

Geology, geochemistry and exploration implications of hydrothermal alteration associated with epithermal Au-Ag deposits

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Abstract

This contribution summarises new knowledge and data, obtained during a three year ARC-AMIRA funded research project, on the mineralogical and geochemical characteristics of hydrothermal alteration associated with low sulfidation, gold-silver epithermal deposits. These data are used to develop exploration vectors for use at both deposit and district scales, plus techniques have been established to distinguish ore grade epithermal systems from barren or low grade systems. Deposits investigated were Ladolam, Papua New Guinea, Gosowong and Mt Muro, Indonesia, Cerro Vaguardia, Argentina and Bimurra and Twin Hills, Australia.

Keywords: *epithermal, hydrothermal alteration and zonation, mineral chemistry, litho-geochemistry, exploration vectors*

Introduction

Low sulfidation epithermal deposits provide a significant contribution towards global silver and gold production (White and Hedenquist, 1990; Hedenquist et al., 2000; Simmons et al., 2005) and are an important target for precious metal explorers. Investigation of modern geothermal systems have led to many new concepts in the understanding of low sulfidation epithermal deposits which aid in the development of genetic and exploration models for this style of mineralization (Reyes, 1990).

While the characteristics of the geology and mineralization of low sulfidation epithermal deposits are generally well known and many papers (e.g. Buchanan, 1981; Heald et al., 1987; Sillitoe, 1993, 1997; White et al., 1995; White and Hedenquist, 1990, 1995; Hedenquist et al., 2000; Cooke and Simmons, 2000; Simmons et al., 2005) have described the alteration mineralogy and zonation, there has been a distinct lack of detailed information and data available on the mineral chemistry and whole-rock geochemical characteristics of the hydrothermal alteration. Alteration zones in epithermal districts are commonly larger than the related ore deposit and consequently the recognition of mineralogical and geochemical zonation within areas of alteration may provide a basis for developing vectors to the ore deposit. Some alteration zones have no known related ore deposit, and therefore the recognition of discriminators between fertile and barren alteration zones is also very important for exploration.

Information presented in this paper is based on the outcomes of a three year (2000-2002) ARC-AMIRA collaborative investigation between researchers based at the Centre for Ore Deposit Research (CODES), University of Tasmania, Australia and the Geothermal Institute, University of Auckland, New Zealand. Deposits investigated were Ladolam, Papua New Guinea, Gosowong and Mt Muro, Indonesia, Cerro Vaguardia, Argentina and Bimurra and Twin Hills, Australia.

Results

Deposits studied were hosted in either basaltic to intermediate-hosted (Ladolam, Mt Muro, Gosowong) or felsic-hosted (Cerro Vanguardia, Twin Hills, Bimurra) volcanic and volcanoclastic rocks with minor amounts of epiclastic sedimentary rocks. The sizes and styles of the deposits varied greatly from a low-grade to barren, small, vein-stockwork systems at Bimurra and Twin Hills to high-grade veins systems at different scales such as Gosowong, Mt Muro and Cerro Vanguardia, to a large, breccia-hosted, low grade, disseminated system at Ladolam. Table 1 summarizes the geologic, mineralization and alteration characteristics for each deposit.

Hydrothermal alteration

At each of the deposits the alteration mineralogy and zonation were determined using a combination of surface mapping, drill core logging, petrology, SWIR (PIMA), XRD and potassium feldspar staining (HF and sodium cobaltinitrite). There is a consistent development and zonation of alteration at each of the deposits. In all cases the development of quartz-adularia-illite is proximal to mineralisation. Moving away from the mineralisation the alteration becomes illite-smectite-rich before passing into a distal propylitic assemblage containing varying proportions of albite, chlorite, epidote and chlorite. Distinct zonation of alteration assemblages is much more pronounced in the mafic-hosted (Gosowong, Mt Muro and Lihir) as compared to the felsic-hosted systems (Cerro Vanguardia, Twin Hills and Bimurra). In the mafic-hosted systems the distal propylitic alteration is better developed compared to the felsic systems.

A key outcome of this project has been the importance of the distribution of adularia. At every case study site the identification and distribution of adularia was vastly underestimated during fieldwork. Determining the presence of adularia is also important for discriminating fertile from non-fertile structures in a district. As the presence of adularia indicates boiling of the hydrothermal fluids, and to the proximity of gold mineralisation, potassium feldspar staining should become a routine part of the exploration program.

Not all propylitic (epidote±chlorite±albite±calcite) alteration is the same. Recognition of two types of propylitic alteration, vein-related and regional, has been critical to the effective evaluation of the propylitic alteration. Care should be taken when evaluating propylitic alteration associated with epithermal systems as their mineralogy and textural characteristics are important in determining if the “green rocks” are related to a mineralising system or part of the background alteration in volcanic terrains.

Whole-rock geochemistry

Multi-element geochemistry was undertaken on over eight hundred whole-rock samples during this project. Major and selected trace elements were analysed by XRF, with the majority of trace elements analysed by ICPMS. Various methods were employed to investigate the whole-rock geochemistry, including down hole element plots, 2D countouring of data, and the development and use of alteration indices and alteration box plots.

The alteration indices determined to be of most use when evaluating lithochemical variations surrounding low sulfidation epithermal deposits were the Alteration Index (AI) = $100(\text{MgO} + \text{K}_2\text{O})/(\text{MgO} + \text{K}_2\text{O} + \text{CaO} + \text{Na}_2\text{O})$; Ishikawa et al., 1976); chlorite-carbonate-pyrite index (CCPI) = $100(\text{MgO} + \text{FeO})/(\text{MgO} + \text{FeO} + \text{K}_2\text{O} + \text{Na}_2\text{O})$; Large et al., 2001); KVI = $100 \cdot \text{LOI} / (\text{LOI} + \text{K}_2\text{O})$; KSI = $100 \cdot (\text{K}_2\text{O} + \text{S}) / (\text{K}_2\text{O} + \text{S} + \text{MgO} + \text{Na}_2\text{O})$; NVI = $100 \cdot \text{LOI} / (\text{LOI} + \text{Na}_2\text{O})$ and SSI = $100 \cdot \text{S} / (\text{S} + \text{Na}_2\text{O})$. In almost all cases, these alteration indices have values that increase towards the deposit on district and/or deposit scale. However, the use (and abuse) of alteration indices at a specific deposit must be coupled with a thorough understanding of alteration mineralogy and processes.

Table 1. Characteristics of Low Sulfidation Epithermal Deposits Investigated in this Study.

Deposit	Host Rocks	Mineralisation	Alteration	Resource*	Source
Ladalam, Papua New Guinea	Pleistocene basalt lavas & breccias	Pleistocene disseminations and stockwork	adularia-pyrite (proximal) smectite-carbonate-chlorite (distal) alumite-kaolinite (surficial)	471 Mt @ 2.7 g/t Au 41 Moz Au	Carmen (2003) Herrmann (2002) Cater (2002)
Gossowong, Indonesia	Miocene andesite lavas & volcanoclastic rocks	Pliocene vein and stockwork	quartz-adularia-illite (proximal) illite-smectite-adularia (intermediate) epidote-chlorite-calcite-albite (distal) kaolinite-alumite-quartz (surficial)	1.0 Mt @ 27 g/t Au, 38 g/t Ag 0.9 Moz Au	Gemmell (2002) Olberg (2001) Olberg et al. (1999)
Mt Muro, