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THE EVOLUTION OF THE ERNEST HENRY Fe-OXIDE-(Cu-Au) HYDROTHERMAL SYSTEM

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Abstract – The >1510-1500 Ma Ernest Henry Fe-oxide-Cu-Au orebody is a hydrothermal deposit hosted in K-feldspar altered ca 1740 Ma plagioclase phyric volcanic rocks in the Cloncurry district, Mount Isa Inlier. Mineralisation occurred late in a post-peak metamorphic hydrothermal system, and the ore is mainly hosted in an infill-supported hydrothermal breccia that grades to crackle veining at the margins. The orebody has a > 1 km down dip extension, and is structurally-controlled between two shear zones that trend NE-SW and dip ~35^o to the SE. The ore is mainly composed of subrounded clasts separated by a fine- to medium-grained infill composed of magnetite, calcite, pyrite, biotite, K-feldspar, chalcopyrite, hematite, garnet, barite, fluorite, quartz and molybdenite.

The deposit exhibits a number of geochemical and isotopic haloes (e.g. K, S and $\delta^{18}O$) that extend to different distances beyond economic mineralisation. Most notably the combination of enriched Mn, K and Ba produce a geochemical halo that is present only around the Ernest Henry and Monakoff deposits, in the northern part of the Cloncurry district. The dominant magmatic stable isotope composition of the ore-related fluids (ca 400-450^{o}C) suggest that magmas were significant contributors of fluid and/or S. However, metals, REE, Ba and U could have been derived from an alternate source (e.g., saline metamorphic fluids). The chemical affinities of the elements enriched in the Ernest Henry ore (e.g., Fe, Cu, Au, K, Ba, S, As, U, LREE, Mo, W, Co, As, F, Ca and C) suggest that they were carried by more than one fluid, and that a mixed origin involving two or more fluids (cf. Olympic Dam and Salobo Cu) is the preferred model for ore deposition. The magnetite-U-, K-, Mo- and As-rich composition and disseminated character of sulphides in the Ernest Henry ore and its related halo suggests that this type of system is readily detectable using airborne (e.g., magnetics and radiometrics) and ground (e.g. EM and IP) geophysical techniques.

Introduction

Fe-oxide-(Cu-Au-U-REE) deposits

The Ernest Henry Fe-oxide-(Cu-Au) deposit occurs beneath Mesozoic cover, and lies 35 km NE of the township of Cloncurry (Fig. 1). The orebody is bound by two anastomosing shear zones and is hosted within variably plagioclase phyric metavolcanic/hypabyssal rocks (ca 1740 Ma). These shear zones have a northeasterly trend in plan section, and dip ca 35° towards the SE (Fig. 2). The deposit has a resource of 167 Mt @ 1.1% Cu and 0.54 ppm Au (Craske, 1995). Mineralisation largely occurs as infill in a hydrothermal breccia/vein pipe-like body (300 m wide x 250 m thick) with a > 1000 m down dip extension, and the margins to economic mineralisation are typically coincident with the transition from infill-supported hydrothermal breccia to peripheral crackle veining.

All of the ingredients (e.g. calc-silicates, coeval intrusions, structural corridors, ironstones etc) required to produce and/or react with the saline, metal-rich fluids associated with Fe-oxide-(Cu-Au) mineralisation are represented in the Cloncurry district, and therefore the district provides a fertile ground for exploration for this style of deposit. The presence of all these components, regardless of genetic model, suggests that the Cloncurry district represents an ideal area to unravel the controls on ore deposition and the composition, mineralogy and size of individual ore bodies. In this sense, the results of our study on the evolution and origin of the Ernest Henry hydrothermal system provides new information that goes part of the way to describe the processes associated with Fe-oxide-(Cu-Au) mineralisation in the Cloncurry district, and has direct relevance to exploration for deposits in similarly mineralised provinces elsewhere.

This paper will present evidence for the geochemical, mineralogical and evolutionary characteristics of the Ernest Henry hydrothermal system, and will discuss aspects (e.g., tectonics, geochemistry and mineralogy) of the ore-forming processes and their relationship to other Fe-oxide deposits in the district and elsewhere.

