REPORT 209

SYNGENETIC GOLD MINERALIZATION AT MOUNT CLEMENT — AN UNDEREXPLORED MINERALIZATION STYLE IN THE NORTHERN CAPRICORN OROGEN

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Cover image: Looking east over outcrop of the Mount Clement deposit that has been significantly transformed by exploration

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Syngenetic gold mineralization at Mount Clement — an underexplored mineralization style in the northern Capricorn Orogen

by

J Guilliamse

Abstract

Past studies have debated whether the Mount Clement gold deposit in the Paleoproterozoic Ashburton Basin is a syngenetic exhalative or an epigenetic, structurally controlled deposit. This study evaluates the stratigraphy, style of mineralization, and the alteration mineralogy of Mount Clement to elucidate its sedimentary depositional environment and controls on gold mineralization. These findings have wider implications for interpreting the timing of mineralization and regional events recorded in the Ashburton Basin.

Field mapping, core logging, and thin section analysis defined a hydrothermally altered wedge of siliciclastic sedimentary rocks containing stratabound intervals of chert and hydrothermal breccia. Gold and (subeconomic) base metal mineralization is mostly stratabound and shows minor structural control, although both styles of mineralization are modified by weathering processes. The Mount Clement deposit is most likely a syngenetic exhalative-style deposit similar to the hot spring Au–Ag Eskay Creek deposit located in British Columbia, and is interpreted as broadly coeval with the deposition of the Ashburton Formation. The Ashburton Basin hosts several other deposit types, including volcanic-hosted massive sulfides, Carlin-like and orogenic gold, and W-skarn mineralization. Some of these deposits are coeval, and probably genetically associated, with the Capricorn Orogeny.

KEYWORDS: gold deposits, hydrothermal deposits, mineral deposits, mineralization, spectral analysis, syngenetic deposits

Introduction

Mount Clement is a gold–silver–copper deposit in the Paleoproterozoic Ashburton Basin in the northern Capricorn Orogen of Western Australia (Fig. 1). Mineralization at Mount Clement was discovered in 1973 when a kangaroo shooter identified gossans exposed along the northern side of the deposit (Sargeant, 1979). A long exploration history followed, although no mining has been undertaken. Mount Clement is one of the largest gold deposits in the Ashburton Basin, with current resources of ~64 000 ounces of Au at 1.77g/t and ~620 000 ounces of Ag at 17 g/t (Border, 2012). Existing genetic models for the Mount Clement deposit include an epigenetic interpretation, where the deposit is formed after deposition of the host rocks, and a syngenetic interpretation, where the deposit formed at the same time as the host rock.

The aim of this study is to evaluate the Mount Clement deposit in terms of its mineralization characteristics and to identify key geological processes affecting the Ashburton Basin. Stratigraphic and mineralization relationships in the deposit are evaluated through deposit-scale mapping, core logging, and sampling. Drillcore was scanned using the Geoscience and Resource Strategy Division's (GRSD) HyLogger spectrometer to evaluate changes in mineral abundance and chemistry. The data are used to constrain the sedimentary depositional environment, geological controls and relative age of mineralization, and relationships with regional deformation events.

Geological setting

The Mount Clement deposit is located in the Paleoproterozoic Ashburton Basin in the northern Capricorn Orogen (Fig. 1). The deposit is hosted by clastic and chemical sedimentary rocks of the Ashburton Formation, which is part of the Wyloo Group (Fig. 2; Thorne et al., 2016).

The Capricorn Orogen is a region of variably deformed rocks in northern Western Australia between the Archean Pilbara and Yilgarn Cratons (Fig. 1). The Orogen records the Paleoproterozoic assembly of the West Australian Craton, initiated by the accretion of the Glenburgh Terrane to the Pilbara Craton during the Ophthalmia Orogeny at 2215–2145 Ma, followed by the collision of this combined entity with the Yilgarn Craton during the Glenburgh Orogeny at 2005–1950 Ma (Sheppard et al., 2010a; Johnson et al., 2013). This was followed by six orogenic events recording more than one billion years of intracratonic reworking of the Capricorn Orogen (Cawood and Tyler, 2004; Sheppard et al., 2010b; Johnson et al., 2013).

The Ashburton Basin is in the northern Capricorn Orogen. It is an intracratonic foreland basin associated with the onset of crustal reworking during the 1820–1770 Ma Capricorn Orogeny (Thorne, 2016). Martin and Morris (2010) interpret an early phase of extension followed by shortening. The Wyloo Group was deposited into the Ashburton Basin following post-Ophthalmia Orogeny deformation and uplift in the southern Pilbara region (Thorne, 2016). The Wyloo Group comprises the Mount McGrath Formation (deltaic deposits of ferruginous conglomerate and sandstone, quartz sandstone, mudstone, and locally developed carbonate), Duck Creek Dolomite (stromatolitic innershelf facies and thin-bedded or conglomeratic outershelf and slope facies), June Hill Volcanics (mixed mafic and felsic volcanic unit), and the Ashburton Formation (Thorne et al., 2011; Fig. 2).

The Ashburton Formation is primarily composed of mudstone, siltstone, and lithic quartz sandstone, with minor pebble- to cobble-conglomerate, felsic to mafic volcanic rock, banded iron-formation with chert, and dolostone (Thorne and Johnson, 2017). Most of the Ashburton Formation lies conformably on the Duck Creek Dolomite (Fig. 2). Exceptions occur at the western closure of the Wyloo Inlier where the Ashburton Formation unconformably overlies the Fortescue Group, and north of the Wyloo Inlier where it displays a disconformable contact with the older 1799 ± 8 Ma June Hill Volcanics (Evans et al., 2003). Paleoproterozoic rocks of the Capricorn, Mount Minnie, Bresnahan, and Bangemall Groups, and Mesozoic rocks of the Carnarvon Basin, unconformably overlie the Ashburton Formation (Thorne and Johnson, 2017).

The Ashburton Formation was deposited in a linear, deep-sea submarine fan environment (Thorne and Seymour, 1991), with clastic sediments attributed to three sources. Most sediment in the southeastern and central Ashburton Basin was derived from a Paleoproterozoic granitic source in the eastern Capricorn Orogen (Thorne and Seymour, 1991; Sircombe, 2003). The central Ashburton Basin also received detritus from a second granitic terrane in the region of the present-day Gascoyne Province. Sediment from the Mount Bruce Supergroup and the June Hill Volcanics was deposited in a restricted setting northwest of the Wyloo Inlier (Thorne, 2016). The Ashburton Formation has been metamorphosed to lower greenschist facies, increasing to upper greenschist to lower amphibolite facies in the west and southwest (Thorne and Johnson, 2017).

Ages for the Ashburton Formation are poorly constrained. A maximum depositional age of c. 2008 Ma is interpreted from the unconformable relationship with northwesterly trending dolerite dykes in the underlying Shingle Creek Group (Müller et al., 2005). A minimum age of c. 1796 is inferred from Sensitive High-Resolution Ion Microprobe (SHRIMP) U–Pb dating of the Boolaloo Granodiorite (Wingate et al., 2014b), which intrudes the Ashburton Formation (Thorne and Johnson, 2017). The maximum age constraint is considerably older than the interpreted age for the Capricorn Orogeny (1820–1770 Ma).

Methods

Geological processes responsible for the genesis of the Mount Clement deposit were assessed through geological field mapping in conjunction with the hyperspectral and visual logging of drillcore. Northern Star Resources and Artemis Resources donated two diamond drillholes from the Mount Clement deposit for this study (ARMCDD001; latitude: –22.8315, longitude: 116.1095 and ARMCRCD002A; latitude: –22.8325, longitude: 116.1096). These drillholes are housed at the Perth Core Library. Both holes intersect the footwall and mineralized section of the Mount Clement stratigraphy. All core was scanned using the HyLogger spectrometer (Hancock and Huntington, 2010), then graphically logged and selectively sampled for thin section petrography to identify host rocks and to validate mineral assemblages interpreted from HyLogger data.

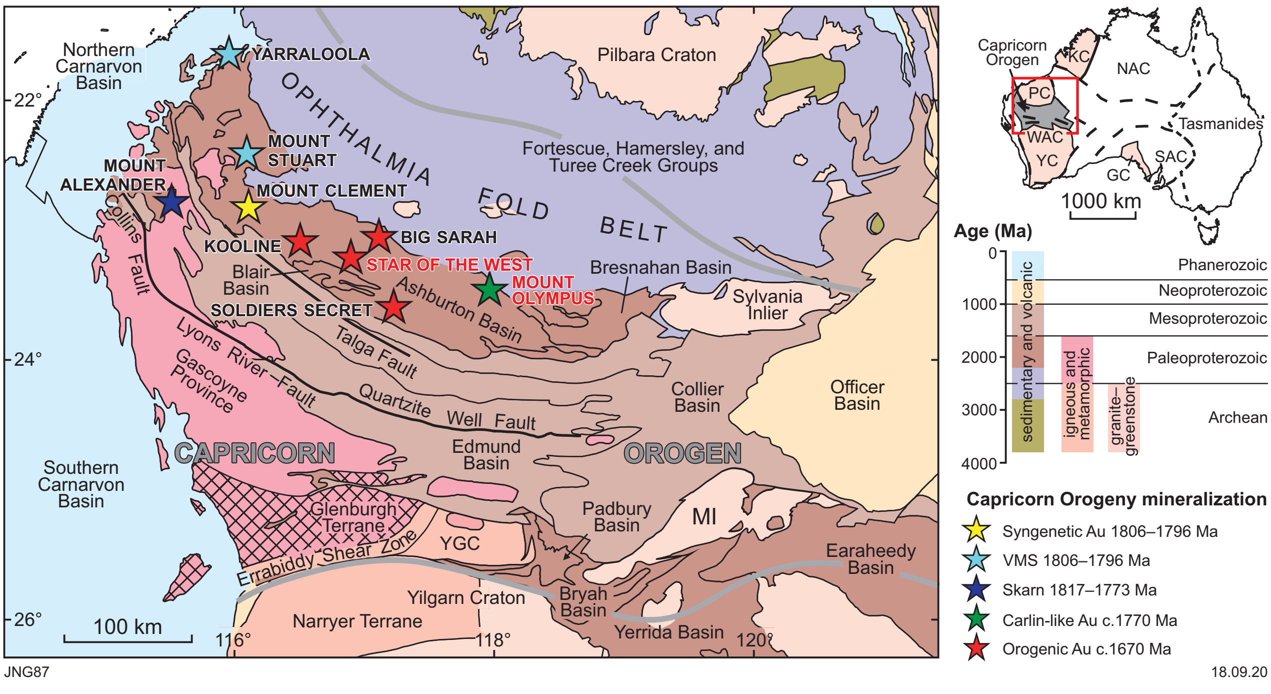

Figure 1. Map of the Capricorn Orogen showing the location of the Mount Clement deposit and other deposits of the Ashburton Basin. Abbreviations: GC, Gawler Craton; KC, Kimberley Craton; MI, Marymia Inlier; NAC, North Australian Craton; PC, Pilbara Craton; SAC, South Australian Craton; WAC, West Australian Craton; YC, Yilgarn Craton; YGC, Yarlarweelor Gneiss Complex

Field mapping

Geological mapping of the Mount Clement deposit spanned a 1 km x 750 m area and was conducted to constrain stratigraphic relationships and gain a better understanding of some of the units not present in drillcore. Trenches and pits provided good access to fresh outcrop.

