The structural, hydrothermal alteration and fluid evolution of the New Celebration lode-gold deposits: multiple deformation events and two stages of gold mineralization

Joanna Hodge[1], Sian Nichols[2], Steffen Hagemann[1] and Peter Neumayr[1]

[1]*pmd*CRC, Centre for Global Metallogeny, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009*

[2]*Harmony Gold Mining Co. Ltd., PO Box 2125, Boulder, WA 6432*

hodgej02@segs.uwa.edu.au

Introduction

The Boulder segment of the Boulder-Lefroy fault zone, a first-order, trans-crustal fault system (Swager, 1989), hosts the Archean New Celebration lode gold deposits. Although first-order fault systems do host gold mineralization (e.g. Kerr Addison gold deposits in the Cadillac Tectonic Zone in Abitibi; Poulsen et al., 2000), second- and third-order fault systems are more typical hosts (e.g. Eisenlohr et al., 1989).

This study aims to: 1) quantify the P-T-X-fO_2-t conditions of fluids associated with different mineralizing events, and 2) constrain the fluids within deposit- and regional-scale tectonostratigraphic frameworks. New Celebration is a key location to evaluate fluid pathways and evolution, and provides valuable insights into the role regional scale structures play in focusing both mineralizing and non-mineralizing fluids.

Regional Geology

The New Celebration deposits are located approximately 35km southeast of Kalgoorlie in the Kambalda domain of the Kalgoorlie terrane of the Eastern Goldfields Province of Western Australia. The deposits are hosted within the Boulder segment of the Boulder-Lefroy Fault Zone, a trans-crustal fault system that forms part of the eastern boundary of the Kambalda domain. The Kambalda domain consists of a 6-9 km thick, elongate volcano-sedimentary sequence, which is metamorphosed to upper greenschist-lower amphibolite facies and bounded to the east and west by wide (up to 1km), NNW-trending anastamosing shear zones (Swager and Griffin (1990).

Lithostratigraphy of the New Celebration deposits

The stratigraphic sequence at New Celebration consists of a basal komatiite overlain by a strongly differentiated mafic unit, intruded by a number of plagioclase and quartz-feldspar porphyries and minor lamprophyres. Apart from the felsic intrusions, all rocks seen at New Celebration are metamorphosed to upper greenschist facies.

Structural and magmatic evolution

Nichols (2003) identified three main deformation events at New Celebration, which are tentatively correlated with regional deformation events. The earliest deformation event ($D2_{NC}$) recognized at New Celebration is defined by vertically dipping conformable stratigraphic contacts such as those between the sub-units of differentiated dolerites and represents regional D2, NNW-striking upright folds of Swager (1989) and Swager and Griffin (1990). Penetrative NNW-trending shear foliation in mafic and ultramafic rocks, well-developed S-C fabric in mafic rocks and plagioclase-rich porphyry dykes, and mineral elongations, S-C intersection lineations and slickenline lineations observed in the open pit define $D3_{NC}$. The S3 foliation has an average orientation of 82° towards 260°

and 87° towards 29°, which represent S- and C-foliation planes, respectively. The $D3_{NC}$ tentatively correlates with regional ENE-WSW shortening, and sinistral strike- and dip-slip faulting of Swager (1989) and Swager and Griffin (1990). Penetrative S- (81° towards 312°) and C- (58° towards 292°) foliation observed in the ultramafic footwall and the mafic hanging wall and NNW dipping structures that crosscut $S3_{NC}$ shear foliation in the pit represent $D4_{NC}$. Late curviplanar faults that crosscut all other structures are assigned to D_{4+nNC}

Nichols (2003) distinguished two magmatic events at New Celebration, based on mineralogy, deformation style and crosscutting relationships. Early, intensely altered, plagioclase-rich M_1 porphyries have a penetrative $S3_{NC}$ foliation and later, weakly hydrothermally altered, M_2 quartz-feldspar porphyries are unfoliated and preserve primary igneous textures. The north-northwest trending $S3_{NC}$ foliation observed in the surrounding mafic and ultramafic rocks wraps around the late porphyries. The development of $S3_{NC}$ deformation fabrics in M_1 porphyries, their lack in M_2 porphyries and the presence of brittle fracture networks on the M_2 porphyry margins suggest that emplacement of both intrusion types occurred during $D3_{NC}$, but at different times within the same deformation event and under changing tectonic conditions.

Gold mineralization and hydrothermal alteration

Evidence from open pit mapping, diamond core logging, detailed geochemistry, and petrography indicates that komatiite, differentiated, metamorphosed dolerite and porphyry dykes host gold mineralization at New Celebration. Nichols (2003) identified two gold mineralizing events and four mineralization styles at New Celebration. The early gold event consists of Mylonite- and Porphyry-style mineralisation and late gold consists of Contact- and Fracture-style mineralization.

Early gold mineralization

Quartz-ankerite-biotite-sericite mylonite hosts Mylonite-style mineralization. Gold either occurs as round inclusions in euhedral, zoned, “dirty” pyrite, also containing other sulfides (galena) and tellurides (calaverite, petzite), or as fine-grained anhedral disseminated grains within silicate. Distal alteration consists of bio-ser-ank-±py±mt whereas proximal alteration comprises ank-bio-py±ser (Nichols, 2003).

