minimum zircon intercept ages ca 1.63 Ga (Kositcin *et al* in prep, Beyer *et al* in prep). These ages are consistent with isotope disturbance associated with magmatism and magmatic-hydrothermal activity during the Liebig Orogeny.

Direct dating of mineralisation

Direct dating of mineralisation was attempted through Re–Os isotope analyses of arsenopyrite and Pb isotope analyses of Pb-rich galena-bearing samples. However, neither method produced clearly definitive results. Petrographic and structural relationships suggest that all dated sulfides have a post-metamorphic origin based on their overprinting relationship with the main S_2 fabric; this suggests ages should match or post-date the ca 1.67 Ga age for S_2 development recorded by Reno *et al* (2018).

An average Re–Os age of ca 1.96 Ga for three arsenopyrite samples from the main mineralised breccia at

Grapple is older than the host rocks and must therefore be considered geologically meaningless. The exact reason for old Re–Os model ages remains unknown and is the current subject of further NTGS work. It is possible that microscale intergrowths of löllingite and pyrrhotite (**Figure 4d**) within the arsenopyrite crystals analysed may have contributed to the artificial model age produced.

Pb model ages of ca 1.84–1.83 Ga for three Pb-rich breccia samples at Grapple using the model of Hussey *et al* (2006) resemble plausible actual depositional ages for the host metasedimentary rocks (ca 1.86–1.81 Ga, Kositcin *et al* in prep). This may suggest a syn-depositional (syngenetic or diagenetic) timing for mineralisation, which was then remobilised or deformed at ca 1.67 Ga. However, caution should be exercised in assessing these results as, in some situations, model ages can be significantly different to the ages of mineralisation. For example, long term depletion of U relative to Pb in the source rocks could produce anomalously old model ages; it is possible that pre-metamorphic Pb isotope signatures were inherited in post-metamorphic sulfide assemblages, thus resulting in older apparent ages. The apparent conflict between the petrographic and structural observations that suggest a syn- to post-1.67 Ga age for mineralisation, and the calculated Pb model ages that suggest a ca 1.84 Ga age for mineralisation, is a topic of ongoing research.

Mineralising processes

The results of this study provide new constraints on the mineralising process at Grapple and Bumblebee. The

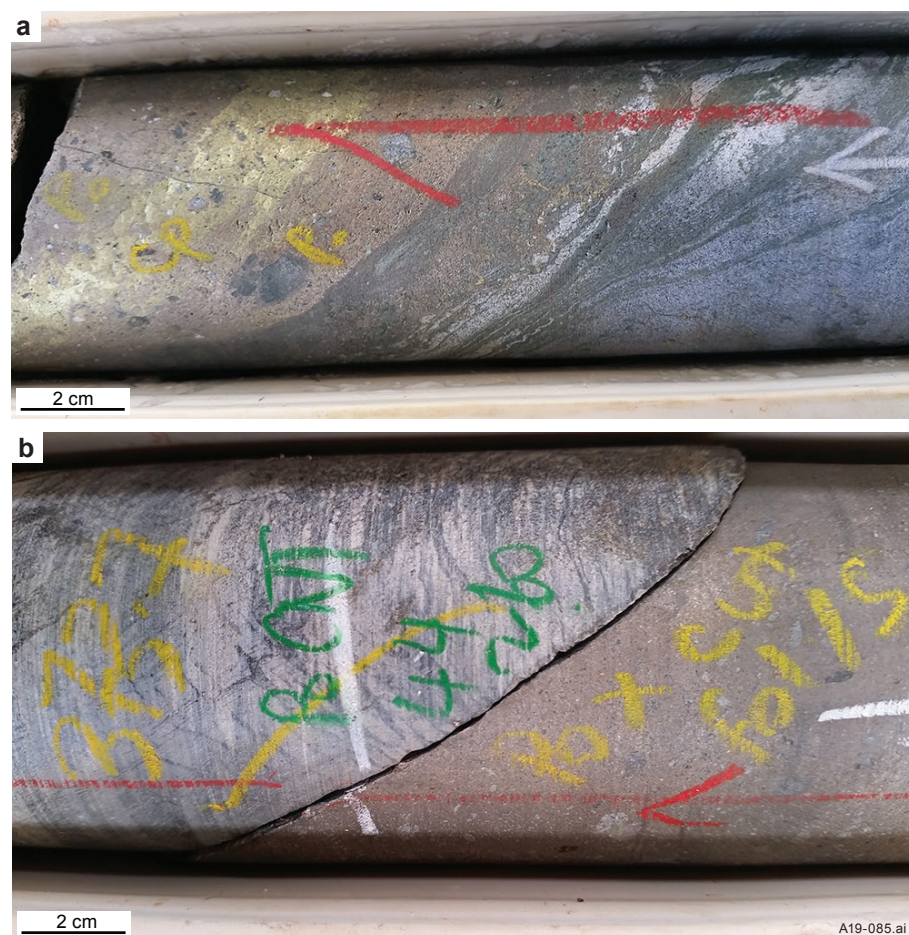


Figure 3. Images of mineralised and altered diamond drill core from the Grapple prospect. (a) Brecciated and stringer pyrrhotite (metallic bronze colour) and chalcopyrite (brass colour) that overprints a pervasive mylonite fabric in schist of the Lander Rock Formation. (b) Massive pyrrhotite breccia (metallic bronze colour) that overprints foliated andalusite schist of the Lander Rock Formation.

