

PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE ERNEST HENRY IRON OXIDE COPPER GOLD DEPOSIT, AUSTRALIA; IMPLICATIONS FOR IOCG GENESIS

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Abstract - The ~1530 Ma Ernest Henry IOCG deposit in the Cloncurry district of the Eastern Succession of the Mount Isa Inlier is one of the largest IOCG deposits in Australia. The deposit is hosted by brecciated and strongly K feldspar altered Mount Fort Constantine metavolcanics (~1740 Ma). Ore-bearing assemblages are dominated by magnetite, chalcopyrite, pyrite, carbonate, quartz and apatite. Most gold is present as electrum, in both pyrite and chalcopyrite. At shallow levels, the ore is dominantly infill between rounded clasts of K feldspar altered metavolcanics. In this setting, ore grade is inversely correlated with breccia clast abundance, reflecting the dominance of ore minerals as infill. At greater depths however, the boundary between clasts and infill becomes diffuse, and ore minerals are not restricted to the space between clasts, but are also present within clasts, indicating that replacement was a key process of ore deposition. At these greater depths, the relationship between grade and clast abundance breaks down, also consistent with ore precipitation by replacement as well as infill. Deep in the deposit, multiple generations of breccias are present, and late "second generation breccias" are iron-rich and contain coarse rounded and corroded fragments of pyrite, chalcopyrite and magnetite in a magnetite-rich matrix. The presence of clasts of ore-related minerals suggests that a feeder zone or region of pre-enrichment exists at depth, and may have been critical in localising ore. The Ernest Henry breccia is texturally similar to some regional unmineralised hydrothermal breccias, which are interpreted to have formed by fluidisation and particle transport over hundreds to thousands of metres by high energy fluids.

Potassic alteration that forms a halo to the deposit, extends for over a kilometre beyond the ore zone. This alteration zone overprints earlier regional sodic and sodic-calcic alteration, and is in turn overprinted by brecciation and copper-gold mineralisation. In addition to K, relative to the host rocks, the deposit is enriched in Ba, Mn, Cu, Au, Fe, Mo, U, Sb, W, Sn, Bi, Ag, F, REE, S, As, Co and Ca. Several lines of evidence, including C, O, and S isotopes, fluid inclusion halogen ratios and fluid inclusion Ar isotope ratios, are consistent with involvement of both magmatic and basinal fluid in the transport and precipitation of these elements. Fluid inclusions indicate that both hypersaline brines (~35 to 70 wt.% NaCl_{equiv}) and CO₂-rich fluids were abundant, although the role of each in the transport of ore-related elements is not clear. The deposit-wide correlation between copper and gold suggest that both travelled in the same fluid.

Pyrite at Ernest Henry is strongly zoned, with arsenic, nickel and cobalt all ranging from a few hundred ppm to a few wt.% within individual grains of pyrite. Such pyrite compositions are not unusual relative to other IOCG deposits or weakly mineralised IOCG-like magnetite-matrix hydrothermal breccias in the Eastern Succession. On the other hand, with up to 1 wt.% Mn, Ernest Henry magnetite is the most manganese-enriched hydrothermal magnetite identified in the Cloncurry region. Mn/Ti ratios in Ernest Henry and several other regional IOCG deposits are consistently greater than those in unmineralised IOCG-like magnetite-matrix breccias from the Eastern Succession. Apatite at Ernest Henry is unusually fluorine and arsenic-rich, and is zoned with variable concentrations of arsenic and sulphur. Around the world, arsenic (and fluorine)-rich apatite is common in iron-manganese-rich seafloor deposits. The strong enrichments of iron within the deposit, manganese in magnetite and arsenic in apatite, may indicate interaction of hydrothermal fluids with iron-manganese-rich seafloor sediments and banded iron formations, such as those in the Overhang Jaspilite, which may be present below the deposit.

We propose that the Ernest Henry IOCG deposit formed where mafic and felsic magmas of the ~1530 Ma Naraku batholith mingled, driving volatile exsolution. Extreme fluid overpressuring resulted, confined by an impermeable carapace formed by regional sodic and sodic-calcic alteration. The eventual failure of this seal led to a high-energy fluid-flow event forming hydrothermal breccias with upwardly transported and milled clasts. Mixing of basinal and magmatic fluids accompanied ore precipitation, although the source of the metals remains unclear. In the upper portions of the deposit, most ore was precipitated as hydrothermal infill between clasts of K feldspar-altered metavolcanics. At greater depths in the orebody, interaction between fluids and rocks was more prolonged, forming both infill and replacement-style ores.

Introduction

Iron-oxide copper-gold (IOCG) deposits are a diverse ore-type whose main shared characteristic is the abundance of iron oxide in association with economic quantities of copper and gold. IOCG deposits exhibit diversity in many features such as age, host rocks, geochemical signature, alteration, mineralogy and geologic setting (Williams

et al., 2005). As such, they remain poorly understood in terms of fluid and metal sources, fluid rock interaction pathways, and the physical and chemical mechanisms of ore formation. It is likely that formation processes differ among various deposits in this ore class (Barton and Johnson, 1996; Groves *et al.*, 2010; Williams *et al.*, 2005).

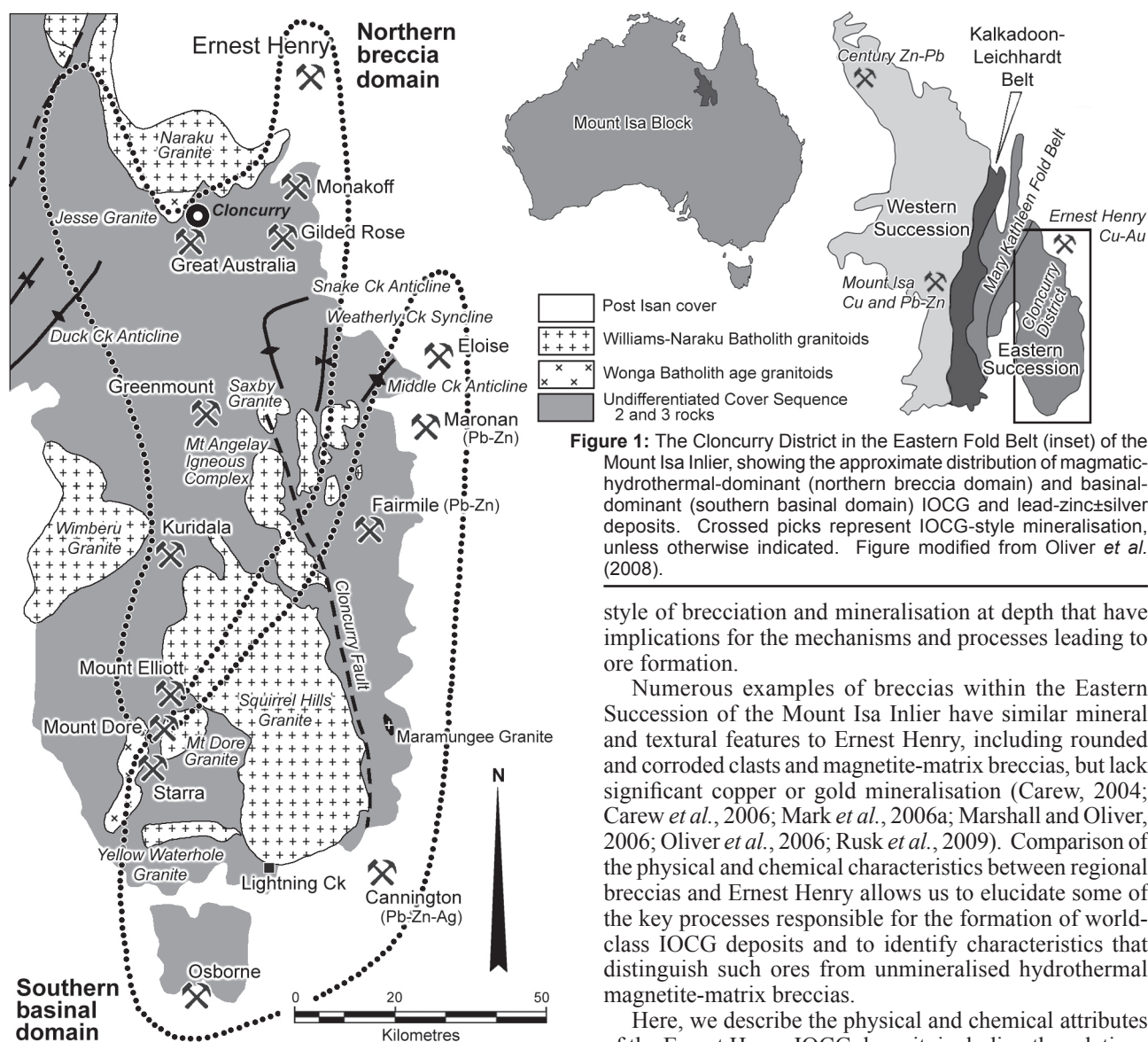


Figure 1: The Cloncurry District in the Eastern Fold Belt (inset) of the Mount Isa Inlier, showing the approximate distribution of magmatic-hydrothermal-dominant (northern breccia domain) and basinal-dominant (southern basinal domain) IOCG and lead-zinc±silver deposits. Crossed picks represent IOCG-style mineralisation, unless otherwise indicated. Figure modified from Oliver *et al.* (2008).

style of brecciation and mineralisation at depth that have implications for the mechanisms and processes leading to ore formation.

Numerous examples of breccias within the Eastern Succession of the Mount Isa Inlier have similar mineral and textural features to Ernest Henry, including rounded and corroded clasts and magnetite-matrix breccias, but lack significant copper or gold mineralisation (Carew, 2004; Carew *et al.*, 2006; Mark *et al.*, 2006a; Marshall and Oliver, 2006; Oliver *et al.*, 2006; Rusk *et al.*, 2009). Comparison of the physical and chemical characteristics between regional breccias and Ernest Henry allows us to elucidate some of the key processes responsible for the formation of world-class IOCG deposits and to identify characteristics that distinguish such ores from unmineralised hydrothermal magnetite-matrix breccias.

Here, we describe the physical and chemical attributes of the Ernest Henry IOCG deposit, including the relations between brecciation and distribution of ore-related minerals. We compare the physical and chemical characteristics of Ernest Henry to regional Cloncurry IOCG deposits including Osborne, Eloise, Mt. Elliot and SWAN, and to several unmineralised or weakly mineralised magnetite-matrix breccias in the region, many of which bear numerous characteristics similar to IOCG deposits, but contain little copper or gold. We interpret the physical and chemical characteristics in light of the geologic processes that led to the formation of this world-class ore body and then propose a model for the genesis of Ernest Henry with applications to both ore genesis and exploration.

Regional Geology

Tectonic and Metallogenic Setting

The Palaeo- to Mesoproterozoic Mount Isa Block is divided into the Western Succession, the Kalkadoon-Leichhardt belt and the Eastern Succession by various authors (Blake, 1987; Fig. 1). Although there is considerable debate, sedimentary-volcanic deposition, igneous intrusive activity and deformation/metamorphism are generally considered to have occurred on a rifted continental margin, giving primarily intra-cratonic geochemical signals to most rock packages. Betts *et al.* (2006; 2007) argue that the ~1650 to 1590 Ma lead-zinc deposits of the Mount Isa Western Succession formed in a 'far-field back-arc' tectonic setting.

