The Rover field: Insights on stratigraphy, age and base metal mineralisation

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Introduction

The Warramunga Province (central Northern Territory) has a history of exploration and production of copper–gold–bismuth mineralisation from ironstone-hosted deposits of the Warramunga Formation in the outcropping Tennant Creek mineral field (**Figure 1**). By comparison, the Rover field, located 80 km southwest of Tennant Creek, is entirely covered by 70–200 m of Wiso Basin sedimentary rocks such that the basement stratigraphy is poorly understood. Nevertheless, geophysical interpretation has guided explorers to the discovery of three significant mineral deposits: Rover 1, Explorer 142 and Explorer 108. Rover 1 has mineral resources of 6.9 Mt at 1.74 g/t Au, 2.07 g/t Ag, 1.2% Cu, 0.14% Bi, and 0.06% Co (Leggo 2019), plus several defined targets hosted in basement rocks. Two of the deposits, Rover 1 and Explorer 142, have similar characteristics to the iron–oxide–copper–gold (IOCG) deposits of the Tennant Creek mineral field (Leggo 2019 and references therein). The Explorer 108 lead–zinc–silver–copper deposit (inferred category mineral resource of 8.7 Mt at 5.6% combined Pb and Zn, 20 g/t Ag, and 0.3 g/t Au; Leggo 2019) and the nearby Curiosity prospect indicate potential for large base metal systems in the Rover field. Given this potential, the Northern Territory Geological Survey (NTGS) under the *Resourcing the Territory* initiative, in collaboration with Geoscience Australia, are undertaking a range of projects to improve understanding of the geological framework and resource potential of the Rover field and broader implications for prospectivity of the Warramunga Province (eg Huston *et al* 2020).

Recent work, in collaboration with the Sustainable Minerals Institute of the University of Queensland (Gunter *et al* 2020a–c, Valenta *et al* 2020) and with Geoscience Australia under the *Exploring for the Future* initiative (eg Hackney *et al* 2020), indicates that large areas of the Rover field comprise basement rocks of the Ooradidgee Group with only minor Warramunga Formation (and equivalents: Huston *et al* 2020). This is in contrast to previous interpretations that the mineralisation in the Rover field was hosted entirely in Warramunga Formation (Donnellan 2013, Walters 2017, Leggo 2019). Herein, we present new petrological, geochemical, structural, and chronologic data that augments previous work and further characterises the basement stratigraphy of the Rover field and its mineral systems, with a focus on the base metal deposit at Explorer 108 and Curiosity (**Figure 1**).

Geological setting

The Rover field is located in Warramunga Province (**Figure 1**) of the Palaeoproterozoic North Australian Craton (Myers *et al* 1996, Cawood and Korsh 2008), which extends across most of the northern Australia and underlies around 80% of the Northern Territory. The Warramunga province is unconformably overlain by the Palaeo- to Mesoproterozoic Davenport Province in the south, and in the north by the Palaeo- to Mesoproterozoic Tomkinson Province (Donnellan 2013 and references therein). To the east, there is the younger Neoproterozoic- to Palaeozoic Georgina Basin and to the west, the dominantly Cambrian Wiso Basin.

The Warramunga Formation and correlative Junalki Formation and Woodenjerrie beds represent the oldest rocks in the Warramunga Province, deposited before the ca 1860 Ma[4] (Compston and McDouglas 1994, Compston 1994, 1995, Ahmad and Munson 2013, Donnellan 2013, Maidment *et al* 2013). Ironstones within the Warramunga Formation hosts most of the copper–gold–bismuth mineralisation in the Tennant Creek mineral field. The Warramunga Formation has no exposed base and is mostly composed of weakly metamorphosed turbiditic greywacke, locally tuffaceous, with lesser siltstone, shale, and argillaceous ironstone, referred in the literature to as ‘haematitic ironstone’ (Donnellan 2013; Huston *et al* 2020 and references therein).

The Warramunga Formation and its equivalent sequences were affected by the tectono-magmatic ca 1860–1850 Ma Tennant Event (Donnellan and Johnstone 2004). This event resulted in extensive syn- to post-tectonic magmatism (Tennant Creek Supersuite) and regional D_1 shortening of the crust, expressed as the east- or east-northeast-trending upright F_1 folds and low-grade metamorphism (Maidment *et al* 2006, Donnellan 2013). The ca 1850–1840 Ma Tennant Creek Supersuite (Wyborn *et al* 1998) comprises mainly granitic intrusions with lesser granodiorite, tonalite, felsic porphyry and dolerite, as well as extrusive felsic volcanic rocks (Donnellan 2013). The Tennant Event folded and thrusted the sedimentary sequences and ultimately exhumed the entire package. This resulted in an erosional angular unconformity between the pre-Tennant Event rocks (Warramunga Formation, Junalki Formation and Woodenjerrie beds) and the overlying volcano-sedimentary successions of the Ooradidgee Group (Donnellan 2013).

The Ooradidgee Group comprises dominantly extrusive volcanic (and volcaniclastic) rocks intercalated with sedimentary sequences that vary upward from deep-water to sublittoral/littoral and finally fluviatile facies (Donnellan 2013). Donnellan (2013) recognised three volcanic episodes in the Ooradidgee Group. The oldest, at ca 1850 Ma, is represented by the Monument and Yungkulungu Formation, and the mafic Edmirringee Volcanics; a second event, bimodal, at ca 1840 Ma, is represented by the Epenarra Volcanics and the Bernborough Formation; and a third event, at ca 1814 Ma, is represented by the Treasure Volcanics.

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4 Ages reported here are SHRIMP U–Pb zircon ages unless otherwise indicate

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The Davenport Event resulted in the folding of Ooradidgee Group and most likely overprinted the Tennant Event deformation in the Warramunga Formation (Donnellan 2013). This phase of deformation is interpreted to be broadly coeval with emplacement of the ca 1710 Ma Devils Suite (Blake *et al* 1987, Donnellan 2013) and correlative with tectonism and magmatism of similar age in the Aileron Province (eg McGloin *et al* 2020). Two phases

