The genesis of Carlow Castle: A unique Australian orogenic Cu-Co-Au deposit in the Archean Pilbara Craton

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SUMMARY

Carlow Castle is a Cu-Co-Au deposit situated within the western Pilbara Craton of Western Australia. Whilst Carlow Castle is the oldest discovered copper deposit in the Pilbara region, having been initially discovered in 1882, no detailed study of the ore mineralisation has ever been undertaken. After being long abandoned, a recent drilling campaign through 2018 uncovered an economically significant and geologically complex system of Cu-Co-Au mineralisation with a current resource estimate for Carlow Castle of 7.7Mt @ 1.06g/t Au, 0.51% Cu, and 0.08% Co, making it one of Australia's most significant Cu-Co-Au deposits. This mineralisation was analysed using a variety of geochemical and mineralogical techniques in order to provide the first constraint on its genesis. This analysis suggests that Carlow Castle is a hydrothermal Cu-Co-Au deposit, with mineralisation hosted in sulphide-rich quartz veins throughout a pervasively chloritised shear zone in an Archaean mafic volcano-sedimentary sequence. Within these ore veins, the sulphide mineralogy is dominated by pyrite (FeS2), chalcopyrite (CuFeS2), chalcocite (Cu2S), and cobaltite (CoAsS). Here we present the findings of the first detailed study on the nature of the Cu-Co-Au mineralisation at Carlow Castle and propose an orogenic model for the genesis of this unique deposit. It is proposed that the orogenic event that gave rise to Carlow Castle is related to the initial assembly of the Pilbara Craton during the Archean.

Key words: Battery metals, orogenic gold, hydrothermal, ore deposits, cobaltite

INTRODUCTION

The Carlow Castle Cu-Co-Au deposit occurs in the West Pilbara region of Western Australia, ~10 km SW of Roebourne, ~25 km SE of Karratha, and ~1500 km NE of Perth. The present JORC (2012) compliant resource for Carlow Castle is 7.7 Mt @ 1.06 g/t Au, 0.08% Co, and 0.51% Cu (Artemis Resources Limited, 2019); making this one of Australia's most significant Cu-Co-Au deposits (Britt et al., 2017). This follows major exploration and drilling campaigns by Artemis Resources through 2017 and 2018 resulting in the discovery of this resource proximal to the previously abandoned Carlow Castle Cu mine. Here it is proposed that Carlow Castle's genesis most closely matches the conventional genetic model for an orogenic Au deposit, however its particularly cobaltiferous ore mineralisation makes it unique among orogenic Au deposits, which are not commonly observed to be strongly enriched in Co (Groves et al., 1998). This is topical given the present broad interest in Co as a critical battery metal and the increasing drive for Co exploration to ensure security of supply as the adoption of electric vehicles increases and renewable energy storage becomes of greater importance to the global energy industry (Olivetti et al., 2017). The necessity to better understand the genesis of Co mineralisation is additionally compounded by existing risks in the supply security of Co pertaining to the fact that >50% of Co is presently sourced from the Democratic Republic of Congo (US Geological Survey, 2018). Given the economic significance of this deposit, the current broad interest in Co deposits, the recency of this discovery, its unique Cu-Co enrichment, and the lack of any existing literature on this deposit this study introduces this unique class of Co-rich orogenic Au deposits with insights into the genesis of Carlow Castle specifically. It is anticipated that by providing insights into the unique combination of processes required to form Co-rich orogenic Au deposits, and determining how these differ from conventional orogenic Au genetic models, that exploration for these deposits can be enhanced.

GEOLOGICAL BACKGROUND

The Pilbara Craton is an Archaean craton that covers ~400,000 km^2 in the northwest region of Western Australia and is divided broadly into the Archean North Pilbara granite-greenstone terrain (3.6-2.8 Ga) and the overlying Mount Bruce Supergroup of Archaean to Paleoproterozoic age (2.77-2.3 Ga), which primarily occurs along the southern edge of the craton within the Hammersley and Fortescue Basins (Ruddock, 1999; Smithies et al., 1999; Van Kranendonk et al., 2002). Carlow Castle is hosted in a volcano-sedimentary sequence within the West Pilbara Superterrane of the northwest Pilbara Craton (Hickman, 2016). This volcano-sedimentary sequence is denoted as the Ruth Well Formation; forming part of the Roebourne Group, which is in turn a component of the Karratha Terrane (Hickman, 2016; Ruddock, 1999). Within the Ruth Well Formation, the mineralisation at Carlow Castle occurs proximal to the Regal Thrust; a regionally significant thrust fault that is interpreted to have formed immediately before or during the original formation of the West Pilbara Superterrane (3.16-3.07 a)

(Hickman, 2016; Van Kranendonk et al., 2007). This may have coincided with the Prinsep Orogeny, where obduction of the Regal Formation onto the Karratha Terrane formed the Regal Terrane and the continued convergence of the Regal Karratha, Regal, and Sholl terranes caused their amalgamation into the West Pilbara Superterrane (Hickman, 2016). This was followed by the collision of the West Pilbara Superterrane and the East Pilbara Terrane from ~3.068-3.066 Ga (Hickman, 2016).