Two general styles of IOCG deposit are present in the Cloncurry District of northwestern Queensland, the (1) Osborne and (2) Ernest Henry types. These types are distinguished from each other on the basis of geochronology, structural association, metal-oxide and sulphide distributions, and radiogenic and stable isotope signals (Fisher and Kendrick, 2008; Kendrick *et al.*, 2007; Mark *et al.*, 2004a; 2005; Oliver *et al.*, 2008; Williams and Pollard, 2001). One of the key physical distinctions is that those of the Ernest Henry style are hosted in breccia pipes containing distinctly rounded and/or corroded clasts, whereas the Osborne type are more commonly associated with shear zones (Gauthier *et al.*, 2001; Mark *et al.*, 2006b; Oliver *et al.*, 2008; Rubenach *et al.*, 2008). In this paper, we focus on the breccia-hosted magmatic-hydrothermal variety (Ernest Henry type), as opposed to the earlier basinal or regional metamorphic variety (Osborne type).

The Ernest Henry deposit had a total pre-mining resource of 226 Mt @ 1.10% Cu and 0.51 g/t Au (Xstrata, 2009). Copper and gold mineralisation is hosted predominantly in a breccia body dominated by strongly K feldspar-altered clasts of metavolcanics (Mark *et al.*, 2006a). Deep drilling at Ernest Henry in the last 5 years has revealed a down-dip extension of the moderately (45°) southsoutheast-plunging orebody, which remains open at down-dip depths of greater than 1600 m. This drilling has also revealed changes in the

Oliver *et al.* (2008) interpreted the Kalkadoon-Leichhardt belt as representing the remnants of a plate boundary-proximal magmatic arc at around 1850 Ma, and that much of the subsequent history involved eastward thinning of the plate with rapid eastwards retreat of that plate boundary in the 1850 to 1600 Ma period. The extremely high iron content of many tholeiitic basalts and gabbros in the Eastern Succession was inferred to be a product of the severe thinning of the crust in the Eastern Succession from 1750 to 1650 Ma (Rubenach *et al.*, 2008). The large volume and protracted history of emplacement of iron-rich basaltic rocks (1780 to 1500 Ma), along with the preservation and reactivation of previously metasomatised mantle are likely reasons for the rich metal endowment of the Eastern Succession and probably the Inlier in general. Mafic rocks may have contributed metals and ligands directly during crystallisation and subsequently through metamorphic or hydrothermal leaching.

In the Eastern Succession, the major events relevant to understanding IOCG mineralisation (e.g. Blake, 1987; Blenkinsop *et al.*, 2008; Rubenach *et al.*, 2008; Oliver *et al.*, 2008; Foster and Austin, 2008) include:

- (1) The 1760 to 1720 Ma deposition of a widespread sequence (Cover Sequence 2) of platformal evaporitic carbonates of the Corella Formation and equivalents (with minor volcanic and clastic rocks) on a flooded earlier rift-fill sequence. The Corella Formation contains the Overhang Jaspilite, which includes BIFs as well as manganiferous sediments (Brown, 2008; Blake, 1987). The top of this sequence contains the Mount Fort Constantine Volcanics, which host the Ernest Henry orebody.
- (2) The 1710 to 1650 Ma deposition (Cover Sequence 3) of clastic sediments and basalts into a rapidly subsiding basin with depositional margins controlled by major north-south structures, forming much of the Soldiers Cap Group, exposed near and south of Ernest Henry and forming the broader hanging wall to the deposit.
- (3) The emplacement of a range of widespread granites, gabbros and rare diorites (e.g., 1740 Ma Wonga batholith, 1650 Ma Ernest Henry Diorite; Pollard

and McNaughton, 1997) into these sequences prior to regional metamorphism and deformation, causing circulation of basinal and magmatic-hydrothermal fluids at and below the surface, and producing the 1740 Ma uraniferous skarns hosting the Mary Kathleen uranium deposit, lead-zinc-silver mineralisation at Cannington (~1670 Ma) and possibly the first phase of IOCG development at Osborne and elsewhere (?1650 to 1590 Ma; Oliver *et al.*, 2008).

- (4) The ~1600 to 1500 Ma Isan Orogeny, with a greenschist to upper amphibolite peak at 1600 to 1580 Ma (D_2) involving positive reactivation of basin-bounding structures, and several retrograde deformations (D_3 , D_4).
- (5) The emplacement of the Williams-Naraku batholiths at 1550 to 1500 Ma, partly controlled by early-formed structures. This batholithic complex contains I- to A-type granites and widespread tholeiitic gabbros, commonly mingled and locally mixed together. Magma emplacement and mingling are interpreted to have driven the release and circulation of voluminous magmatic-hydrothermal and basinal fluids, resulting in widespread alkali metasomatism, particularly around some IOCG ore deposits, including Ernest Henry (Cleverley and Oliver, 2005; Mark *et al.*, 2006a, 2006b; Williams and Pollard, 2001; Mark and Foster, 2000).

Both regionally and locally at Ernest Henry, zones of local deformation accompany granite emplacement during D_3 at around 1530 to 1520 Ma. This resulted in: (1) anastomosing shear zones with widths from a few to ~500 m and strike lengths of up to 50 km, (2) zones of locally intense veining, and (3) both focused and broad zones of hydrothermal brecciation (Marshall and Oliver, 2006). At Ernest Henry and Mt Elliott, the ore-related veins or breccias are nested within albite-altered ductile shear zones, with veins and breccias developed synchronously and/or later than the shearing. It is likely that the local zones of deformation at Ernest Henry and other IOCG deposits relate to long-lived structures that may have formed as early as during Cover Sequence 3 deposition, and have been reactivated and mineralised during the Isan orogeny (Blenkinsop *et al.*, 2008).

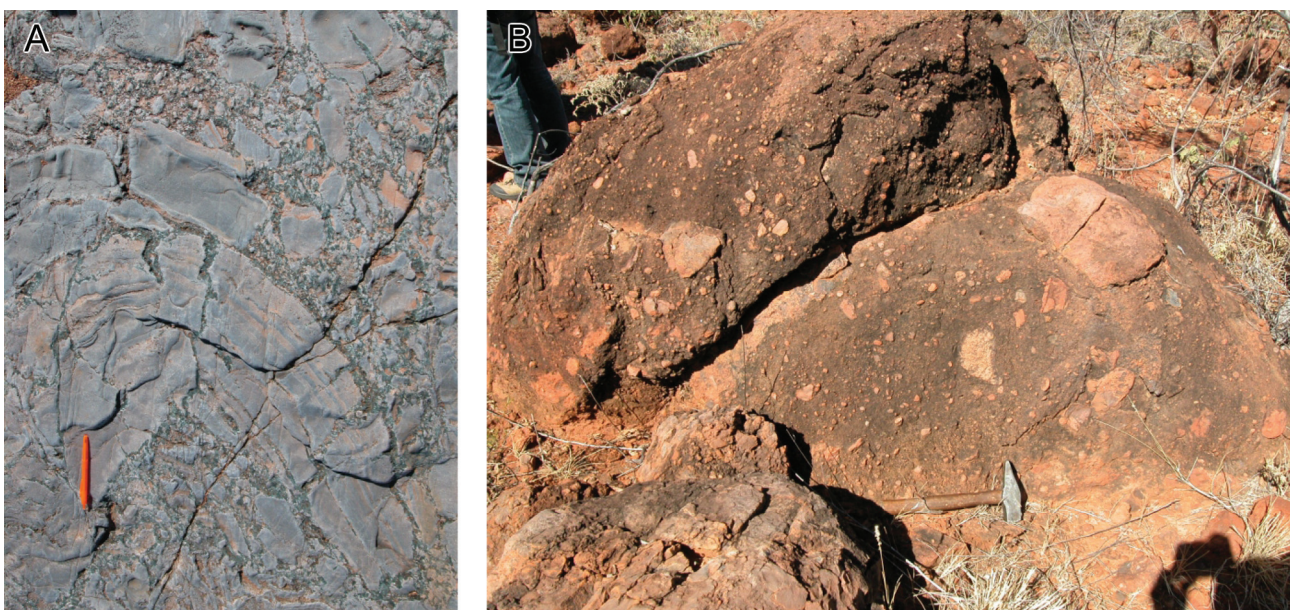
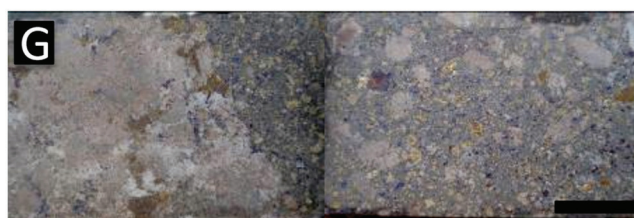
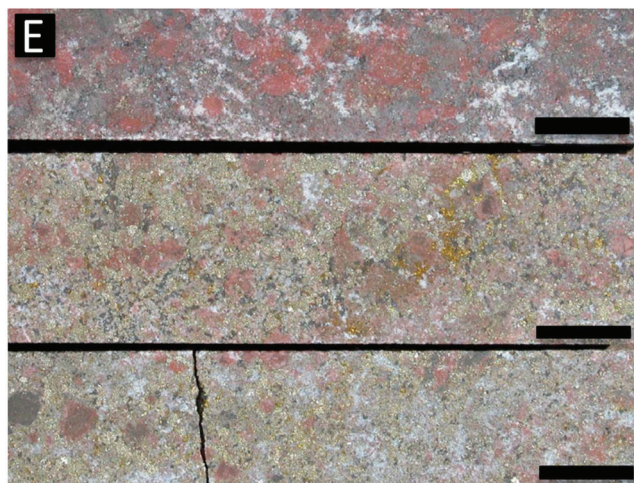
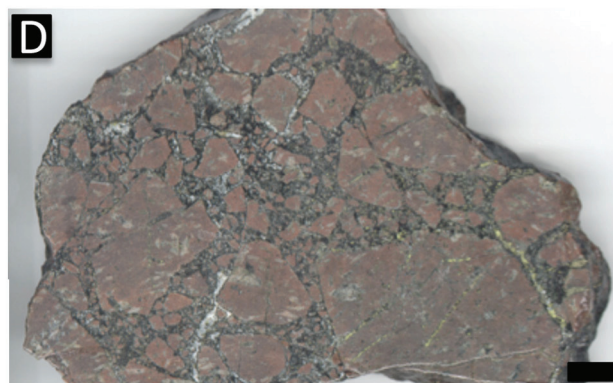
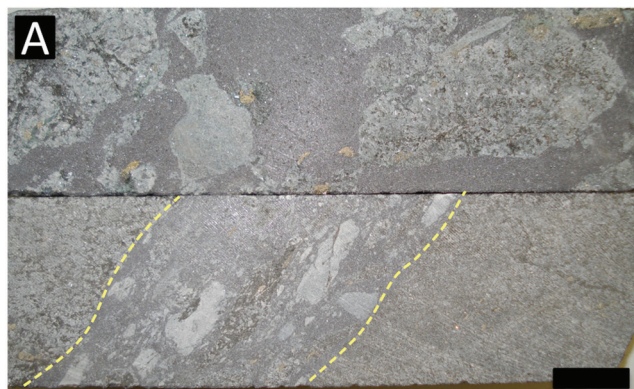


Figure 2: **A** - Classic type I Corella Breccia from Roxmere waterhole, 20 km south of Cloncurry in the Snake Creek Anticline. The outer arc extension fractures and axial planar orientation of the breccia veins suggests a link between folding and brecciation. The irregular margins of the clasts demonstrate that solution, as well as fracturing, has been a significant process. **B** - A classic type II breccia from the western Snake Creek area. Clasts with hematite-stained albite are rounded, polymictic, variably sized, and set in a matrix of infill (actinolite mostly) and micro-clasts (albitic also).



Mineralisation in the Eastern Succession

The Eastern Succession hosts a large number and diverse range of ore deposits (Williams, 1998; Williams *et al.*, 2005; Williams and Skirrow, 2000). For simplicity, these can be grouped into: (1) early skarn and mineralisation (gold, uranium ?) related to emplacement of the 1740 Ma Wonga batholith, mostly in the Mary Kathleen Fold Belt (Oliver *et al.*, 1999), (2) "basinal" to early metamorphic lead-zinc and IOCG deposits (1670 to 1590 Ma), including the Cannington lead-zinc-silver (Bodon, 1998) and Osborne copper-gold (Oliver *et al.*, 2008) ores, produced by surface exhalation, diagenesis, and/or mixing of basinal and metamorphic fluids during inversion at the start of the Isan Orogeny, and (3) fault-, shear- and breccia-related IOCG, copper±cobalt, uranium-REE, and molybdenum-rhenium deposits (Florinio and Tamal, 2009), which formed synchronously with the emplacement of the Williams-Naraku batholiths, with some involvement of magmatic-hydrothermal fluids (Williams, 1998; Williams *et al.*, 2005).

Early sodic- and sodic-calcic-alteration affected a region of more than several hundred km² (de Jong and Williams, 1995). This type of alteration is common throughout the Eastern Succession and is not limited to areas around IOCG deposits. Geochronologic and structural relations suggest the majority of the Na-Ca alteration is related to the emplacement of the 1550 to 1500 Ma Williams-Naraku batholiths (Oliver *et al.*, 2004; Perring *et al.*, 2000; Pollard, 2001), although some albitisation preceded intrusion and was probably related to circulation of basinal brines during early basin inversion and metamorphism (Rubenach, 2005; Rubenach *et al.*, 2008).

Breccias

Breccias are common throughout the Eastern Succession and fall into two broad categories referred to as types I and II. Type I breccias are volumetrically the most significant and are "tectonic-hydrothermal" in origin. Much of the Corella Formation that is mapped as breccia (Blake, 1987) is a type I breccia. Type II breccias are of fluidised hydrothermal origin and are volumetrically minor, but are more likely to host ore deposits, based on evidence for high-energy fluid and clast transport over the scale of kilometres.

At a regional scale, many type I breccias (Fig. 2A) are associated with sodic±calcic alteration, in which any rock type in the district is replaced by albite-rich assemblages with breccia matrix (infill and micro-clasts) of calcite, actinolite, albite, clinopyroxene, epidote, hematite and magnetite (Oliver *et al.*, 2004). Most of these breccias contain angular clasts, have a high clast/matrix ratio, and are poorly sorted. Adjacent fragments are commonly rotated, but transported little. In these breccias, original sedimentary bedding is preserved within clasts, which fit together like a jigsaw puzzle if the breccia infill is removed. These

tectonic- and tectonic-hydrothermal breccias developed by: (1) cycles of fault movement and/or fluid over-pressuring and subsequent under-pressuring along faults, with clast collapse and simultaneous matrix precipitation, or (2) fracturing during multiple fold overprinting (Marshall and Oliver, 2008) and ensuing strain incompatibilities. These processes overlap because of the tendency for both faulted and multiply-folded rocks to show a high degree of structurally controlled permeability.

Type II breccias (Fig. 2B) typically form pipes or dykes that cut through bedding or other foliations. They are polymictic, poorly sorted, and show evidence of clast transport and rounding during fluidised flow. These breccias are commonly matrix supported with no continuity of original bedding. Many are dominated by magnetite infill, along with lesser carbonate, actinolite, pyrite and sometimes chalcopyrite. The composition of the rounded clasts relative to wall rock indicates particle transport on a scale of hundreds of metres to several kilometres (Oliver *et al.*, 2006). Fig. 3A for example, shows a magnetite-matrix breccia from a regional, weakly mineralised IOCG prospect that is hosted completely within a gabbro body, but wherein the clasts are dominated by albite-altered calc-silicate sediments. The closest sedimentary package from which these clasts could have originated is located several hundred metres below.

Some type II breccias form "caps" above the ~1530 to 1500 Ma Williams Granite, but extend laterally and vertically out and up into discrete breccia dykes and pipes that crosscut the overlying rocks (Bertelli and Baker, 2010). Oliver *et al.* (2006) infer that these breccias formed during high-energy fluidisation events that resemble diatreme emplacement. Type II breccias include regional brecciation such as that found at the Gilded Rose type locality, as well as similar bodies extending south from Cloncurry to the Saxby Granite (Oliver *et al.*, 2004, 2006; Bertelli, 2008; Marshall and Oliver, 2006), many regional magnetite-matrix IOCG prospects, and the brecciated host to the Ernest Henry IOCG deposit (Mark *et al.*, 2006a).

The Ernest Henry IOCG Deposit

Physical Characteristics

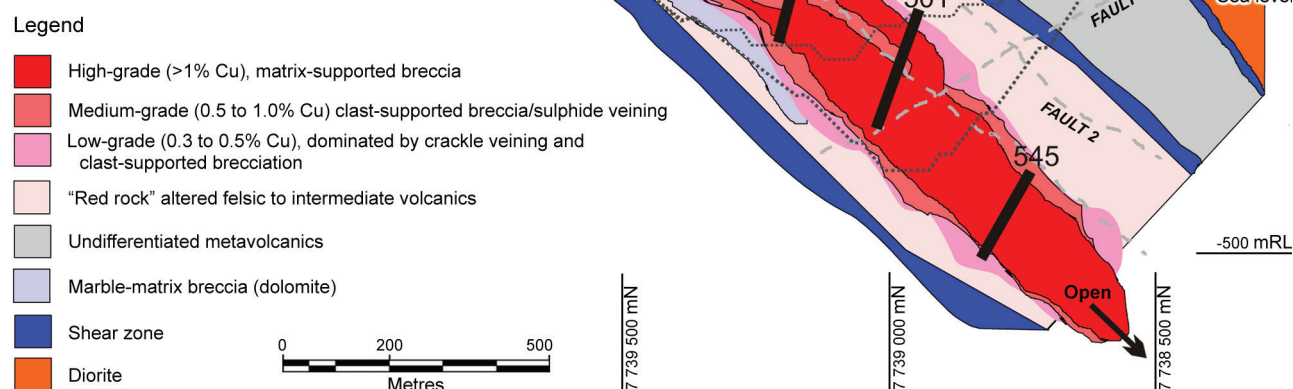
Structural Setting

The Ernest Henry IOCG deposit is hosted by a breccia body dominated by strongly K feldspar-altered clasts of the ~1740 Ma Mount Fort Constantine metavolcanics (dacite and andesite) with subordinate metabasalts and calc-silicate metasediments (Twyterould, 1997; Mark *et al.*, 2006a). The orebody lies between northeast trending shear zones. At a kilometre-scale, the Ernest Henry orebody is a breccia pipe plunging approximately 45° to the southsoutheast, nested between ductile shear zones (Fig. 4).

The main ore breccia grades upwards into the hanging wall through a narrow zone of clast-supported mosaic

Figure 3 (Facing page): **A** - Drillcore from a weakly mineralised regional IOCG prospect showing type II magnetite-rich breccias cutting gabbro. Imported clasts of albite-altered sediments are present within the host gabbro in both examples; **B** - Textures are very similar between regional unmineralised type II breccias (lower; Western Snake Creek Anticline) and the ore breccia that hosts typical Ernest Henry ore (above; upper orebody); **C** - The K feldspar-altered Mount Fort Constantine volcanics host the Ernest Henry deposit. This sample is overprinted by minor carbonate crackle veinlets; **D** - Clast-supported breccia with ore solely as infill between clasts (ROM pad sample); **E** - Several examples of matrix-supported ore (drillhole EH545); **F** - SGBX cutting previously mineralized K feldspar-altered breccia ore. The SGBX is dominated by clasts of magnetite, pyrite, chalcopyrite and K-feldspar altered volcanics (drill hole EH690); **G** - Second generation breccia (SGBX) with clasts of rounded Mt. Fort Constantine volcanics, magnetite, pyrite, and chalcopyrite. The matrix is dominated by infill of magnetite. The SGBX has a sharp contact against weakly mineralized volcanics (drillhole EH665); **H** - unusual ore texture known as "spotted dog" consisting of granoblastic magnetite, calcite, quartz, sulphides, and microclasts of K-feldspar (drillhole EH691); **I** - bands of "graded" magnetite and calcite inferred to result from density-sorting of fluidised particles. These features are most pronounced in the area where very high FeO contents are recorded in the orebody (drillhole EH691). All scale bars are two centimetres.

Figure 4: Longitudinal section through the Ernest Henry deposit, based on Xstrata company reports, Collier and Bryant (2003) and Coward (2001) (see also Marshall and Oliver, 2008). The positions of three drill holes (438, 501, 545) discussed in the text are shown.



breccia, into crackle-brecciated volcanic rocks, and then into the Hanging Wall Shear Zone (HWSZ), an approximately 100 m thick zone of heterogeneous shearing, dominated by biotite-magnetite-actinolite alteration of the Mount Fort Constantine metavolcanics. Below the HWSZ, the orebody is hosted in milled breccias that range from clast- to matrix-supported. The ore-hosting breccias are commonly texturally very similar to regional type II breccias (Fig. 3B). The main ore breccia passes downwards into a zone of variably brecciated and intensely sheared intercalated metavolcanic and metasedimentary rocks that comprise the Footwall Shear Zone (FWSZ). Much of the FWSZ consists of a medium- to coarse-grained calcite-dominated unit termed 'marble matrix breccia', characterised by a well-developed shear fabric defined by the alignment of actinolite±biotite, magnetite and sulphide grains (Marshall and Oliver, 2008). This fabric strongly anastomoses around clasts of felsic to intermediate volcanic rocks contained within the marble matrix breccia. Sodic-calcic altered metasediments of the Corella Formation are found structurally below the footwall, although at depth, it is not known what lies beneath the FWSZ.

Coward (2001) suggested that the HWSZ and FWSZ form part of a linked duplex of at least four faults or shear zones. The strike of this combined structure varies between approximately northnortheast and eastnortheast on a 10 km scale. The orebody is located at a pronounced flexure in the shear fabric of this structure. Coward (2001) demonstrated that in the vicinity of the mine, kinematic indicators suggest normal displacement on the shear zones, and that northnortheast-southsouthwest directed shortening resulted in dilation, brecciation and mineralisation localised at the flexure in the shear zones.

Alteration and Mineralisation

Hydrothermal alteration and mineralisation at Ernest Henry is characterised by a regional pre-ore sodic-calcic event, overprinted by a pre-ore potassic-(manganese-barium) phase that is represented by an intense biotite-magnetite assemblage, and less common K feldspar-garnet (manganese-rich) alteration. The host breccia clasts are commonly pervasively altered to microcrystalline barian K feldspar. K feldspar alteration is most intense in the vicinity of copper-gold mineralisation, but forms a halo extending from several hundred meters up to 2 km beyond the ore body (Mark *et al.*, 2006a; Fig. 3C). Mineralisation

is divided into two main stages: (1) associated with brecciation, and (2) a later vein-dominated episode. Similar mineral assemblages characterise both. The dominant ore-bearing assemblage comprises magnetite, pyrite, chalcopyrite, carbonate and quartz, with lesser apatite, barite, titanite, actinolite, biotite and fluorite. The vast majority of the ore occurs as hypogene chalcopyrite that infills between K feldspar-altered breccia clasts at shallow levels (Fig. 3D), and both infills between, and replaces clasts at greater depths (Fig. 3F). Gold is dominantly present in its native form or in electrum, and is commonly accompanied by chalcopyrite within fractures in pyrite or at grain boundaries between pyrite and chalcopyrite (Foster *et al.*, 2007). Post-ore carbonate±quartz veins are present that contain minor coarse chalcopyrite, lack magnetite, and only carry a little gold. These late veins are volumetrically minor and are likely derived from the remobilisation of pre-existing ore. Deeper in the deposit, breccias include rounded clasts of previously mineralised breccias containing magnetite, pyrite and chalcopyrite, and indicate multiple superimposed brecciation events (Fig. 3B).

The style of brecciation changes from the hanging wall to the footwall, from a "crackle type" breccia (CRBX in mine terminology), especially near the upper margins, to clast-supported (CSBX) and matrix-supported (MSBX) breccias with variable degrees of physical and chemical corrosion in the core of the deposit (Fig. 3E). Down plunge, in the deepest drill holes, there is a further breccia type, referred to as 'second generation breccia' or 'SGBX', which is rich in magnetite and contains calcite, quartz, pyrite, chalcopyrite and microcrystalline K feldspar in varying proportions. SGBX developments are discordant, cutting the surrounding main ore breccias, although their margins may be diffuse over 0.5 to 5 mm scales. SGBX varies in style and appearance and commonly exhibits the following features: (1) Bands of magnetite-rich, chalcopyrite-bearing and calcite-poor material with a minor component of microcrystalline K feldspar clasts. These bands may form by infill or replacement (Fig. 3G); (2) Sections up to several metres in extent dominated by magnetite-quartz-calcite-sulphides with an equigranular granoblastic texture (referred to as "spotted dog" by mine geologists; Fig. 3H). Locally, internal banding exists with 'grading' (magnetite versus calcite) aligned parallel to the edges of the zone (Fig. 3I). (3) Discordant bands up to tens of centimetres in thickness dominated by a matrix of

magnetite and containing distinctive, irregularly corroded clasts of K feldspar, magnetite, coarse (centimetre-scale) pyrite and chalcopyrite (Fig. 3G). The increased abundance of the SGBX at depth is taken to infer that brecciation was repeated, at least near the bottom of the orebody.

Relationship Between Brecciation and Ore Grade

A strong mechanical and chemical control on grade distribution is implied by the correlations between ore-grade and breccia characteristics (Collier and Bryant, 2003; Laneyrie, 2004). In the upper orebody, there is a strong inverse correlation between the percentage of clasts (clast%) and copper grade (Cu%), reflecting the predominance of chalcopyrite in the hydrothermally precipitated breccia matrix, and the relatively simple K feldspar-dominant mineralogy of the clasts (Fig. 5A). Dilation within the forming breccias appears to have allowed the quantitative precipitation of chalcopyrite in the matrix (Fig. 5B). In the middle part of the orebody, the correlation between clast% and Cu% breaks down, and both clast-supported and matrix-supported breccias are recorded in high amounts and both appear to contain high grades (Fig. 5A). In this region, magnetite and sulphides are found internally within clasts, not just in the matrix as an infill component (Fig. 3F), suggesting that replacement is important in the formation of ore (c.f. Twyrould, 1997). This trend continues in the bottom part of the orebody, where it is narrower, slightly steeper, and the copper and gold grades are higher. There are local patches deep in the orebody containing >30% Fe; concentrations not common higher in the mineralised system. The region of high Fe coincides with an abundance of SGBX, rich in magnetite and sulphides, and commonly associated with an increase in the grade of the deposit (Fig. 5C). In some places, SGBX shows evidence of re-worked sulphides with edges that have been abraded and possibly resorbed (Fig. 3F). The correlation between the logged amounts of SGBX (expressed as centimetres of SGBX per 2 metre core interval to allow a comparison with the grade assays) and the Cu% in the lowest parts of the orebody is strong (Fig. 5C). This suggests that the SGBX is not a simple reworking of the adjacent main ore breccias, but that it has introduced more copper into the system.

Chemical Characteristics

Metal Distribution

The Ernest Henry deposit has a regionally distinctive geochemical signature, differing from other Cloncurry IOCG deposits and from regional unmineralised breccias. It has a strong potassic alteration halo, which is common in some IOCG mineralised systems around the world (Williams *et al.*, 2005), but not abundant in all. Barium and manganese are also anomalously enriched in the zone of potassic alteration. In addition, Ernest Henry is enriched in Cu, Au, Fe, Mo, U, Sb, W, Sn, Bi, Ag, F, REE, K, S, As, Co and Ca relative to the intermediate volcanic host rocks. Mark *et al.* (2006a) and Foster *et al.* (2007) discuss the relation of these elements with respect to timing, spatial location, and the minerals that control the chemical distribution.

Ernest Henry is unique among Cloncurry IOCG deposits in the strong correlation between gold and copper. Fig. 6 shows correlations between the key elements in the ore assemblage: copper, gold, nickel, arsenic and cobalt. The data are from the mine multi-element database (N = 23655) and the plots have been density contoured to highlight the key correlation trends. Gold and copper (Fig. 6A) are strongly correlated (log correlation $r = 0.91$), as are arsenic

and cobalt (Fig. 6B). However, comparisons between arsenic and copper concentrations show two distinct trends, where at grades of >1% Cu, the arsenic to copper ratio increases dramatically (Fig. 6C). As the concentrations of arsenic, nickel and cobalt are strongly controlled by pyrite, and pyrite trace element concentrations are not observed to change dramatically between high grade and low grade samples (see below), we infer that the correlations of nickel, cobalt and arsenic with copper reflect more abundant pyrite with high copper grades than in low grade ore.

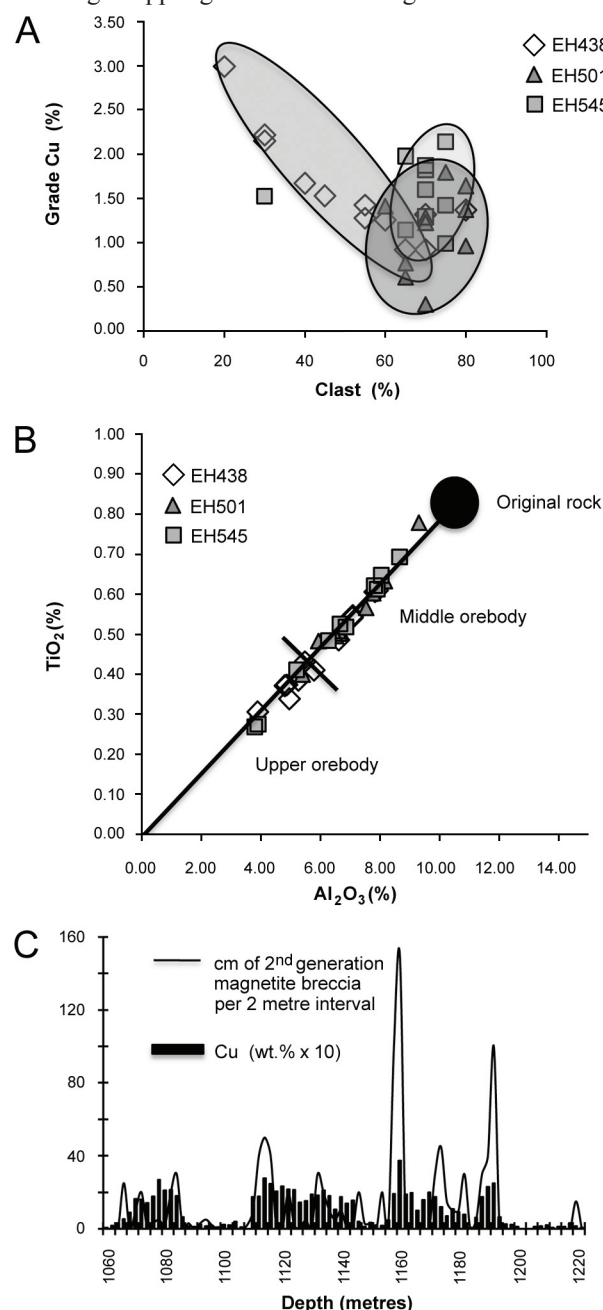


Figure 5: **A** - Percentage of clasts vs. copper grade showing that shallow in the ore body, copper grade increases as clast abundance decreases, indicating ore is dominantly infill, as observed. At greater depths within the deposit, this relationship breaks down as replacement-style mineralisation becomes more important (Laneyrie, 2004); **B** - TiO₂ vs. Al₂O₃ suggesting more dilation in the upper than in the lower orebody, where replacement-style mineralisation is common. The concentrations of immobile elements Ti and Al decrease, while their ratios remain constant, in response to dilution by infill. If Ti and Al are immobile, their concentrations should not decrease significantly during replacement mineralisation; **C** - Plot showing the correlation between the abundance of second generation magnetite and copper grade.

Pyrite Composition

Pyrite is the most abundant sulphide mineral at Ernest Henry, and accompanies magnetite and chalcopyrite in most ore samples. Ernest Henry pyrites are commonly enriched in arsenic, cobalt and nickel, with concentrations of up to 2 wt.% As, 2 wt.% Co and 1 wt.% Ni. Trace element mapping of pyrite grains shows that in nearly all Ernest Henry pyrites within and outside the main ore zone, these elements are strongly zoned with no consistent correlation among them (Fig. 7) or between trace element abundance and gold concentrations (see also Foster *et al.*, 2007). Any one of these three elements may be correlated or anti-correlated with either or both of the other elements. For example, in Fig. 7, three different pyrite grains located within one millimetre of one another contain three different patterns with respect to the zonation of nickel, cobalt and arsenic. There is no consistent progressive trend of any of these elements from core to rim. Sharp concentration gradients of up to thousands of ppm exist within adjacent growth zones in individual grains. Such sharp boundaries suggest physical and chemical conditions fluctuated abruptly at times. The specific physical and chemical processes that led to this zonation are not clear. However, as most gold is present at pyrite grain boundaries, or in fractures that cut pyrite, and not within pyrite grains, it appears that these fluctuations did not directly control gold precipitation. Pyrite from both copper-mineralised and unmineralised samples exhibit this zonation, although there is no clear relationship between elemental abundance or distribution and spatial location within the deposit. Some individual grains of pyrite show multiple generations of pyrite growth, punctuated

by precipitation of other minerals, and in some cases dissolution.

In situ ion probe sulphur isotope analyses across fluctuating zones of high and low arsenic, nickel and cobalt concentrations in several pyrite grains show no isotopic trend from core to rim and no obvious correlation between $\delta^{34}\text{S}$ and trace element concentration among the various growth zones (Mark *et al.*, 2004b). In all zones, $\delta^{34}\text{S}$ ranges between ~ 2 and $\sim 4\text{‰}$, consistent with the majority of bulk sulphur isotope analyses (Mark *et al.*, 2005a, Mark *et al.*, 2006b). This lack of correlation between sulphur isotope abundance and trace element geochemistry suggests that even though conditions of sulphide precipitation vary enough to cause large and abrupt shifts in trace element composition, the sulphur source remained relatively constant during pyrite precipitation.