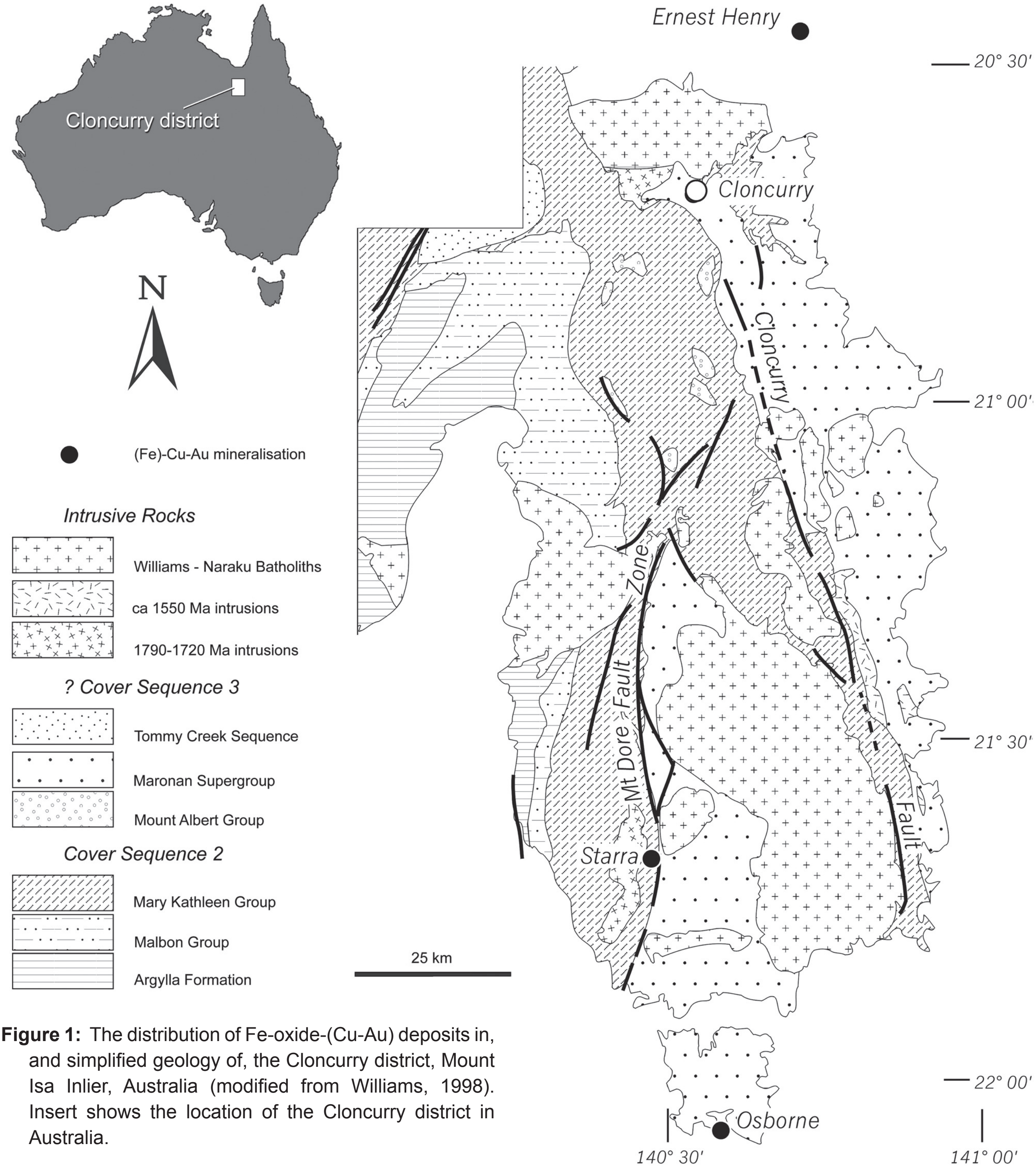


Figure 1: The distribution of Fe-oxide-(Cu-Au) deposits in, and simplified geology of, the Cloncurry district, Mount Isa Inlier, Australia (modified from Williams, 1998). Insert shows the location of the Cloncurry district in Australia.

Cloncurry District

The Cloncurry district mainly comprises the eastern exposed margin of the Mount Isa Inlier, and contains Fe-oxide-(Cu-Au) deposits that are hosted in Paleoproterozoic (ca 1760-1660 Ma; cf. Page and Sun, 1998) siliciclastic metasedimentary and metavolcanic rocks (Fig. 2). The district is largely composed of cover sequences 2 and 3 (ca 1740 Ma and ca 1670 Ma, respectively) that were deposited during periods of ensialic rifting, and overlay crystalline basement formed during the Barramundi Orgeny (ca 1880-1850 Ma; Etheridge *et al.*, 1987). Basement is not exposed in the Cloncurry district. The deposition of the evaporite-rich cover sequence 2 rocks and siliciclastic-rich cover sequence 3 rocks was also accompanied by the emplacement of various intrusions and volcanic rocks. These cover sequences were deformed and metamorphosed during the Isan orogeny, which peaked with a regional greenschist to upper amphibolite facies metamorphism associated with a major horizontal east-west compression (D2) (Rubenach and Barker, 1998). The timing of metamorphism is poorly constrained, and is further complicated by evidence for multiple metamorphic episodes (Rubenach and Barker, 1998; Foster and Rubenach, 2000) with two apparent metamorphic peaks at ~1584 Ma (M1) and ~1530 Ma (M2). Age determination of the syn-D2 granite intrusions (Williams and Phillips, 1992) has constrained D2 in the SE margin of the district to be ca 1550 Ma (Page and Sun, 1998).

Three main periods of tectonism have been described across the inlier (Page and Bell, 1986; Conners and Page, 1995), although more tectonic events have been recorded locally (Adshead-Bell, 1998; Mares, 1998; Rubenach and Barker, 1998). A regional association between localised corridors of intense D3 deformation, typically formed as NW to NE trending steep tectonic fabrics, and Cu-Au mineralisation has been recognised by many workers in the Cloncurry district (Rotherham, 1997; Adshead-Bell, 1998; Baker and Laing, 1998; Laing, 1998; Mark and Crookes, 1999).

Intrusions

The intrusions of the Williams and Naraku Batholiths (ca 1550-1500 Ma) that largely post-date D2 and the regional metamorphic peak represent the youngest felsic intrusions in the inlier, and have an outcrop exposure >1500 km^2. The ca 1540-1500 Ma intrusions were emplaced in an intracratonic environment, and have a pre-, syn- and post-D3 timing (Mark, 1998a; Pollard *et al.*, 1998). These intrusions are largely composed of alkaline to subalkaline, K-rich, magnetite-bearing granitoids (cf. Pollard *et al.*, 1998; Wyborn, 1998) that typically plot as ‘A-type’ (Whalen *et al.*, 1985). These younger intrusions range from diorite to syenogranite in composition (cf. Pollard *et al.*, 1998; Mark, 1999) and are typically more oxidised than similar older (ca. 1670 Ma) granitoids in the Western Fold Belt (Wyborn, 1998). Sodic intrusions of similar age are rare. The K-rich igneous rocks are similar to the intrusions that host Olympic Dam, and form part of a larger series of geochemically-similar Proterozoic intrusions that have a global distribution (Creaser, 1996; Mark, 1999).

Regional Alteration Systems

Formed over the same period as the Williams and Naraku Batholiths, the regionally extensive Na-Ca hydrothermal system in the Cloncurry district (>100 km^2) affected all rock types, especially the calc-silicate-rich rocks within cover sequence 2. The regional extent of Na and Na-Ca (e.g. actinolite, albite and diopside) alteration appears to have been formed by multiple periods of hydrothermal activity that locally overlapped (cf. de Jong and Williams, 1995; Mark and de Jong, 1996; Mark and Foster, 2000). This style of alteration is most intense in breccia zones along large structural conduits (e.g. Mount Dore and Cloncurry Faults) and within calc-silicate-rich units, and affects the host rocks to all major Cu-Au deposits prior to sulphide mineralisation (Rotherham, 1997; Adshead, 1996; Blake *et al.*, 1997; Baker, 1998; Mark and Crookes, 1999). This consistent relationship is complicated by overlap in the apparent ages of Cu-Au mineralisation (ca 1540 to <1500 Ma; Perkins and Wyborn, 1998), and Na-Ca (ca 1530-1515 Ma; cf. Mark, 1998a) and Na alteration (ca 1476 Ma; Perkins and Wyborn, 1998), which suggests that Na and Na-Ca alteration within individual deposits were probably formed by separate hydrothermal systems with different ages. The origin of the fluids associated with Na-Ca alteration in the district is controversial, and de Jong and Williams (1995) suggest a non-magmatic origin, whereas Mark *et al.* (1999) and Mark and Foster (2000) have argued for a magmatic component to Na-Ca alteration. Na-Ca alteration commonly depletes rocks in K, Fe, U, REE, S and Cu. These resultant fluids may play a significant role in providing metals for mineralisation (cf. Williams, 1994; Mark, 1998b; Oliver *et al.*, 2000).

