Hydrothermal alteration footprints and gold mineralization in the St Ives gold camp

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Introduction

This research project focuses on delineating hydrothermal alteration patterns in three dimensions and through time as well as at different scales from camp- to deposit-, to ore-shoot scale. The analyses of these hydrothermal “footprints” are primarily guided by the geometry and kinematics of fault zones at all scales and geophysical signatures such as magnetics and gravity that delineate porphyry bodies at depth. Detailed field and petrographical analyses are then complemented by whole rock and trace element analyses of alteration zones, mineral analyses of key hydrothermal alteration minerals as well as fluid inclusion and stable isotope analyses. The spatial distribution of hydrothermal alteration types and their mineralogical and chemical signals are then interpreted with respect to fluid sources, ore transport and depositional processes to provide guides to gold mineralization. The key to unravelling hydrothermal alteration footprints and their use for exploration targeting is to understand the relative timing of alteration types as well as their spatial distribution. In addition, spatial information on the variation of stable isotope compositions is vital to determine metal transport and depositional processes, and in combination with multi-element geochemistry and fluid end-member composition data sets, provide critical input parameter into geochemical modeling of metal transport and depositional processes.

The aim of this paper is to summarize the key results of current studies (some are still on-going) and also discuss potential models to explain the mineralogical and chemical footprints with respect to ore deposition.

Geological setting

The St Ives gold camp is located in the southern part of the Norseman-Wiluna greenstone belt within the Eastern Goldfields Province of the Yilgarn Craton of Western Australia. The St Ives gold camp is hosted in predominantly mafic-ultramafic lavas and intrusions that have been metamorphosed to upper greenschist and lower amphibolite facies. The greenstone sequence has been intruded by felsic to intermediate porphyry stocks which predate, are synchronous with and post-date gold mineralization.

The St Ives gold camp is bounded by two major NNW-trending regional structures: the Boulder-Lefroy fault to the east and the Merougil fault to the west, and has undergone four major Archaean deformation events. The first (D1) produced regional south-over-north thrusts. The second (D2) produced upright, NNW-trending, gently plunging folds, such as the Kambalda anticline. The third event (D3) generated brittle-ductile, NNW-trending, oblique-sinistral strike-slip fault systems that localized major N-trending, reverse, gold-bearing shear zones. During the fourth event (D4), NE-trending, dextral faults offset stratigraphy and earlier fault systems, and
caused dextral-reverse reactivation of these earlier faults. Gold mineralization is mainly controlled by the D3 and D4 deformation events.

Hydrothermal alteration

In the St Ives camp, a range of alteration styles are documented. Oxide and sulphate assemblages are correlated to reduced and oxidized conditions using $f_{O_2}$-$a_{\Sigma S}$ diagrams at 400°C and 2 kbars. Documented styles are: 1) carbonate associated with deformation along transcrustal structure (Lefroy), 2) epidote-calcite-magnetite$_1$-pyrite-chalcopyrite-quartz, 3) magnetite$_2$ halo around gold-bearing structures (interpreted as oxidized hydrothermal fluid), 4) pyrrhotite±pyrite alteration flanking oxidized domains on a camp scale (interpreted as reduced hydrothermal fluid), and 5) Au-associated, zoned chlorite-biotite-feldspar-carbonate-pyrite quartz alteration. Widespread carbonation is typically recorded in ultramafic hostrocks. Its spatial distribution and textural setting is being studied by Heydari (this volume) and is not discussed further.

Epidote-calcite-magnetite$_1$-pyrite-chalcopyrite-quartz alteration is spatially associated with felsic to intermediate porphyries at a camp scale. At a drill core scale, this alteration style is developed typically adjacent to the contact of porphyry intrusions. Epidote and magnetite$_1$ occur in massive bands and replace pre-existing amphibole. Carbonate-pyrite±quartz veins and quartz±chalcopyrite±magnetite$_1$±carbonate? veins overprint epidote and magnetite$_1$ assemblages. Importantly, epidote dominant alteration pre-dates gold mineralization, but is locally spatially associated with gold-bearing structures.