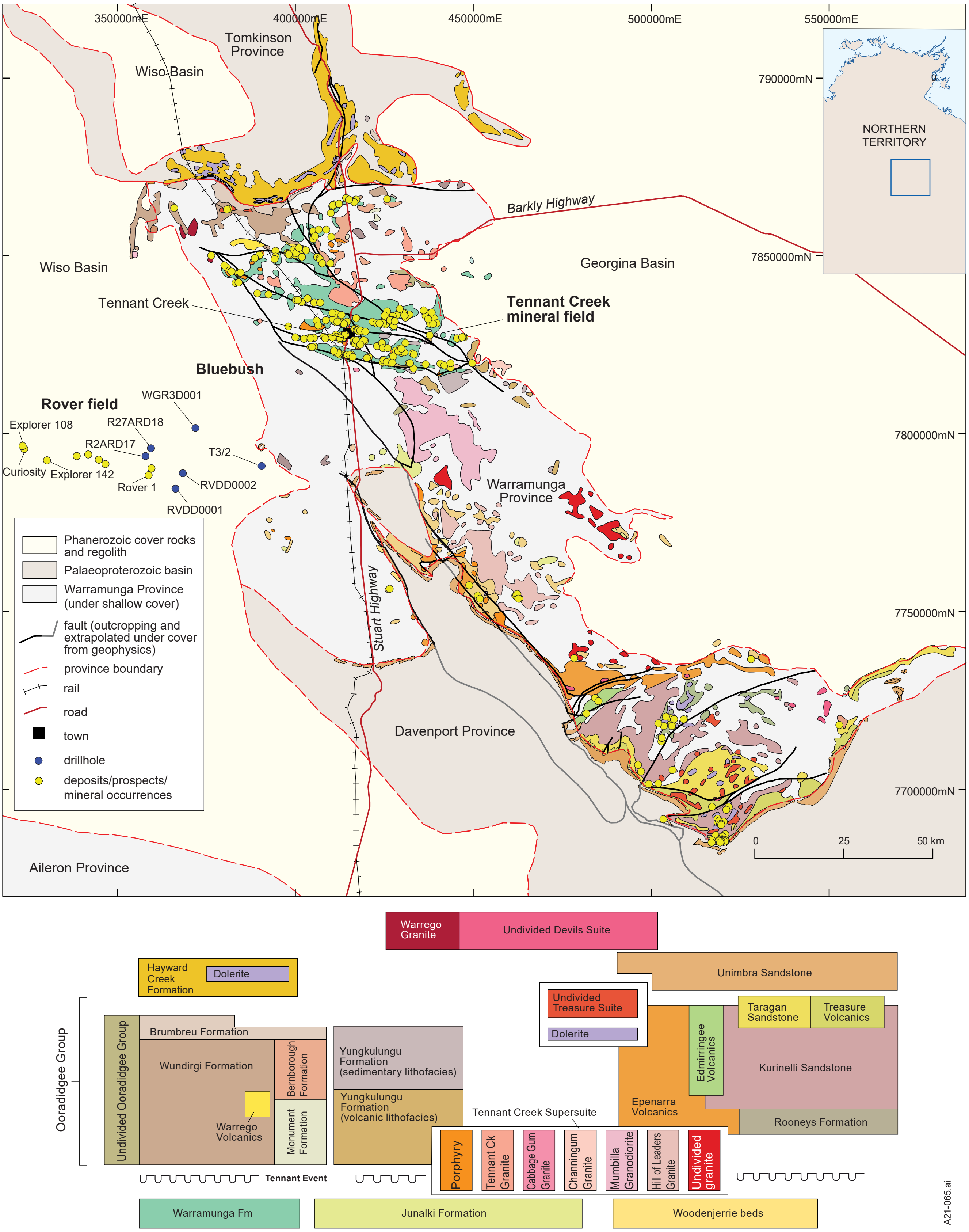

Figure 1. Generalised geology map of the Warramunga Province, modified after Donnellan (2013). Map shows location of the Rover field and drillholes relative to the Tennant Creek mineral field.

of concentric folding overprint the Ooradidgee and Hatches Creek groups (Blake *et al* 1987): a first folding event that resulted in northwest-trending folds; this was superimposed by a second event with northeast-trending folds.

The Rover field

The nature of the basement in the Rover field has been a matter of discussion. Donnellan (2013), Walters (2017), and Leggo (2019) interpreted the Rover field basement to be composed of weakly metamorphosed Warramunga and Junalki formations imbricated with the younger Ooradidgee Group. Recent work by Valenta *et al* (2020) interpreted the basement to be mostly post-Tennant Event Ooradidgee Group. The interpretation of Ooradidgee Group in the Rover field is mainly based on the felsic volcanic and volcaniclastic nature of the rocks and the geochronology reported by Smith (2001), Maidment (2013) and Huston *et al* (2020).

The Rover field hosts three major deposits with mineral resources reported in accordance with the JORC code: The Rover 1 and Explorer 142 (copper–gold–bismuth), and Explorer 108 (lead–zinc–silver–copper). There are several other prospects. Curiosity is a satellite prospect with lead–zinc–copper mineralisation located ~1.3 km southeast of Explorer 108. The recent work by Valenta *et al* (2020) summarises the current understanding of the three main deposits.

The sequence that hosts mineralisation in Explorer 108 is described in Savage (2020) as a folded volcano-sedimentary sequence. Burke (2015) describes two main horizons of volcaniclastic rocks, the lower and upper units, both comprising volcaniclastic sandy siltstones, separated by a 100–150 m thick felsic volcanic unit. Leggo *et al* (2019) interpreted that the mineralisation in Explorer 108 is hosted in brecciated dolomite on top of a sedimentary siliciclastic package. The dolomite, mineralisation, and siliciclastic rocks are in between a 'lower and upper felsics' (felsic volcaniclastic rocks). Mineralisation at the Explorer 108 deposit consists of overlapping lead–zinc–silver zones hosted in volcaniclastic sequences, closely associated with dolomitic breccias near the unconformity with the Wiso basin. There is also remobilised secondary copper mineralisation hosted in the Wiso basin close to the unconformity (Leggo 2019). The nature of the overlapping zones of lead, zinc, and silver, and their relationship with the dolomite breccia remains somewhat unclear (Valenta *et al* 2020). All resources are reported together in Leggo *et al* (2019).

Methodology

To characterise the stratigraphy of the Rover field, 13 key mineralised and 7 unmineralised drillholes from the NTGS core repository and Castile Resources Limited's core farm were re-logged and sampled for a range of analytical techniques (**Figure 1**). Techniques used include petrology, whole rock geochemistry, mineral liberation analysis (MLA) mineral mapping, and hyperspectral logging.

The petrology, geochemistry and geochronology results from Curiosity prospect drillholes MXCURD001 and MXCURD002 are presented and discussed in Huston *et al* (2020). The rest of the drillholes were logged and sampled during 2020. The reader is referred to Farias (in prep) for details on petrology and comments on the NTGS-owned drillholes.

Regional stratigraphy

Unmineralised drillholes from regional Rover field (**Figure 1**), mineralised drillholes from Explorer 108, Rover 1 and Explorer 142 deposits, and one drillhole from the Bluebush area (**Table 1**) were re-logged and core samples were collected for petrographic analysis. Herein we follow terminology from McPhie and Allen (1993) for volcanic rocks.

The basement rocks in unmineralised holes are mostly volcanic and volcaniclastic of variable bulk mineralogy and composition **(Figure 2)**. The Rover 1 and Explorer 142 deposits and the Curiosity prospect are hosted in siliciclastic, turbiditic packages (**Figure 2d**). In summary, the intersected rocks in the Rover field are grouped into four packages:

1. Drillholes R2ARD17, T3/2, RVDD0001 and RVDD0002 in the eastern part of the field intersected mostly coherent flow-banded feldspar-phyric dacite, porphyritic and glomeroporphyritic dacite and andesite interlayered with minor rhyodacitic volcaniclastic sandstones. Drillholes R2ARD17 and RVDD0002 intersected 20–25 m of quartz-feldspar porphyritic intrusions.
2. Drillhole R27ARD18, Explorer 108 drillholes and the top half of the Curiosity drillholes (~250–450 m depth in MXCURD001 and MXCURD002; Huston *et al* 2020) in the northern and western parts of the Rover field are dominated by fine- to very-coarse grained, immature polymict volcaniclastic sandstone with intervals of rhyolitic lavas.