Fe-oxide-(Cu-Au) Mineralisation

All significant deposits discovered in the Cloncurry district since the early ‘90s have been blind ore deposits found beneath unconformably overlain Mesozoic and Tertiary cover, and were primarily delineated by their positive magnetic anomalies detected by airborne magnetic surveys. A number of significant Fe-oxide-(Cu-Au) deposits (e.g. Ernest Henry, Osborne and Starra) have been discovered and exploited in the district. The timing of Cu-Au mineralisation in these deposits has historically been controversial, and the relationship to the regional magmatic and hydrothermal system was, until recently, largely speculative (de Jong and Williams, 1995; Oliver, 1995; Williams *et al.*, 1995; Mark, 1998a; Pollard *et al.*, 1998). However, as discussed above, new age determinations (Mark, 1998a; Page and Sun, 1998; Perkins and Wyborn, 1998; Pollard *et al.*, 1998) suggest that mineralisation was synchronous with granite intrusion and regional alteration, and up to 200 Ma after formation of the host rocks to ore. Conflict over the timing of these deposits arises for both the magnetite-rich ironstones and Cu-Au-U-REE mineralisation. Syngenetic hypotheses have been suggested for ironstones (Adshead, 1996; Davidson, 1998). Recently published stable isotope and fluid inclusion data (Adshead, 1996; Rotherham, 1997; Twyerould, 1997; Rotherham *et al.* 1998) suggests that the fluids associated with mineralisation were highly saline and had a significant magmatic component. However, the origin of the metals is still controversial.

Ernest Henry Host Rocks

Three main rock types occur around the orebody: (1) plagioclase phyric andesitic volcanic/hypabyssal rocks (ca 1740 Ma) (Figs. 3a-b); (2) various siliciclastic, calc-silicate-rich and graphitic metasedimentary rocks; and, (3) medium-grained metadiorite.

Meta-volcanic/Shallow Intrusive Rocks

The metavolcanic rocks are mainly composed of fine- to medium-grained euhedral plagioclase phenocrysts in a fine-grained, plagioclase-rich groundmass (Figs. 3a-b). Amygdales are rare, and are typically composed of quartz and/or carbonate. The age of these rocks at Ernest Henry has not been determined, although U-Pb age determination of zircon from similar rocks to the southwest suggest a crystallisation age ca 1740 Ma (Page and Sun, 1998).

Meta-sedimentary Rocks

Metasedimentary rocks are rare, and occur as (<10 m) intercalations within the metavolcanic rocks. Metasedimentary units with widths <1-2m are poorly preserved in the orebody. The main metasedimentary

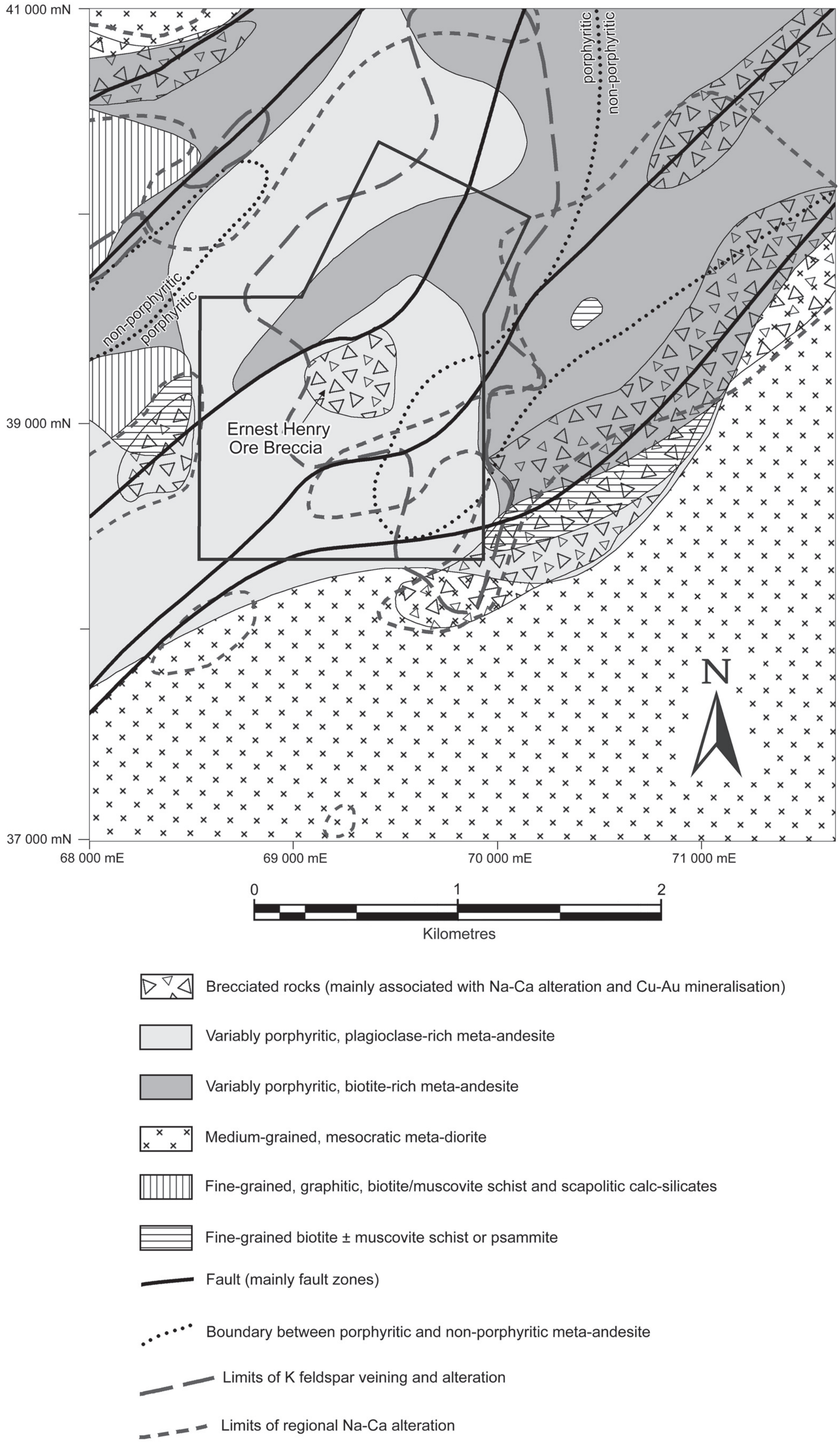


Figure 2: The interpreted plan section (1947 m RL) geology of the term lease around the Ernest Henry deposit. This map also shows the distribution of both regional and later K-feldspar alteration. The extent of hydrothermal breccias associated with mineralisation and regional alteration is also outlined.

rocks that occur within the mine lease are fine-grained muscovite-biotite psammite, and rare fine-grained scapolitic calc-silicate rock. These rocks display some control on the distribution of hydrothermal minerals produced via mineralisation, where muscovite-bearing psammite and calc-silicate rocks localise enriched quantities of arsenopyrite and garnet respectively.