Sampling

Twenty-four hand specimens were collected from drillcore for petrographic analysis. Most samples were from the interpreted stratigraphic footwall and lower hydrothermal alteration zones because upper parts of the drillholes are strongly weathered.

Mineralogy

All drillcore was scanned in the visible to near-infrared (VNIR, 380–1000 nm), short-wave infrared (SWIR, 1000–2500 nm), and thermal infrared (TIR, 6000–4000 nm) spectral ranges using the HyLogger and operational parameters and scanning procedures as described by Hancock and Huntington (2010). Raw spectral data were analysed using 'The Spectral Geologist' (TSG v8) commercial software that assists with mineral identification, provides estimates of mineral abundance, and measures positions of specific absorption features by matching collected spectra against a library of known mineral responses (Merry et al., 1999). This study used 'The Spectral Assistant' (TSA) approach, a routine within TSG v8 that uses a training library of spectra either to match the unknown project spectrum against a single mineral spectrum, or to create a simulated mixture of two mineral spectra that match the observed spectrum. Major minerals are predicted on the basis of the match that returns the lowest error result (Pontual, 2008).

Twenty-four polished thin sections were prepared and examined using transmitted and reflected light microscopy. Five of these were examined using a desktop scanning electron microscope to test for the presence of monazite and xenotime suitable for in situ U–Pb geochronology.

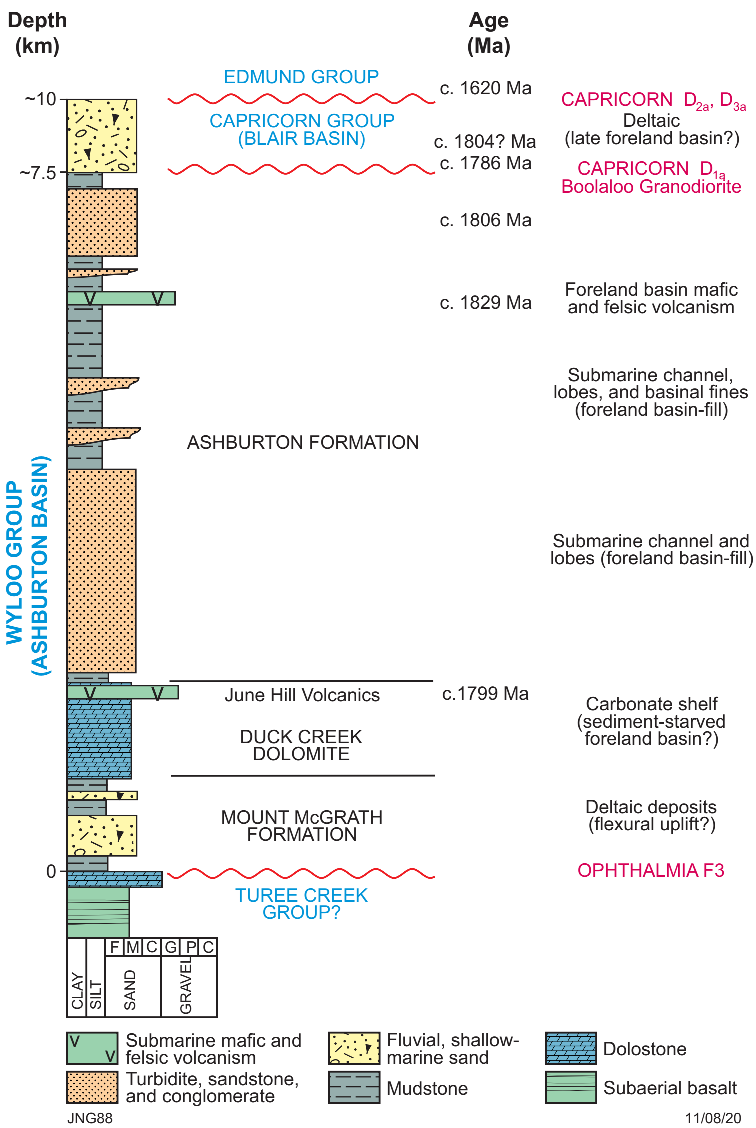

Figure 2. **Stratigraphy of the Wyloo Group showing ages, depositional environments, and deformation events**

Results

Stratigraphy

The Mount Clement deposit is hosted by metasedimentary rocks of the Ashburton Formation. Rocks located beneath the Au–Ag–Cu mineralization zone are referred to as stratigraphic footwall rocks, whereas those located above are hangingwall rocks. The mineralization zone contains massive carbonate with varying amounts of talc alteration overlain by altered clastic sedimentary rocks interlayered with minor intervals of stratabound breccia and chert (Fig. 3).

The stratigraphic footwall is composed of finely laminated, quartz-rich siliciclastic metasedimentary rocks (Fig. 4a). The beds range from millimetre to centimetre in thickness and are dark- to light-grey in colour. Grain size is mainly mud and silt, with some coarser, sandy beds becoming abundant towards the top of the section (i.e. to the south). These rocks are overlain by a massive carbonate interval that defines the base of the mineralized zone. The massive carbonate interval lies subparallel to bedding in the footwall siliciclastic metasedimentary rocks and comprises mostly dolomite with minor calcite, siderite, and ankerite (carbonate mineral species identified using the HyLogger). The transition to the carbonate interval is either gradational or sharp. Gradational transitions contain interstitial carbonate minerals (Fig. 4b) and carbonate veinlets that grade into massive carbonate over distances of about 10 m. In contrast, sharp contacts between the footwall metasedimentary rocks and the massive carbonate are defined by a weathered chert (-goethite) breccia at surface (Fig. 4c). Equivalent breccias have not been observed in the drillholes examined in this study; however, unexamined drillholes confirm the breccia horizon is strataform in the central and eastern parts of the deposit, although geometry at depth is poorly constrained (Voermans, 2008). The upper stratigraphic margin of the massive carbonate interval becomes increasingly brecciated and silicified to the south.

The massive carbonate interval is overlain by fine-grained metasedimentary rocks that are compositionally and texturally similar to those in the footwall. These metasedimentary rocks are a continuation of the mineralized zone and include finely bedded siltstones and sandstones interbedded with layers of stratabound chert, conglomerate, breccia intervals and minor banded iron-formation (Fig. 5a–c). Chert and breccia layers are stratabound and typically less than 10 m thick. Breccias comprise fragments of chert and siliciclastic rock and are most prominent at the eastern end of the deposit (Fig. 3).

Up to 100 m thick massive chert unit overlies the mineralized zone and marks the transition to hangingwall metasedimentary rocks (Fig. 3). The chert is widely distributed at surface, but is not intersected in studied drillcore due to the positioning of drillhole collars near mineralized zones and footwall rocks. Fine-grained metasedimentary rocks similar to the footwall overlie the massive chert unit (Fig. 5d).

Au–Ag–Cu mineralization

The mineralized zone at Mount Clement is a mixed hydrothermal–siliciclastic zone up to ~200 m thick, comprising massive carbonate at the base overlain by finely bedded siltstones and sandstones interbedded with layers of stratabound chert and minor breccia (Fig. 3). Supergene alteration is a key feature of the mineralized zone in outcrop, extending down to more than 100 m below surface (Davy et al., 1991). The mineralized zone contains gold concentrations greater than 5 ppb (Fig. 3), with the highest values associated with gossans, stratabound breccia horizons, hematite-altered metasedimentary rocks, and talc-altered carbonate (Davy et al., 1991). In drillcore, elevated gold grades (<3 ppm) are associated with quartz–pyrite–pyrrhotite–chalcopyrite–arsenopyrite veins and altered metasedimentary wall rocks (Fig. 6a,b).

Visible gold (<100 µm) is free and fine grained and most prominent in the supergene zone, typically associated with quartz or goethite pseudomorphs after sulfide minerals (Fig. 6c; Davy et al., 1991). The highest concentrations of gold have a close spatial relationship with supergene arsenate minerals chenevixite ($Cu_2Fe^{3+}{}_2(AsO_4)_2(OH)_4$) and conichalcite ($CaCu(AsO_4)(OH)$) (Fig. 6c,d). In drillcore, very fine-grained gold is associated with quartz in quartz–pyrite–pyrrhotite–chalcopyrite–arsenopyrite veins (Fig. 6a,b). Some very fine-grained gold is also present in the chlorite–white mica alteration haloes that surround these veins. Copper occurs as chalcopyrite within quartz–pyrite–pyrrhotite–chalcopyrite–arsenopyrite veins in footwall metasedimentary rocks (Fig. 6b). In the supergene zone, copper is present within chenevixite and conichalcite (Fig. 6c,d). Silver is also present within chenevixite and conichalcite, or has been converted to halide (Davy et al., 1991).

Hypogene alteration

Stratabound massive carbonate and chert layers described above are likely the products of hydrothermal fluids associated with more dispersed alteration zones in metasedimentary rocks of the footwall and mineralized zone.

Footwall metasedimentary rocks are altered to chlorite and white mica within ~10 m of the contact with the overlying massive carbonate interval (Figs 7a,b, 8a). Hyperspectral data indicates that alteration has a much larger halo than what is seen in thin section (Fig. 8b,c), with footwall chlorite decreasing in abundance downhole from the contact with the mineralized zone (Fig. 8d). Furthermore, detected chlorite shows a gradual shift from more Mg-rich chlorite distal to the contact, to more Fe-rich chlorite proximal to the contact (Fig. 8e). White mica abundance is uniformly distributed throughout footwall metasedimentary rocks; however, the composition shows a gradual shift in Al-abundance, with Al becoming less abundant with proximity to the contact (Fig. 8f). Subhedral to euhedral hydrothermal magnetite grains (<1 mm) have a more extensive distribution in footwall metasedimentary rocks, extending from the contact with the massive carbonate to the bottom of the drillhole (Fig. 7b). Hydrothermal carbonate begins replacing metasedimentary rocks within 10 m of the massive carbonate interval (Figs 4b, 8b,c). Minor quartz–pyrite–pyrrhotite–chalcopyrite–arsenopyrite veins cut through the footwall metasedimentary rocks, typically associated with chlorite–muscovite alteration (Fig. 6a,b). Fine-grained gold is associated with quartz in these veins, and is also recorded in the surrounding chlorite–muscovite alteration. Only a small portion of the footwall metasedimentary rocks was intersected in ARMCDD001, so the relationship between white mica and chlorite alteration and the overlying mineralized zone was not able to be tested in this drillhole (Fig. 9a).