Plagioclase-rich porphyry dykes (M_1) host Porphyry-style mineralization. All M_1 dykes are pervasively alb-bio-py-ank±ser altered. Accessory sulfides (chalcopyrite, galena), oxides (hematite, magnetite), phosphates (monazite) and tellurides (hessite, altaite, melonite and tetradymite) also occur (Nichols, 2003). Pyrite hosts gold as rounded inclusions or along grain fractures. Disseminated gold also occurs along albite grain boundaries adjacent to pyrite.

In both early mineralization styles, pyrite predominantly hosts gold. Pyrite is aligned parallel to $S3_{NC}$ foliation planes. Ankerite and hydrothermal quartz pressure shadows are developed at pyrite grain margins, which indicates pyrite and gold were deposited prior to, or contemporaneous with, $D3_{NC}$ deformation (Nichols, 2003).

Late gold mineralization

The high-Mg basalt-M_2 porphyry contacts host Contact-style gold mineralization. Contact-style mineralization has a well-developed alteration halo, which consists of a distal ank-bio-chl zone with accessory mt, an outer proximal ank-bio-ser zone and an inner proximal ank-ser zone. Abundant coarse-grained pyrite immediately adjacent to the contact is characteristic. Gold forms inclusions in pyrite or along pyrite grain boundaries, and within disseminated pyrite along foliation planes in the high-Mg basalt (Nichols, 2003).

Thin (1-2mm wide) fractures filled with hydrothermal alteration minerals are developed at the margins of M_2 quartz-feldspar porphyries and host Fracture-style mineralization.

Distal alteration consists of widespread (>20m) pervasive ank-ser alteration whereas proximal alteration consists of py-ser-ank restricted to the fracture fill. Pyrite hosts gold as inclusions or along grain boundaries (Nichols, 2003).

Vein Paragenesis

Preliminary investigations indicate that the New Celebration vein system consists of (Table 1): (1) syn-$D2_{NC}$ veins that developed prior to the early gold event; (2) $D3_{NC}$ veins which predate early gold mineralization; (3) $D3_{NC}$ syn-early gold veins; (4) $D4_{NC}$ veins which predate late-stage gold mineralization; and (5) $D4_{NC}$ veins synchronous with late-stage gold mineralization.

$D2_{NC}$ Veins

Type 1 $D2_{NC}$ veins consists of foliation-parallel quartz-calcite "boudins" which are only observed in mylonites and strongly foliated M_1 feldspar porphyries. Quartz and calcite grains within pre-$D3_{NC}$ veins show dynamic recrystallization by grain boundary migration (Passchier and Trouw, 1996). Grain boundaries are commonly highly irregular and bulge into adjacent grains. Calcite twins typically terminate before grain boundaries. Undulose extinction and lattice-preferred orientation in quartz grains suggest recrystallization by sub-grain rotation (Passchier and Trouw, 1996).

Table 1: Summary of the geological characteristics of the New Celebration vein system

Deformation Event	Vein Generation	Host Rock	Vein Type	Mineralogy	Width	Structure	Alteration Halo
$D2_{NC}$	Pre-gold veins -Early gold event	Bio-ank mylonites, M1 plg porphyries	1	qtz, cb	200-1200μ	Foliation parallel deformed quartz boudins	Ankerite?
$D3_{NC}$		Bio-cb mylonites, chl schists	2	qtz, cb	400-2000μ	Zoned veins, cross-cut by foliation	Ankerite
$D3_{NC}$		Mafic, ultramafic chl-cb schists	3	cc	400μ	Thin veins, cross-cut By foliation	None
$D3_{NC}$	Syn-gold veins -early gold event	M1 plg porphyry	4	qtz, cc, py,	600-2400μ	Foliation sub-parallel. Biotite edges veins	Ankerite
$D4_{NC}$	Pre-gold veins -Late gold event	M2 fsp-qtz porphyry	5	qtz, (cb, ser)	400-4000μ	Buck quartz, forms vein breccia arrays	None
$D4_{NC}$	Syn-gold veins -late gold event	M2 fsp-qtz porphyry	6	ser, chl, py	20-200 μ	Thin fracture veinlets	None

Abbreviations: ank – ankerite; bio – biotite; cb – carbonate; cc – calcite; chl – chlorite; plg – plagioclase; py – pyrite; qtz - quartz

$D3_{NC}$ Veins

Types 2 and 3 veins consist of quartz-calcite and calcite-only veins, and have developed oblique to foliation. The veins and the foliation exhibit mutually crosscutting relationships. These veins predominantly occur within mylonites, and mafic and ultramafic schists. Partial recrystallization of quartz has occurred where foliation planes crosscut the veins. In these areas, quartz grains have irregular grain boundaries, show sub-grain development and exhibit undulose extinction, indicating they have undergone dynamic recrystallization. The M_1 feldspar porphyries host type 4 veins, which are predominantly composed of quartz and calcite with accessory pyrite and are surrounded by a wide ankerite alteration zone. Zoned, inclusion-rich pyrite often clusters along vein selvedges. Grains typically exhibit a "dirty", inclusion-rich core surrounded by a "clean", inclusion free rim. Inclusions typically comprise abundant silicates, minor sulfides (galena, sphalerite) and rare gold. Quartz grains within the veins have undergone partial dynamic recrystallization by grain boundary migration and sub-grain rotation. Sub-grain development is minor, and predominantly concentrated along the vein edge. Relict grains exhibit undulose extinction and lattice-preferred orientation.

$D4_{NC}$ veins

Type 4 veins consist of quartz, calcite and sericite. The veins are composed almost entirely of coarse-grained clear quartz overprinted by accessory calcite and rare sericite. The veins locally form breccias within M_2 quartz-feldspar porphyries. Quartz within type

4 veins show evidence of dynamic recrystallization by grain boundary migration. Evidence for this includes diffuse and highly irregular grain boundaries.

Type 5 late gold event-related veins are composed of sericite, chlorite and pyrite and form thin stringer veins. These veins only occur in M_2 quartz-feldspar porphyries. Where the $D4_{NC}$ veins crosscut the earlier quartz breccia, they have generally developed along the quartz grain boundaries. Pyrite occurs as large subhedral to euhedral grains or as aggregates of fine subhedral to euhedral crystals, and commonly contains abundant silicate and sulfide inclusions. Pyrite hosts gold as rounded inclusions and localized gold occurs along pyrite grain boundaries.

Preliminary Fluid Inclusion Data

Detailed fluid inclusion petrography on primary, pseudosecondary and secondary fluid inclusions trapped in type 2 qtz-cb veins in Mylonite-style and type 5 qtz veins in Fracture-style samples revealed five inclusion types: (1) dark, irregularly shaped single-phase inclusions, possibly CH_4; (2) two-phase, clear, ovoid liquid-rich inclusions; (3) clear, rounded vapour-rich two-phase inclusions; (4) darkish, irregularly shaped, three-phase H_2O-CO_2 inclusions; and (5) clear, irregularly shaped, three-phase liquid-vapour-solid inclusions. A fluid inclusion assemblage consisting of types 1 and 2 occur in clusters of primary inclusions in quartz grains within $D2_{NC}$ quartz boudins. Quartz within the boudins has likely been recrystallized, based on petrographic evidence, therefore, the fluid inclusion assemblages may represent $D3_{NC}$ fluids and not the original $D2_{NC}$ vein-forming fluids. Types 1, 2, 3 and 4 form a fluid inclusion assemblage that occurs in primary clusters and pseudosecondary trails in $D3_{NC}$ qtz-cb veins. Primary inclusion clusters occur in quartz grains immediately adjacent to gold-hosting pyrite crystals, whereas pseudosecondary inclusion trails occupy fractures that parallel foliation planes, which crosscut Type 2 qtz-cb veins. Inclusion types 1 through 5 consist of a fluid inclusion assemblage that occurs as primary clusters in $D4_{NC}$ gold-hosting quartz veins.

Preliminary Sulfur Isotope Results

Bulk sulfur isotope analysis of pyrite from 10 representative samples from the four mineralization styles reveals distinctly different $\delta^{34}S$ wrt CDT signatures that do not overlap significantly. The values range from -7.12‰ $\delta^{34}S$ wrt CDT from Fracture-style mineralization, to +2.03‰ $\delta^{34}S$ wrt CDT from Mylonite-style mineralization.

Further Work

Planned work includes further detailed fluid inclusion petrography, microthermometry, Laser Raman analysis and LA-ICP-MS analysis to constrain the P-T-X-fO_2-t conditions of the hydrothermal fluids associated with the evolution of the New Celebration gold deposits. Further work also includes dating of hydrothermal monazite, $^{40}Ar/^{39}Ar$ dating of pyrite and Pb-Pb step leaching of sulfides and oxides to establish the timing of different mineralizing events, and further detailed in situ sulfur isotope analysis to constrain redox conditions and fluid sources.

References

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, 1-8.

Nichols, S., 2003. Structural Control, Hydrothermal Alteration and Relative Timing of Gold Mineralization at the New Celebration Gold Deposits, Kalgoorlie, Western Australia. BSc (Hons) thesis, University of Western Australia, Crawley, WA.

Passchier, C. W. and Trouw, R. A. J., 1998. Microtectonics. Springer, Berlin, 289 p.

Poulsen, K.H., Robert, R. and Dube, B., 2000. Geologic classification of Canadian gold deposits. Geological Survey of Canada, Bulletin 540, 106p.

Swager, C.P., 1989. Structure of Kalgoorlie greenstones-regional deformation history and implications for structural setting of the Golden Mile deposits. Geological Survey of Western Australia Report 25, 59-84.

Swager, C. P. and Griffin, T. J., 1990. Geology of the Archaean Kalgoorlie Terrane, (northern and southern sheets): Western Australia Geological Survey, 1:250,000 Geological Map.