Cobalt, nickel and arsenic are common in pyrite from numerous hydrothermal environments (Deer *et al.*, 1992). However these elements are far more enriched in Ernest Henry pyrites than in porphyry copper or epithermal deposits (Deditius *et al.*, 2009; Rusk *et al.*, 2006). Whereas Ernest Henry pyrites have high cobalt and nickel concentrations relative to many magmatic-hydrothermal ore deposits, regional unmineralised magnetite-matrix breccias are similarly enriched, as are other IOCG mineralised systems in the Cloncurry region (Fig. 8). On the other hand, many pyrites from Ernest Henry and Osborne are enriched in arsenic by an order of magnitude relative to pyrites from regional unmineralised hydrothermal breccias. This arsenic-enriched pyrite may reflect fluids or fluid processes unique to IOCG formation that differentiate them from barren breccias in the Cloncurry region.

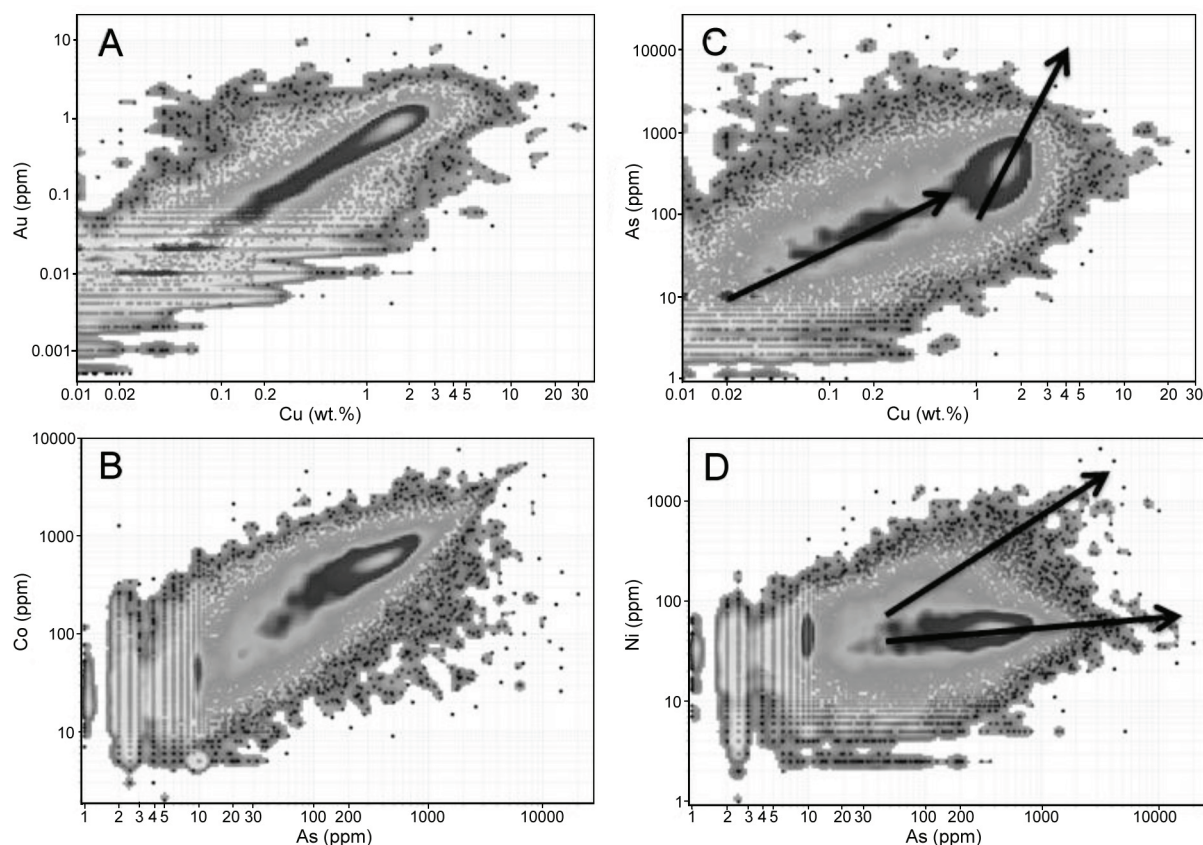


Figure 6: Geochemical relationships among Cu, Au, As, Co, and Ni. Data are derived from the Ernest Henry mine multi-element dataset ($n = 23655$; Xstrata, 2009). Data on plots are density contoured to enhance trends. **A** - Cu (wt.%) vs. Au (ppm), illustrating a strong positive correlation between the two; **B** - There is also a strong trend between As and Co, both of which are dominantly hosted by pyrite; **C** - Cu (wt.%) vs. As (ppm) illustrating two distinct trends with increasing grade; and **D** - As (ppm) vs. Ni (ppm) showing two diverging trends in the data. Note the effects of analytical precision at low concentrations.

Magnetite Composition

Magnetite is common to many, but not all IOCG deposits world-wide. Understanding the conditions of magnetite precipitation could therefore be useful in targeting potential mineralised systems, or in deciphering the complex hydrothermal formation conditions of deposits (c.f. Beaudoin and Dupuis, 2009). However, magnetite trace element chemistry is complex owing to the presence of Fe^{3+} and Fe^{2+} , allowing for numerous chemical substitutions (Deer *et al.*, 1992). Currently the relations between trace element compositions and the physical and chemical conditions of precipitation of magnetite are not well constrained. Trace element variations likely reflect variations in temperature, fluid composition, pH, redox state, and/or fluid-rock reaction.

Electron microprobe trace element maps indicate that, unlike pyrite, magnetite is not zoned with respect to trace element distribution. LAICPMS analyses of magnetite at Ernest Henry show that it commonly contains detectable quantities of numerous elements, the most common of which are Mg, Al, Ti, V, Cr, Mn, Co, Ni, Zn and Ga. Magnetite compositions vary widely across the deposit and most of these trace elements vary over two to three orders of magnitude between samples or even within a single sample. No obvious correlations exist between magnetite trace element composition and location within the deposit, paragenesis, rock type, or ore grade (Zhang *et al.*, 2009).

Carew (2004) suggested that Ernest Henry magnetite was anomalously low in vanadium, relative to magnetite from unmineralised rocks in the Cloncurry district. However, Rusk *et al.* (2009) showed that whereas Ernest Henry magnetite is depleted in vanadium relative to many igneous magnetites in the region, it is not depleted in vanadium relative to hydrothermal magnetite from non-mineralised hydrothermal magnetite-matrix breccias in the Cloncurry region, nor is it significantly different in vanadium concentration from the other IOCG deposits in the Eastern Succession (Fig 9). On the other hand, much of the Ernest Henry magnetite is more enriched in manganese than magnetite from other ore bodies and from unmineralised hydrothermal breccias. While high manganese concentrations distinguish some of the Ernest Henry magnetites from those of some of the regional IOCG occurrences, the Ti/Mn ratio more clearly discriminates between ore deposits and barren magnetite matrix hydrothermal breccias. Most unmineralised breccias have a higher concentration of titanium relative to manganese than most mineralised breccias. It is not currently clear

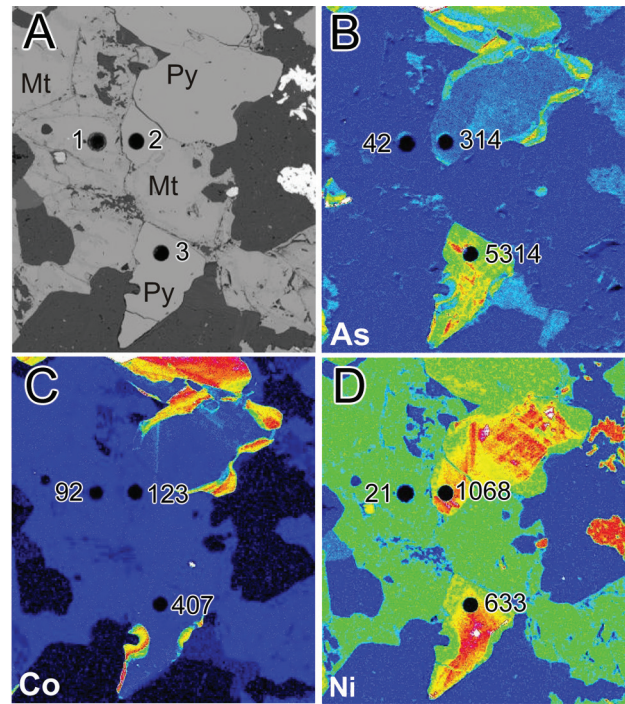


Figure 7: Electron microprobe trace element maps showing the distribution of As, Co and Ni in three nearby pyrite grains (EH554-680). Several laser ablation-ICPMS holes are present and the values from those analyses (in ppm) are shown. LAICPMS hole 1 is in magnetite, whereas holes 2 and 3 are in pyrite. Various pyrite grains show different correlations among the trace elements. The upper grain is As- and Co-rich, but Ni depleted throughout. The middle grain is zoned from a core which is As- and Co-poor, but Ni-rich to a rim which is As- and Co-rich, but Ni-poor. The bottom pyrite grain is zoned from a Ni- and As-rich core to Co- and As-rich rim.

what controls the relationship between titanium and manganese concentration in magnetite, but it likely reflects a complex combination of fluid composition, temperature, redox conditions, and fluid rock interaction. Magnetites in IOCG deposits from the Carajas region have markedly different trace element signatures (Xavier *et al.*, 2009), which suggests that local factors such as fluid composition or host rock composition control magnetite composition as opposed to extrinsic factors such as pressure or temperature (Fig. 9).