The massive carbonate interval at the base of the mineralized zone is largely made up of Mg-rich carbonate with local talc alteration (Figs 8a–c,g,h, 9a–e, 10a,b). Some Fe-rich carbonate occurs at the margins of the massive carbonate unit in ARMCRCD002A, typically associated with talc (Fig. 8g,h). Minor brecciated areas are defined by carbonate-rich fragments separated by coarse-grained carbonate and quartz-filled fractures. Minor sulfides are disseminated throughout the carbonate-rich interval and are commonly associated with hydrothermal muscovite and Mg-chlorite (Fig. 10c,d).

Metasedimentary rocks of the mineralized zone contain stratabound chert and breccia layers with minor quartz alteration and boxwork textures. The recognition of hypogene alteration minerals is obscured by later supergene processes; however, substantial boxwork textures in the mineralized zone indicate that sulfide minerals were a prominent hypogene alteration (Fig. 6c). Hangingwall metasedimentary rocks are mostly unaffected by hypogene alteration (Fig. 5d).

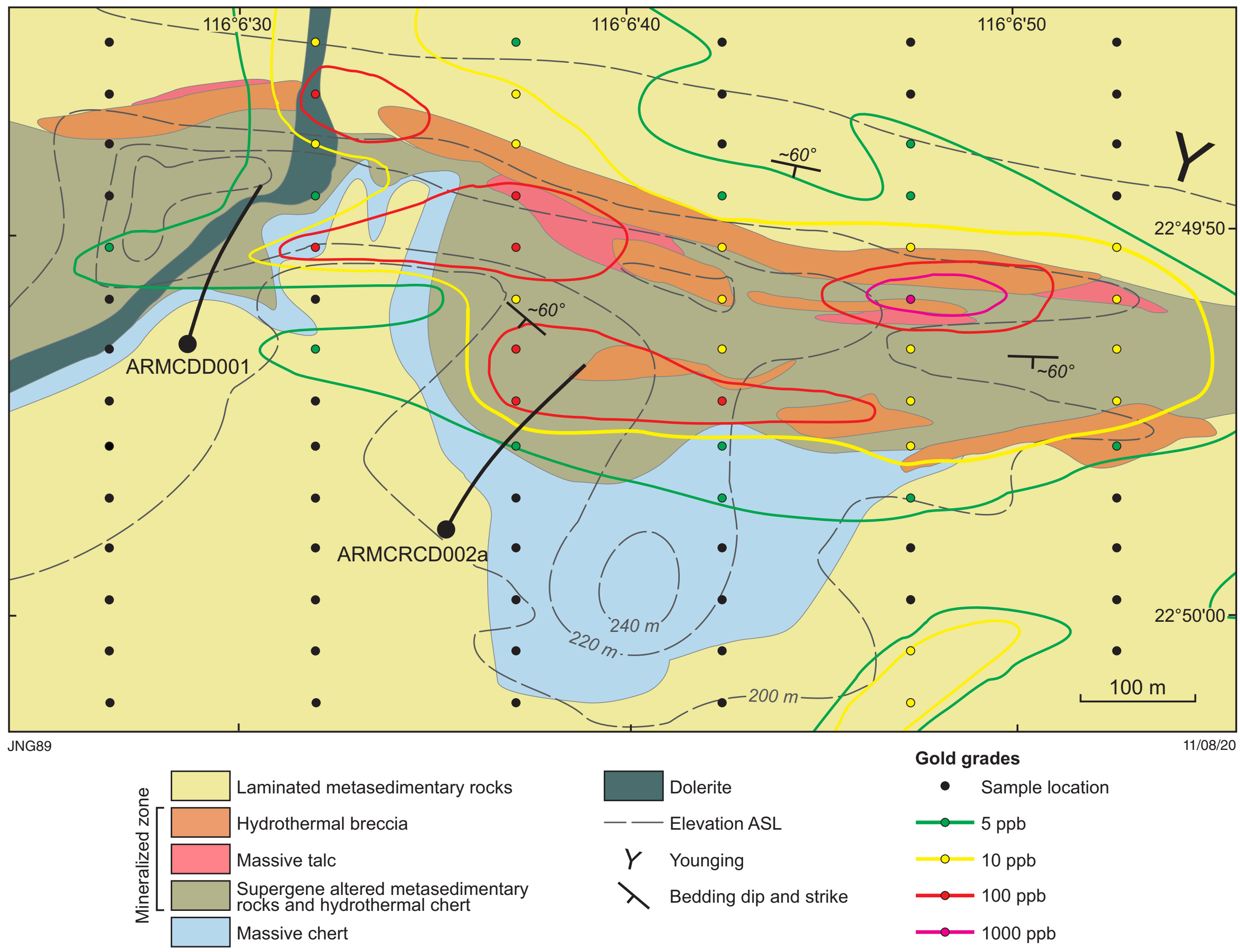

Figure 3. Deposit-scale outcrop map of the Mount Clement deposit. Sample locations are from soil sampling conducted by Taipan Resources in 2003

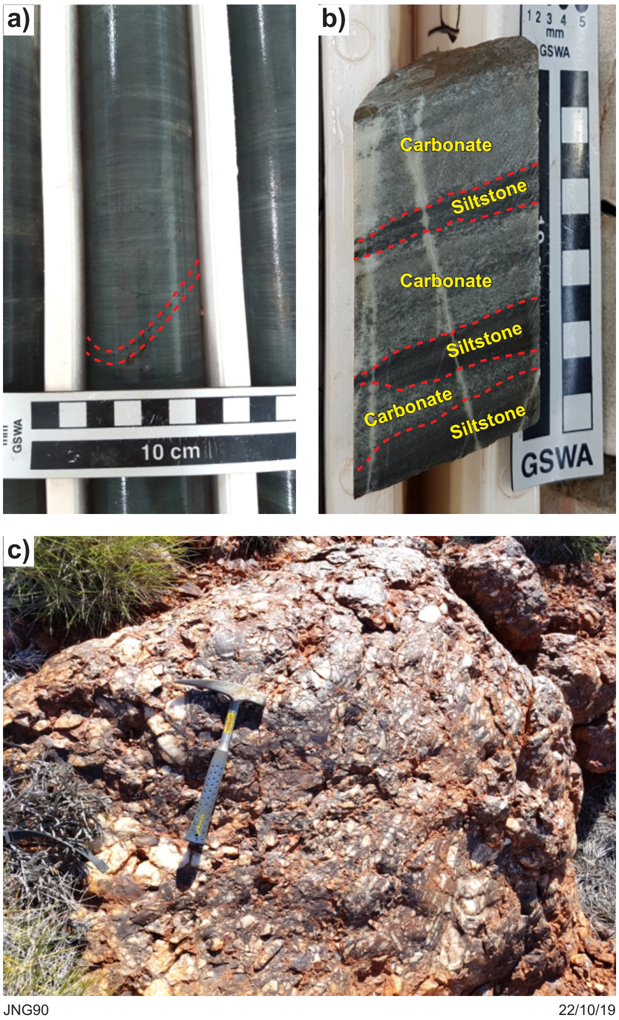

Figure 4. **Drillcore and outcrop photos of footwall rocks from the Mount Clement deposit: a) finely laminated, quartz-rich siliciclastic metasedimentary rock, red line indicates bedding-parallel magnetite grains, 301.2 m, ARMCRCD002A; b) mixture of finely laminated metasedimentary rock and carbonate vein/alteration at the gradational contact between the footwall metasedimentary rocks and overlying massive carbonate units, 242.2 m, ARMCRCD002A; c) ferruginous breccia with up to boulder-size, angular chert clasts surrounded by a quartz and goethite cement**

Supergene alteration

Supergene alteration is most prevalent within the mineralized zone and extends down to more than 100 m below surface (Davy et al., 1991). Iron oxides and kaolinite are the dominant minerals within the supergene zone (Figs 8b,c,i,j, 9b,c,f,g), while secondary arsenate minerals chenevixite and conichalcite are common in gossans, talc, and breccia horizons (Fig. 6c,d). At surface, zones of massive talc enclose narrow intervals of quartz and fine-grained metasedimentary rocks. These zones are interpreted as equivalent to massive carbonate in drillholes.

Discussion

Paleodepositional environment

Field mapping and core logging at Mount Clement defined a wedge of hydrothermally altered clastic sedimentary rock with localized intervals of stratabound breccia and chemical sedimentary rocks. These spatial and timing relationships suggest that the hydrothermal fluid event broadly coincided with regional clastic sedimentation.

The carbonate unit displays mixed clastic input at the stratigraphic base and grades upwards into massive carbonate (Fig. 4b), implying the carbonate and the underlying metasedimentary rocks were syndepositional during the initial phase of carbonate crystallization. Stratabound chert layers are interspersed with clastic sedimentary rocks within the zone of hydrothermally altered metasedimentary rocks (Fig. 5a), indicating short pulses of chemical sedimentation took place during more sustained periods of clastic sedimentation. Stratabound breccia horizons that are entirely composed of chert clasts are interpreted to have formed in situ, based on breccia clasts being confined to individual layers and not present within bounding siliciclastic layers (Fig. 5b).

The Mount Clement deposit is most likely a product of localized seafloor hydrothermal alteration that formed at the same time as deposition of the Ashburton Formation. Venting of hydrothermal fluids most likely occurred as multiple pulses, resulting in spatial and temporal gradations in the crystallization of chemical precipitants from the fluid, subsequent brecciation of these layers, and intermittent deposition of clastic materials of the Ashburton Formation.

Mapping of hypogene alteration zones in weathered outcrop

Weathering processes have modified hypogene alteration mineral zonation in the Mount Clement study area; however, primary gradients in hypogene minerals are locally preserved or can be inferred from secondary weathering minerals. Stratigraphic footwall metasedimentary rocks display an increase in chlorite abundance, and a transition from Fe-rich to Mg-rich chlorite with proximity to the mineralized contact (Fig. 9d,e). Hydrothermal chlorite is also present in the interval of metasedimentary rocks that separate two carbonate-rich zones located proximal to mineralization (Figs 9b, 10b). Talc alters carbonate at the base of the mineralized zone and is a useful vector for hypogene mineralization given that it is more resistant than other ore-related minerals, such as sulfides. Although carbonate minerals are accurate indicators of hypogene alteration in fresh to moderately weathered rocks, they are rarely preserved in areas of strong weathering and are therefore of limited value when mapping surface rock exposures.