Meta-diorite

The two metadiorite bodies to the north and south of the orebody have a crystallisation age ca 1660 Ma (Pollard and McNaughton, 1997). These intrusions have been metamorphosed to amphibolite facies and are largely composed of hornblende, plagioclase, magnetite, quartz and rare K-feldspar. The intrusions are composed of typically homogenous, medium-grained, mesocratic diorite, although they are locally coarse-grained, and have quartz- and K-feldspar-rich leucocratic segregations.

Structure

Three generations of ductile fabric have been observed in drill core, and various matrix-porphyroblast relationships in andalusite-bearing graphitic schist and scapolitic calc-silicate suggest a syn-D2 timing for the metamorphic peak around the Ernest Henry deposit. The growth of andalusite + biotite and meionitic scapolite + biotite metamorphic assemblages in pelite and calc-silicate respectively suggest that the metamorphic grade around the orebody reached lower to middle amphibolite facies, and was overprinted by retrograde hydrothermal alteration associated with mineralisation and syn-D3 ductile/brittle movement along shear zones. Evidence for pre-D3 tectonic fabrics in the host rocks to the ore is rarely preserved due to intense alteration and deformation between the host shear zones after D2.

The immediate hanging wall contact is marked by a sequence of strongly foliated felsic meta-volcanic rocks. The footwall contact represents a sharp change from brecciated felsic volcanic rocks associated with mineralisation, to sheared, strongly foliated rocks that are variably brecciated and veined by a post-mineralisation carbonate-rich hydrothermal event. A differentiated and penetrative cleavage is coincident with, and parallel to, the formation of the variably sheared contacts along the footwall and hanging wall, and locally affects mineralisation by boudinaging breccia clasts and matrix. This period of syn- to post-mineralisation deformation locally reactivated folds and tectonic fabrics that were produced earlier during D2.

Kinematic indicators (e.g. birds-wing-textures syn-ore veins) suggest that during ore deposition reverse-fault movement along the bounding shear zones formed a pipe-like zone of dilation in the K-feldspathised metavolcanic rocks between the two shear zones. The orientation of this dilational zone is consistent with the shape and dip of the Ernest Henry ore breccia. The relative timing of the syn-mineralisation fabric to other published studies in the region is unknown. However, $^{40}Ar/^{39}Ar$ age determination of biotite coincident with mineralisation (ca 1510-1500 Ma; cf. Twyerould, 1997) places broad constraints on the timing of these fabrics and the mineralisation event.

Hydrothermal Alteration

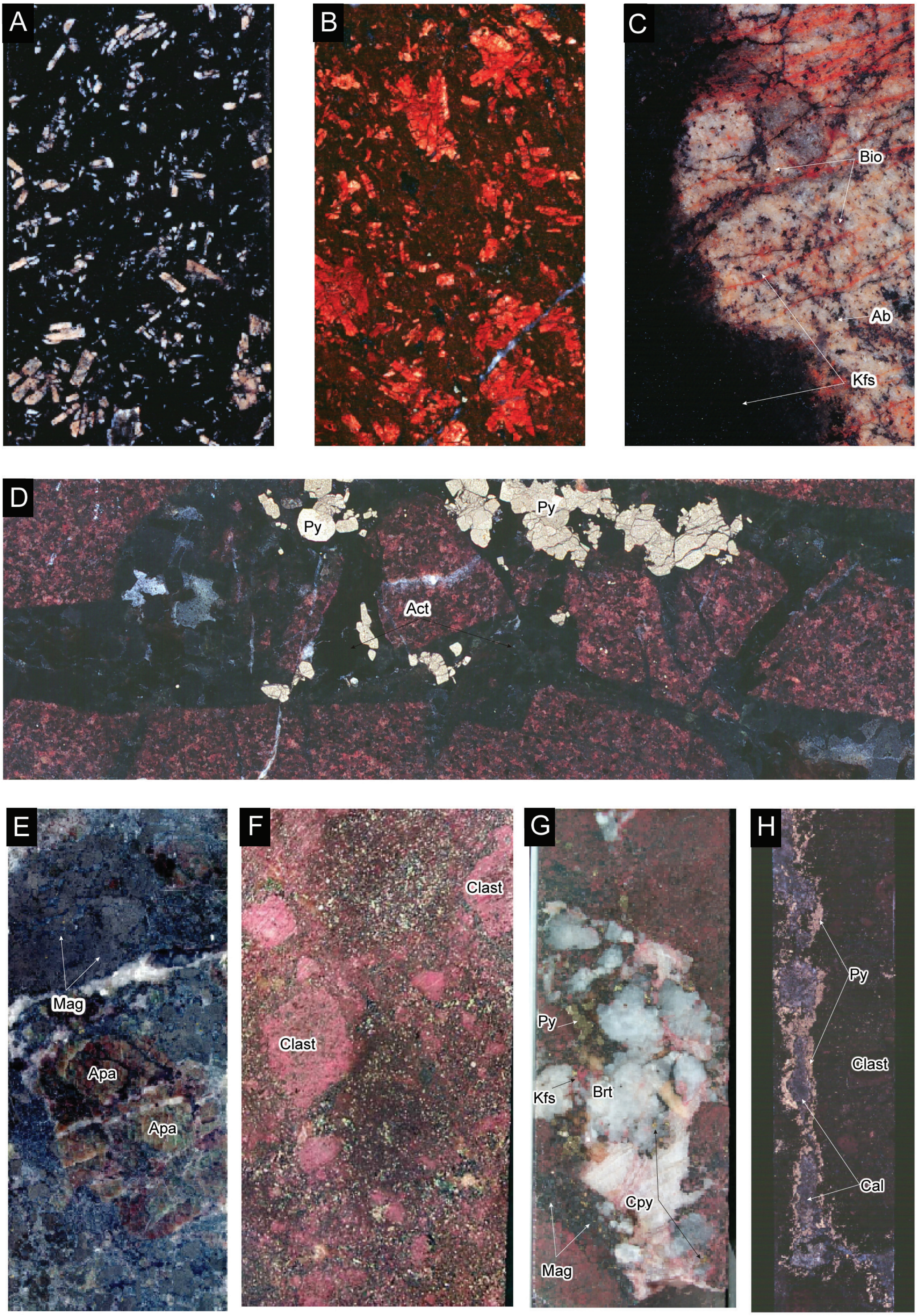
The rocks surrounding the Ernest Henry orebody preserve evidence for a complex post-peak metamorphic hydrothermal system. This system contains numerous generations of veining, alteration and brecciation simplified into four main mineral associations: (1) Regional Na-Ca alteration (Fig. 2); (2) Early mineralisation-related alteration; (3) Cu-Au mineralisation; and, (4) Post-Cu-Au mineralisation.