Table 1. Drillholes logged and sampled for this study with details of their location and current custodians.

Area	Drillholes	Source
Regional Rover field, unmineralised drillholes	WGR3D001, R27ARD18, R2ARD17, T3/2, RVDD0002, RVDD0001	NTGS core repository
Bluebush	TDD01	NTGS core repository
Rover 1	WGR1D011, WGR1D002, WGR1D003-1, WGR1D034	Castile Resources
Explorer 142	DDH3, DDH4, DDH5, NR142D001	Castile Resources
Explorer 108	NR108D002, NR108D024, NR108D026	Castile Resources
Curiosity	MXCURD001, MXCURD002	NTGS core repository

3. Drillholes WGR3D001 and TDD01 in the northern part of the Rover field and into the Bluebush area respectively (**Figure 1**) include mafic volcanic rocks. WGR3D001 intersected two 10–20 m thick clinopyroxene basalt horizons hosted in rhyolitic and rhyodacitic coherent rocks on top of a rhyodacitic volcaniclastic sequence. TDD01 intersected mostly high-Mg porphyritic actinolite basalt interlayered with minor siliciclastic rocks.
4. The lower section of the Curiosity drillholes and all drillholes in Rover 1 and Explorer 142 intersected layered siliciclastic rocks with similar characteristics to proximal turbiditic facies. The layers are variable in thickness, from 2–3 m thick, coarse-grained, massive sandstone and greywacke layers to cm-scale layers of interlayered siltstone-mudstone from more distal turbiditic facies. These rocks are the host of the copper–gold–bismuth mineralisation in Rover 1 and Explorer 142, and the base metal mineralisation in Curiosity.

Whole rock geochemistry

Whole rock geochemistry of the immature volcaniclastic and volcanic rocks confirms the wide range of compositions observed in thin section (**Figure 3**). Coupled with geochemical data discussed in Huston *et al* (2020), the new data acquired during this study shows that the volcanic and volcaniclastic rocks in Rover field vary from andesite to rhyolite, with some outliers from the basalt (WGR3D001) and alkali basalt fields (TDD01), (**Figure 3a**). Andesitic and dacitic compositions are dominant in the northern and eastern portion of the field, and fractionated rhyolitic to rhyodacitic compositions in the western end. The more fractionated compositions are similar to that of the plutonic rocks of the Tennant Creek Supersuite that crops out in the Tennant Creek mineral field.

Figure 3b shows the variation of composition reflected in the immobile element ratio Nb/Ti (representing fractional crystallisation of zircon) versus Hf/Zr (magmatic fractionation). This diagram seems to better discriminate

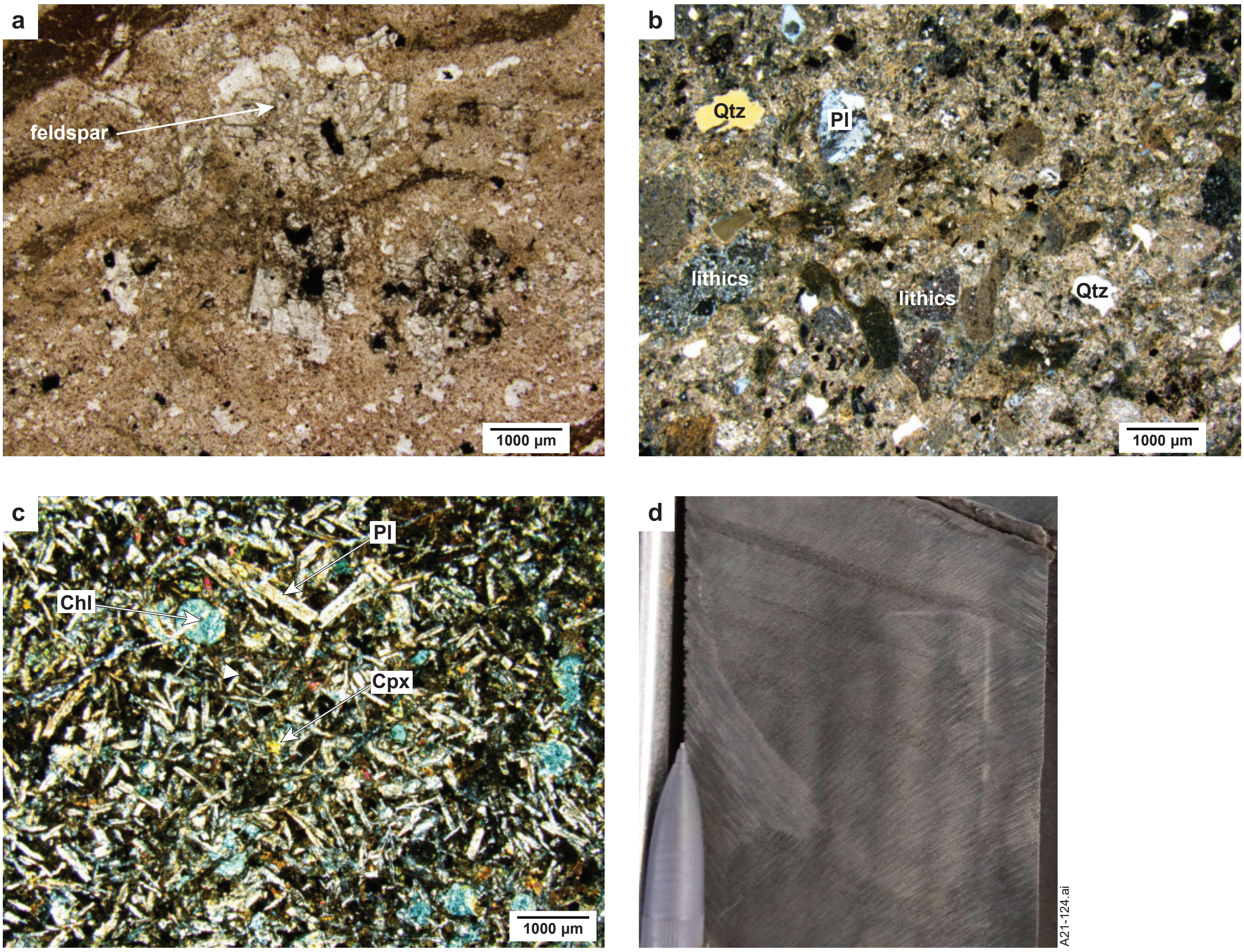

Figure 2. Examples of the different lithology in Rover field. (**a**) Sample TC20PGF038, 119 m, from R2ARD17. Feldspar-phyric flow-banded rhyolitic lava. Transmitted light, plane polarisers. (**b**) Sample TC20PGF040, 131.8 m, from R27ARD18. Lithic-rich polymict volcaniclastic sandstone. Transmitted light, crossed polarisers (**c**) TC20PGF057, 258.8 m, from WGR3D001. Fine-grained clinopyroxene basalt with microphenocrysts of plagioclase and pyroxene in ophitic texture. Olivine? completely replaced by chlorite. The groundmass is made by the same plagioclase-pyroxene-chlorite, and rare quartz. Transmitted light with crossed polarisers. (**d**) Sample GS20PGF084 at 468.1 m, from MXCURD002. Thinly layered fine- to medium-grained sandstone part of the turbiditic sequence that hosts the Curiosity prospect. Chl = chlorite; Cpx = clinopyroxene; Qtz = quartz; Pl = plagioclase.

the ill-defined clusters from the Winchester and Floyd (1977) diagram. In the same figure, the Nb/Ti–Hf/Zr compositions from different Tennant Creek Supersuite granites overlaps partially on the fractionated volcanic and volcaniclastic rocks of the western Rover field.