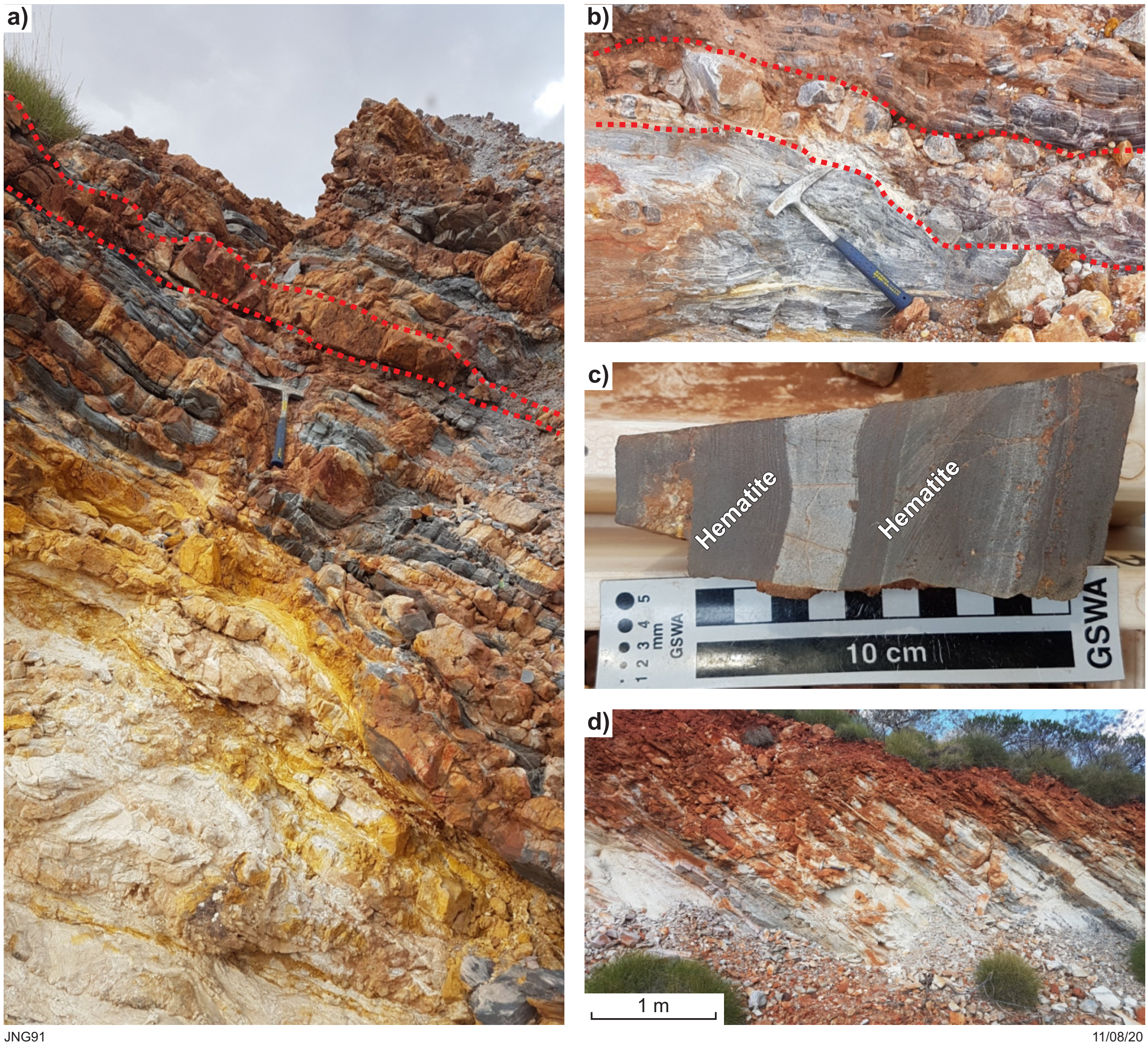

Figure 5. Photos of outcrop and drillcore from the mineralized zone and hangingwall at the Mount Clement deposit: a) stratabound chert layers (within red lines) interlayered with altered laminated sediments; b) stratabound chert breccia layer (within red lines) between altered laminated sediments; c) primary hematite bands between altered laminated sediments; 107.6 m, ARMCDD001; d) hangingwall laminated metasedimentary rocks. Interpreted to be representative of regional sedimentation similar to footwall sediments

Hypogene and supergene alteration

The timing of hypogene and supergene alteration assemblages are based on mineral relationships seen in outcrop, hand specimen, and thin section. Hypogene alteration began as carbonate–ion-bearing hydrothermal fluids that deposited massive carbonate on the ancient ocean floor. Deposition of massive carbonate was followed by pulses of silica-rich fluids that carried metals. In the footwall metasedimentary rocks these fluids formed quartz–sulfide–gold veins with associated white mica and chlorite alteration (Fig. 6a,b). In the massive carbonate they caused talc-alteration, disseminated sulfides and associated white mica and chlorite alteration (Figs 9e, 10a–d). As they reached the ocean floor, silica-rich fluids formed stratabound chert layers and deposited base metals as semimassive and disseminated sulfides within chert, breccia, and interlayered siliciclastic sediments. The presence of fine-grained gold within quartz veins in the footwall metasedimentary rocks may indicate that gold in the mineralized zone was also free and fine grained, likely disseminated through chert, breccia, and siliciclastic layers.

Supergene alteration resulted in the widespread breakdown of sulfides, leading to the formation of gossans and boxwork textures within breccia, talc, and metasedimentary rocks. Based on the shape of the voids and the nearby presence of scorodite and arseniosiderite, Davy et al. (1991) interpreted original sulfides to be pyrite and arsenopyrite (Fig. 6c). The presence of kaolinite from the HyLogger may indicate original mica, while widespread Fe-oxide alteration may be from the breakdown of sulfides

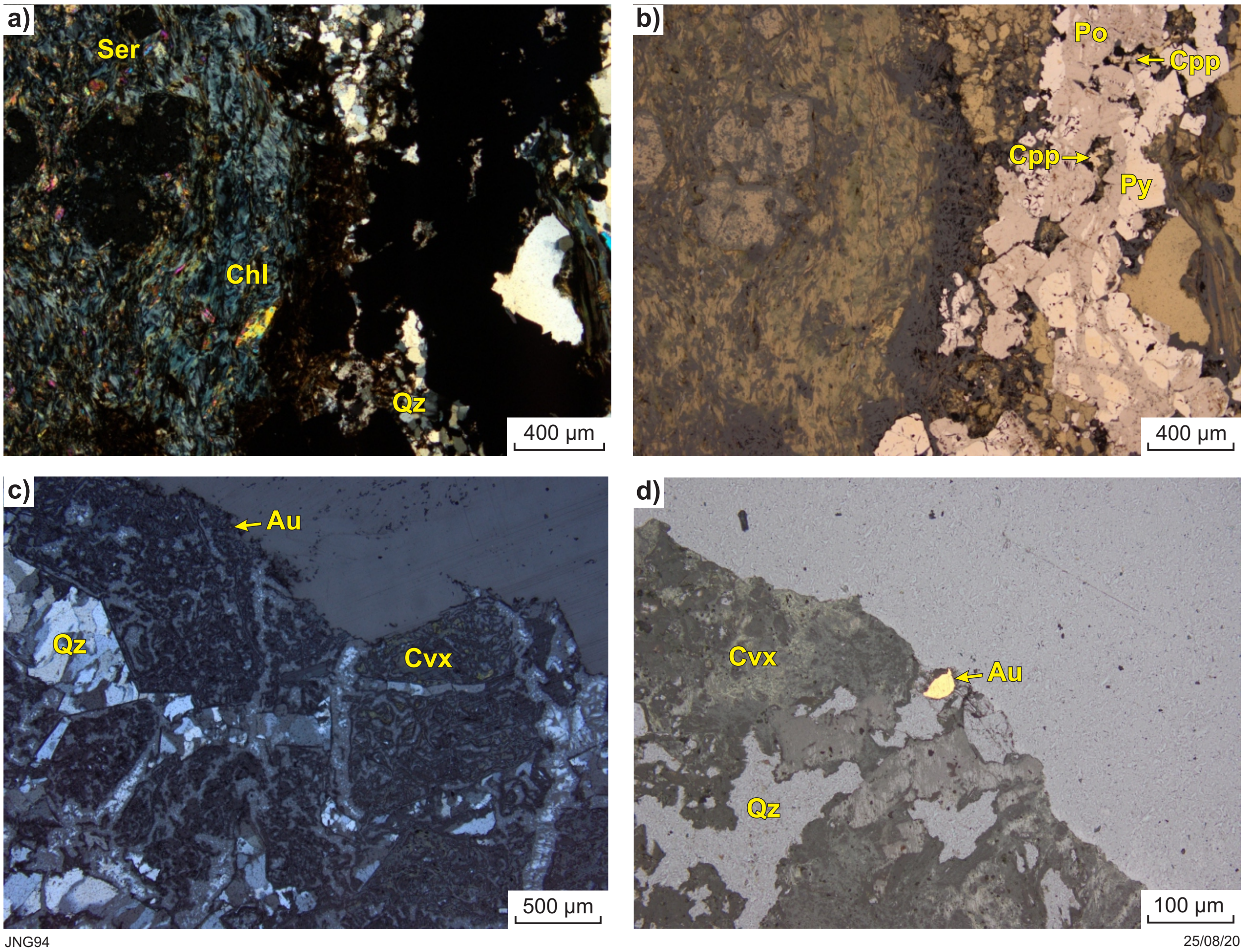

Figure 6. Photomicrographs of sulfides, gold, and associated hypogene and supergene alteration from the Mount Clement deposit: a) polarized transmitted light photo showing contact between finely laminated sedimentary rocks and a quartz–sulfide vein. Sedimentary rocks are rich in chlorite and sericite at contact. Quartz in vein is coarse grained, 225 m, ARMCDD001; b) plane-polarized reflected light photo of Fig. 6a showing pyrrhotite (Po) and pyrite (Py) vein with minor chalcopyrite (Ccp). Vein has quartz at the rim and a sulfide interior, 225 m, ARMCDD001; c) polarized reflected and transmitted light photo showing quartz (Qz) and chenevixite (Cvx) pseudomorphs after sulfide minerals. Based on the shape of the pseudomorphs, sulfides are most likely arsenopyrite. Small gold grain associated with chenevixite. Grab sample from outcrop: d) plane-polarized transmitted and reflected light photo showing a gold grain with supergene chenevixite (Cvx) and quartz (Qz). Grab sample from outcrop