The four groups were divided largely on mineralogical and chemical associations, where hydrothermal events that have a similar mineralogy (e.g. regional Na-Ca alteration assemblages), chemistry and/or timing were grouped together. Consequently, the assemblages that contain albite, actinolite and so on were grouped into (1) (Fig. 2), whereas hydrothermal vein assemblages that are chemically linked to the Ernest Henry hydrothermal system, but pre-date Cu-Au mineralisation were grouped into (2) The hydrothermal mineral assemblages that were spatially and temporally associated with Cu-Au mineralisation comprise group three, and the vein and alteration assemblages that post-date Cu-Au mineralisation were assigned to group four.

The distribution of hydrothermal alteration assemblages in the term lease is largely controlled by the NE trending faults and fault zones that occur near the contacts with the metadiorite intrusions, and along the extensions of the fault/shear zones that bound Cu-Au mineralisation (Fig. 2). For the most part, hydrothermal alteration associated with regional Na-Ca alteration is restricted to vein, breccia and alteration assemblages that are distal to the deposit (Figs. 2, 3c-d), where most brecciation is coincident with extensive alkali alteration (albite or K-feldspar). These extensively altered areas are also overprinted by hydrothermal assemblages associated with Cu-Au mineralisation. The Cu-Au related hydrothermal assemblages are largely restricted to the mine lease, although K-feldspar- and garnet-rich alteration and veining extend NE of the mine lease. (Figs. 2, 3b-c, f and g).

1. Regional Na-Ca Alteration

Na-Ca alteration mainly occurs as albitic plagioclase-, magnetite-, clinopyroxene- and amphibole-rich veining, fault-related breccia-fill and associated alteration (cf. Figs. 3c-e). These hydrothermal stages are identical to styles of regional Na-Ca alteration (ca. 400-500^{o}C; de Jong and Williams, 1995; Oliver, 1995; Mark and Foster, 2000) that is prevalent throughout the Eastern Fold Belt. This alteration affected earlier albitised rocks. The strong antipathetic relationship between Na-Ca and K-feldspar alteration is largely related to overprinting by the latter. Some evidence for this interpretation is represented by albitised rocks cut and replaced by hematitic K-feldspar in the hanging wall of the deposit (Fig. 3c).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2. Pre-mineralisation-related Alteration

This group of pre-mineralisation alteration has many chemical and mineralogical characteristics of the ore, but contains only minor sulphides, are typified by multiple stages of K-feldspar-, biotite-, amphibole-, magnetite-, garnet- and carbonate-bearing veins, fault-related breccia and alteration. Homogenisation temperatures from populations of primary fluid inclusions and oxygen isotope geothermometry suggest temperatures between 400 and 550^{o}C (Blake *et al.*, 1997; Mark, unpublished). Two of the most significant hydrothermal associations within this group are represented by fine-grained biotite-magnetite alteration and garnet-K-feldspar-biotite-pyrite-bearing veining and alteration. Other stages include medium- to coarse-grained magnetite-biotite alteration closer to the ore and localised K-feldspar veining sporadically distributed throughout the term lease area. The two volumetrically significant stages are discussed in more detail below.

Fine-grained biotite-magnetite Alteration

Fine-grained biotite, magnetite and rare K-feldspar alteration cuts albitised rocks (Figs. 3a and c) and is commonly most intensive in volcanic rocks surrounding the Ernest Henry orebody. The pathways for this alteration are particularly difficult to discriminate, although minor cracks filled with biotite and magnetite in plagioclase phenocrysts testify to their hydrothermal origin. The intensity of this alteration is highly variable and is typically more prevalent in more mafic host rocks, which suggests an apparent selective nature to this stage of alteration. This style of alteration is largely unique to the host rocks around Ernest Henry. The original distribution and intensity of this style of alteration is overprinted by later intense Na-Ca and hematitic K-feldspar alteration, although current data suggests that this style of alteration occurred up to kilometres from the deposit.

Garnet-K-feldspar-Biotite Veining and Alteration.

The Mn-rich garnet- and K-feldspar (Ba)- and biotite (Mn)-bearing hydrothermal veining and alteration associations within the Ernest Henry hydrothermal system formed prior to economic mineralisation, but have mineralogical and chemical affinities with mineralisation. The rocks affected by this association occur largely near or within the rocks in the footwall to the deposit, and also extend to the NE along the footwall shear zone, up to 1.5 km from the orebody. The close spatial relationship between garnet-rich veining and alteration and Cu-Au mineralisation suggests that these two stages could be genetically related, and as such the larger distribution of the earlier non-economic alteration could represent a useful mineralogical and chemical indicator toward Cu-Au mineralisation.

3. Mineralisation

K-feldspar Veining and Alteration.

K-feldspar veining and alteration occurs largely within the bounds of the mine lease, and also NE-trending fault zones distal to mineralisation (Figs. 2, 3b-c). Hematitic K-feldspar veining and alteration is commonly associated with quartz, calcite, magnetite, fluorite and titanite (+ rutile) vein fill and hematitic K-feldspar (+ titanite) alteration. The veins typically vary between <2 to >80 mm. The veins are variably affected by syn- to post-mineralisation tectonic fabrics, and are commonly necked and boudinaged. The hematitic K-feldspar alteration is typically fine-grained and commonly affected plagioclase in the host rocks. This hydrothermal association is most intense around the orebody, and decreases in the intensity outwards (<2 km from the orebody). This crude zonation is interpreted to be coincident with a decrease in the degree of fluid flow during this stage, where the most altered rocks represent the core of the system.

Figure 3: (Facing page) Photographs of various host rocks and alteration phases associated with the Ernest Henry hydrothermal system.

- **a**. A plagioclase-phyric meta-volcanic rock with a dark, fine-grained, biotite-rich matrix. The biotite-rich matrix is a product of fine-grained biotite-magnetite alteration. The field of view is ca 50 mm across.
- **b.** An extensively hematitic K-feldspar altered plagioclase-phyric meta-volcanic rock with a fine-grained plagioclase-rich matrix. This rock preserves a remnant flow banding defined by aligned feldspar grains, and contains few quartz amygdales. The field of view is ca 50 mm across.
- **c.** A partly albitized fine-grained meta-volcanic rock showing extensive fine-grained albitisation (left). This rock preserves evidence for three stages of hydrothermal alteration: 1) early fine-grained albitization (pale); 2) fine-grained biotite and magnetite veining; and, 3) thin hematitic K-feldspar veining and alteration. Abbreviations: Ab, Albite; Bio, biotite; Kfs, K-feldspar. The field of view is ca 50 mm across.
- **d**. A fracture-controlled breccia (diorite) associated with Na-Ca alteration and veining. The breccia infill is composed of actinolite, magnetite, titanite, diopside and pyrite. Abbreviations: Act, actinolite; Py, pyrite. The field of view is ca 200 mm across.
- **e.** A hydrothermal vein associated with regional Na-Ca alteration containing coarse-grained magnetite, apatite and minor actinolite, and cut by later calcite veins. The field of view is ca 50 mm across.
- **f.** A typical hydrothermal ore breccia at Ernest Henry with a matrix composed of magnetite and sulphides (pyrite and chalcopyrite). The field of view is ca 50 mm across.
- **g.** A typical sulphide mineralised vein associated with the later stages of Cu-Au mineralisation. Note that the vein cuts ore breccia, and contains coarse-grained barite, fluorite, quartz, pyrite and chalcopyrite. Abbreviations: Brt; barite, Cpy; chalcopyrite, Kfs; K-feldspar, Mag; magnetite, Py; pyrite. The field of view is ca 50 mm across.
- **h.** A pyrite-rich vein associated with late carbonate flooding that cuts the hydrothermal ore breccia. Note the clasts and disseminated sulphides in the previous breccia. Abbreviations: Cal; calcite, Py; pyrite. The field of view is ca 70 mm across.