CU-CO-AU MINERALISATION

Style of Mineralisation

The mineralisation at Carlow Castle deposit is hosted in a heavily altered dominantly mafic volcano-sedimentary sequence, within the Ruth Well Formation (Ruddock, 1999). With this considered, it is often difficult to constrain the primary lithology within which Carlow Castle's mineralisation is hosted due to extensive hydrothermal alteration that has produced a pervasively chloritised and silicified host lithology. However, based on previous studies of the Ruth Well Formation, it is likely that this host lithology was dominated by a volcanic sequence of mafic to ultramafic rocks with minor chert and carbonaceous shale beds (Hickman, 2016; Ruddock, 1999; Van Kranendonk et al., 2006). Within the Ruth Well Formation, the Co-Cu-Au mineralisation typically occurs within 100 m of the surface and this mineralisation occurs broadly in two styles. The first, and most significant, style of mineralisation is structurally-hosted, where mineralisation occurs in quartz-carbonate and sulphide veins through brecciated and sheared basalt. The second style of mineralisation occurs near to the surface, overlying the structurally-hosted sulphide mineralisation, as an oxidised supergene layer. Within this oxidised layer, there is partial to complete replacement of the original sulphide mineralisation with secondary Cu-oxide and carbonate minerals.

Structure and Extent

Carlow Castle occurs within a heavily tectonised zone through the Ruth Well Formation, proximal to the regionally significant Regal Thrust. Reflecting this, the Ruth Well Formation at Carlow Castle hosts evidence of several generations of deformation. Brittle deformation is intense through portions of Carlow Castle, where the Ruth Well Formation proximal to the ore zone is heavily brecciated and this brecciation forms a network of quartz infilled fractures. In addition to these brittle structures, there is also extensive evidence of ductile deformation at Carlow Castle, where quartz and sulphide veins throughout the Ruth Well Formation in portions of the ore zone are heavily sheared and folded. These brittle and ductile structures at Carlow Castle are both observed to host mineralisation, which occurs infilling these structures as networks of quartz-sulphide veins. The formation of these structures was clearly critical to the genesis of this mineralisation as they provided permeable structures to allow Carlow Castle to act as a regional focus for migrating mineralising fluids. This includes those that may have flowed along the proximal Regal Thrust, which is strongly associated with gold mineralisation more broadly (Hickman, 2016).

Mineralogy

The structurally-hosted mineralisation at Carlow Castle occurs broadly in two sulphide-dominated mineral assemblages. The first of these is a chalcocite-cobaltite-gold assemblage, whilst the second is composed predominantly of a pyrite-chalcopyrite assemblage. In addition to these minerals, other minerals are observed to occur in these assemblages in minor or trace volumes. These mineral assemblages are summarised in Table 1.

Table 1. Summary of two distinct ore mineral assemblages that occur through Carlow Castle Cu-Co-Au deposit.

	Mineral Assemblage One	Mineral Assemblage Two
Cu	Chalcocite (Cu_2S), ±Chalcopyrite ($CuFeS_2$)	Chalcopyrite, ±Chalcocite
Co	Cobaltite (CoAsS)	± Cobaltite
Au	Gold (Au)	± Gold
Other	±Pyrite (FeS_2), ±Uraninite (UO_2)	Pyrite, ±Tellurobismuthite (Bi_2Te_3), ±Hessite (Ag_2Te)

The two mineral assemblages appear to occur independently of one another; they do not appear to reflect a broad scale mineralogical or geochemical zonation within the ore body at Carlow Castle. With this considered, Assemblage Two forms the majority of the structurally-hosted sulphide mineralisation throughout Carlow Castle, whilst Assemblage One occurs primarily in vein networks that are limited to the particularly Cu-, Co-, Au-rich portions of Carlow Castle.