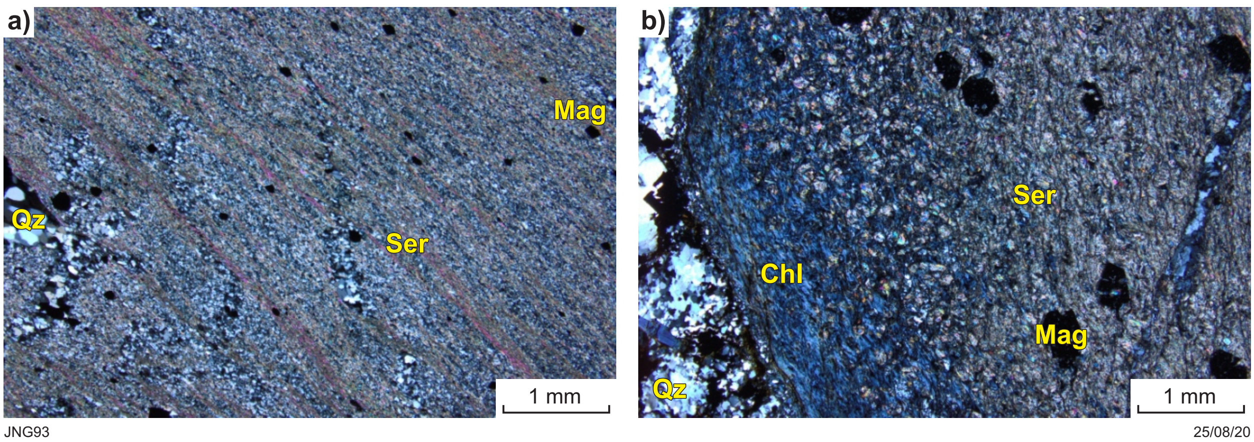

Figure 7. Photomicrographs of alteration zones intersected in drillcore from the Mount Clement deposit: a) pervasive sericite alteration (Ser) with minor subhedral magnetite (Mag); 249.3 m, ARMCRCD002A; b) proximal chlorite (Chl) and sericite (Ser) alteration surrounding a quartz vein. Note subhedral magnetite crystals (Mag), 225 m, ARMCDD001

and chlorite. Copper–arsenate minerals chenevixite and conichalcite are common supergene minerals around boxwork zones. In thin section, free, fine-grained gold is most commonly associated with chenevixite and conichalcite (Fig. 6c,d), most likely indicating supergene remobilization of gold rather than remobilization during later deformation, as is the case in other northern Capricorn deposits (Fielding et al., 2020).

Epigenetic vs syngenetic

Mount Clement has previously been interpreted as either an epigenetic, structurally controlled deposit or a syngenetic exhalative deposit (Novak, 1982; Davy et al., 1991). Examples of both epigenetic and syngenetic-style deposits have been recorded in the Ashburton Basin. Epigenetic examples are well studied, and include numerous small orogenic vein-hosted Au deposits, such as Star of the West (Fielding et al., 2020), and the sedimentary- and vein-hosted Carlin-like Mount Olympus deposit (Fielding et al., 2019). Syngenetic-style deposits in the Ashburton Basin are less well studied, but include volcanic-associated massive sulfide (VMS) mineralization at Mount Stuart and Yarraloola (Fig. 1; Doust, 1984).

Epigenetic quartz-hosted deposits such as Star of the West are dominated by fault-controlled mineralized quartz veins that display minimal to no stratigraphical control (Groves et al., 1998; Fielding et al., 2020). An epigenetic, orogenic-style gold mineralization model for the Mount Clement deposit is unlikely due to the absence of shear zone or fault-hosted, gold-bearing quartz veins cutting layering in the metasedimentary rocks. Novak (1982) interpreted a major west northwest – east northeast fault in the Mount Clement deposit area that controls stockwork vein-style gold and base metal mineralization, based on underground mapping of an exploratory adit into the southern side of the ridge. The lack of access to the adit due to safety concerns meant that this interpretation could not be tested. No evidence for a major fault is apparent in outcrop or in available drillcore, and further work would be required to test the hypothesis for a large-scale fault. The presence of a quartz vein stockwork is not definitive evidence for orogenic gold systems because similar structural styles of veins are documented for a range of deposits that include epithermal, porphyry Cu–Au, and VMS deposits. At the Mount Olympus deposit, gold mineralization is controlled by the faulted contact between the Duck Creek Dolomite and the Mount McGrath Formation (Fielding et al., 2019). Silica-rich fluids are interpreted to have moved along the Zoe fault and deposited both quartz vein and stratabound gold within sediments of the Mount McGrath Formation (Fielding et al., 2019). Although faulting is interpreted to have sourced hydrothermal fluids at Mount Clement, the faulting was syndepositional and allowed hydrothermal fluids to reach the ocean floor. No evidence for post-depositional faults controlling mineralization is observed at Mount Clement.

Evidence for syngenetic hydrothermal fluids has been outlined previously, but include stratabound chert and breccia layers within bedded siliciclastic sediments; the lack of quartz veins in the mineralized zone; and the massive chert at the top of the mineralized zone. Syngenetic exhalative deposits that form at the sediment–water interface include hydrothermal submarine ‘hot spring’ systems related to basinal fluids (Emsbo et al., 1999; Gu et al., 2002), and those related to volcanic activity, such as VMS (Shanks III and Thurston, 2012) and epithermal-like shallow hot spring deposits (Massey et al., 1999). Davy et al (1991) favoured an epithermal interpretation for Mount Clement, based on the presence of hydrothermal breccias, enrichment of elements that are known to be enriched in epithermal deposits (Ag, As, Au, Cu, Hg, Pb, Sb, U, W, Zn), fluid temperature estimates of 300–490°C, and the massive chert at the top of the deposit being similar to a siliceous sinter that occurs at the top of epithermal deposits.

This study favours a similar interpretation to Davy et al. (1991), with Mount Clement being analogous to subaqueous hot spring Au–Ag deposits that were first identified and documented in the Eskay Creek area of British Colombia (Alldrick, 1995), and have since become more widely recognized (e.g. Hannington, 1998; Roth et al., 1999). These deposits are transitional between deep water VMS deposits, and subaerial epithermal Au–Ag hot spring deposits, and display characteristics of both deposit types (Massey et al., 1999). The genetic model for these deposits involves magmatic-derived fluids venting into a shallow water environment, typically sourced from a shallow magmatic body (Massey et al., 1999). They are Au and Ag rich, and leave geochemical signatures similar to epithermal deposits (Cu, Pb, Zn, As, Sb, Hg), but also display large sericite–pyrite–chlorite alteration zones that are typical of VMS deposits.

Hydrothermal-structural model for the Mount Clement deposit

Syndepositional faulting of the Ashburton Formation is interpreted to have provided a conduit for magmatic fluids derived from shallow plutons below the Mount Clement deposit (Hronsky, 2000; Fig. 11a). Ascending carbonate–ion-bearing fluids deposited massive carbonate minerals near the interface with the ocean floor (Fig. 11a). The waning of these hydrothermal fluids led to a gradual decrease in the proportion of carbonate minerals relative to siliciclastic sediment (Fig. 11b). Subsequent pulses of silica-rich hydrothermal fluids locally replaced carbonate-rich zones with talc (Fig. 10a,b) and deposited as stratabound chert layers at the ocean floor between more extended periods of sedimentation of siliciclastic material (Figs 5a, 11b).

Venting hydrothermal fluids deposited chemical sedimentary rocks around vent sites, forming seals that led to increasing hydrostatic pressures as more fluid entered the system. This overpressuring led to hydraulic fracturing and potential hydrothermal eruptions that created multiple breccia horizons, typically separated by episodes of more dominant siliciclastic sedimentation (Fig. 11b; Nelson and Giles, 1985). Silica-rich hydrothermal fluids transported gold and base metals. Gold was deposited as free gold within quartz veins in the footwall metasedimentary rocks, and disseminated in carbonate, siliciclastic sediments, chert, and breccias within the mineralized zone. Base metals were deposited as sulfides within quartz veins in the footwall metasedimentary rocks, and as disseminated and semimassive accumulations in carbonate, siliciclastic sediments, chert, and breccias within the mineralized