Explorer 108 deposit and Curiosity prospect

Host stratigraphy

Recent petrology confirm the main units interpreted by Leggo *et al* (2019). The upper volcaniclastic unit is dominated by a sericite-chlorite-carbonate altered and sheared immature volcaniclastic rock. The texture suggests a possible welded pumice with eutaxitic texture: 2–5 cm elongated crystal-rich chlorite-altered pseudoclasts in a fine-grained quartz-sericite-rich groundmass (**Figure 4a**). The quartz is typically present in the groundmass as 0.1–0.5 mm angular and embayed fragmented phenocrysts. Chlorite and carbonate are completely replacing a 0.5–1 mm blocky mineral that makes about 5–10% of the rock. The lower volcaniclastic unit is similar in composition and texture to the large elongated crystal-rich chlorite-altered pseudoclasts from the upper unit. This unit is more coherent and sheared than the upper unit; it is composed of subhedral and typically embayed 0.1–1 mm quartz eyes (porphyroclasts, 20–30%) and 0.1–0.5 mm subhedral and sericite-altered feldspar porphyroclasts in a fine-grained chlorite-sericite-quartz groundmass. The quartz porphyroclasts typically have a rim of fine-grained recrystallised quartz. The sense of shearing is top-to-east (**Figure 4b**); this is a relative sense of shearing as the samples were not taken parallel to the mineral stretching lineation.

At Curiosity, three broad geological units were recognised by Huston *et al* (2020): a very fine- to fine-grained, foliated quartz-sericite rock interpreted as a volcaniclastic sandstone; very coarse-grained volcaniclastic rock with quartz eyes and local feldspar phenoclasts; and a massive to moderately bedded, very fine- to medium-

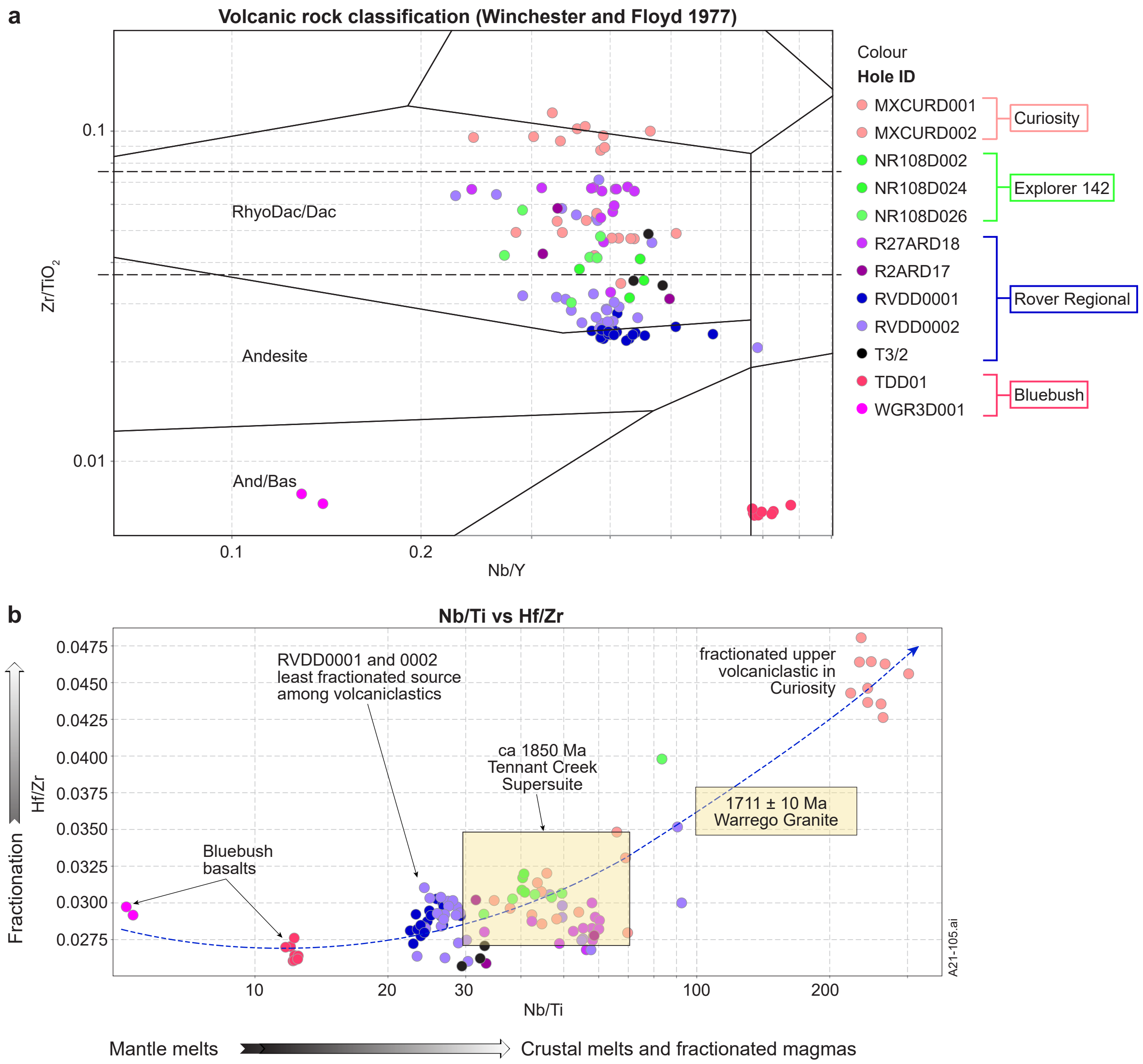

Figure 3. (**a**) Volcanic rock classification (Winchester and Floyd 1977) with all samples from volcanic and volcaniclastic rocks in Rover field and Bluebush area. (**b**) Magmatic fractionation diagram (Halley 2017) with same samples plotted in (**a**). The Hf/Zr ratio relates to the increasing fractional crystallisation of zircons; the Nb/Ti is dependent of the magma fractionation.

grained sandstone (**Figure 5a**). The latter package is the host of the mineralisation in Curiosity.

