The Wafi-Golpu porphyry Cu-Au deposit: Mineralisation and alteration zonation, surface geochemical expression and paragenesis.


Presenter: Doug Menzies

Introduction

The Miocene Wafi-Golpu gold-rich porphyry Cu-Au deposit, and associated epithermal Au mineralisation is located in the Morobe Province of PNG, and has a currently published resource of 28.5 million ounces of gold, 9.06 million tonnes of copper and 50.6 million ounces of silver (Newcrest, 2012; Harmony, 2012). The Wafi-Golpu porphyry Cu-Au system is bounded by a NE to NNE trending fault zone known as the Wafi Transfer, and intrudes a basement sequence of weakly metamorphosed well-bedded siltstones and conglomerates of the Oligocene Langimar Formation (previously interpreted to be the Owen Stanley Metamorphics). The Langimar Formation dipping between 50-80° to the E-NE has been intruded by several copper-gold mineralised hornblende phric to feldspar phric diorite porphyry bodies (Harris, 2010, 2011) and a late phase phematomagmatic diatreme breccia. The diatreme breccia is 800 x 600m in diameter, bounded by pebble dykes, and is inferred to have vented due to the presence of accretionary lapilli in layered bands at surface.

Mineralisation and alteration zonation

Four discreet mineralising systems have been identified to date including: the Golpu porphyry Cu-Au system; the Nambonga porphyry Cu system; the Wafi Zones A and B high sulphidation Au mineralisation; and later Au-bearing Mn-Carbonate veined and Au-rich, As-bearing pyrite epithermal mineralisation within Link Zone. The Golpu porphyry mineralised system exhibits a concentric alteration zonation consisting of a K-feldspar rich core (330 x 760m in diameter), grading out into a biotite–magnetic rich zone (650 x 1000m in diameter), an actinolite rich zone (640 x 1030m in diameter), grading out into a chlorite dominated zone. Strong sericite alteration overprint occurs at the eastern and western edges of the Golpu porphyry and also centrally within cross cutting fault/shear zones. The first appearance of actinolite alteration correlates with the first appearance of chalcopyrite and is coincident with the 0.1% Cu shell. A zone of intense silicification and quartz veining occurs on the upper north-western margin of the Golpu porphyry mineralised system, where pyrite is dominant over chalcopyrite mineralisation. This zone also displays minor crenulated and layered quartz veining exhibiting unidirectional solidification texture as reported by Seedorff et al. (2005), who proposed this texture represents the transition between magmatic and hydrothermal conditions and demonstrates that fluids accumulated in the apex of a porphyry stock during crystallisation. The Golpu porphyry Cu-Au sulphide species have a concentric zonation from a bornite rich core grading out into chalcopyrite rich then pyrite rich zones. Au:Cu ratios are typically 0.6:0.9, and in several drill holes (WR416, WR426) Au has a positive correlation with observed bornite mineralisation (r=0.21, n=1890). This relationship is consistent with experimental work by
Simon et al. (2000) who proposed bornite can accommodate one order of magnitude more gold than chalcopyrite. However, hand-specimen samples show evidence to suggest that Cu and Au may have been remobilised in zones of intense sericite alteration, where chalcopyrite is observed rimming bornite with appreciable Au grades, a relationship similar to that reported at Batu Hijau by Arif and Baker (2004). Molybdenite mineralisation is typically found on the margins and lower portions of the porphyry Cu-Au systems often associated with potassic alteration within quartz-anhydrite veins, and occurs strongly in K-feldspar altered zones with later sercice overprint. Statistically analysis of drill core assays demonstrates a strong positive Pearson correlation between Cu and Au ($r=0.607$, $n=32653$), a negative correlation between Mo and Au ($r=-0.024$, $n=32653$) and a neutral correlation between Cu and Mo ($r=0.031$, $n=32653$). Similarly the Golpu block model shows Cu+Au rich zones off-set from Mo-rich zones. On the south-eastern margin the Golpu porphyry A and B stockwork mineralisation is overprinted by a telescoped high sulphidation covellite-ennargite-pyrite epithermal mineralisation and associated advanced argillic alteration. This high sulphidation epithermal Au-Cu mineralisation exhibits a zonation from a vuggy (or residual) quartz-alunite bearing core, out to alunite-dickite, dickite-kaolinite with lesser pyrophyllite and diaspore, then illite-smectite alteration. Advanced argillic alteration dips to the east, sub-parallel to dominant bedding, is indicative of a lithological control to the alteration and mineralisation producing fluids (Erceg et al., 1991). This style of mineralisation exhibits sulphide species zonation from enargite-luzonite, to tennantite-tetrahedrite, covellite and As-bearing pyrite (Erceg et al., 1991). This high sulphidation mineralisation is cut by later Au-bearing Mn-carbonate bearing (Zhang et al., 1997) and As-bearing pyrite veins, interpreted to have affinities with Carbonate Base Metal Au mineralisation as defined by Corbett and Leach (1998). Zhang et al. (1997) interpret the occurrence of Au associated with Mn-carbonate (rhodochrosite) in the Link Zone core to be indicative of Au deposition associated with the mixing of bi-carbonate bearing meteoric waters with pregnant Au-bearing magmatic fluids.

**Surface Geochemical Expression**

Surface geochemical data describes a broad annulus 2.94km x 2.7km which contains >140ppm Zn rimming the entire system, centred on the diatreme and is broadly coincident with the propylitic alteration zone. Zone A and B high sulphidation epithermal Au mineralisation occurs (manifests at surface) as a zone of anomalous Au values in soil samples (1.0 x 0.4km @ > 0.48 g/t Au). The southern portion of the Golpu porphyry Cu-Au mineralisation is identified at surface by spotty Cu (>150ppm) and Mo (>35ppm) anomalism in soil samples. The surface geochemical expression for both the Golpu and Nambonga porphyry Cu deposits is well defined using the multi-variant statistical analysis method, Principle Component Analysis (PCA). The PCA Cu-Mo and Au-Cu-Mo factors are the best indicator of both the Golpu and Nambonga porphyry Cu-Au mineralisation at depth.

**Paragenesis of Wafi-Golpu mineralisation**

Wafi-Golpu porphyry Cu-Au and associated epithermal Au mineralisation are localised within a zone of extension associated with a left stepping sinistral fault jog, as part of the Wafi transfer structure as described by Corbett (1994). The porphyry mineralisation is interpreted to have been introduced
by a two-phase fluid as proposed by Fournier (1999) comprising a hypersaline liquid rich in Fe, K and Cl and a low density S-rich and Cu-Au-bearing phase (Sillitoe 2010, Corbett and Leach, 1998). The negative correlation between Mo and Au-Cu is indicative of a separate transportation method for Mo into the system, possibly associated with the hypersaline Fe, K and Cl rich brine as oxochloride complexes as suggested by Ulrich and Mavrogenes (2008) and Li et al. (2012) or a separate intrusion phase of the complex. It is believed the diatreme intruded and vented due to a phreatomagmatic eruption resulting from the ingress of meteoric water onto a high level intra/late mineral porphyry during rapid uplift (Corbett and Leach, 1998). Current drill hole WR457 shows a transition from hydrothermal breccia (diatreme) to a more magmatic-hydrothermal breccia with an aplitic-quartz-silica matrix, and eventually to a quartz lacking feldspar-biotite-hornblende phryic porphyry at depth below the diatreme. The lithologically controlled Zone A and B high sulphidation epithermal Au mineralisation (Erceg et al., 1991) then overprinted both the Golpu porphyry mineralisation and the diatreme, and were followed by later Au-bearing carbonate-base-metal and Au-As pyrite epithermal mineralisation commonly known as the Link Zone (Ryan and Vigar, 1999; Erceg, 2008). Cross-cutting relationships and petrological analysis of core from the Link Zone by Zhang et al. (1997) and discussions by Ryan and Vigar (1999), as well as core from the recently discovered Northern Diatreme Gold Zone (WR392) indicate this is the latest mineralising event to have resulted from the mixing of pregnant metal bearing fluids with bi-carbonate bearing meteoric waters (Zhang et al., 1997; Corbett and Leach, 1998). Post-mineral thrust faulting is believed to be part of a Pliocene (5.0 - 2.5Ma) E-W compressional event (Reid, 2012, and Cloos et al., 2010) and has offset the Golpu porphyry mineralisation to the NW. Copper mineralisation has undergone later supergene enrichment forming a chalcocite-rich zone with associated supergene kaolinite and alunite.

References:


Erceg, M., 2008. Terry Leach: Contribution to the understanding of the hydrothermal ore-forming processes of the Wafi High Sulphidation Epithermal Gold Deposit and his role in the
discovery of the Wafi Porphyry Copper Deposit. AIG Bulletin 48 – Terry Leach Symposium.


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Plate A. Structural emplacement of porphyry intrusion associated with left-stepping sinistral fault jog, showing zonation of blue potassic (biotite-K-feldspar-Magnetite) to green propylitic alteration (chlorite-actinolite+/ epidote) produced by hyper-saline fluids rich in K, Na, Fe chlorides.

Plate B. Intrusion of the diatreme due to meteoric incursion on a magmatic source. Sericite alteration overprint on porphyry due to meteoric drawdown. Deposition of clarkopyrite-bornite mineralisation by a low density S-rich and Cu-Au-bearing phase, and later molybdenite by hypersaline Fe, K and Cl rich brine as oxochloride complexes.

Plate C. High sulphidation epithermal vuggy silica-alunite-pyrophyllite to dickite-kaolinite alteration produced by an early volatile rich event resulting from the dissociation of H2S6 to H+. A later liquid-rich event carrying Au-Cu-As produces a zonation from enargite-luzonite, tennantite-tetrahedrite to covellite.

Plate D. Quartz-carbonate-base metal + quartz-As-pyrite-rich low sulphidation epithermal mineralisation produced by the mixing of pregnant Au-As-Pb-Zn bearing magmatic fluids with bicarbonate surface waters.

Plate E. Post mineral thrust faulting during the Pliocene (Cloos et al., 2010) off-setting the porphyry mineralisation.

Figure 1. A paragenetic model for the formation of the Wall-Golpu porphyry Cu-Au mineralisation, and high and low sulphidation Au mineralisation using field observations, work by [Ercog et al, 1991] and Ryan and Vigar (1999), petrology by Zhang et al. (1997) and drawing on models from Sillitoe (2010), Corbett and Leach (1998), Ulrich and Mavrogenes (2008) and Li et al. (2012).
Geochemical/alteration zonation and structural controls on the Wafi-Golpu porphyry Cu-Au resource, a world class deposit in PNG

Geology and mineral exploration East Asia: from Russia to PNG, 2013

Doug Menzies – Acting Geology Manager (Wafi-Golpu Project)

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Competent Persons Statement
The information in this presentation that relates to Exploration Results is based on information compiled by Colin Moorhead, EGM Minerals for Newcrest Mining Limited who is a Fellow of The Australasian Institute of Mining and Metallurgy, and a full-time employee of Newcrest Mining Limited. Mr Moorhead has sufficient experience which is relevant to the styles of mineralisation and types of deposit under consideration and to the activity which he is undertaking to qualify as a Competent Person as defined in the 2004 Edition of the “JORC Code”. Mr Moorhead consents to the inclusion in this presentation of the matters based on this information in the form and context in which they appear.

Exploration Target
The potential quantity and grade related to Exploration Targets in this report is conceptual in nature as there has been insufficient exploration to define a Mineral Resource. It is uncertain if further exploration will result in the determination of a Mineral Resource.
Morobe Mining Joint Venture

50 : 50 Joint Venture [2008]
Wafi-Golpu

- Location
- Regional/structural Geology
- Wafi-Golpu geology model
- Alteration and mineralisation zonation
- Surface Geochemical expression
- Paragenetic model
Wafi-Golpu

- Location
- Regional/structural Geology
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Regional structural controls – Wafi Transfer Structure
Regional magnetic and radiometric data
Structural model for emplacement

Plate A

Plate B

Dobatan Fault Trend

Extension

Rafferty's Fault

Golpu porphyry
Wafi Golpu

- Location
- Regional/structural Geology
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Wafi-Golpu Mineralised System

- Telescoped mineralisation events/systems
  - Multiple Porphyry Cu-Au centres (Golpu, Nambonga)
  - High Sulphidation epithermal overprint (Wafi (Au))
  - Intermediate sulfidation Carbonate-Base metal (Quartz-Rhodochrosite) veins

- Total resource inventory Wafi-Golpu to 28.3 Moz of Au and 9.06 Mt of copper or 73.5 Moz of Au equivalent.
The Golpu porphyry intrusive complex.

- Five separate porphyries coalesce in central area.
- All can be described as 'Hornblende Porphyry'.
- Can be mineralised or barren at different locations.
- Meta-sediments caught up in the complex and in the halo are mineralised.
- Bounded on east and west by Rafferty’s and Dokaton Faults.
Diatreme

- Conical / "wine glass" geometry
- Milled and angular clasts in feldspar & pyrite after hornblende rich matrix.
- Dominantly matrix supported.
- Pervasive silica-sericite-koalinite-pyrite alteration
- Accretionary lapilli at surface – suggestive of venting
- Pebble dykes on the margins
- Produced by meteoric incursion on a magma chamber
Local structural geology – Post mineral thrust Faults

- Post mineral thrust faulting during the east-west compression
- Off-set to the 0.5% Cu shell, porphyries and diatreme
- Pliocene (2.5-5.0 Ma) Cioos et al., (2010).
- Reactivation and compression of original extensional structures.
Wafi Golpu

- Location
- Regional/structural Geology
- Wafi-Golpu geology model
- Alteration and mineralisation zonation
- Surface Geochemical expression
- Paragenetic model
Alteration Model

Hot spot of alteration is much larger than known intrusions.
Zone of intense silicification

- On western and upper parts of Golpu
- Locally exhibits Uni-directional Silica Textures (UST), indicative of transition between magmatic and hydrothermal conditions (Sedorff et al., 2005)
Golpu Alteration/mineralisation zonation

Porphyry (Golpu):
Concentric Shells

- Alteration Kf - Bi+Mt - Act - Bi - Chl
- Sulphides Bn - Cpy - Py
- First Cpy is coincident with first actinolite
Porphyry Style Mineralisation

Chalcopyrite veins and veinlets

~1% volume proportion of chalcopyrite = 10 wt.% Cu

Borite

Spectacular Cu and Au grades for a porphyry ore deposit
Au vs Cu vs Mo zonation

- Au:Mo Pearson correlation $r = -0.024$, $n=32653$ (negative correlation)
- Cu:Au Pearson correlation $r = 0.607$, $n=32653$ (positive correlation)
- Au:bornite Pearson correlation $r = 0.21$, $n = 1890$ (positive correlation)
- Cu:Mo Pearson correlation $r = 0.031$, $n=32653$ (neutral correlation)

**Interpretation:**
- Greater Au deposition associated with bornite as proposed by Simon et al. (2000).
- Separate metal deposition event for Mo vs Cu/Au. Molybdenite deposited by hypersaline Fe, K, Cl rich brine as oxochloride complexes as proposed by Ulrich and Mavrogenes (2008) and Li et al. (2012).
High Sulphidation Epithermal alteration overprint

- Lithological control to advance argillic alteration
- Zonation from vuggy silica, alunite, pyrophyllite to dickite/kaolinite caused by a volatile rich event
- Later Au-Cu producing event giving a sulphide zonation from enargite-tennantite-tetrahedrite-to covellite.
Advanced argillic alteration overprint

