Peter Neumayr, Steffen Hagemann, John Walshe, Leo Horn, Robert S. Morrison, Karen Conners.[1]

Sulfide-oxide redox mineral distribution in the St. Ives gold camp: vectors to gold mineralization?

Abstract Hydrothermal sulfide-oxide-gold mineral assemblages in gold deposits in the Archean St. Ives gold camp in Western Australia indicate extremely variable redox conditions during hydrothermal alteration and gold mineralization in space and time. Reduced alteration assemblages occur in deposits in the southwest of the camp (e.g., Argo, Junction deposits), and moderately to strongly oxidized assemblages occur in deposits in the Central Corridor in the northeast (e.g., North Orchin, Revenge deposits). Reduced mineral assemblages flank the Central Corridor of oxidized deposits and, locally, cut across it along E-W-trending faults. Oxidized mineral assemblages (magnetite-pyrite, hematite-pyrite) in the Central Corridor are focused on gravity lows which are interpreted to reflect abundant felsic porphyritic intrusions of about 1000 m below present surface. Hydrothermal magnetite pre-dates, and is synchronous with, early phases of gold-associated chlorite-carbonate-biotite-pyrite hydrothermal alteration. Later-stage gold-associated pyrite is in equilibrium with hematite. The spatial distribution and temporal sequence of sulfide-oxide-gold assemblages indicate either a progressive change in redox conditions of one hydrothermal fluid, or more likely, the presence of, at least, two spatially restricted hydrothermal fluids with variable redox states. Preliminary spatial analyses of the distribution of sulfides, oxides and gold in the St. Ives camp suggest that gold grades are highest where the redox state of the hydrothermal fluid switches from pyrrhotite-pyrite to magnetite-pyrite and hematite-pyrite both in space and time.

Keywords Redox minerals, orogenic gold, St. Ives gold camp, high-grade ore body

Introduction

Many genetic models for orogenic lode-gold deposits (see \Groves, #XXXXX; Hagemann and Cassidy, 2000 #, Table 1 for references), proposed in the past 20 years, provide detailed information on the diversity of characteristics of deposits (i.e., the trap-site). These models provide a detailed synthesis on the structural-hydrothermal, and to a lesser extent, hydrothermal fluid characteristics of deposits at different crustal levels and provide general explanation for the fluid sources and processes involved in ore formation.

[1] **Peter Neumayr, Steffen Hagemann**

Centre for Global Metallogeny, School of Earth and Geographical Sciences, University of Western Australia, Nedlands-WA 6009, Australia

John Walshe, Leo Horn

CSIRO-Exploration and Mining, 26 Dick Perry Ave, Kensington, Perth WA 6151, Australia

Robert S. Morrison, Karen Conners

St. Ives Gold Mining Company Pty. Ltd., Kambalda-West WA 6444, Australia

There is a general consensus that these deposits formed during compressional to transpressional deformation processes at convergent plate margins in accretionary and collisional orogens (Barley et al. 1998; Wyman et al. 1999). They are typically hosted in, and controlled by, second- and third-order brittle to ductile shear zones and associated quartz-carbonate vein and/or breccia systems, which are spatially, and most likely hydraulically, connected to first-order or transcrustal fault systems (e.g., Eisenlohr et al. 1989; Neumayr Hagemann 2002; Neumayr et al. 2000) {Cox XXXX, #XXXX; Robert XXXX, #XXXX}. Examples are the Boulder-Lefroy fault system immediately west of the giant Golden Mile in Australia or the Cadillac Tectonic Zone south of the Sigma and Lamaque gold deposits in Canada (Hagemann and Cassidy, 2000 #).

On a camp scale, the location of gold deposits is controlled by inhomogeneities in structures such as flexures, bends, fold hinges, jogs and fault intersections, lithological heterogeneities such as porphyry stocks or dikes, the intersection of a mineralization-hosting/controlling structure with a particular favorable lithology, and rheological contrast between rock types, dilatent structures in favorable far-field-stress orientations and suitable host lithologies and rheologies (cf Hronsky, 1998 # for a summary).

Despite the large descriptive database on these deposits and the myriad of genetic models our predictive capability of delineating high-grade (>5 g/t Au) gold deposits within a gold camp is still limited. For example, based on empirical observations most gold deposits within a camp are hosted in second- and third-order structures, which are considered to be favorable dilational sites for gold deposition. Yet there are numerous examples of gold camps (e.g., St. Ives camp) that show shear or fault zones with the same geometrical pattern and fluid plumbing system but only specific sites at these structures are well-endowed with respect to gold. Furthermore, controlling factors many of the camp-scale geological controls (as listed above) may be developed but devoid of significant gold mineralization.

In this contribution we are proposing that the structural ground preparation of depositional sites may not always be the only dominant factor in locating gold deposits within a camp. A new scale- and method-integrated research project on the 4-dimensional oxide-sulfide redox distribution in the St Ives gold camp near Kambalda, in Western Australia, points towards a significant chemical control in the location of gold systems within a given structural camp-scale architecture. This *Letter* briefly summarizes the distribution of redox minerals, fault zones and igneous rocks in the St Ives camp and provides a preliminary structural-hydrothermal alteration model that attempts to predict the location of high-grade gold systems.

Geological setting of the St. Ives gold camp

The St. Ives gold camp, which contains >12M oz of gold within 13 different deposits (and Cassidy, 2000 #), is located in the southern part of the Norseman-Wiluna greenstone belt within the Eastern Goldfields Province of the Yilgarn craton of Western Australia (Fig. 1). 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. It is bounded by the regional NNW-trending Boulder- Lefroy fault zone to the east and the Merougil fault zone to the west, and has undergone four major Archean deformation events (e.g., Nguyen et al. 1998): D1 produced regional south-over-north thrusts, D2 caused upright, NNW-trending, gently plunging folds, such as the Kambalda anticline, D3 generated a brittle-ductile, NNW-trending, oblique-sinistral wrench fault systems that localized major N-trending, reverse, gold-bearing shear zones, and D4 produced NE-trending, dextral faults that offset the stratigraphy and earlier fault systems, and caused dextral±reverse reactivation of D2 and D3 faults. Gold mineralization is mainly controlled by the D3 and D4 deformation events.

Intermediate and felsic porphyry stocks are particularly abundant in the Victory-Defiance and Revenge gold deposits (Fig. 2a) and zones of greatest porphyry abundance are centered on distinct lows in detailed gravity data (Fig. 2b). Deep diamond drill core intersections and detailed seismic data, coupled with gravity analyses, suggest stocks of porphyry intrusions at about 1000 m below the present surface (Stolz et al., 2002 #).

Sulfide-oxide redox mineral distribution

Methodology

The principle distribution of selected oxide and sulfide mineral assemblages in the Central Corridor of the St. Ives gold camp was initially compiled using the St. Ives Gold Mining Company Pty Ltd drill log database. This was then verified by logging the spatial variation of critical redox assemblages (Fig. 3) in selected diamond drill core. Temporal relationships between different mineral assemblages were determined using textural criteria in diamond drill core and polished thin sections. In order to compare the redox assemblages from various locations in the camp, redox indicator mineral assemblage distribution maps were produced for major rock types individually to avoid any host rock influence on the formation and distribution of alteration assemblages (cf. McCuaig Kerrich 1998). Interflow metasedimentary rocks such as the Kapai Slate are an excellent indicator horizon for the redox state of the hydrothermal fluids, because it is omnipresent in the camp and has a similar, simple initial (pre-alteration) composition throughout (i.e., it is a pyrite-bearing shale). Although mafic rocks have a more variable chemical composition throughout the camp, camp-scale hydrothermal alteration redox patterns are similar in interflow sedimentary rocks and mafic rocks. All maps were compiled into a GIS 'layer system' which also included detailed gravity and aeromagnetic 'layers' of the same area.

Redox zonation at the camp scale

The distinct pattern of gold-associated sulfide and oxide assemblages (Fig. 4a) suggest a hydrothermal fluid chemistry zonation within the St. Ives gold camp. The deposits at the northeastern flank of the F2 Kambalda anticline are characterized by pyrite-magnetite and pyrite-hematite assemblages (Fig. 1). Deposits in the northwest, proximal to the Kambalda Dome, typically contain pyrite-only as the main sulfide mineral (Fig. 1). In the Central Corridor, relatively oxidized hydrothermal magnetite-pyrite assemblage occurs to the southeast of the Victory-Defiance deposits and Greater Revenge area (Fig. 4a, b) and spatially above felsic porphyry stocks. This assemblage is also aligned along major structures, such as the NW-trending, D3 Playa fault zone (Fig. 4a).

In contrast, relatively reduced pyrrhotite and pyrrhotite-pyrite assemblages broadly flank the axis of the Kambalda anticline and hence the main oxidized deposits in the Central Corridor (Fig.

4a, b). Reduced assemblages also occur in approximately E-W trending, 50 m wide bands north and south of the Revenge, West Revenge and Delta deposits as well as in isolated locations between the Revenge and the Victory-Defiance deposit groups (Fig. 4a, b). A cross-section through the Central Corridor (Fig. 5) also demonstrates that in the third dimension the oxidized assemblages are also surrounded by reduced assemblages.

Deposits in the southwest of the camp, such as Argo and Junction, are apparently dominated by reduced arsenopyrite-pyrrhotite and pyrrhotite-pyrite assemblages, respectively (Fig. 1), however, presently the lack of data prohibits a more detailed interpretation of these deposits.

Redox mineral zonation at a deposit scale

In this *Letter*, hydrothermal alteration at a deposit scale is discussed mainly in mafic host-rocks and exemplified by the Revenge and Conqueror gold lodes. At Revenge and Conqueror, gold lodes are rimmed by a >100m wide halo of hydrothermal, fine-grained magnetite, which is best monitored via variations in the magnetic susceptibility (Fig. 6a). Elevated magnetic susceptibility is clearly centered on gold lodes. However, the zones of highest gold grades are characterized by low magnetic susceptibility and less abundant hydrothermal magnetite (Fig. 6a). Hydrothermal sulfides and oxides are absent in distal alteration zones at Revenge, but show a distinct zonation of pyrrhotite-only in distal and pyrite-magnetite assemblage in proximal alteration zones at the Conqueror lode (Fig. 6a). In lodes of both deposits, there is also a distinct gold-associated, silicate/carbonate alteration zonation. The most distal zone of gold-associated alteration contains hydrothermal chlorite, and less abundant biotite and dolomite. The intermediate alteration zone is comprised of hydrothermal biotite, carbonate, and lesser albite and pyrite, with traces of magnetite. The most proximal areas to the gold lodes are bleached zones adjacent to hydrothermal quartz veins and contain albite, ankerite, dolomite, quartz, pyrite, and minor biotite, muscovite, and calcite. Gold associated pyrite grains contain magnetite inclusions in their cores and hematite inclusions in their rims (Fig. 6b).

Spatial relationship of gold mineralization and redox mineral distribution

Major gold lodes in the St. Ives gold camp are structurally controlled (Roberts and Elias, 1990 #). However, within the structures there is a strong spatial correlation of gold lodes and the switch from domains with reduced pyrrhotite and pyrrhotite-pyrite assemblages into domains with oxidized magnetite-pyrite and hematite-pyrite assemblages. This spatial relationship is illustrated in Figure 4b where gold intersections with grades greater than 1ppm are located in zones of overlapping pyrrhotite-pyrite and magnetite-pyrite domains or close to the domain interfaces. The boundary between the relatively reduced to oxidized domains crosscuts a number of open pits, e.g., Victory-Defiance, Britannia-Sirius, North Orchin, South Revenge, Revenge, West Revenge, Mars (Figs 1, 4b). This relationship is repeated from camp- to drill core- and to thin section-scale. Figure 6b shows gold-bearing pyrite from the Revenge gold lode where the core of the pyrite crystal contains magnetite inclusions, whereas the rim is surrounded by hematite suggesting a dramatic increase of f_{O2} during the growth of the pyrite.