Petrographic analysis of the sulphide mineralisation within the Carlow Castle ore body provide insights into the genesis of this mineralisation. Within Assemblage One (Figure 1) the dominant sulphide minerals are chalcocite and cobaltite, occurring in varying amounts from almost entirely cobaltite to almost entirely chalcocite. Generally, within these veins cobaltite occurs as aggregates of euhedral-subhedral crystals hosted in a mix of quartz and siderite. Networks of thin chalcocite veinlets commonly occur through these cobaltite-rich veins, typically surrounding cobaltite grains and filling in networks within these larger quartz-carbonate veins. Notably, there is a clear genetic relationship, within this assemblage, between cobaltite and gold mineralisation as the native gold is observed to occur virtually exclusively as inclusions within grains of cobaltite. Additionally, trace inclusions of chalcopyrite and uraninite are also observed within these grains of cobaltite. Finally, it is interesting to note that pyrite, when it does occur within this assemblage, is commonly observed to be partially replaced by chalcocite; where chalcocite surrounds pyrite and occurs as penetrating lamellae throughout.

Assemblage Two (Figure 2) is defined by an intergrown assemblage that is composed primarily of chalcopyrite and pyrite. Where this assemblage occurs in in quartz-carbonate veins, pyrite and chalcopyrite tend to be anhedral and form stringy veinlet networks infilling space between quartz. These veinlet network of chalcopyrite and pyrite are occasionally associated with blocky grains of euhedral to subhedral cobaltite. Assemblage Two also occurs in particularly sulphide-rich veins where gangue quartz-carbonate is limited and instead the chalcopyrite and pyrite compose virtually all of these veins, here these sulphides are massive with intergrown anhedral pyrite and chalcopyrite but are commonly also intergrown with chlorite from the pervasively altered host rock. Interestingly, in massively textured samples of Assemblage Two cobaltite is less common in comparison to the more quartz-rich veinlet textured samples. Further within assemblage Two, gold is notably less common in general in comparison to Assemblage One. However, gold does occur within Assemblage One in trace quantities and it is commonly associated with chalcopyrite. Finally, there is a clear association between the tellurides hessite and tellurobismuthite and pyrite as these tellurides occur exclusively as inclusions within pyrite.

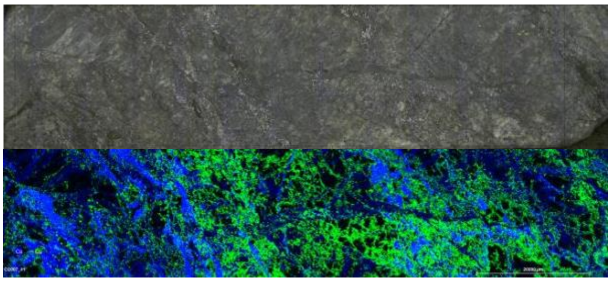

Figure 1. Mosaic and XRF map of veined chalcocite and cobaltite-rich Assemblage One. Note here that on the XRF map green corresponds to Cu and blue corresponds to Co. This sample is ~22 cm long.

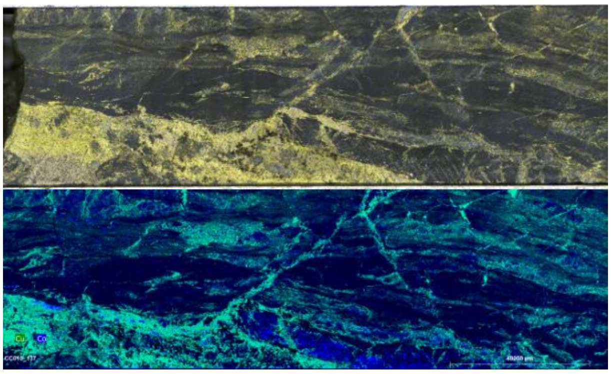

Figure 2. Mosaic and XRF map of veined chalcopyrite and pyrite-rich Assemblage Two with minor cobaltite. Note that on the XRF map green corresponds to Cu and blue corresponds to Co. This sample is ~20 cm long.

Geochemistry

Strong enrichments are observed in Cu, Co, Au at Carlow Castle. Several interesting relationship are observed between elements within the ore body; most notably correlation coefficients of 1.00 for Co:As, 0.95 for Ag:Cu, 0.83 for Au:Co, 0.69 for Au:Cu, 0.61 for Cu:Co. The perfect positive correlation between Co and As confirms mineralogical observations that all of the Co within the deposit is hosted in cobaltite. Additionally, the strong positive correlation between Au and Co provides additional geochemical evidence of the previously mentioned genetic relationship between Co and Au mineralisation observed in Assemblage One. Conversely, the comparably less strong positive correlation between Co and Cu suggests that these two metals do not always occur in association, as has been observed mineralogically above.