- Vuggy quartz (alunite-pyrite)
- Quartz-alunite (pyrophyllite)
- Quartz-alunite-kaolinite
High Sulphidation Epithermal Sulphide Zonation

Southern Section

Northern Section

Legend Sulphides:
- In - Co
- Cu - Bi
- Co - Bi
- Py
- Py - Cu
- Molybdenite Cutline
- Gangue Outline
- Enbloc West Outline

Notes:
- ZVE OR AAS
- ENBLOC - OR
- HIGH SULPHIDE
Carbonate base-metal Au-mineralisation

- Occurs at Link Zone, Northern Zone, Upper Nambonga
- Vein assemblages of quartz-rhodochrosite-Au-As+/− galena-sphalerite
- Produced by the mixing of magmatic fluid with bicarbonate waters
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- Paragenetic model
Surface geochemical
Wafi Golpu

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- Paragenetic model
Paragenetic model – porphyry intrusion

Structural emplacement of porphyry intrusion associated with left-stepping sinistral fault jog, showing zonation of blue potassic (biotite-K-feldspar-Magnetite) to green propylitic alteration (chlorite-actinolite+/- epidote) produce by hyper-saline fluids rich in K, Na, Fe chlorides.
Intrusion of the diatreme due to meteoric incursion on a magmatic source, causing a phreatomagmatic eruption. Sericite alteration overprint on porphyry due to meteoric draw-down. Deposition of chalcopyrite-bornite mineralisation by a low density S-rich and Cu-Au-bearing phase (Sillitoe 2010, Corbett and Leach 1998) and separate molybdenite deposition by hypersaline Fe, K and Cl rich brine and Mo as oxochloride complexes (Ulrich and Mavrogenes, 2008 and Li et al., 2012).
Paragenetic model – High sulphidation

Porphyry intrusion and alteration

Diatreme emplacement and venting

High sulphidation epithermal vuggy silica-alunite-pyrophyllite to dickite-kaolinite alteration produced by an early volatile rich event resulting from the dissociation of $\text{H}_2\text{SO}_4$ to $\text{H}^+$ (Corbett and Leach, 1998). A later liquid-rich event carrying Au-Cu-As producing a zonation from enargite-luzonite, tennantite-tetrahedrite to covellite.
Paragenetic model – Carbonate BM

Porphyry intrusion and alteration  Diatreme emplacement and venting  High Sulphidation epithermal overprint

Quartz-carbonate-base metal + quartz-As-pyrite-rich low sulphidation epithermal mineralisation produced by the mixing of pregnant Au-As-Pb-Zn bearing magmatic fluids with bicarbonate surface waters (Corbett and Leach, 1996).
Paragenetic model – post mineral faults

Porphyry intrusion and alteration  Diatreme emplacement and venting  High Sulphidation epithermal overprint

Quartz-carbonate

Post mineral thrust faulting during the Pliocene (Cloos et al., 2010) off-setting the porphyry mineralisation and diatreme.
Paragenetic model

Porphyry intrusion and alteration → Diatreme emplacement and venting → High Sulphidation epithermal overprint

Quartz-carbonate-base metal Au epithermal veins → Post mineral thrust faulting
Summary

- Wafi–Golpu mineralisation emplacement in extensional zone within a left-stepping sinistral–Wafi Transfer fault.

- Porphyry Cu-Au mineralisation was deposited separate to Mo mineralisation.

- Diatreme vented due to $\text{H}_2\text{O}$ incursion on magma.

- High Sulphidation overprint depositing Au-Cu-As

- Later Au associated with quartz-carb-base metal veins produced by mixing with bi-carbonate waters

- Post mineral thrust fault during E-W compression

- Surface geochemistry analysis highlights Cu-Mo anomalism over porphyry Cu deposits. Principle Component Analysis good tool for identifying targets.
Questions?

Contact details:
Doug.menzies@cmcgeos.com