Discussion

Oxidation state of hydrothermal alteration

The oxidation state of the hydrothermal fluids is monitored by their sulfide-oxide mineral assemblages**.** The most reduced gold-related hydrothermal assemblages in the St. Ives gold camp are documented in the Argo and Junction deposits, with arsenopyrite-pyrrhotite, pyrrhotite-only and pyrrhotite-pyrite assemblages. The Revenge and Victory-Defiance lodes in the Central Corridor contain hydrothermal magnetite-pyrite which predates hydrothermal hematite-pyrite. These assemblages reflect the introduction of oxidized fluids in the camp which is synchronous with the deposition of gold in these deposits. On a camp-scale, the relatively oxidized assemblages in the deposits in the Central Corridor are flanked by domains of the reduced assemblages. On a deposit-scale, for example the Conqueror lodes, the switch from the reduced to the oxidized zones occur symmetrically around the gold lodes. Here the proximal zones of oxidized gold lodes are symmetrically bounded by distal, reduced alteration zones. In many deposits, the redox boundary actually cross cuts the open pit part of the deposits.

Relative timing of hydrothermal alteration

Mineral textures and overprinting relationships indicate that hydrothermal magnetite, which rims gold lodes in mafic host rocks at the Revenge and Conqueror gold deposit (Fig. 4b), pre-dates and locally is synchronous with early stages of typical gold-associated alteration. This timing relationship is also supported by the low abundance or absence of magnetite in the gold lodes. Most importantly, magnetite inclusions in the core of gold-associated pyrite, and hematite inclusions in the rims of pyrite at the Revenge deposit indicate that f_{O2} conditions during pyrite growth changed to stabilize hematite over magnetite. The replacement of hydrothermal magnetite in the Kapai Slate by gold-associated alteration and gold mineralization has also been documented previously in the Victory gold deposit (Marsh 1988).

Interpretation of camp- to deposit-scale redox mineral distribution

Oxidized hydrothermal fluids were focused into the rock volume adjacent to and above felsic and intermediate porphyry stocks. Reduced hydrothermal fluids infiltrated the flanks of the main porphyry intrusions and locally E-W corridors south and north of the Revenge and Delta deposits (Figs 2a, b and 4a, b).

The spatial association of hydrothermal magnetite and magnetite-pyrite and abundance of felsic and intermediate porphyries suggests that there is a genetic link between them. Hydrothermal fluids in equilibrium with magnetite- and magnetite-pyrite-bearing assemblages were likely associated with, and/or released by, felsic magmatic intrusions. These fluids subsequently hydrothermally altered metasedimentary and mafic rocks immediately above the porphyry stocks and along third- and fourth-order reverse faults. Hydrothermal magnetite and magnetite-pyrite assemblages in metasedimentary and mafic rocks along the Playa fault, which has been interpreted as the main fluid conduit for gold-bearing hydrothermal fluids (Nguyen et al. 1998), indicates that oxidized hydrothermal fluids also accessed these NW-trending, second-order fault zone. It is likely that these hydrothermal fluids in the Playa fault were also either associated with, or released from, the felsic magmatic intrusions at depth. The spatial distribution of reduced fluids, as indicated by the distribution of hydrothermal pyrrhotite and pyrrhotite-pyrite assemblage surrounding the main oxidized domains and locally within the oxidized domains, as well as the relatively early timing of pyrrhotite may indicate that the reduced fluids predated the main pulse of oxidized fluids.