GENESIS

As no detailed study of Carlow Castle has previously been conducted, very little beyond superficial ideas regarding the metallogeny of this deposit exist (Hickman, 2016; Ruddock, 1999). With this considered, the interpretation proposed here is that Carlow Castle represents an orogenic hydrothermal Cu-Co-Au deposit, this is congruent with suggestions regarding Carlow Castle's genesis posited by Ruddock (1999) and Hickman (2016) based on broad-scale observations. This is proposed due to the fact that Carlow Castle exhibits several geological characteristics that are typical of orogenic gold deposits. On a broad scale, the first of these characteristics is Carlow Castle's regional situation in an Archaean greenstone belt and, on a smaller scale, within a rift-related volcano-sedimentary succession (Groves et al., 1998; Hickman, 2016; Van Kranendonk et al., 2010). Additionally, the occurrence of Carlow Castle within the West Pilbara Superterrane, a collisional accretionary superterrane that formed at ~3.068 Ga during the Prinsep Orogeny (Hickman, 2016), provides a classic tectonic setting for an orogenic gold system (Goldfarb et al., 2001; Groves et al., 1998). On a deposit scale, the strong structural control on mineralisation, occurrence through a heavily tectonised zone proximal to the regionally significant Regal Thrust fault, pervasive quartz-carbonate veining, extensive chloritic hydrothermal alteration, and the otherwise clear hydrothermal origin of Carlow Castle are similarly typical of orogenic mineral systems (Goldfarb et al., 2001; Groves et al., 1998; Saunders et al., 2014).

As Carlow Castle has been classified here as an orogenic Cu-Co-Au deposit, its genesis is most likely inextricably linked to the ~3.068 Ga Prinsep Orogeny during the amalgamation of the Karratha, Regal, and Sholl Terranes into the West Pilbara Superterrane and the subsequent convergence of the West Pilbara Superterrane and the East Pilbara Terrane (Hickman, 2016; Van Kranendonk et al., 2007). Given its close proximity to the Regal Thrust, which is believed to have formed during the Prinsep Orogeny or the prior convergent 'Karratha Event' around ~3.16 Ga (Hickman, 2004; Van Kranendonk et al., 2010), the formation of this thrust and the associated tetanisation at Carlow Castle was key to the genesis of the Cu-Co-Au mineralisation. This is because although the timing of the mineralisation at Carlow Castle is not yet constrained relative to these tectonic events and the formation of the Regal Thrust, the Regal Thrust and the tectonised zone at Carlow Castle were at very least key to the genesis of this mineralisation in that they provided conduits and a regional fluid focus for migrating ore fluids. Whilst the source of these fluids and their metal enrichment is not yet constrained, Hickman (2016) suggested that the proximal sediments of the Nickol River Formation may have provided a source of gold due to the deposition of detrital gold into these sediments; shed from eroded gold deposits in the East Pilbara Terrane. However, there is no strong evidence to directly support this hypothesis and further study is required to constrain the metal source for Carlow Castle. With this considered, the uniquely strong enrichment of Co and Cu in this deposit implies a unique metal source relative to other orogenic Au systems. If the formation of this mineralisation was synchronous to the Prinsep Orogeny then it is likely that this ore fluid would have been produced by metamorphic devolatilization (Cox, 2005; Tomkins, 2013). The Cu-Co-Au rich ore fluid would have been channelled through permeable structures along the Regal Thrust and focused into the brecciated and sheared zone at Carlow Castle. Once channelled into third-order structures, metal deposition would have most likely occurred due to wall rock interaction with the mafic volcanic rocks and carbonaceous shales of the Ruth Well Formation (Hickman, 2016; Morey et al., 2007; Phillips and Powell, 2010).

CONCLUSIONS

The primary significance of Carlow Castle stems from its unique Cu-Co-Au metal association and, reflective of this, its unique ore mineralogy given its interpreted genesis as an orogenic Au deposit. Given the recency of the discovery of major structurally-hosted Cu-Co-Au mineralisation at Carlow Castle (Artemis Resources Limited, 2019), the purpose of this research is to provide the first overview of the geology of Carlow Castle and nature of its mineralisation, as there is no other existing literature focused on Carlow Castle. This work is particularly topical due to the strong cobalt enrichment within Carlow Castle and the current broad interest in Co deposits due to the dramatic increase in cobalt prices through 2017 and 2018 (London Metal Exchange, 2019), driven by projections of increased demand from the battery sector due to cobalt's status as a key metal in Li-ion batteries (US Geological Survey, 2018). Because of its unique enrichment in copper and cobalt, understanding the unique combination of processes necessary to form this deposit and how they differ from the conventional model for orogenic Au deposits are of broad significance as they could assist with exploration efforts for other cobaltiferous orogenic Au deposits. This is particularly significant given the present lack of supply security for cobalt.

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