Apatite Composition

Apatite is common in the Ernest Henry breccias, occurring in assemblages with chalcopyrite and pyrite. Apatites from Ernest Henry are fluorine-rich relative

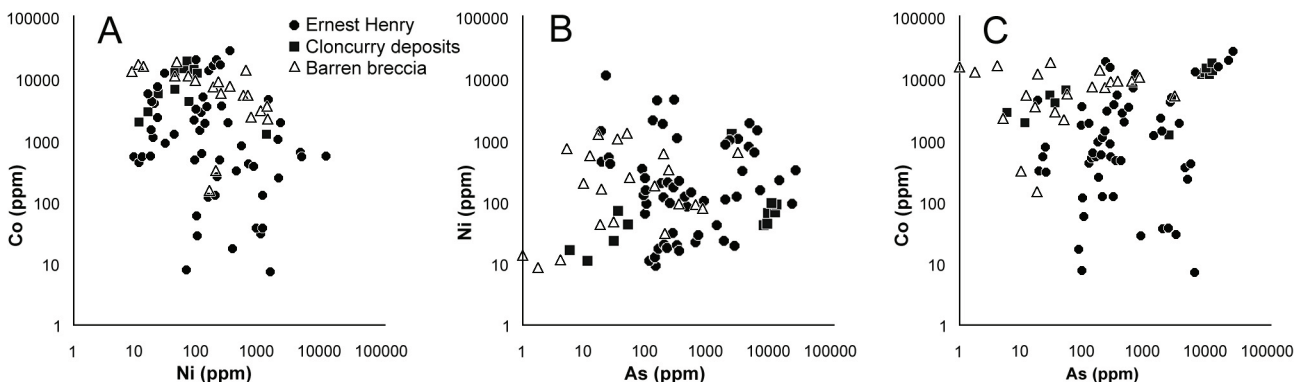


Figure 8: Bivariate plots showing pyrite trace element data measured by LAICPMS. Data from Ernest Henry, other Cloncurry IOCG deposits, and from regional unmineralised magnetite-matrix hydrothermal breccias are compared. **A** - Ni vs. As; **B** - Co vs. As; **C** - Ni vs. Co. No strong correlations exist between any of the trace elements, and there is no distinction between the composition of pyrite from Ernest Henry, other Cloncurry IOCG deposits, or regional breccias.

to metamorphic rocks, including the Corrella marbles, regional unmineralised type II breccias, and relative to Williams-Naraku igneous rocks (Fig 10). Probe analysis of a fluorine-apatite standard shows that the measured fluorine concentrations are real and are not affected by electronic fluorine-migration (Stormer *et al.*, 1993). Such fluorine-rich apatites are common in many hydrothermal ore deposits and are consistent with the fluorine-rich compositions of the biotite at Ernest Henry (Twyerould, 1997). Apatite with >2 atoms per formula unit (apfu) of fluorine results where $\text{CO}_3^{2-} + \text{F}^-$ substitute for PO_4^{3-} (Deer *et al.*, 1992). Apatites from Ernest Henry contain up to 3 apfu fluorine, and so likely contain considerable CO_3 . Most apatites from regional type II breccias show a progressive distribution of halogen compositions between those of regional metamorphic rocks and Ernest Henry ore. Igneous apatites from the Williams batholith are significantly more chlorine-rich than most breccia-related apatites (Fig. 10). The few analyses of chlorine-enriched apatites from type II breccias may be remnant igneous apatites from resorbed clasts of igneous rocks rather than

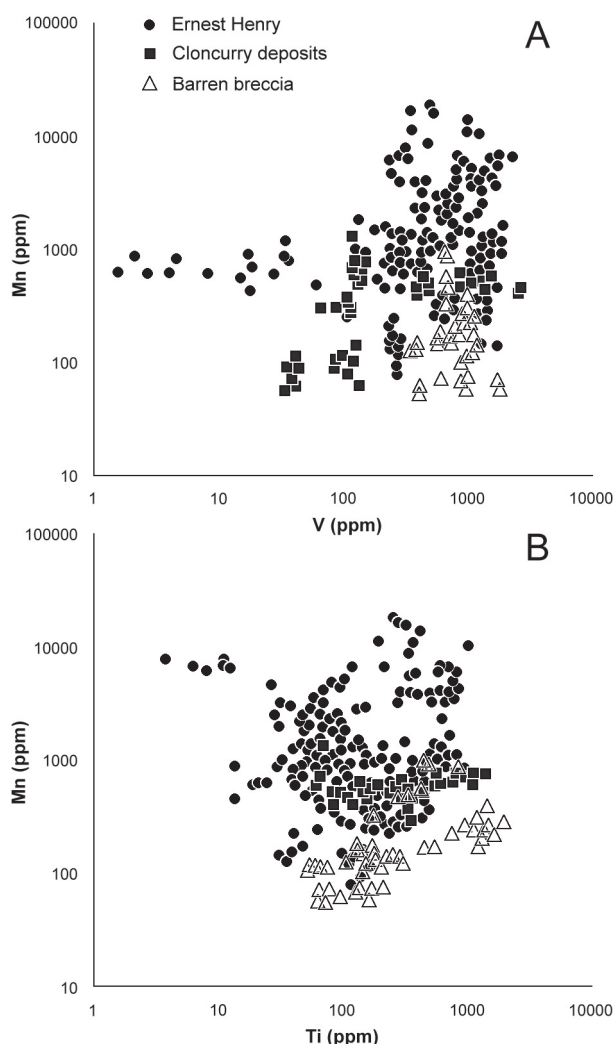


Figure 9: Bivariate plots showing magnetite trace element data measured by LAICPMS. Data from Ernest Henry, other Cloncurry IOCG deposits, and from regional unmineralised magnetite-matrix hydrothermal breccias are compared. **A** - Mn vs. V; **B** - Mn vs. Ti. Strong correlations do not exist among these elements. Ernest Henry magnetites range over three orders of magnitude in Mn concentration and are Mn-enriched relative to magnetites from both regional IOCG deposits and from regional unmineralised magnetite-matrix breccias. Most magnetite from mineralised deposits has higher Mn/V and Ti/Mn ratios than magnetite from regional breccias.

hydrothermally-precipitated apatites, the majority of which contain far less chlorine and far more fluorite.

The apatite at Ernest Henry also differs from that of regional brecciated rocks in that it is strongly zoned from dark cores to light rims in back-scattered electron images (Fig. 11a). This zonation results from variations in the sulphur and arsenic contents of these apatites. All from Ernest Henry displayed this zonation from sulphur-rich cores (0.5 wt.% SO_3) to arsenic-rich rims (maximum of 5 wt.% As_2O_5 ; Fig. 11b). This concentration of sulphur is not unusual for apatites related to magmatic hydrothermal systems (Streck and Dilles, 1998; Piccoli and Candela, 1994), although arsenic-rich apatites are rare. A solid solution exists between apatite and johnbaumite (svabite and ferromite), the arsenate end-members of apatite $\text{Ca}_5(\text{AsO}_4)_3(\text{OH})$. Arsenic-rich fluorine-apatites are not common in hydrothermal ore deposits, but they are primarily recognised in metamorphic-related manganese ores world-wide including the Sitipar deposit, Chindwara district, India (Hughes and Drexler, 1991), several mining districts in Varmland, Sweden (Nysten, 2004), the Starlera deposit, Val Ferrara, Switzerland (Brugger and Gieré, 2000) and the St. Marcel - Praborna mine in the Val d'Aosta, Italy (Perseil *et al.*, 2000). This suggests a very strong correlation between arsenic-rich apatites and manganese mineralisation, and the observation of arsenic-rich apatite at Ernest Henry and anomalous manganese enrichment at the deposit scale, especially in magnetite, is consistent with this trend.

None of the regional samples contain the extreme arsenic enrichment of Ernest Henry apatites. The evolution from sulphur to arsenic-rich apatite compositions in Ernest Henry apatites could be related to mixing of external fluids or an *in-situ* change in the redox state of the carrier fluid (due to fluid mixing or phase separation). The extremely high arsenic content of the Ernest Henry apatites relative to the regional breccias, suggests unique processes or fluid compositions at Ernest Henry that did not exist in the unmineralised hydrothermal breccias, despite similar structural and physical settings.

Fluid Composition

Mark *et al.* (2005a) report hyper-saline brines containing up to 55 wt.% $\text{NaCl}_{\text{equiv.}}$, CO_2 liquid-dominated fluid inclusions, and liquid-vapor inclusions where the vapor occupies ~20 to 30 vol.% of the inclusion. Such inclusions are characteristic of IOCG deposits world-wide (Baker *et al.*, 2008; Hunt *et al.*, 2007; Niiranen *et al.*, 2007; Dreher *et al.*, 2008). A key difference between fluid inclusions in mineralised Cloncurry IOCG systems, including Ernest Henry, and those in regional unmineralised rocks, is the prevalence of multi-solid fluid inclusions (those containing halite plus multiple daughter minerals including sylvite, magnetite, ferropyrrosmalite and others) in the IOCG deposits. Halite-saturated brines are common in regional breccias, but tend to contain only halite or halite and one or two other daughter minerals. Multi-solid inclusions have higher homogenisation temperatures and higher salinities and therefore more dissolved solutes than inclusions containing halite alone.

Fluid inclusion compositions were quantified by PIXE analysis (Baker *et al.*, 2008; Mark *et al.*, 2005b) and these data for Ernest Henry are shown in Table 1. Halite-saturated multi-solid inclusions from Ernest Henry generally contain <200 ppm Cu. These copper concentrations are consistent with those in fluid inclusions from Osborne

(Fisher and Kendrick, 2008) but are significantly lower than values measured at Starra (Williams *et al.*, 2001). This may result from unintentionally sampling “spent ore fluids” (those that have already precipitated their copper) at Ernest Henry. However even the fluids trapped in pre-ore assemblages at Ernest Henry contain no more than a few hundred ppm copper, concentrations only slightly higher than syn-ore inclusions. Syn-ore samples are extremely enriched in barium, strontium, lead and calcium relative to inclusions from pre-ore alteration samples, which may reflect enrichment in these elements by alteration of feldspars to albite, liberating them to the fluid. Most Br/Cl ratios vary widely from 0.05×10^{-3} to 2.45×10^{-3} , consistent with multiple sources of salinity, including evaporite dissolution, bittern brine and/or a magmatic halogen source. These values largely overlap with Br/Cl ratios measured by Kendrick *et al.* (2007). Br/Cl ratios do not correlate directly with copper concentration at Ernest Henry, although across the district, the highest copper concentrations are measured in fluids that have Br/Cl ratios consistent with a magmatic source (Baker *et al.*, 2008). This led Baker *et al.* (2008) to conclude that regionally, magmatic-derived hydrothermal brines play a more important role in copper transport than do halite dissolution or bittern brines.

Mechanisms of Formation of the Ernest Henry IOCG Deposit

Fluid Sources

Early research on IOCG deposits proposed either basinal fluid circulation and metal leaching (Barton and Johnson, 1996; Hitzman *et al.*, 1992), or release of magmatic-hydrothermal fluids (Gow *et al.*, 1994; Marschik and Fontbote, 2001; Perring *et al.*, 2000) as alternative end-member genetic models. More recent reviews suggest the likely involvement of multiple fluid sources in which magmatic/mantle and basinal and/or meteoric fluids play a role, even within a single district (Kendrick *et al.*, 2007; Monteiro *et al.*, 2008; Williams *et al.*, 2005; Xavier *et al.*, 2008; Groves *et al.*, 2010).

Whereas Osborne-style IOCG deposits in the Eastern Succession are characterised by formation before or at the time of peak metamorphism, are structurally controlled, and appear to have formed dominantly from basinal fluids

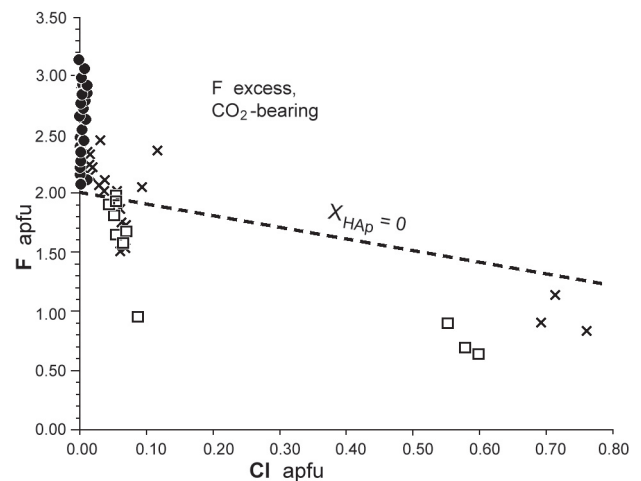


Figure 10: Halogen contents of ore-related Ernest Henry apatite (black circles), regional breccias (crosses) and regional metamorphic rocks (squares) plotted as atomic formula units (calculated to 10 Ca). The dashed line represents the limit for stoichiometric halogen replacement in the OH-site. Points above this line contain excess halogens, which indicates substitution onto the PO₄-site. Ernest Henry apatites are more fluorine-rich and chlorine-poor than any other apatites measured in the region.