In the camp, two main domains of hydrothermal alteration are mapped out: 1. Magnetite$_2$ and magnetite$_2$-pyrite assemblages (oxidized), and 2. pyrrhotite and pyrrhotite-pyrite assemblages (reduced). The oxidized assemblage is focused around massive porphyry stocks. This spatial association is well developed around a kilometre-scale gravity low which is interpreted to reflect buried intrusions beneath the Victory-Defiance gold deposits, but also around smaller-scale porphyry stocks at the Revenge deposits. The domains with reduced alteration assemblages flank those of oxidized alteration assemblages on a camp scale. They are well developed to the SW and NE of the Victory-Defiance deposits and the Revenge deposits. Locally, reduced and oxidized alteration assemblages occur intermingled at the Revenge deposits.

At a drill core scale, reduced alteration assemblages are fine-grained and disseminated within mafic host rocks and occupy zones distal to gold mineralization. Reduced assemblages occur also in quartz-pyrrhotite veins which cross cut mafic host rock with disseminated pyrrhotite-pyrite alteration. Outer proximal zones (to gold) are characterized by a broad halo of magnetite$_2$ around gold-bearing structures, whereas inner proximal zones contain magnetite$_2$ and magnetite$_2$-pyrite assemblages. The magnetite$_2$ halo overlaps partially with typically gold-associated distal chlorite-carbonate and intermediate biotite-chlorite-carbonate alteration zones.

At a micro-scale, magnetite$_2$ appears to be in equilibrium with biotite, as indicated by biotite inclusions in the magnetite. Magnetite$_2$ (oxidized assemblage) forms inclusions in the cores of gold-associated pyrite grains and is replaced by hematite inclusions (very oxidized assemblage) in the outer zones of the pyrite grains. Importantly, magnetite$_2$ inclusions in pyrite have locally a thin rim of hematite. Within the proximal (to gold) feldspar-carbonate-pyrite zone, magnetite is least abundant to absent. Locally, clusters of magnetite are present, but texturally in disequilibrium with feldspar-carbonate-pyrite alteration. Magnetic susceptibility readings are high outside the feldspar zones and drop to a minimum within the feldspar zones.

Relative timing of hydrothermal alteration

Spatial relationships indicate that epidote-dominated alteration developed early in the alteration sequence. However, in most places it does not spatially overlap with later magnetite$_2$ and gold-related feldspar alteration. Locally, relict (?) epidote is present in feldspar alteration zones. Most of the magnetite$_2$ halos pre-date gold mineralization. However, the presence of magnetite$_2$ inclusions within gold-associated pyrite indicate that this magnetite was stable during the early phases of gold mineralization. Subsequently, hematite was stabilized over magnetite, as
indicated by hematite inclusions in the rims of gold-associated pyrite. The relative timing of the reduced pyrrhotite-pyrite assemblage is unclear at present. The reduced domains are typically separated from oxidized alteration domains by unaltered or poorly altered wallrock. Within the reduced assemblage, textures indicate that one generation of pyrite pre-dates pyrrhotite. The evolution of the redox state of hydrothermal alteration can only be safely assessed in the oxidized to very oxidized domains. Textural relationships clearly indicate that the very oxidized pyrite-hematite assemblage post-dates the oxidized magnetite2-pyrite assemblage.