Base metal mineralisation and associated alteration

The polished thin sections of the mineralised rocks in Explorer 108 indicate lead–zinc and minor copper mineralisation in a chlorite–talc–carbonate-rich altered rock. The alteration is intense and obliterates all features of the protolith making its interpretation difficult. However, the fragments of less-altered rock indicate that protolith material was a fine grained clastic sedimentary rock (eg psammopelite) that experienced low grade metamorphism, deformation and, in places,

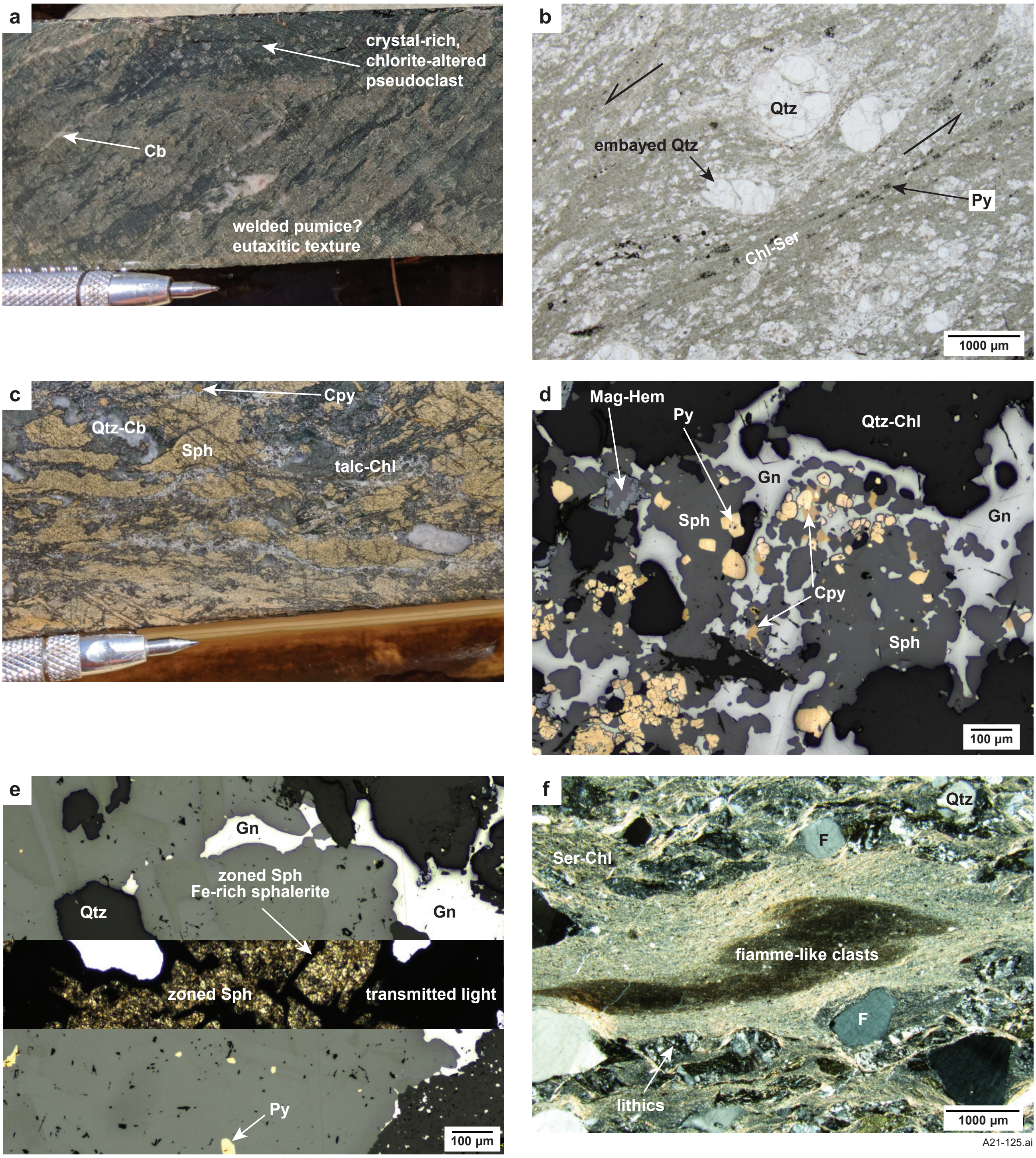

Figure 4. Lithology and mineralisation in Explorer 108. (**a**) Eutaxitic texture in half core from the upper volcaniclastic unit. (**b**) Sheared and chlorite-sericite-altered lower volcaniclastic unit. Notice the embayed quartz porphyroclasts with asymmetrical sigma tails suggesting a top-to-left (east) kinematics. Transmitted light, plane polarisers. (**c**) High-grade zinc–lead zone with sphalerite in talc-chlorite-carbonate rock. (**d**) Sphalerite, galena and minor chalcopyrite, pyrite, magnetite partially replaced by hematite in quartz-chlorite. Plane polarised reflected light. (**e**) Zoned sphalerite only visible in the transmitted light with plane polarisers (central band). (**f**) Detail of the upper volcaniclastic unit with fiamme-like elongated clasts in a polimict volcaniclastic. Quartz and lithics are rounded; groundmass altered by sericite and chlorite. Transmitted light, crossed polarisers. Cb = carbonate; Chl = chlorite; Cpy = chalcopyrite; F = K-feldspar; Gn = galena; Hem = hematite; Mag = magnetite; Pl = plagioclase; Py = pyrite; Qtz = quartz; Ser = sericite; Sph = sphalerite.

strong hydrothermal alteration. In the high-grade samples, the intensity of overprinting hydrothermal alteration, deformation, and likely metamorphism under low-grade conditions, precludes an interpretation of protolith type.

The mineral paragenesis associated with the alteration in Explorer 108 and Curiosity is dominated by chlorite (Mg-chlorite), magnetite (partially altered to hematite), quartz, and locally, talc-chlorite-carbonate-rich zones. The hyperspectral data (shortwave infrared) indicate unusually high levels of phengite on top of the main mineralised horizon in Curiosity (Smith 2015). Huston *et al* (2020) interpreted a much wider alteration footprint in the Curiosity drillholes based on the whole-rock geochemistry that indicates sericite and chlorite-talc enrichment across the entire drillhole.

In the high-grade zones of Explorer 108, the sphalerite (zinc) is volumetrically dominant (**Figure 4c**), intergrown with galena (lead) and chalcopyrite (copper), and overprinted by later euhedral pyrite (**Figure 4d**). The galena is typically composited with chalcopyrite. In the lower grade zones, magnetite is partially replaced by hematite, which become less common towards the higher grade zones. The sphalerite is zoned (**Figure 4e**) with semi-translucent cores and opaque rims (Fe-rich sphalerite).