Stage 1- Cu-Au Mineralisation

The first stage of economic Cu-Au mineralisation represents the main ore-forming event, and was associated with a matrix-supported hydrothermal breccia that is enveloped by crackle veined K-feldspar altered meta-volcanic rocks (Fig. 3f). The transition from hydrothermally brecciated to crackle veined rock typically marks a change from economic to uneconomic mineralisation. The breccias typically contain 5-20 mm subrounded to rounded meta-volcanic and rare biotite altered meta-sedimentary clasts. The matrix is largely composed of magnetite, calcite, pyrite, biotite, chalcopyrite, K-feldspar titanite and quartz. Accessory minerals include garnet, barite, molybdenite, fluorite, amphibole, apatite, monazite, arsenopyrite, a LREE fluorcarbonate, galena, cobaltite, sphalerite, scheelite, uraninite, and tourmaline.

The breccias are most strongly deformed where biotite- and/ or carbonate-rich, and commonly contain elongate, aligned clasts and recrystallised breccia infill. Economic grade, veining and brecciation, pyrite content and clast rounding are all strongly correlated and suggest that the mineralised zone was the strongest locus of dilatency and fluid flow.

Stage 2 - Cu-Au Mineralisation

The second stage of mineralisation occurs mainly as a network of veins that cut earlier infill-supported ore-breccias (Fig. 3g), but contains a mineralogy that is largely identical, suggesting a strong relationship to earlier mineralisation. These veins are largely composed of calcite, quartz, K-feldspar, magnetite (including hematised magnetite), hematite, chalcopyrite, pyrite, biotite, barite, apatite, fluorite, titanite, garnet, amphibole, molybdenite, arsenopyrite, sphalerite, galena, monazite, a LREE-rich fluorcarbonate and scheelite. Three populations of primary fluid inclusions are trapped within ore-stage quartz, and they represent: 1. hypersaline fluids; 2. saline aqueous fluids, and; 3. CO_2-rich fluids. Fluid inclusion homogenisation temperatures from heating experiments suggest that mineralisation occurred over a range temperature >350-450°C.

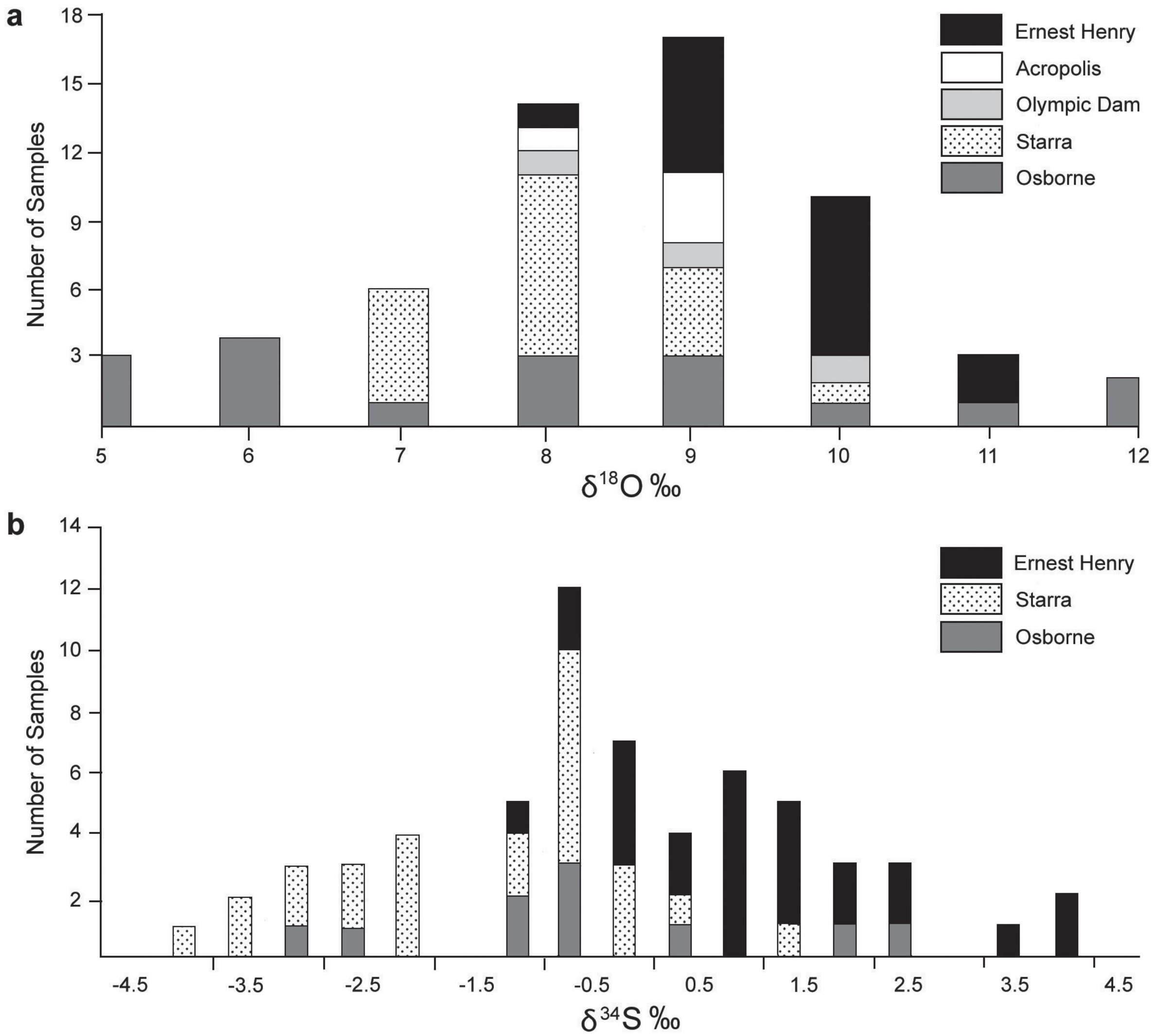

Figure 4: **a**. Distribution of the calculated $\delta^{18}O$ composition of fluids using magnetite associated with selected Fe-oxide-(Cu-Au) deposits in the Cloncurry district and Stuart Shelf, Australia (cf. Oreskes, 1990; Adshead, 1996; Twyerould, 1997; Rotherham *et al.*, 1998; Mark and Crookes, 1999). The fractionation constants of Zheng and Simon (1991) were used to calculate the fluid $\delta^{18}O$ using the interpreted ore-stage temperature conditions for each deposit.
b. Distribution of the $\delta^{34}S$ of chalcopyrite at the Ernest Henry, Osborne and Starra Fe-oxide-(Cu-Au) deposits in the Cloncurry district (Adshead, 1996; Twyerould, 1997; Rotherham *et al.*, 1998; Mark and Crookes, 1999).