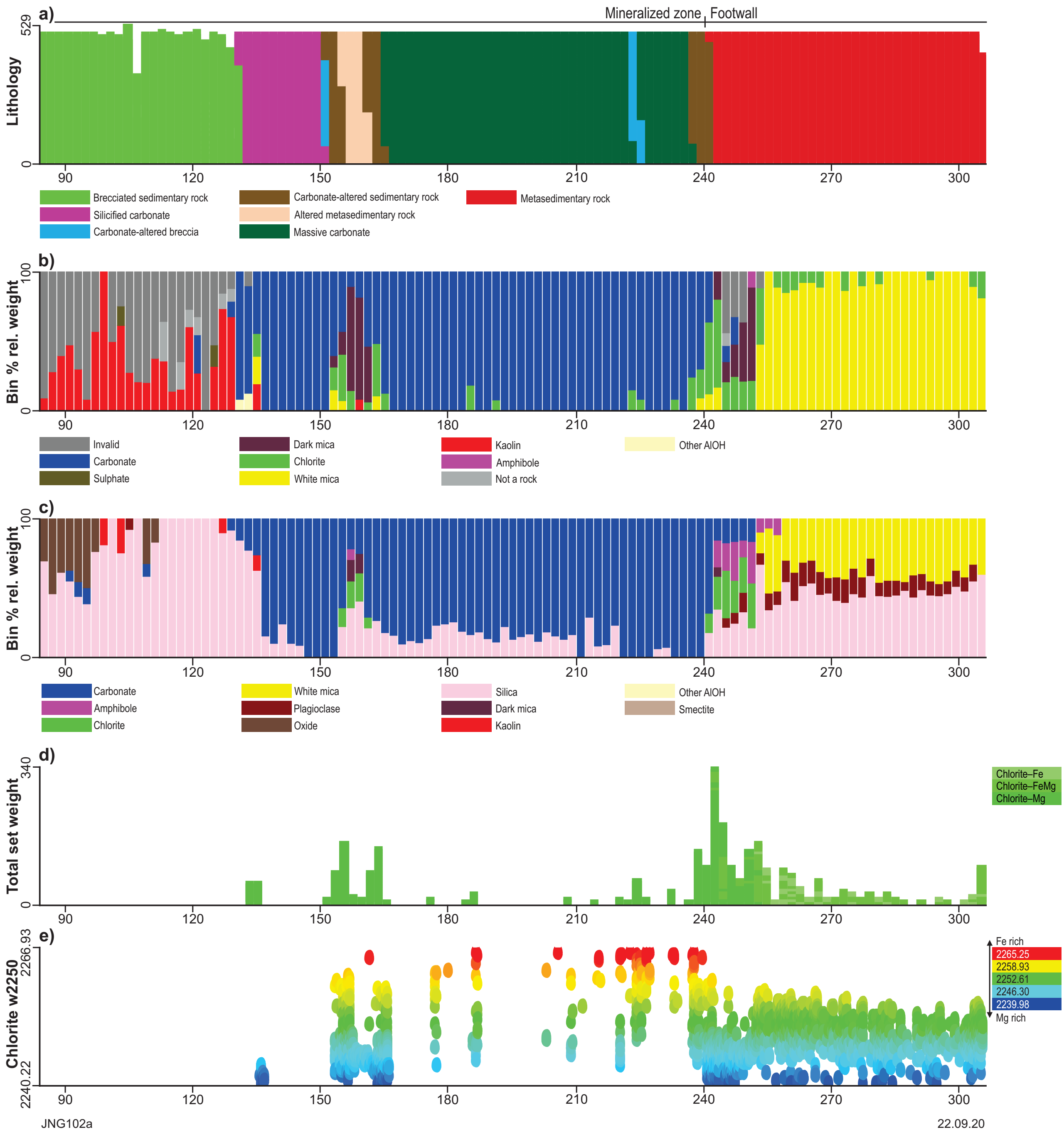

Figure 8. **Downhole plots exported from TSG for ARMCRCD002A: a) lithology interpretation based on inspection of drillcore and company logging for weathered sections; log is split into footwall and mineralized zones; b) interpreted mineral groups from SWIR TSA data; c) interpreted mineral groups from TIR TSA data; d) interpreted chlorite species from SWIR TSA data; e) intersection of the FeOH absorption feature related to chlorite; warmer colours indicate more Fe-rich chlorite while cooler colours indicate more Mg-rich chlorite; f) intersection of the AlOH absorption feature related to white mica; warmer colours correspond to Al-poor white mica while cooler colours correspond to Al-rich white mica; g) carbonate abundance and composition interpreted by TIR; warmer colours indicate more Fe-rich carbonate while cooler colours indicate more Mg-rich carbonate; h) talc interpreted from TIR TSA; i) kaolinite abundance and crystallinity; warmer colours indicate more ordered crystallinity while cooler colours indicate poorly ordered kaolinite; j) total ferric oxide abundance diagram interpreted from VNIR spectra, with warmer colours corresponding to goethite-rich zone and cooler colours indicating hematite-rich zones**

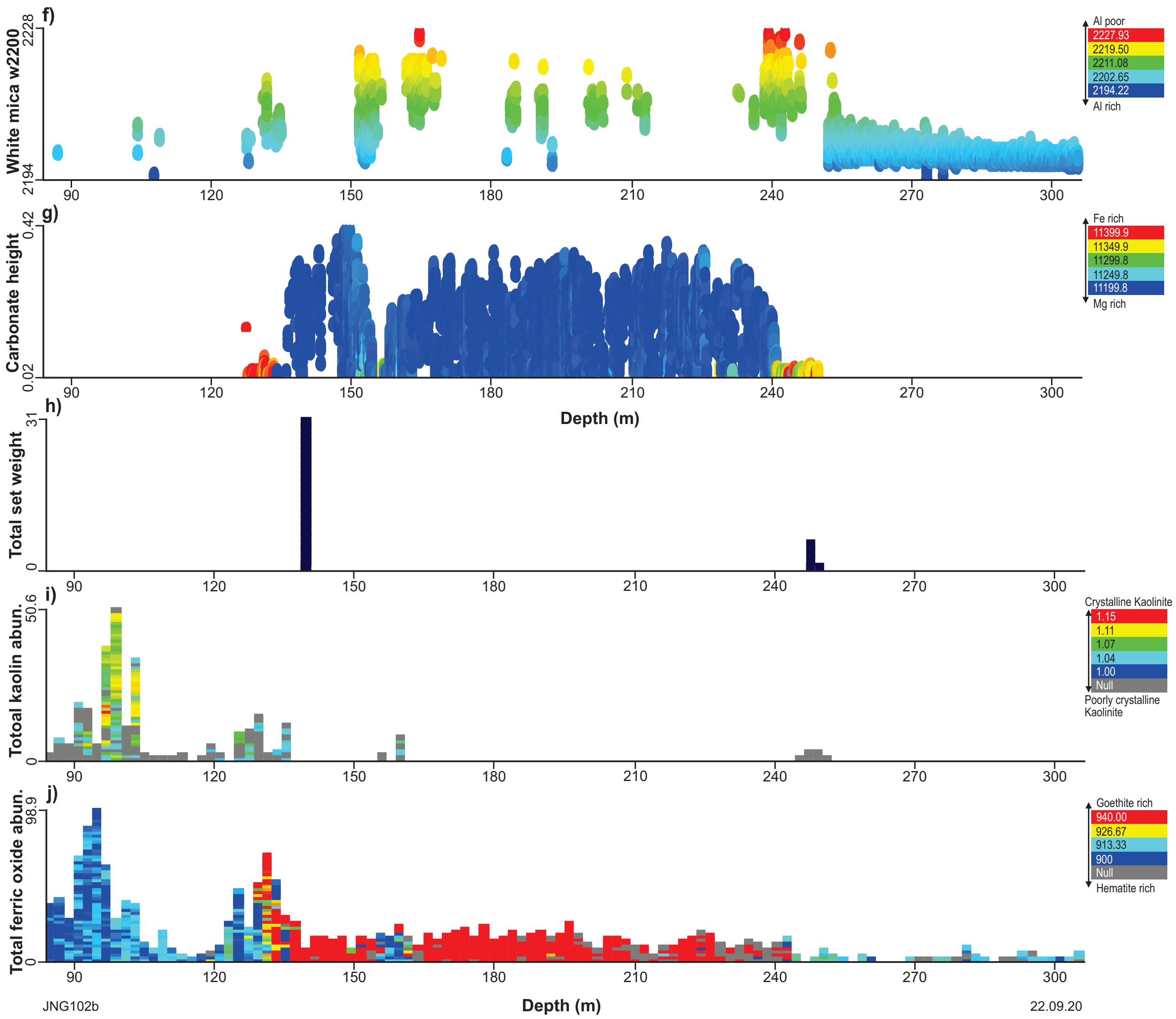

Figure 8. continued

zone. The last pulse of hydrothermal fluid activity resulted in a massive chert at the top of the mineralized sequence (Figs 3, 11b). Resumption of sedimentation resulted in the thick clastic sedimentary hangingwall sequence.

Supergene processes remobilized gold and broke down base metal sulfides, which redeposited as copper–arsenate minerals, chenevixite and conichalcite (Fig. 6c,d). Gold was preferentially redeposited with chenevixite and conichalcite (Fig. 6c,d).

Relative timing of mineralization

A syngenetic exhalative interpretation for the Mount Clement deposit has important implications in terms of constraining the apparent age of the mineralization. This study indicates that mineralization at the Mount Clement deposit is syndepositional and interpreted to be the same age as the Ashburton Formation. Attempts to date hydrothermal monazite and xenotime associated with mineralized veins and altered rocks were made; however, no suitable hydrothermal minerals were identified in polished thin sections.

The Ashburton Formation has a maximum age of c. 2008 Ma, which is the older age limit for the Wyloo Group and is based on an unconformable relationship to northwesterly trending dolerite dykes in the underlying Shingle Creek Group (Müller et al., 2005). The minimum age of 1796 ± 9 Ma is taken from the Boolaloo Granodiorite that intrudes the Ashburton Formation (Wingate et al., 2014a). Despite the poorly constrained depositional ages, many studies have interpreted the Ashburton Basin to have formed during the 1820–1770 Ma Capricorn Orogeny (e.g. Tyler and Thorne, 1990; Thorne and Seymour, 1991; Evans et al., 2003).

The small number of dated samples from the upper part of the Ashburton Formation range in age between c. 1829 and 1806 Ma (Thorne and Johnson, 2017). A felsic volcaniclastic unit within the middle to upper part of the Ashburton Formation yielded a SHRIMP U–Pb age of 1829 ± 5 Ma (Sircombe, 2003). A slightly younger age of c. 1819 Ma was reported from the youngest zircon population from seven Ashburton Formation sandstones (Sircombe, 2002, written comm. in Martin et al., 2005).