The Curiosity prospect, with a similar style but lower grade lead-zinc mineralisation, is hosted in mature siliciclastic rocks (**Figure 5a**) in contrast to the immature volcaniclastics of the Explorer 108 deposit. The mineralised rocks are characterised by folded and sheared stratabounded semi-massive sulfides and stringers (common at depth, below the main mineralisation). The dominant sulfide is pyrite, which occur as disseminated and semi-massive agglomerates with magnetite-hematite. Magnetite occurs in semi-massive, finely granular aggregates (**Figure 5b**), varying to disseminated, medium-grained subhedra that commonly replaces and forms pseudomorph of carbonate (**Figure 5c**). Much magnetite shows minor replacement by hematite. Pyrite forms

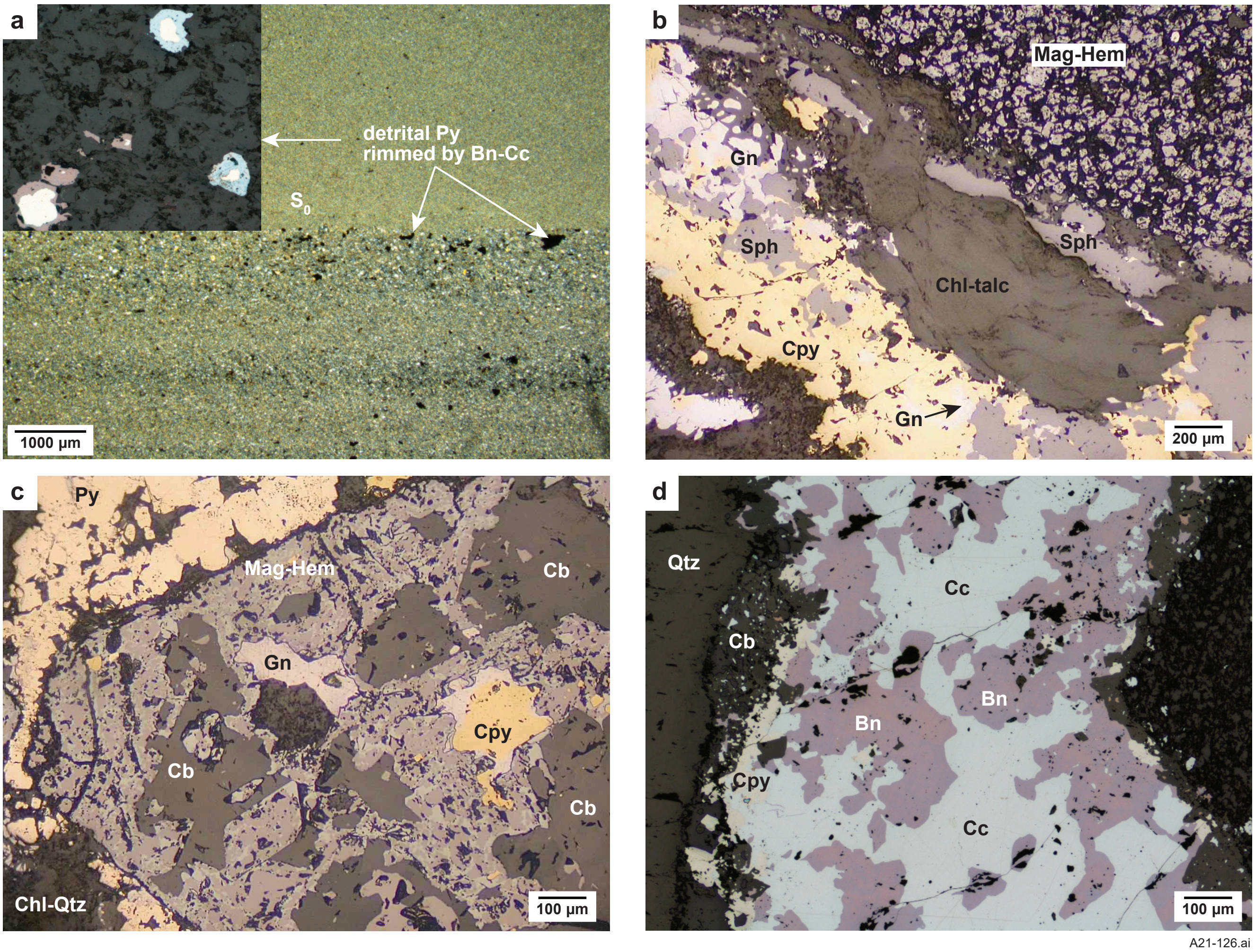

Figure 5. Mineralisation at Curiosity prospect. (**a**) Host rock of mineralisation in Curiosity. Siltstone (top half) in contact with sandstone (lower half) from the turbiditic package that host mineralisation. Transmitted light with crossed polarisers. The disseminated pyrite in the sandstone has rims of chalcocite and bornite (inset of plane polarised reflected light in the top-left corner). (**b**) Elongate aggregate of chalcopyrite (yellow), with sphalerite (mid grey) and galena (whitish) hosted in chlorite (dark grey) and with an adjacent domain of finely granular magnetite (upper). Plane polarised reflected light. (**c**) Detail of large subhedral magnetite grain that pseudomorphed carbonate (darker grey), galena (pale silvery grey), chalcopyrite (yellow) and fine grained hematite (pale bluish grey), with an adjacent pyrite aggregate at upper left (pale creamy). Plane polarised reflected light. (**d**) Detail of vein below main mineralisation. Chalcocite (pale grey), with vermicular intergrowth of bornite (pink-mauve), and carbonate and quartz (left). Plane polarised reflected light. Bn = bornite; Cb = carbonate; Cc = chalcocite; Chl = chlorite; Cpy = chalcopyrite; Gn = galena; Hem = hematite; Mag = magnetite; Pl = plagioclase; Py = pyrite; Qtz = quartz; Ser = sericite; Sph = sphalerite.

semi-massive granular aggregates and disseminations and is paragenetically later than magnetite. Base metal sulfides (chalcopyrite, sphalerite, lesser galena) form irregular to vein-like masses (commonly as composites, **Figure 5b**) that are interstitial to (and paragenetically later than) magnetite and pyrite; they are commonly hosted in Mg-chlorite and talc (**Figure 5b**). At depth, some metres below the main mineralisation, there are copper-rich carbonate-quartz stringers and veins (**Figure 5d**). These veins are composited chalcocite and bornite with minor chalcopyrite and pyrite. In the siltstone-sandstone, detrital pyrite grains are rimmed by chalcocite or bornite, and sometimes chalcopyrite (**Figure 5a**). This suggests mineralising fluids or brines reacted with detrital sulfides and precipitated part of the metal load.

Structure

The orientation of structural features like foliation, shearing planes, and bedding were measured from oriented core at the Explore 108 deposit. **Figure 6** shows the lower hemisphere stereonet projections of the dominant foliation and shear zone planes. The orebody and stringer zones in Explorer 108 are typically associated with a strong foliation marked by the preferred orientation of chlorite and talc. The foliation is east–west-trending and steeply south-dipping, and less frequently north-dipping, similar to the other deposits in Rover field. Overprinting this foliation are 5–10 m thick shear zones with a north-south-trending and subvertical foliation with ill-defined kinematics. The kinematic is unclear as the mineral stretching lineation was not identified in the core. Breccias and fault zones (fragile regime of deformation) typically overprints all previous foliation.

Age of host stratigraphy

Samples of the host stratigraphy were collected from each of the main deposits to constrain a maximum timing of deposition and timing of volcanism. Rover 1, Explorer 142 and Curiosity are all hosted in turbiditic packages; Explorer 108 is hosted in immature rhyolitic volcaniclastic rocks. The results are summarised in **Figure 7**. The three samples from the turbiditic packages yielded a maximum depositional age (MDA) of ca 1850 Ma, indistinguishable from the crystallisation ages reported for the volcanic rocks in Rover field (Huston *et al* 2020). It is important to note that the detrital zircon grains from these samples are euhedral, suggesting minor transport and close proximity to their source.