Calcite, quartz, K-feldspar, chalcopyrite, barite and magnetite are the dominant mineral constituents. These veins exhibit a number of differences to the earlier ore breccia as they contain coarser grained barite, quartz, fluorite, magnetite and chalcopyrite, and significantly more hematite. The presence of extensive hematisation of magnetite, rare bladed magnetite, crystalline hematite and fluorite in these veins suggests that they were deposited from more evolved, lower temperature, and possibly more oxidised fluids, which probably represent an evolution of stage 1 fluid through cooling and/or fluid/rock interaction.

4. Post-mineralisation Alteration

Group 4 is mostly comprised of multiple stages of calcite-dolomite- and/or quartz-rich veining and alteration. Late carbonate flooding represents the most volumetrically significant stage of hydrothermal activity after Cu-Au mineralisation, and is discussed in more detail below.

Late Carbonate Flooding

This hydrothermal vein and breccia association post-dates Cu-Au mineralisation (Fig. 3h), and is mainly composed of medium-grained carbonate (calcite and dolomite), quartz, biotite, actinolite, pyrite, magnetite and minor garnet and chalcopyrite. Late carbonate flooding is largely characterised by irregular veins (5 to >50 mm) and hydrothermal infill-supported breccia which is predominantly restricted to rocks in the footwall of the deposit. Calcite and dolomite are the main constituents, and are typically extensively recrystallised to equigranular fine- and medium-grained polygonal grains. Biotite, magnetite and minor garnet alteration occurs at the margin of these veins. Pyrite alteration is also observed. The breccias typically contain subrounded to rounded clasts (*ca.* 10-100 mm) that were affected by previous stages of mineralisation-related alteration**.**

Discussion

Detailed paragenetic studies of the rocks around the Ernest Henry ore deposit show that hydrothermal activity associated with mineralisation largely post-dated regionally-extensive Na-Ca alteration. The age and duration of this activity is not fully constrained, although the age of mineralisation is probably >1510-1500 Ma (Twyerould, 1997), given that they represent biotite Ar^{40}/Ar^{39} ages which have a closure temperature down to 250°C. The different timings of regionally-extensive Na-Ca alteration and Cu-Au mineralisation, combined with their contrasting mineral and fluid compositions, suggests these were probably two separate hydrothermal systems that overlapped in space. However, the occurrence of Na and/or Na-Ca alteration prior to mineralisation at deposits of different ages throughout the district suggests that they apparently have a closer relationship (cf. Williams, 1994; Oliver *et al.*, 2000). On a broad-scale the effects of these two systems exhibit a strong antipathetic association that is defined by a potassic-rich core with Na-Ca-rich outer halo. However, on closer inspection, relics of earlier Na-Ca alteration are found in the core of the system, and suggest that the antithetic association was produced by the younger mineralising system overprinting previously altered rocks. This is interpreted to suggest that host structures to mineralisation were active during earlier Na and Na-Ca alteration.

The Ba, Mn, K and Fe enriched geochemistry of the altered rocks associated with the Ernest Herny hydrothermal system differs from the alteration haloes associated with the Starra and Osborne deposits, and is most closely associated with the chemical characteristics of the Monakoff Cu-Au deposit north of Cloncurry (cf. Davidson and Davis, 1997). However, the K-feldspar-, magnetite-, calcite- and garnet-rich mineralogy and K-, Ba-, Mn-rich chemistry of the Ernest Henry hydrothermal system is a unique alteration mineralogy in the district. The deposition of the disseminated magnetite-, pyrite- and chalcopyrite-rich ore during hydrothermal brecciation suggests that mechanisms for ore deposition at Ernest Henry differed between the other main replacement-style Fe-oxide-(Cu-Au) deposits (e.g. Osborne and Starra) in the district. However, even though these deposits exhibit significant differences in their mineralogy and chemistry, stable isotope data from ore-stage sulphides, oxides and silicates suggest that they were formed by fluids with similar $\delta^{18}O$ and $\delta^{34}S$ (Figs. 4a-b). The calculated $\delta^{18}O_{fluid}$ and $\delta^{34}S_{fluid}$ of the ore-stage fluids mainly range between 7-10‰ and –3 to 2‰ respectively (cf. Davidson and Dixon, 1992; Adshead, 1995; Twyerould, 1997; Rotherham *et al.*, 1998; Mark and Crookes, 1999; Baker *et al.*, submitted), and suggest a dominant magmatic component to fluids in all of these deposits.

The consistent typical magmatic $\delta^{18}O$ and $\delta^{34}S$ composition of fluids associated with these ores suggest that the different mineralogy and geochemistry could reflect variations in: 1) the composition of the source intrusions at the time of fluid saturation; 2) changes in the intensive parameters (e.g. T, P, fO_2); 3) cooling; 4) mass exchange with wall rocks of varying composition; 5) fluid mixing, or; 6) a combination of influences described in 1 to 5; which do not affect the stable isotope composition of the fluids. As a consequence, the mineralogy and chemistry of the deposits, rather than their $\delta^{18}O$ and $\delta^{34}S$ composition, appear to be the most important indicators allowing interpretation of their depositional mechanisms, and therefore have significant implications for defining effective methods for their exploration.

Physical Controls on Ore Deposition

All deposits in the Cloncurry district record an earlier period of extensive pre-mineralisation alkali metasomatism. In most of the deposits albitisation is the dominant style of alkali alteration, although at Ernest Henry K-feldspathisation is dominant around the ore. The effects of these styles of alteration, whether they be sodic or potassic, act in the same manner and produce homogeneous, competent bodies of rock that form the locus of fluid flow associated with veining and brecciation during subsequent tectonism (cf. Adshead-Bell, 1998; Mark, 1998b).