sulfide-bearing breccias, stringers, and veins cross-cut the ca 1.67 Ga mylonitic fabric; this is interpreted to constrain breccia formation, as observed, to a syn- to post-deformation timing at or after ca 1.67 Ga. However, the available data do not preclude the possibility that mineralisation was syn-depositional and then was subsequently deformed or remobilised. Hence, genetic models and exploration targets must consider two different models.

If the prospects formed at ca 1.84 Ga, ie during formation of the host succession, the two options would be volcanic-

hosted or sediment-hosted massive sulfide mineralisation; in both cases the prospects would form syn-genetically on the seafloor, or diagenetically or epigenetically just below the seafloor. The location of the prospects would be controlled by stratigraphy and/or syn-depositional faults. Such mineralisation might be associated with meta-exhalites and/or metavolcanics. Based on present data, there are no rocks at Grapple or Bumblebee that could be interpreted as metaexhalites or metavolcanic rocks. However, many districts that contain metamorphosed volcanic-hosted or

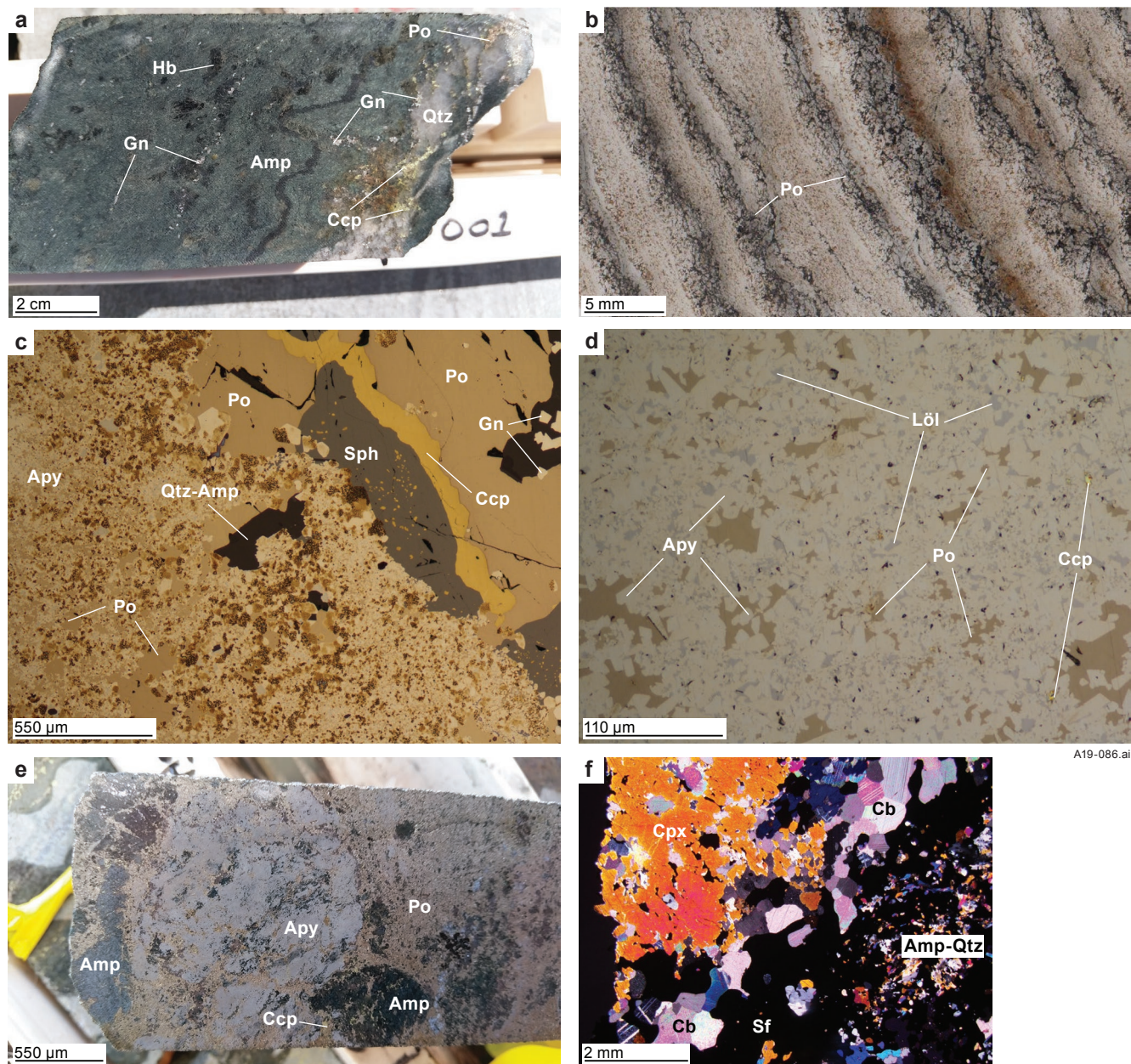


Figure 4. Images of mineralised and altered diamond drill core and associated photomicrographs from the Grapple and Bumblebee prospects. (a) Photograph of a chalcopyrite-pyrite-bearing quartz vein that cross cuts the S₂ foliated amphibole-quartz rock of the Lander Rock Formation. The quartz vein is also associated with minor galena mineralisation. (b) Thin section image in plane polarised light of net-textured pyrrhotite (opaque) foliated within S₂ fabric in metasandstone of the Lander Rock Formation. (c) Photomicrograph in reflected light showing coarse arsenopyrite crystals within a pyrrhotite breccia. The amphibole has an unusual mottled texture. The pyrrhotite-arsenopyrite breccia engulfs clasts of amphibole-quartz. Pyrrhotite, sphalerite, chalcopyrite, and galena occur on grain boundaries of the breccia. Note the chalcopyrite disease within sphalerite grains. (d) Photomicrograph in reflected light showing complex intergrowths within the arsenopyrite grains. Arsenopyrite is intergrown with löllingite, pyrrhotite and occasional chalcopyrite. (e) Photograph of coarse-grained arsenopyrite within a pyrrhotite breccia. Blebbly chalcopyrite is also evident in macroscale. The breccia engulfs clasts of amphibole-quartz rock. (f) Photomicrograph of sulfide stringers overprinting an amphibole-quartz-clinopyroxene-carbonate assemblage. Ccp = chalcopyrite; Qtz = quartz; Amp = amphibole; Gn = galena; Po = pyrrhotite; Apy = arsenopyrite; Sph = sphalerite; Löl = löllingite; Sf = sulfide; Cpx = clinopyroxene; Cb = carbonate.

sediment-hosted massive sulfide deposits do not contain metaexhalites or metavolcanic rocks. Hence, although there is no compelling evidence for an ‘early’ origin, such an origin cannot be excluded.