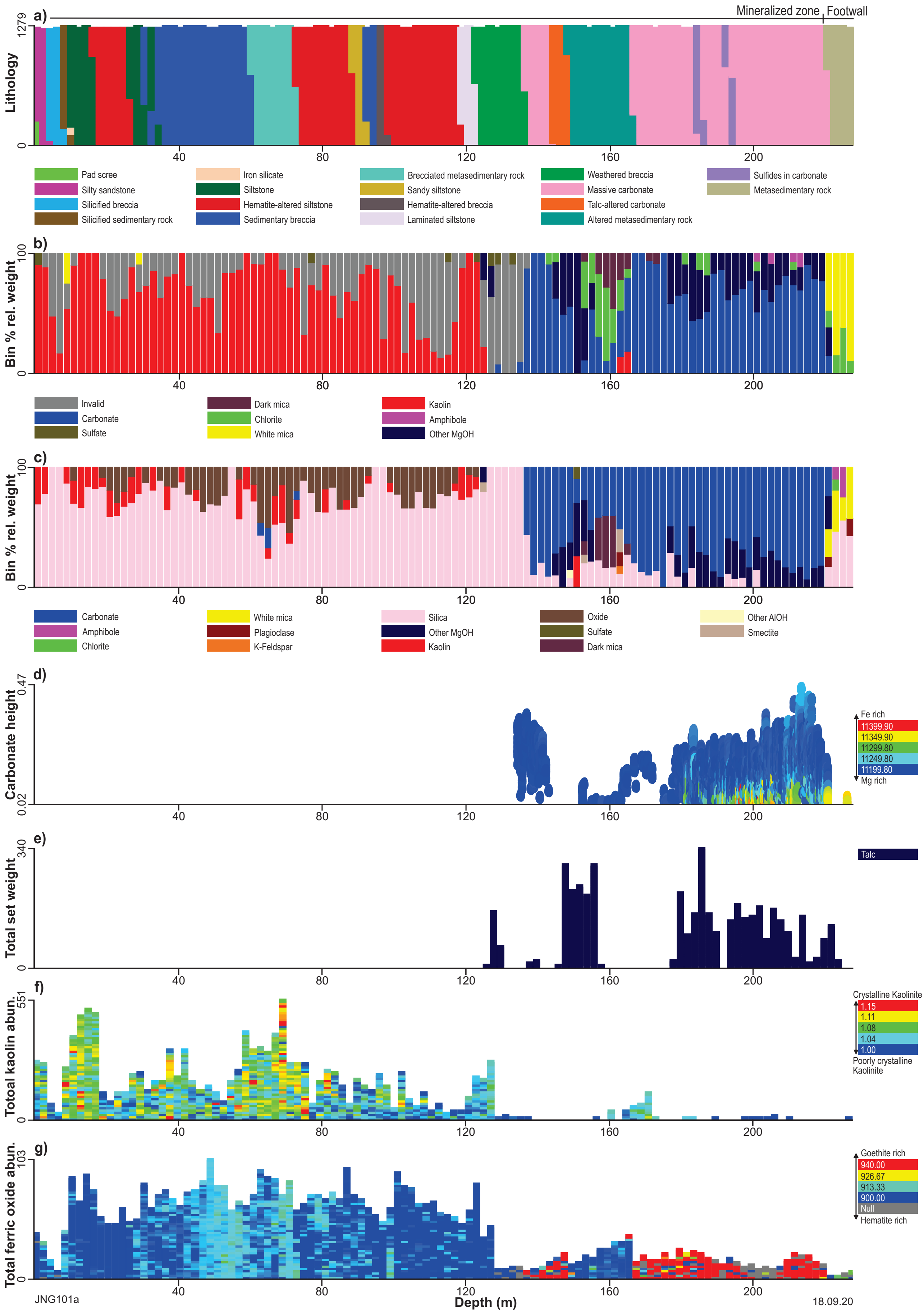

Figure 9. Downhole plots exported from TSG for ARMCDD001: a) lithology interpretation; log is split into footwall and mineralized zones; b) interpreted mineral groups from SWIR TSA data; c) interpreted mineral groups from TIR TSA data; d) carbonate abundance and composition interpreted by TIR; e) talc interpreted from TIR TSA; f) kaolinite abundance and crystallinity interpreted from SWIR spectra; g) total ferric oxide abundance diagram interpreted from VNIR spectra

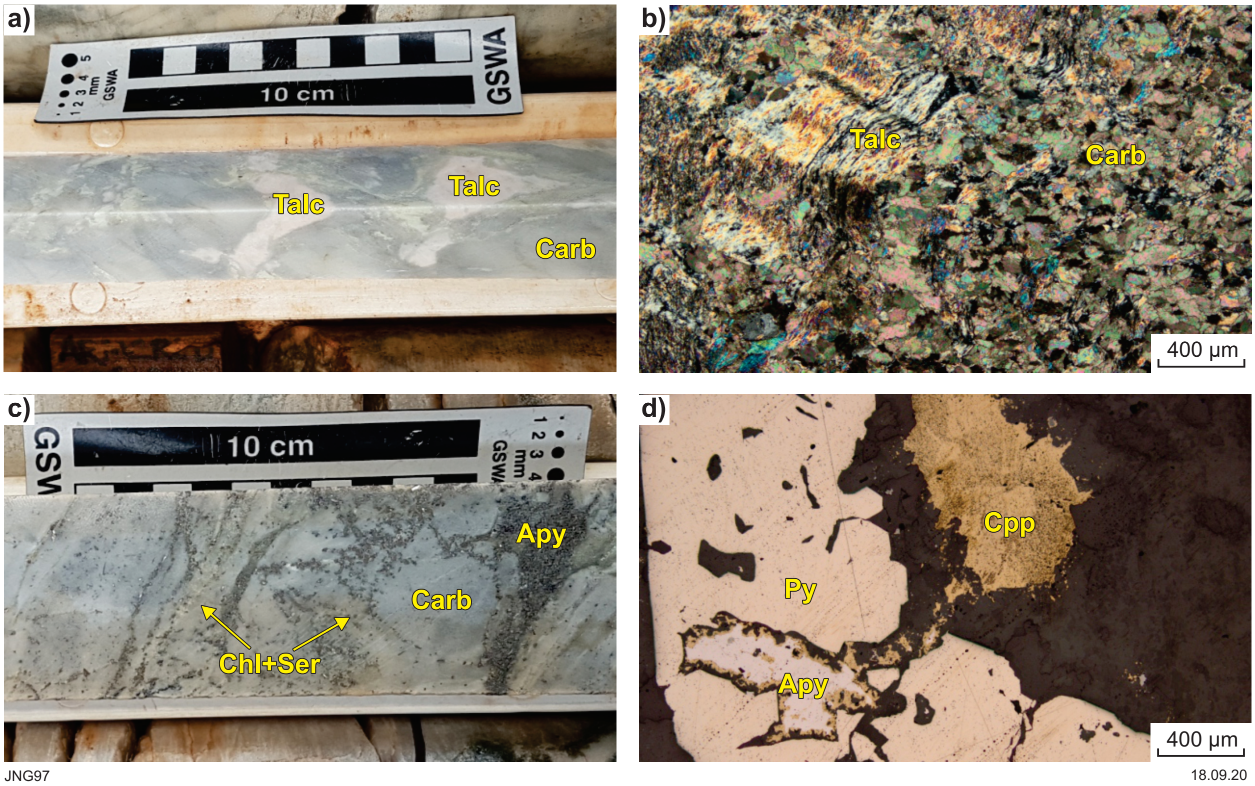

Figure 10. Drillcore photos and photomicrographs of carbonate rocks from the Mount Clement deposit: a) talc and chlorite alteration of massive carbonate, 146.2 m, ARMCDD001; b) polarized transmitted light thin section showing talc alteration of carbonate, 184.8 m, ARMCDD001; c) disseminated and veinlets of arsenopyrite in massive carbonate. Chlorite and sericite are associated with arsenopyrite (grey to green minerals), 194.8 m, ARMCDD001; d) plane-polarized reflected light photo showing skeletal pyrite (Py) with minor arsenopyrite (Apy) and chalcopyrite (Ccp). Arsenopyrite is replacing chalcopyrite, 184.8 m, ARMCDD001

A crystal-vitric tuff that sits at a similar stratigraphic position as the Mount Clement deposit was dated by the Geological Survey of Western Australia (GSWA) at 1806 ± 9 Ma (Nelson, 2004). The fact that this sample sits at a similar stratigraphic interval to Mount Clement and also records at least localized volcanic activity in the Ashburton Formation at this time leads to its interpretation as the most reliable maximum age estimate for the Mount Clement deposit.

Comparisons with different mineral systems in the Ashburton Basin

The interpreted age of c. 1806 Ma for gold–base metal mineralization at the Mount Clement deposit overlaps the 1820–1770 Ma Capricorn Orogeny (Fig. 12). During this orogenic event, two episodes of regional deformation, coinciding with low-grade metamorphism, resulted in tight to isoclinal, non-cylindrical folds and associated strike-slip faults (Thorne et al., 2016). Granitic rocks of the 1820–1770 Ma Moorarie Supersuite intruded the Ashburton Formation, coinciding with more localized volcanism that resulted in the 1799 ± 8 Ma June Hill Volcanics (Evans et al., 2003) and 1806 ± 9 Ma tuffaceous layers within the Ashburton Formation (Nelson, 2004; Thorne, 2016; Thorne and Johnson, 2017). Recently published studies on ore deposits located in the Capricorn Orogen (Fielding et al., 2017, 2019, 2020), demonstrate a co-temporal relationship between dated mineralization occurrences and regional-scale geologic events. Such events are considered to be important for controlling major episodes of mineralization because they provide the required geological processes, such as heat for fluid convection and structures for fluid pathways (e.g. Huston et al., 2016).

Interestingly, the Ashburton Basin hosts a range of mineral systems. For example, numerous small-scale orogenic gold and base metal deposits are locally present in all units of the Wyloo Group (Fig. 1). In situ U–Pb dating of xenotime linked to mineralization at the Star of the West orogenic deposit returned an age of c. 1670 Ma (Fielding et al., 2020; Fig. 1). This age is used to infer that mineralization at Star of the West, and most likely the other orogenic deposits in the Ashburton Basin (Fig. 1), is a result of intracratonic reworking during the Mangaroon Orogeny (Fig. 12; Fielding et al., 2020). In situ U–Pb dating of xenotime from the Carlin-like Mount Olympus deposit recorded the same event (Fig. 1), as well as two earlier events: a c. 1770 Ma age related to gold mineralization, and a younger c. 1730 Ma age related to hydrothermal activity (Fig. 12; Fielding et al., 2019).

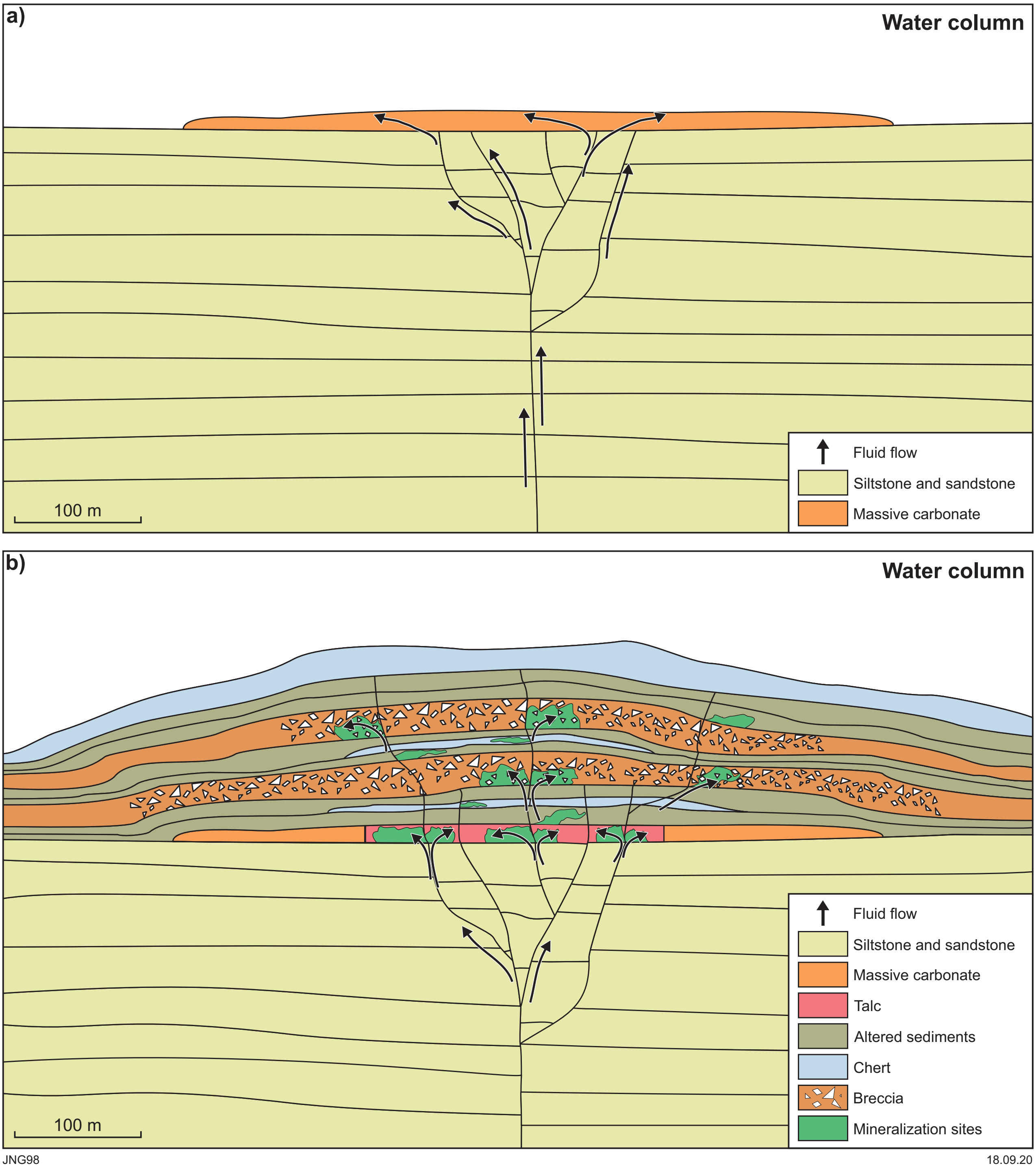

Figure 11. Simplified section showing the genesis of the Mount Clement deposit. Arrows indicate fluid flow: a) early venting of carbonate-rich fluids and deposition of massive carbonate; b) later venting of silica-rich, gold-mineralizing fluids