Within the Ernest Henry term lease there are two main stages that formed hydrothermal infill-supported breccia. These breccia stages were either associated with regional Na-Ca alteration, or with later Cu-Au mineralisation, and are mainly localised along the major faults or fault zones within the lease. More importantly, these breccias are largely localised in previously alkali feldspar altered (albite or K-feldspar alteration) rocks, and this association suggests that: 1) the rocks affected by extensive alkali alteration were more likely to exhibit brittle failure during subsequent periods of deformation, and, 2) the NE-trending faults or fault zones had a prolonged history which recorded multiple periods of hydrothermal activity.

This extensive alkali alteration and later coincident brittle failure are common at most Cu-Au deposits in the Cloncurry district, and are particularly emphasised where hydrothermal activity along fault or shear zones produced heterogeneity in the mechanical behaviour between feldspathic and phyllosilicate/carbonate-rich rocks. Rheological heterogeneities, whether primary or related to early alteration, are important controls at nearly every deposit in the district (cf. Adshead-Bell, 1998; Baker, 1998; Baker and Laing, 1998; Mark, 2000) However, even though these features were probably crucial for the localisation of mineralisation, other factors (e.g. age and orientation of the host structure; age and composition of proximal intrusions; ore fluid(s) composition; host rock composition; proximity to source; and degree of fluid mixing or unmixing) must also control the final site of ore deposition.

Chemical Controls on Ore Deposition

At Ernest Henry sulphide deposition was not related to the replacement of previous ironstone bodies (e.g. Starra Au-Cu), and most of the magnetite in and around the orebody was deposited during the ore-stage event. This lack of a Fe-rich reactive host implies that a mechanism other than redox reactions associated with hematisation of magnetite ($2Fe_3O_4 + 0.5O_2 \leftrightarrow 3Fe_2O_3$) was responsible for ore deposition. Twyerould (1997) suggested that hot, chemically reactive fluids deposited the ore selectively digesting K-feldspathised rock during mineralisation, which buffered the fluid a_{HF} and produced biotite with a fluoro-phlogopite component. This mechanism was also interpreted to have produced the breccia-texture of the ore. However, our interpretation is that the Ernest Henry breccia formed largely by dilation in response to reverse fault movement along shear zones that bound extensively K-feldspar altered volcanic rocks which behaved brittely during this period of deformation.

The ore at Ernest Henry averages 1.1 % Cu and 0.54 g/t Au, and this ratio of Cu to Au in the hypogene ore is largely consistent throughout the ore body, and is mainly independent of grade. This close association suggests that both Cu and Au were broadly deposited at the same time, and probably via the same mechanism. The high temperature (>400^{o}C) and high salinity (>26 wt% $NaCl_{equiv.}$) nature of ore-stage fluids at Ernest Henry are similar to other Cu-Au deposits in the district (cf. Williams and Skirrow, this volume), and suggest that both Cu and Au, and probably Fe and Ba, were carried as metal-chloride complexes. Given the propensity of these complexes to be less soluble at increasing lower fluid temperatures and salinities, the ore minerals (e.g. pyrite, chalcopyrite, magnetite and barite) were probably deposited via a mechanism(s) that involved fluid mixing and/or cooling during hydrothermal brecciation. The barite- and fluorite-rich character of the ore assemblage also suggests that, given the low solubility of barite in sulphur-bearing oxidised fluids, and fluorite in cooling conditions, their component elements were most likely carried by different fluids. A fluid mixing model for the Ernest Henry ore is consistent with the interpretation of Gunton *et al.* (2000), who also suggest that the Re/W composition of molybdenite in the ore is compatible with being derived from a magmatic fluid. The complicated composition (e.g. K, Ba, S, Fe, Cu, U, CO_2, F and Cl) and mineralogy (e.g. barite, fluorite, magnetite, pyrite and chalcopyrite) of the ore suggests that more than one source type is required to produce fluids with significant chemical diversity to deposit this ore association. The origin of all of the fluid sources at Ernest Henry is unconstrained, but further work involving radiogenic isotope characterisation (e.g. Sr, Sm, Nd and Pb) of the ore and associated hydrothermal phases is ongoing. A similar fluid mixing hypothesis has also been invoked at Olympic Dam (Haynes *et al.*, 1995), Salobo (Lindenmayer, 2000), in the Great Bear Magmatic Zone (Goad, 1999), and is also considered an important component in the Tennant Creek field (Skirrow, 1999).

Breccia-hosted Fe-oxide-(Cu-Au) Deposits: Fluid Mixing a Common Link to Their Diverse Chemistry?

The brecciated, and mineralogically and chemically diverse character of the Ernest Henry ore is comparable to the ore at Olympic Dam, South Australia and Sue-Dianne, North West Territories, Canada. The three deposits all have a common association with potassic alteration, taking the form of K-feldspathisation at Ernest Henry and Sue-Dianne, and sericitisation at Olympic Dam. This change in mineralogy, from K-feldspar to sericite, may reflect a temperature and/or pH difference in the systems, with K-feldspathisation representing alteration from higher temperature and higher pH fluids. Studies of the hydrothermal conditions associated with ore deposition at Olympic Dam (Oreskes and Einaudi, 1990; 1992) and Ernest Henry (Twyerould, 1997; Mark and Crookes, 1999) are consistent with Olympic Dam representing a lower temperature and shallower style of mineralisation. The dominant Fe-oxide association with mineralisation also suggests some continuum between the temperature and fO_2 of the three deposits, where the hematite-dominant systems at Olympic Dam and Sue-Dianne probably represent both lower temperature and/or higher oxygen fugacity than the magnetite-dominant system at Ernest Henry. This continuum is also observed in the nature of the Cu sulphide association in the ore, where Ernest Henry contains chalcopyrite, Sue-Dianne contains chalcopyrite-bornite, and Olympic Dam contains chalcocite-bornite-chalcopyrite. Consequently, the three hydrothermal systems probably represent a spectrum of deposit styles within the Fe-oxide-(Cu-Au) family, where Ernest Henry represents a relatively lower fO_2, hotter and deeper example of the Olympic Dam system, with the Sue-Dianne deposit representing a style of mineralisation between the two.

A magmatic component to at least one of the ore fluids has been interpreted for all of these deposits (Haynes *et al.*, 1995; Goad *et al.*, 2000; Gunton *et al.*, 2000), and is consistent with the deposits being associated with coeval intrusions. This association may play an important role in defining the geochemistry of these systems as the coeval intrusions are commonly enriched in a suite of elements (e.g. K, Ba, U, Th and REE) that are also associated with mineralisation. If these deposits share a common underlying geochemical relationship to coeval intrusions, their apparent continuum in characteristics must be directly related to changes in crustal depth magmatic fluid chemistry, chemistry of other fluid reservoirs, host rock chemistry and geology at deposit site. This variation influnces both the geochemical and geophysical expressions of these systems, and is significant for developing exploration programs that have the flexibility to explore Fe-oxide-(Cu-Au) deposits that exhibit a spectrum of mineralogical and chemical associations.

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