If the prospects formed at or after ca 1.69 Ga, they could have formed in association with ca 1.69–1.63 Ga magmatism that affected both the Aileron and Warumpi provinces. At the prospect- to regional-scale, both prospects are spatially associated with ultramafic, mafic and lesser felsic intrusions with ages of ca 1.67–1.63 Ga (eg local mafic, intermediate and felsic intrusions and the Andrew Young Igneous Complex), which indicates the possibility of a magmatic-hydrothermal origin to the mineralisation. In this case, an exploration target would be spatially-associated 1.69–1.63 Ga magmatic bodies, an obviously different criteria to the ‘early’ origin for mineralisation. Intrusion-related deposits associated with mafic rocks are commonly magnetite-rich and base-metal-poor (Einaudi *et al* 1981; Černý *et al* 2005; Goldfarb *et al* 2005; Meinert *et al* 2005), although relatively reduced base metal and gold mineralisation does occur in some settings (eg Meinert 1995). However, intrusion-related base-metal- and gold-bearing deposits are predominantly associated with felsic to intermediate magmatic rocks. There are no abundant ca 1.69–1.63 Ga felsic to intermediate igneous rocks occurring locally at Grapple or Bumblebee. Only minor granite and aplite is associated with the ca 1.64 Ga Andrew Young Igneous Complex (Young *et al* 1995), and extensive felsic- to intermediate-magmatism is present in the Yaya Domain of the Warumpi Province to the south (Waluwiya Suite, Illili Suite and Papunya Igneous Complex; Scrimgeour *et al* 2005a,b). For this ‘late’ model of mineralisation, potential exploration targets would extend southward into the Warumpi Province.

Because current geochronological and textural characteristics do not definitively determine the origin of the Grapple and Bumblebee prospects, additional samples were submitted for sulfur and oxygen isotope analysis. The sulfur isotope analyses have a very limited $\delta^{34}\text{S}$ range near 0‰, which is consistent with derivation of the sulfur from igneous rocks, either directly from magmatic-hydrothermal fluids or indirectly from the leaching of volcanic or other magmatic rocks. The sulfur isotope data are consistent with a ‘late’ magmatic-hydrothermal model, but they are also consistent with an ‘early’ syn-depositional model as > 1.8 Ga volcanic-hosted and sediment-hosted deposits generally have $\delta^{34}\text{S}$ values near 0‰ (Huston *et al* 2015).

Samples of both unaltered and altered host rocks have been submitted for whole rock oxygen isotope analysis as a critical test of the origin of the ore fluids. In either of the ‘early’ options, the ore fluid, in most cases, would be evolved seawater; whereas in the ‘late’ option, the ore fluid would be magmatic-hydrothermal. These fluids have quite different oxygen isotope characteristics that will be imparted into the altered rocks. Hence, the data should provide a reasonably robust test of the presence of magmatic-hydrothermal fluids in the mineral system that formed the Grapple and Bumblebee prospects. These results will be the subject of a future NTGS–GA record.

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