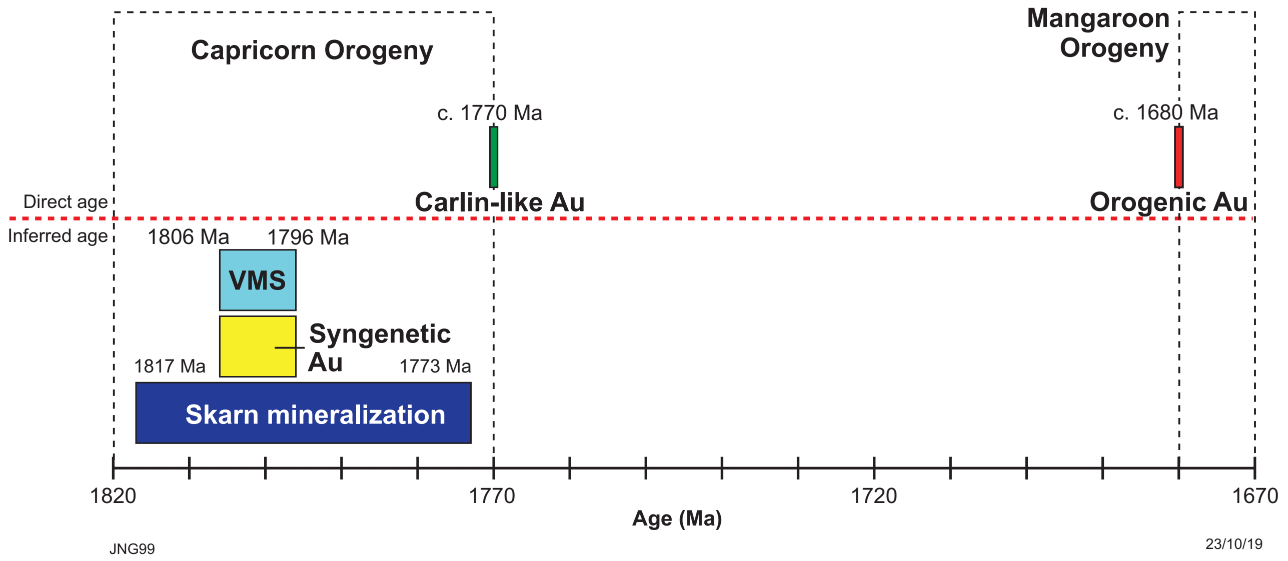

Figure 12. Time–space diagram of the Ashburton Basin and associated deposits. Deposits that have been directly dated are above the dashed red line; deposits with inferred ages are below. The Capricorn Orogeny and the start of the Mangaroon Orogeny are marked by dashed boxes

The intrusion of the Moorarie Supersuite between c. 1817 and 1773 Ma (Nelson, 1999; Wingate et al., 2014a) produced localized tungsten-skarn mineralization in the Ashburton Formation at Mount Alexander and Kilba Well (Davies, 1998; Fig. 1), while localized volcanism formed syngenetic VMS mineralization in the Ashburton Formation at Mount Stuart and Yarraloola (Doust, 1984). The timing of these mineralizing events demonstrates a general evolution from inferred early syngenetic gold and base metal deposits formed during deposition of the Ashburton Formation; skarn mineralization associated with emplacement of Moorarie Supersuite granitic rocks; and widespread structurally controlled hydrothermal events at c. 1770 and 1680 Ma associated with orogenic events and crustal reworking along existing lithospheric-scale faults (Fig. 12; Fielding et al., 2019, 2020). These temporal and spatial associations between different mineral systems have implications for regional exploration in the Ashburton Basin and suggest a range of geologic processes over a ~160 million-year interval (Fig. 12).

Mount Stuart and Yarraloola provide potential local analogues for the formation of the Mount Clement deposit (Fig. 1). Doust (1984) notes that the mineralized zone at Mount Stuart comprises varyingly iron-altered siltstone beds that enclose a number of stratiform chert and banded iron-formation layers. The siltstone beds contain boxwork textures after disseminated pyrite. Yarraloola has a similar mineralized zone, with sericite-, chlorite-, and carbonate-altered shales underlying an alternating sequence of mineralized shales, mineralized siliceous units, and massive sulfide beds. The mineralized zones at both these deposits are similar to Mount Clement (Fig. 5a). The coincidence of volcanic activity is an important process for both VMS and epithermal-like hot spring deposits. Hronsky (2000) used regional aeromagnetic data to interpret plutons at depth below Mount Clement as the potential driver of mineralization. The interpreted age for Mount Clement also coincides with local volcanic events, including intrusion of the 1820–1770 Ma Moorarie Supersuite into the Ashburton Formation, the 1799 ± 8 Ma June Hill Volcanics (Evans et al., 2003) and 1806 ± 9 Ma tuffaceous layers within the Ashburton Formation (Nelson, 2004; Thorne, 2016; Thorne and Johnson, 2017).

Exploration potential

Despite being noted as a highly prospective terrane for mineral exploration, the Capricorn Orogen has few major discoveries (Johnson et al., 2013). The Ashburton Basin itself has only one major gold deposit discovery: the >1Moz Mount Olympus Au deposit. The reason for the apparent absence of large economic deposits in the Ashburton Basin is unknown, and may simply be due to a lack of exploration. Recent studies in the Ashburton Basin have focused on orogenic and Carlin-like deposits, with syngenetic deposits largely ignored. For orogenic and Carlin-like deposits, exploration is best suited towards areas surrounding major crustal-scale faults, with multiple mineralizing events likely responsible for gradually upgrading gold grades (Fielding et al., 2020).

Other than orogenic and Carlin-type gold, most deposits in the Ashburton Basin are associated with localized volcanism and intrusion of the Moorarie Supersuite granitic rocks. Even at Mount Clement, Hronsky (2000) indicated plutons at depth as the potential driver of mineralization. Further exploration for syngenetic deposits in the Ashburton Basin would be best focused proximal to volcanic centres and plutons. As hydrothermal deposits are typically known to form in clusters, initial exploration would be best targeted at the Mount Clement, Mount Stuart, and Yarraloola regions.

Globally, syngenetic gold deposits have been identified in a number of important gold provinces. Emsbo et al. (1999) outlined evidence for syngenetic gold deposits in the Carlin trend, typically in the form of SEDEX deposits, and their importance in providing initial gold concentrations that were upgraded during Carlin-style mineralization. Similar observations have also been made for hydrothermal vent deposits in northwest Sichuan in China (Gu et al., 2002). Wood and Large (2007) outlined syngenetic hydrothermal vents enriching gold in pyrite in marine black mudstone and chert in western Victoria, outlining a potential metamorphic source for hydrothermal fluids.

Conclusions

The Mount Clement Au–Ag–Cu deposit is interpreted to be a syngenetic hydrothermal exhalative deposit, similar to subaqueous hot spring Au–Ag deposits that were first identified and documented in the Eskay Creek area of British Colombia (Alldrick, 1995). This interpretation is based on: i) the stratabound nature of the deposit, including stratabound breccias and chemical sedimentary rocks; ii) the stratabound nature of mineralization; iii) the abundance of elements that are known to be enriched in epithermal deposits (Ag, As, Au, Cu, Hg, Pb, Sb, U, W, Zn); iv) sericite and chlorite alteration haloes that demonstrate hydrothermal alteration indicative of VMS systems; and v) the lack of a major fault or shear zone controlling mineralization.

The Mount Clement deposit most likely has a mineralization age of c. 1806 Ma based on an existing date for a crystal-vitric tuff that sits at a similar stratigraphic position to the deposit. This interpreted mineralization age has a similar timing to the age of the Ashburton Formation (2008–1796 Ma), the intrusion of the Moorarie Supersuite (1817–1773 Ma); and the age of the Capricorn Orogeny (1820–1770 Ma). The Ashburton Basin in the Capricorn Orogen hosts a range of mineral systems that evolved through time from syngenetic gold and base metal deposits; to W-rich skarn mineralization associated with the emplacement of Moorarie Supersuite granitic rocks; to several episodes of gold mineralization associated with regional deformation events (e.g. Mount Olympus).

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This study evaluates the stratigraphy, style of mineralization, and the alteration mineralogy of the Mount Clement gold–silver–copper deposit in the Paleoproterozoic Ashburton Basin in the northern Capricorn Orogen of Western Australia.

The Mount Clement deposit is interpreted to be a syngenetic hydrothermal exhalative deposit, similar to subaqueous hot spring Au–Ag deposits that were first documented in the Eskay Creek area of British Colombia. This interpretation is based on:
i) the stratabound nature of the deposit; ii) the abundance of elements that are known to be enriched in epithermal deposits; and iii) sericite and chlorite alteration haloes that demonstrate hydrothermal alteration indicative of VMS systems.

The Mount Clement deposit most likely has a mineralization age of c. 1806 Ma based on an existing date for a crystal-vitric tuff that sits at a similar stratigraphic position to the deposit. This interpreted mineralization age overlaps the age of the Ashburton Formation (2008–1796 Ma), the intrusion of the Moorarie Supersuite (1817–1773 Ma), and the Capricorn Orogeny (1820–1770 Ma). The Ashburton Basin hosts several other deposits including VMS, Carlin-like and orogenic gold, and W-skarn mineralization. Some of these deposits are coeval and probably genetically associated with the Capricorn Orogeny.

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