Stable isotope variations in the St Ives Camp

Compilation of the significant historic data sets of C, O isotopes in carbonate and S isotopes in sulphates, as well as acquisition of new data, is providing a significant constraint on the variation of fluid temperatures and redox state of hydrothermal fluids in the St Ives gold camp. The variation of $\delta^{18}O$ in carbonate is particularly sensitive to temperature with the lightest $\delta^{18}O$ values reflecting the highest temperature fluids. In contrast, the variations in $\delta^{13}C$ in carbonate and $\delta^{34}S$ in pyrite are sensitive to redox changes in the hydrothermal fluid. Redox variations in the carbon and the sulphate systems are interpreted to mirror variations in the CH$_4$/CO$_2$ and H$_2$S/sulfate ratios, respectively. In the Revenge area, the lightest $\delta^{18}O$ values occur in the central part of the field west of Revenge (LD7114: 7.5 to 9.5 ‰ $\delta^{18}O$, VSMOW) and are heavier to the east in the vicinity of the Playa Shear (LD70426 and LD70449: 9.3 and 12.5 ‰ $\delta^{18}O$) consistent with carbonate precipitation at progressively cooler temperatures distal to mineralization and also to the main porphyry intrusions. The limited variation in $\delta^{13}C$ over this interval (-6.8 and -3.2 ‰ $\delta^{13}C$, PDB) is an indication that the fluid is dominated by CO$_2$. The inferred $\delta^{13}C$ of the CO$_2$ in the fluid is close to zero suggesting that the dominant (?) reservoir for CO$_2$ was seawater with little reduction of the CO$_2$ during recycling within the greenstones.

In the Revenge, Victory-Defiance, Argo and Junction deposits, significant variations of $\delta^{13}C$ in carbonate with limited variations of $\delta^{18}O$ are indicative of a variation in CH$_4$/CO$_2$ in the fluid. The lighter $\delta^{13}C$ signal in proximal carbonate in pyrrhotitic (reduced) assemblages is taken to reflect CH$_4$ in the fluids, which is consistent with CH$_4$-rich fluid inclusions in the Junction deposits. In the Victory-Defiance profile across the central corridor, $\delta^{13}C$ values are lighter (-8.7 to -7.1 ‰) in the altered Flames Porphyry in the central part of the Victory-Defiance deposit and again Britannia Shear on the eastern side of the central corridor. At both these locations, the reduced and oxidized alteration domains overlap. From available data, $\delta^{13}C$ values are heavier (-7.4 to -4.4 ‰) in domains of the oxidized alteration assemblage.

Within in the Victory-Defiance area, the sulphate isotope values also vary with respect to reduced and oxidized mineral domains. Within the oxidized domains, $\delta^{34}S$ ranges from -7.9 to -6.8 ‰. However, $\delta^{34}S$ ranges from +1.6 ‰ to -6.5 ‰ in reduced domains or in domains where reduced and oxidized domains overlap, which indicates that the gradient in $\delta^{34}S$ in pyrite across the Victory-Defiance deposit corresponds with the change in sulphate/oxide mineralogy. Available $\delta^{34}S$ values for background pyrite in the Kapai Slate, Black Flag and Merougil beds, west of the Kambalda Dome and in the Tramways area, distant from the St Ives Camp, range from 0.3 to 0.7 ‰. Two samples of least altered carbonaceous, pyritic Kapai Slate from the Central Corridor of the St Ives camp have values of 0.7 and 1.8 ‰ $\delta^{34}S$. In the absence of any evidence that the sulphate isotope values within the camp, either negative or positive, were influenced by the background sulphate in the rock mass, they are interpreted in terms of the chemical processes that operated within the hydrothermal system. The negative signals in sulphate are taken to reflect the presence of sulphate in oxidized fluid(s) and the positive signals are taken to reflect reduction of this sulphate to H$_2$S in the reduced environments within the gold system. Locally, a heavy $\delta^{18}O$ in carbonate, up to 18-25 ‰, with $\delta^{13}C$ around -5 to -7 ‰ in the Revenge and Victory deposits could reflect magmatic CO$_2$. The signal is unconstrained paragenetically.
Discussion

Hydrothermal alteration types show a clear spatial and temporal variation in the St Ives gold camp. Epidote-dominated alteration appears to develop early and is focused around porphyry intrusions. Significant Te anomalies are spatially associated with epidote-dominated alteration and are interpreted to be driven by porphyry intrusion and associated epidote alteration.