Explorer 108 and Curiosity model

Structure

The north-trending and sub-vertical shear zones in Explorer 108 are also interpreted from gravity and airborne magnetic imagery (Valenta *et al* 2020). In these geophysical images, there are north-northwest-trending structures that overprint the east–west and west-northwest–east-southeast trending structures (D_1?) with a clear dextral shear sense (Valenta *et al* 2020). The early east–west-trending structures are interpreted to be associated with the ca 1850 Ma Tennant Event; they developed contemporaneous with similar east–west-trending structures in the Tennant Creek mineral field (D_1 in Donnellan 2013). The north- to north-northwest-trending shear zones are interpreted to have formed with the northwest- to north-northwest-trending structures elsewhere in the Warramunga Province assigned to ca 1710 Ma Davenport event (Donnellan 2013). It is known that this later tectono-thermal event was associated with copper–molybdenum–tungsten mineralisation in the Warramunga and Davenport provinces (McGloin and Creaser 2019). We interpret that the early east–west-trending and sub-vertical foliation represents an axial planar foliation, similar to other deposits in Rover (Leggo, 2019). This foliation is later overprinted by the north- to north-northwest-trending sub-vertical high-strain zone/s, which are only observed at the Explore 108 deposit. Burke (2015) interpreted the orebodies in Explorer 108 to be hosted in a gentle anticline that trends parallel to the north-northwest-trending shear zone. We interpret that the folding of Burke (2015) and the shearing and faulting/brecciation are part of the same progressive shortening event, based on their

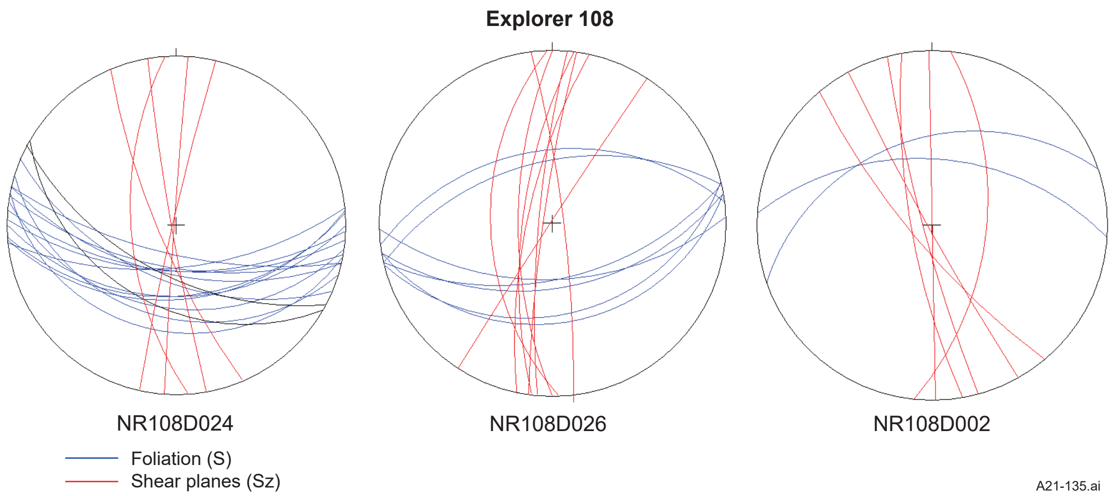

Figure 6. Stereonet projections from drillholes in Explorer 108 deposit with foliation and shear zones.

orientations, potentially overprinting each other as the area changed the P–T conditions. The east–west foliation and north–south-trending shearing are partially overprinting mineralisation; however, the absolute timing of these events are not yet resolved.

Mineralisation

There are some similarities and differences when comparing the Curiosity and Explorer 108 mineralisation. They both contain lead–zinc–silver–copper mineralisation, although Curiosity has lower grade. They are hosted in different rocks and affected by different degrees of strain. Explorer 108 is hosted in volcaniclastic rocks overprinted by a high-strain zone, whereas Curiosity is more stratabound and hosted in a turbiditic sequence affected by gentle folding and shearing. The base metal paragenesis is similar in both areas with lead–zinc associated with dolomite and chlorite–talc alteration in the main mineralised zone, and copper in deeper discrete stringers and veins. The mineral paragenesis of the main lead–zinc zone shows that: (i) the magnetite replaces and pseudomorphs earlier carbonate; (ii) the magnetite is partially altered to hematite; and (iii) magnetite and hematite are overprinted by sphalerite and galena, which is composited with chalcopyrite.

Based on geochemistry and mineral paragenesis, it can be implied that the protolith probably experienced considerable hydrothermal influx of Mg, Fe, S, CO_2, Cu, Pb and Zn. In addition to that, we consider that the bulk of the mineralisation in Explorer 108 has been deposited under relatively oxidising, hydrothermal conditions (as indicated by the presence of magnetite and paragenetically, later Fe-poor sphalerite and hematite, with associated hypogene texture chalcocite-bornite) and affected by syn -to post-shearing and brecciation.