(Fisher and Kendrick, 2008), Ernest Henry type deposits are breccia-hosted and their timing is coincident with regional magmatism. Mark *et al.* (2006a) propose that the diverse geochemical signature at Ernest Henry requires the ingress of multiple fluids of differing composition. This interpretation is also suggested by the multiple brecciation and vein-forming events described above, and by the presence of sodic-calcic alteration overprinted by a potassic-iron-manganese-barium episode. A magmatic fluid contribution to the Ernest Henry mineralised system is suggested by the coincident timing of Ernest Henry mineralisation and the regional emplacement of batholiths. U-Pb ages for titanite (in textural equilibrium with ore chalcopyrite) of 1527 Ma (Mark *et al.*, 2006a; Oliver *et al.*, 2004), are the same as for the Mt Margaret granite, which, at 12 km northeast of Ernest Henry, is the nearest exposed pluton of the Williams-Naraku batholiths (Page and Sun, 1998). Ernest Henry is hosted by a type-II breccia, similar to those that regionally also temporally coincide with emplacement of the Williams-Naraku batholiths and have been shown to emanate from the carapace of granites that have undergone magma mingling (Bertelli and Baker, 2010; Oliver *et al.*, 2006).

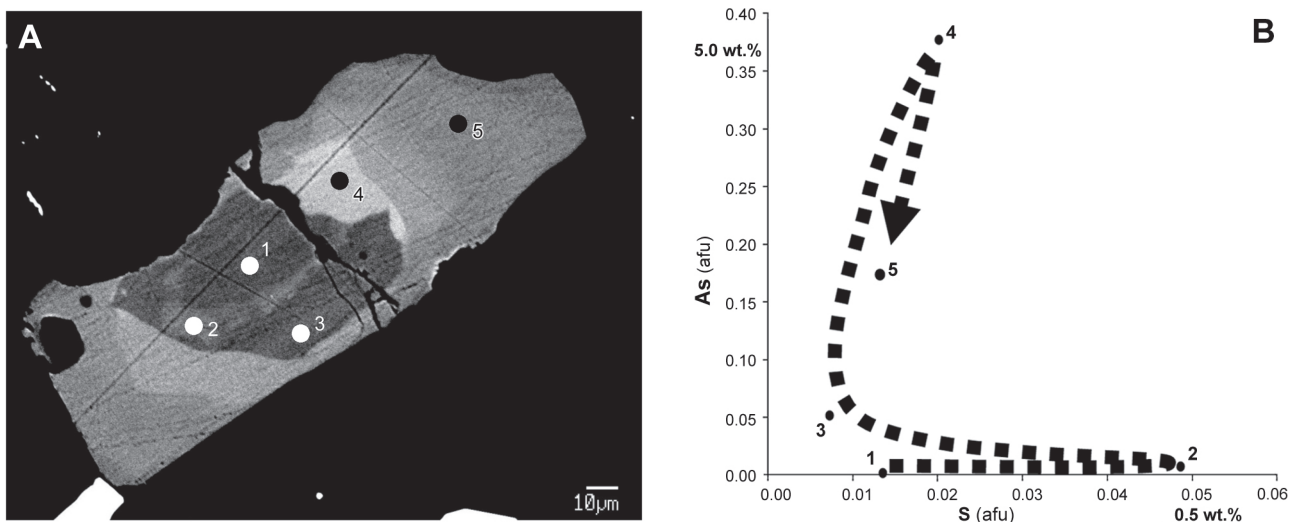


Figure 11: **A** - Back-scattered electron image of typical apatite from Ernest Henry showing zonation in As and S. This chemical zonation is very consistent across the ore body. **B** - Arsenic and S concentrations in spots 1 to 5 (shown as afu calculated to 10 Ca). The location of 5 wt.% As and 0.5 wt.% S are also shown (EH440-156). Ernest Henry contains unusually As-rich apatites.

Table 1: Compositions of multi-solid fluid inclusions from Ernest Henry as determined by PIXE (data from Mark *et al.*, 2005b; Baker *et al.*, 2008).

Locality	Cl	K	Ca	Mn	Fe	Cu	Zn	Br	Rb	Sr	Ba	Pb	Br/Cl (x1000) mol ratio
Pre-ore Grt	384 000	26 800	19 800	83 200	67 100	203	812	88	251	375	3490	225	0.10
Pre-ore Grt	466 000	175 000	33 300	159 000	8700	191	2510	320	2818	1139	11500	723	0.30
Pre-ore Grt	292 000	24 100	8340	474	6800	70	101	48		70	1730	149	0.07
Pre-ore Grt			21 700	146 000	191 000	256	292	610				3200	
Pre-ore Grt	222 000	69 600	21 200	90 900	30 900	119	1920	246	765	1040	18 100	425	0.48
Pre-ore Grt	177 000	43 800	12 000	84 000	74 400	90	1000	212	944	319	2240	1150	0.52
Pre-ore Grt	302 000	3370	3280	7800	3200	68	526	129	197	660	4050	203	0.19
Pre-ore Grt		772	1970	41 700	30 000	68	100	88		80	1650	267	
Pre-ore Kfs	180 000	4 810	3950	2870	2050	130	224	152	106	715	3530	384	0.37
Pre-ore Kfs	256 000	8560	7450	2270	1730	112	878	265	150	915	5020	429	0.45
Pre-ore Kfs		24 600	14 400	5330	4110	767	1560	819			18 500	2490	
Pre-ore Kfs	180 000	3980	22 600	288	98	143	99	1007		690	2200	246	2.45
Pre-ore Kfs		13 000	12 200	4340	2300	53	1230	272	124	1230	5680	414	
Pre-ore Kfs	142 000	7820	7220	2190	256	164	161	182		700	3810	393	0.56
Pre-ore Kfs	146 000	8630	12 100	861	753	293	359	330		991	8880		0.99
Pre-ore Kfs	146 000	17 500	5950	780	629	655	603	586			9470	1834	1.76
Syn-ore	515 300	14 450	40 610	14 130	1070	47	2450	94		1080	1910	800	0.08
Syn-ore	437 900	1630	20 180	7480	464	68	1240	50		600	860	420	0.05
Syn-ore	307 800	9520	12 000	13 520	2150	30	2680	81		4190	26 030	1343	0.12
Syn-ore	286 900	10 240	17 030	20 190	2720	37	4510	127		9650	48 470	2970	0.19
Syn-ore	227 600	4560	17 630	32 860	5164	69	6540	109		10 320	38 950	3520	0.21
Syn-ore	253 600	2950	12 020	18 670	2630	119	3230	101		4760	19 550	970	0.17
Syn-ore	330 000	7420	32 890	47 520	4270	110	9100	291		16 390	69 550	4750	0.39
Syn-ore	297 400	16 360	32 030	12 770	874	105	8410	212		13 170	23 230	3980	0.31
Syn-ore	283 000	5910	20 600	25 900	1810	40	4210	76		6713	4540	1350	0.12

Several other lines of evidence, including carbon, oxygen, and sulphur isotopes, fluid inclusion halogen ratios and fluid inclusion argon isotope ratios are consistent with both a magmatic and a basinal fluid contribution to the hydrothermal system. Stable isotopes (Marshall *et al.*, 2006) indicate a mixing trend between $\delta^{13}\text{C}$ values of $\sim 0\text{‰}$ and $\delta^{18}\text{O}$ of $\sim 21\text{‰}$, to $\delta^{13}\text{C}$ of around -7‰ and $\delta^{18}\text{O}$ of around 11‰ . This was interpreted to result from mixing between carbon and oxygen from marine metacarbonates and a magmatic fluid at temperatures of $\sim 450^\circ\text{C}$ (see below). Sulphur isotopes in chalcopyrite are mostly between $\delta^{34}\text{S}$ of 0 and 4‰ , but up to $\sim 8\text{‰}$ (Mark *et al.*, 2005a; Twyerould, 1997), which are also consistent with a magmatic source for sulphur. The spread to the most positive values for δS does not preclude a component of sulphur derived from marine metacarbonates. The signals recorded by argon isotopes and Cl/Br ratios in fluid inclusions from Ernest Henry also indicate mixing between a mantle source ($^{40}\text{Ar}/^{36}\text{Ar} \sim 29000$ and molar Cl/Br ~ 1000) and a fluid derived from dissolution of evaporites ($^{40}\text{Ar}/^{36}\text{Ar} < 1000$ and Cl/Br ~ 1000 ; Kendrick *et al.*, 2007). This is in agreement with fluid inclusion halogen data from Baker *et al.* (2008) that also show fluid salinity derived from mixed magmatic and basinal brine components. It is important to bear in mind that even though these lines of evidence are consistent with a contribution from a magmatic fluid, none indicate that a magmatic fluid was dominant or supplied the crucial ingredients of copper, gold and sulphur.

Pressures and Temperatures of Formation

Little fluid inclusion microthermometry has been carried out at Ernest Henry. Homogenisation behavior of halite-saturated brines and CO_2 -rich fluids suggests a wide range in temperatures and pressures of trapping of between 200 and 520°C , at pressures of 1.3 to 3.7 kilobars (Mark *et al.*, 2005a). It is not clear whether these temperatures and pressures represent real variation or whether the inclusions have suffered post-entrapment modifications. Regardless of trapping conditions, the fluid inclusions present suggest that the most prevalent fluids that contributed to IOCG mineralisation at Ernest Henry were hypersaline brines and CO_2 -dominated fluids.

Twyerould (1997) applied a number of geothermometers to the Ernest Henry system, including several mineral oxygen isotope pairs, coexisting carbonate compositions, coexisting biotite and garnet compositions, and sulphide sulphur isotope pairs. Results from these various techniques vary significantly, owing to the nature of the geothermometers and the complexity of the geologic system. Twyerould (1997) concluded that temperatures of between 400 and 500°C are likely to be the most reliable. Previously unpublished oxygen isotope data on several mineral pairs (Table 2) agree with interpretations of Twyerould (1997) and Mark *et al.* (2005a), and are also similar to those suggested for many other IOCG deposits, including Olympic Dam (Bastrakov *et al.*, 2007; Haynes *et al.*, 1995; Oreskes and Einaudi, 1992).

Table 2: Oxygen isotope ratios of Ernest Henry ore-related minerals and calculated temperatures and fluid compositions (data from Mark *et al.*, 1999).

$\delta^{18}\text{O}_{\text{mineral}}$ (SMOW)						T°C calculated from indicated mineral pairs					
Sample	qz	bt	mt	kf	cc	qz-bt (1)	qz-bt (2)	qz-mt (3)	qz-mt (4)	kf-mt (5)	cc-mt (6)
DA732619			1.7		12.9						360
DA732670			1.5		11.0						425
DA732684			2.0		9.5						510
FTCD28			2.0		11.6 12.1						420 400
FTCD34	11.9	5.4	2.2			445	440	445	485		
JK003/4	11.6	5.8				485	490				
J27	13.8	5.9				385	375				
9907*	11.9		4.5	10.5	10.9			560	>600	>600	600
9927*			3.4		11.6						440
9941	13.9	6.5				415	400				
9942*			0.5		7.1						590
9955*			-0.3		11.7						330
9957	11.2		1.2	9.4				435	470	470	

Mineral separate data from samples from ore stage paragenesis, both proximal and distal to Ernest Henry, * = distal. Silicates analysed with CIF3 according to McCrae (1956), and calcite using phosphoric acid at the Monash University Stable Isotope facility.