Preliminary hydrothermal alteration model

Hydrothermal alteration in the St. Ives gold camp shows a temporal progression from pre-gold magnetite alteration, which is preserved in suitable host rocks, such as the Kapai Slate and some mafic volcanic rocks, to typical gold-related albite, carbonate, chlorite and biotite alteration. Magnetite and magnetite-pyrite alteration is likely to be derived from, or associated with, felsic to intermediate porphyry intrusions at depth as indicated by the spatial association of hydrothermal magnetite and distinct gravity lows. The large variation of the oxidation state of the hydrothermal alteration assemblages in the camp, as well as changing redox conditions during the growth of ore pyrite at the Revenge deposit, can be explained in two ways: 1) the presence of at least two different (end-member) hydrothermal fluids of different redox states, or 2) a change in the redox state of one hydrothermal fluid with time. If two fluids of different redox states were present, it is likely that the oxidized and the reduced end-members of the hydrothermal fluids were transported in different fluid conduits. The interaction of a second fluid with hydrothermal alteration minerals that were deposited from the first fluid, or the mixing of these two fluids, resulted in the deposition of gold-associated hydrothermal alteration. Equally, the interaction of two fluids, or the reaction of a second fluid with alteration mineral assemblages, which were deposited by an earlier fluid, and the drastic change of redox conditions, is a powerful gold precipitation mechanism (Mikucki 1998). Furthermore, pre-existing magnetite provides an ideal environment for sulphidation reactions that resulted in the precipitation of gold (Phillips and Groves, 1984 #).

On-going research into the absolute timing of magmatism and gold deposition, as well as detailed fluid inclusion and stable isotope analyses on the end-member fluids, will further constrain the evolution of hydrothermal alteration and gold mineralization in the St. Ives camp. We are confident that the proposed ‘redox’ model for the St. Ives gold camp will significantly improve the delineation of high-grade gold deposits in this camp and probably in other camps that contain orogenic gold deposits worldwide.

Conclusions

The distribution of sulfide and oxide redox assemblages in the St. Ives gold camp near Kambalda suggests a progressive change in redox conditions. The spatial analyses of the location of high grade gold lodes and distribution of reduced and oxidized assemblages in the camp illustrates that highest gold grades overlap zones where oxidized and reduced assemblages are observed in space and time. The technique of mapping redox assemblages and correlating them with geophysical data and gold distribution is an effective vector towards gold mineralization in the St. Ives gold camp.

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References

Barley, M. E., Krapez, B., Groves, D. I., and Kerrich, R. (1998) The Late Archaean bonanza: metallogenic and environmental consequences of the interaction between mantle plumes, lithospheric tectonics and global cyclicity. Precambrian Research 91: p. 65-90.

Eisenlohr, B. N., Groves, D. I., and Partington, G. A. (1989) Crustal-scale shear zones and their significance to Archaean gold mineralization in Western Australia. Mineralium Deposita 24: p. 1-8.

Marsh, S. (1988) Origin of the magnetite-rich facies Kapai Slate, Kambalda, Western Australia. Unpub. Unpub. Honours thesis, The University of Western Australia.

McCuaig, T. C., and Kerrich, R. (1998) P-T-t-deformation-fluid characteristics of lode gold deposits: evidence from alteration systematics. Ore Geology Reviews 12: p. 381-453.

Mikucki, E. J. (1998) Hydrothermal transport and depositional processes in Archean lode-gold systems: a review. Ore Geology Reviews 13: p. 307-321.

Neumayr, P., and Hagemann, S. G. (2002) Hydrothermal fluid evolution within the Cadillac Tectonic Zone, Abitibi greenstone belt, Canada: Relationship to auriferous fluids in adjacent second- and third-order shear zones. Economic Geology 97: p. 1203-1225.

Neumayr, P., Hagemann, S. G., and Couture, J. F. (2000) Structural setting, textures and timing of hydrothermal vein systems in the Val-d'Or Camp, Abitibi, Canada: Implications for the evolution of transcrustal, second- and higher-order fault zones and gold mineralization. Canadian Journal of Earth Sciences 37: p. 95-115.

Nguyen, T. P., Cox, S. F., Harris, L. B., and Powell, C. M. (1998) Fault-valve behaviour in optimally oriented shear zones: an example at the Revenge gold mine, Kambalda, Western Australia. Journal of Structural Geology 20: p. 1625-1640.

Wyman, D. A., Kerrich, R., and Groves, D. I. (1999) Lode gold deposits and Archean mantle plume - island arc interaction, Abitibi Subprovince, Canada. Journal of Geology 107: p. 715-725.