Magnetite\textsubscript{2} alteration appears to postdate epidote alteration, but is largely predating gold. The spatial distribution of magnetite\textsubscript{2} with respect to gravity lows and porphyry distribution in the camp indicates also a close genetic link. Minor magnetite\textsubscript{2} inclusions in gold-related pyrite indicate that magnetite\textsubscript{2} was stable at the onset of pyrite growth but was replaced by hematite during most of the pyrite growth and gold mineralization. This suggests that the oxidation state of the hydrothermal fluid changed to extremely oxidized conditions during gold mineralization. The relative timing of pyrrhotite and pyrrhotite-pyrite assemblages is unconstrained at present. However, the fact that the reduced assemblage occurs distal to the oxidized assemblage (and gold), and that pyrrhotite does not overprint the oxidized assemblage, indicates that the reduced assemblage either pre-dates or is synchronous with oxidized alteration assemblages.

The textural relationships may be explained either by mixing of two different fluids of grossly different redox state or by sequential precipitation of hydrothermal alteration out of these fluids. In the sequential precipitation model, pulses of fluids with grossly different redox conditions precipitated a sequence of alteration assemblages. Subsequent pulses reacted with previously precipitated alteration assemblages, thus explaining the presence of reduced and oxidized alteration mineral assemblages.

The co-variance of $\delta^{13}$C and $\delta^{34}$S with oxidized and reduced assemblages, together with the paragenetic link of $\delta^{15}$C and $\delta^{34}$S variations with high grade gold zones, may be explained by the presence of both methane-rich (reduced) and sulphate-rich (oxidized) fluids in the gold zones at about the time of gold deposition. The mixing of fluids of contrasting redox state provides a powerful gold precipitation mechanism and can account for the stable isotope relationships. In the sequential precipitation model, a heavy S isotope source must be inferred to account for co-variation of heavy S and light C isotopes. Other commonly discussed mechanisms such as sulfidation and fluid unmixing (boiling) do not account adequately for the spatial, textural and stable isotope relationships. In order to rigorously test the two competing models, detailed textural, stable isotope, fluid inclusion and geochronological studies are currently being conducted in high-grade gold zones with co-variation of carbon and sulphate isotopes.

The spatial association of oxidized assemblages with porphyry intrusions at the drill core to camp scale strongly suggests that magmatic volatiles were the source of oxidation. This conclusion is supported by similarities in the hydrothermal evolution of deposits in the Central Corridor with the evolution of the Wallaby deposit. Recent detailed mapping of this deposit has identified both close spatial and paragenetic links between gold mineralization and syenite magmatism (Drieberg et al., this volume).

Integration of the stable isotope data with detailed fluid inclusion data (Petersen et al., this volume) provides some clues to the specific fluid-flow events that may be correlated across the St Ives Camp and to the sources of the fluids. Low salinity carbonic-aqueous fluids in carbonate most likely correlate with fluids locally recycling CO\textsubscript{2} within the greenstones, driven by granitic/porphyry heat sources at depth. The more saline aqueous-carbonic fluids, particularly associated with late quartz may represent an injection of a magmatic brine component to a high level in the system during depressurization, heat loss and quartz precipitation. It is suggested that the magmatic volatile phase probably consisted largely of CO\textsubscript{2} as evidenced by the carbonic fluids in albite and for which there is some cryptic C and O isotope evidence. The SO\textsubscript{2} in magmatic volatile phase could have produced the high oxidation conditions seen in the high grade gold zones. Other components in the magmatic volatile phase included tellurium, possibly vanadium species as well as trace Mo, W and As (?) Au (?). The source(s) of the CH\textsubscript{4} –rich
fluids remain problematical. They could be derived from local sedimentary basins, from deeper in the crust or mantle, or from as yet unidentified magmatic source of reduced fluids.

High-grade gold mineralization (>100g/t) is preferentially located in domains where reduced and oxidized alteration assemblages overlap, or close to the border of the domains, but within the oxidized domain. In combination with the fact that oxidation state of the hydrothermal fluid changed to extremely oxidized conditions during mineralization, this suggests that large gradients in redox conditions specifically, and large chemical gradients in general, are powerful gold precipitation mechanisms.

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