Thus, exact pressures and temperatures of formation of the Ernest Henry breccia and of ore precipitation remain elusive, perhaps reflecting the transient conditions resulting from multiple brecciation episodes. Relatively high temperatures, in the range of 400 to 500°C are likely. Depths of formation are loosely constrained to <8 km by the emplacement of Williams-Naraku batholith plutons, which underlie the orebody and from which some volatiles are likely derived. Pressures of magma emplacement, based on contact metamorphic assemblages, are inferred to be up to 3 kilobars (Betts *et al.*, 2006; Pollard *et al.*, 1998; Rubenach *et al.*, 2008). Variable fluid pressures, intermittently higher than lithostatic, are also likely, based on brecciation textures.

Physical and Chemical Conditions of Formation

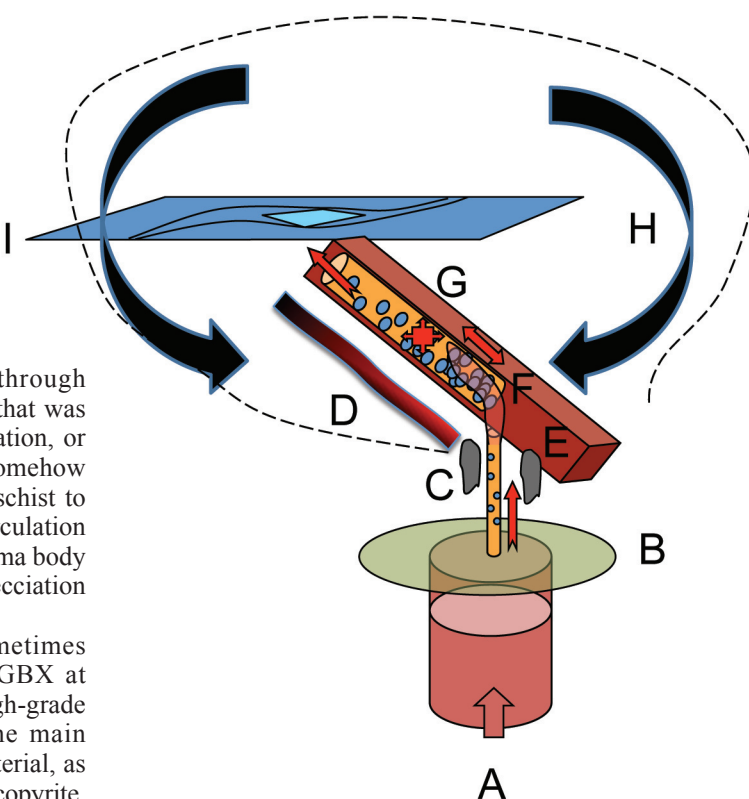
Whereas it is clear from the several lines of evidence above that fluids responsible for the formation of Ernest Henry originated from multiple sources, including magmatic and basinal, the role of each of these fluids in metal and sulphur transport are not well constrained. The abundance of multi-solid fluid inclusions at Ernest Henry and in other IOCG deposits, and their absence in regional rocks suggests that such solute-rich fluids are key in transporting essential ingredients for IOCG formation. The strong correlation between copper and gold throughout the majority of the ore suggests that they were transported in the same fluid. Chlorine is known to be an effective ligand for the transport of gold and copper, and it is possible that brines similar to those trapped in multi-solid fluid inclusions transported these metals. However, copper concentrations in all measured Ernest Henry brines are much lower than is typical in clearly magmatic-dominated hydrothermal systems, such as porphyry copper deposits. In porphyry-type deposits, hypersaline fluids may contain several wt.% Cu and chalcopyrite daughter minerals are commonly identified in halite-saturated inclusions (Audetat *et al.*, 2008; Rusk *et al.*, 2004; Roedder, 1984; Beane and Bodnar, 1995). The relatively low copper concentrations measured in multi-solid fluid inclusions at Ernest Henry suggest that if these fluids transported ore, they were highly undersaturated with respect to copper and the mechanism of precipitation must have been very efficient, as proposed in epithermal systems (Simmons and Browne, 2006). Alternatively, it is possible that none of the fluid inclusions analysed have sampled

the important ore-bearing fluids, even though inclusions were analysed in both pre- and syn-ore assemblages. The most copper rich fluids identified in the Cloncurry region (containing up to 1% Cu) are found in high temperature magmatic-hydrothermal hypersaline brines in the Lightning Creek complex (Perring *et al.*, 2000). This area lacks copper mineralisation but contains copper-rich saline brines. Such fluids could resemble the ore fluids that may have been present at Ernest Henry, but that have not been identified.

In addition to copper and gold, there is a strong arsenic anomaly at the Ernest Henry deposit that is spatially correlated with copper-gold mineralisation. Arsenic, copper and gold are some of the few elements that are also effectively transported as a vapor phase, probably as sulphur complexes (Williams-Jones *et al.*, 2005; Heinrich *et al.*, 1999; Simon *et al.*, 2007). It is possible, in the absence of the identification of metal-enriched hypersaline brines, that a magmatic vapor phase may be responsible for transporting metals into the Ernest Henry IOCG deposit. However, even though fluid phase separation, leading to volume expansion of the hydrothermal fluids is a viable mechanism to drive brecciation, no direct evidence for fluid unmixing has been identified at Ernest Henry.

Oliver *et al.* (2006) proposed that regional fluidised brecciation was driven by the release of overpressurised magmatic volatiles. These breccias formed when complex hydrogen-carbon-oxygen-sulphur fluids and saline brines were released at supra-lithostatic pressure from the tops of mingled intrusive bodies. The similarity with the Ernest Henry ore breccia provides circumstantial evidence that such processes operated during ore genesis. The top of the orebody reflects high energy rock fracturing, transport and mechanical abrasion, with rapid precipitation of magnetite, calcite and sulphides resulting in cementation of the clast-supported breccia. In the mid- and deeper-sections of the orebody, chemically corroded and replaced clasts suggest that fluid residence time was longer, and interaction between fluids and rocks was more intense. This mechanism could be responsible for breccia formation, although the ingress of basinal fluids (derived from the Corella Formation) during brecciation is hydrodynamically difficult because the host sequences had already been through greenschist to amphibolite facies regional metamorphism and major contact metamorphism around the Williams-Naraku

Figure 12: Schematic cartoon illustrating the likely formation mechanisms of the Ernest Henry IOCG deposit. See text for description. **A** - Mingling of mafic and felsic magmas; **B** - carapace or seal above the magma chamber; **C** - early mineralised feeder zone that telescoped upwards; **D** - potential presence of Mn-Fe rich sediments of the Overhang Jaspilite below the footwall of the deposit; **E** - Mount Fort Constantine Volcanics act as barrier to fluid flow; **F** - Lower ore body: abundant chemical corrosion and repeated brecciation; **G** - Upper orebody: dominated by infill; **H** - Circulation and mixing of basinal brines; **I** - present day erosion surface at estimated palaeodepths of 3 to 5 km.



batholiths. These basinal fluids, identified through numerous techniques, either came from a basin that was present above Ernest Henry at the time of formation, or the fluids buried with the Corella Formation somehow retained their basinal signal even through greenschist to amphibolite metamorphism. In either case, the circulation of basinal fluids was driven by heat from the magma body below and increased porosity resulting from brecciation (Fig. 12).

The abundance of reworked clasts of sometimes coarse grained sulphides and magnetite in SGBX at depth, may suggest that there is a relatively high-grade body of magnetite-chalcopryrite ore below the main orebody. Upward fluidised streaming of this material, as evidenced by the physically corroded clasts of chalcopryrite, contributed to an increase of grade at depth, and may represent the 'feeder' zone to the deposit. This feeder zone may represent an earlier stage of mineralisation directly related to the hydrothermal system at Ernest Henry, 'telescoped' upwards in the later stages of ore genesis to overprint the bulk of the ore. It is also possible that these sulphide- and magnetite-rich rocks are derived from a pre-existing massive magnetite-chalcopryrite-pyrite ore body (e.g., Osborne-style) that exists below Ernest Henry and played a critical role in localising ore.

Comparison between regional unmineralised breccias and the Ernest Henry IOCG deposit indicates that similar physical and chemical processes were involved in the formation of both, but some essential fluids or processes necessary for significant copper and gold deposition were missing in the formation of the regional breccias. Whereas pyrite compositions are similar between Ernest Henry and unmineralised breccias, magnetite and apatite compositions are markedly different at Ernest Henry compared to the regional breccias. Magnetite Mn/V and Mn/Ti ratios are high at Ernest Henry and other Cloncurry deposits, relative to unmineralised breccias, and apatites are unusually rich in fluorine and arsenic. Around the world, arsenic-rich apatites are only reported in manganese-rich seafloor deposits. The Overhang Jaspilite is a manganese-iron-rich sea floor deposit, containing some banded iron formations (Foster and Austin, 2008; Brown, 2008; Blake, 1987), that regionally forms an important correlative of the Corella Formation. Although the Overhang Jaspilite has not been identified at Ernest Henry, it is possible that it exists at depth below the deposit footwall and had a role in localising mineralisation.

Model of Ore Formation

Despite the evidence for a geologically rapid precipitation phase at Ernest Henry, the very broad potassic-iron alteration halo (Mark *et al.*, 2006), itself overprinting regionally extensive sodic alteration, attests to a prolonged history of fluid focusing through the broader

region surrounding the deposit. By combining all of the above lines of evidence and speculation, we propose the following sequence of events leading to the formation of the Ernest Henry IOCG deposit (Fig. 12).

- (1) Mingling of mafic and felsic magmas at depths of ~10 km, transfer of CO₂ to volatile rich A-type granites, leading to rapid devolatilisation (possibly both chloride-rich brines and CO₂-rich fluids).
- (2) Fluid overpressurisation occurred in the roof of the magma chamber resulting from volatile exsolution and vapour expansion, perhaps assisted by a seal created by magma solidification, sodic-calcic alteration and/or contact metamorphism in the carapace of the igneous complexes.
- (3) Possible leakage of overpressured magmatic fluid or circulation of basinal fluids along structures that controlled the location of the later breccia pipe may have produced the pre-ore potassic alteration halo that embraces the Ernest Henry deposit.
- (4) The eventual failure of the seal led to the sudden release of fluid pressure, and of fluids. This high-energy fluid-flow event drove type II breccia formation, accompanied by upwardly transported and milled clasts. The resultant breccia mass permitted the mixing and/or subsequent ingress of basinal brines circulating within rocks above the magma chamber.
- (5) Fluid mixing, rapid depressurisation and resultant cooling led to ore precipitation within the matrix porosity between breccia clasts at the top of the orebody. As the fluid flow subsided, the temperature and pressure declined in the upper parts of the deposit and the breccia was sealed.
- (6) At depth, closer to the heat source, the temperature and pressure gradient degraded more slowly, allowing for fluid-rock reaction to be more protracted. Prolonged chemical interaction between K feldspar-rich host rocks and ore fluids led to replacement style mineralisation with the same mineral assemblage as observed in the shallower parts of the deposit.

- (7) At the deepest levels, repetition of the cycle may have resulted in the release of a new pulse of fluids which brecciated and tapped earlier-formed magnetite-chalcopyrite rich rocks, telescoping mineralised clasts upwards into the orebody along narrow channels, thereby upgrading ore.

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