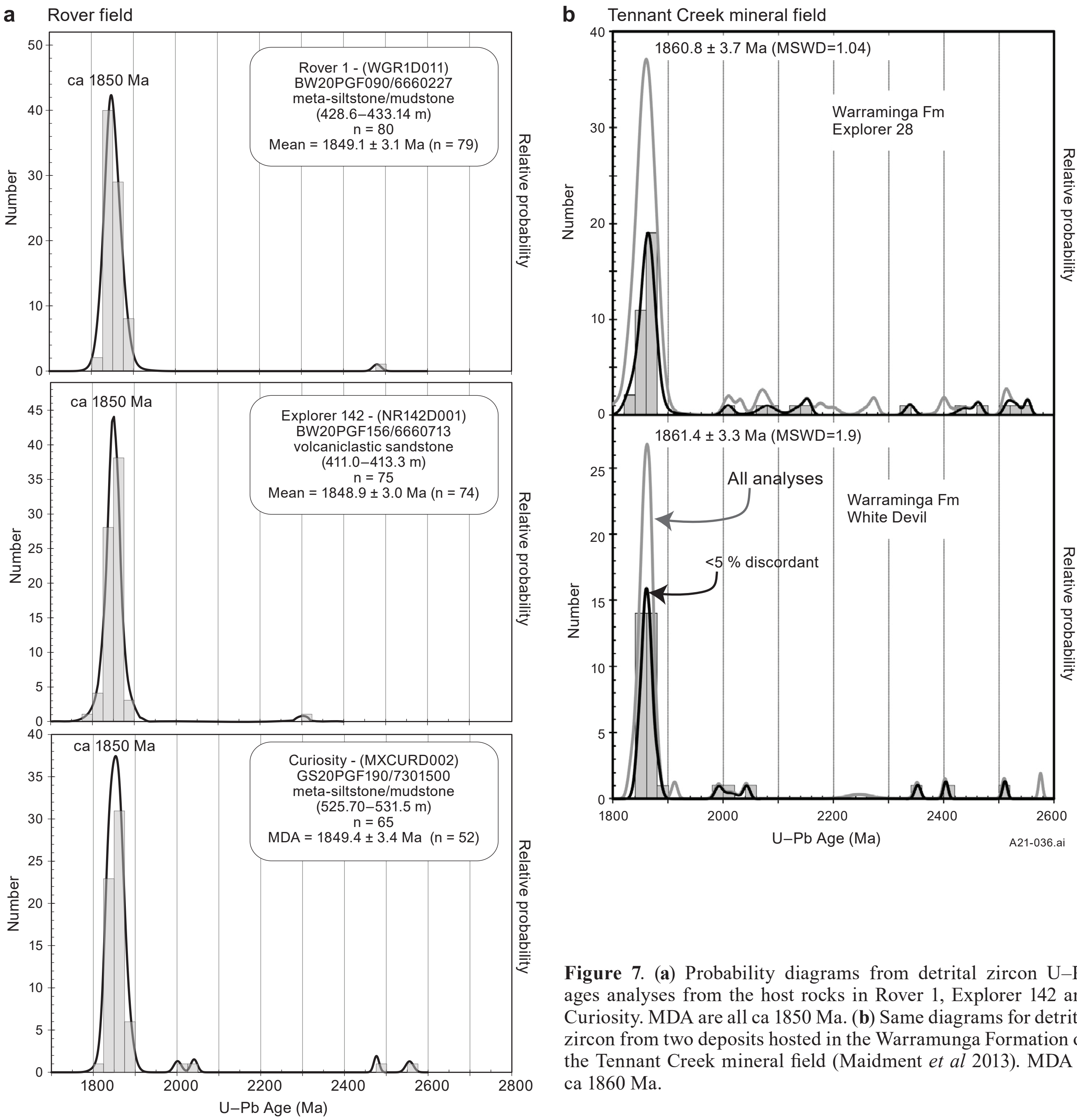

Figure 7. (**a**) Probability diagrams from detrital zircon U–Pb ages analyses from the host rocks in Rover 1, Explorer 142 and Curiosity. MDA are all ca 1850 Ma. (**b**) Same diagrams for detrital zircon from two deposits hosted in the Warramunga Formation on the Tennant Creek mineral field (Maidment *et al* 2013). MDA is ca 1860 Ma.

Metallogenic models

Based on the metal zonation and large alteration footprint, Savage (2020) interpreted the Explorer 108 and Curiosity as a sediment-hosted massive sulfide mineralisation system analogue to the Mount Isa lead–zinc–silver–(copper) mineralisation (Valenta 2018a,b). This model considers the lead–zinc-dominated mineralisation at Explorer 108 as the distal phase of a zoned mineralisation system, with Curiosity potentially being the copper-rich member (Savage 2020). We noticed elements that relates to a volcanic-hosted massive sulfide system with a large alteration footprint (see Huston *et al* 2020 for details on alteration in Curiosity). However, it is noted that the mineralisation in Curiosity: (i) is hosted in siliciclastic distal facies (eg turbiditic sequence) within thin volcaniclastic horizons; (ii) has stratiform stratabound mineralisation consisting of stacked lens-like, concordant, tabular bodies of massive-to- semi-massive sulfides of thin but continuous laminations of pyrite>galena–sphalerite and minor chalcopyrite that are conformable to the bedding of the host rock; (iii) has a large alteration footprints; (iv) has copper-rich vein-type stringers in the deeper parts of the deposit; and (v) related with (iv), has copper separated from the more lead–zinc zones. These are characteristics shared with some volcanic-hosted massive sulfide (VHMS) deposits (Large 1992 for Australian deposits, and Ohmoto 1996 for generic descriptions). Explorer 108 and Curiosity could represent an altered version of a felsic-siliciclastic-hosted VHMS (Galley *et al* 2007 and references therein) or an analogue of magnetite-rich VHMS, eg the Archaean Gossan Hill deposit in the Yilgarn craton (Sharpe and Gemmell 2002). Alternatively, they could represent a low-grade form of Broken Hill-type deposit based on the predominantly volcanic and volcaniclastic nature of the host sequence.

As noted above, Explorer 108 and Curiosity show features that are typical of these VHMS deposits: (i) metal zonation, with a lead–zinc zone (low temperature), associated with magnetite, on top of a copper-rich stringer zone (higher temperature); (ii) potential zone refining, typical of these deposits (Ohmoto 1996) with high temperature fluids remobilising lead–zinc, replacing them with copper minerals where chalcopyrite partially replaces sphalerite (chalcopyrite disease in sphalerite rims); (iii) framboidal pyrite with chalcopyrite suggesting biogenic sulfides formed at the sub-seafloor that nucleated later copper mineralisation (Piercey 2010); and (iv) alteration mineralogy typical of VHMS, such as sericite, phengite, Mg-chlorite, talc, and magnetite.

The connection between Curiosity and Explorer 108 is unclear as they could represent different events; Explorer 108 could represent the product of epigenetic remobilisation of the deeper Curiosity mineralisation. However, more studies (eg fluid inclusions, sulfur isotopes, sphalerite GGIMF geothermometry) are needed to better understand these base metal systems, particularly the nature of the mineralising fluids and source of sulfur.

About the age of the host sequence in Curiosity, Rover 1 and Explorer 142

Huston *et al* (2020) reported crystallisation ages of ca 1850 Ma for the volcanic and immature volcaniclastic rocks across the Rover field. The volcaniclastic package on top of the mineralisation in Curiosity yielded a crystallisation age of 1849.3 ± 4.2 Ma (Huston *et al* 2020). These immature volcaniclastic rocks are petrographically similar and close to the volcaniclastic rocks that host the Explorer 108. We interpret that the 1849.3 ± 4.2 Ma age for the immature volcaniclastic rocks from Curiosity is also representative of the volcaniclastic rocks that host Explorer 108.

The relatively more mature turbiditic sequences in Curiosity, Rover 1 and Explorer 142 yielded a MDA of ca 1850 Ma. This age is 10 million years younger than the MDA of the Warramunga Formation (Maidment *et al* 2013, **Figure 7b**). We interpret that the turbiditic packages, as well as the volcanic and volcaniclastic rock in the Rover field, are all part of the basal Ooradidgee Group. The turbiditic rocks are part of the sedimentary lithofacies of the Yungkulungu Formation, and the volcanic and volcaniclastic rocks are part of the volcanic lithofacies of the same formation. These results have important implications for exploration in the Warramunga Province. The younger Ooradidgee Group, particularly the Yungkulungu Formation, is a potential host for base metals and copper–gold–bismuth mineralisation, opening exploration ground in previously underexplored areas.

The volcanic and volcaniclastic rocks in the Rover field may represent the extrusive counterparts of the 1850 Ma plutonic rocks of the Tennant Creek Supersuite. This interpretation is consistent with the observation that the rocks in the Rover field seem to be affected by the same tectonic event that folded the packages into east–west-trending folds in the Tennant Creek mineral field.

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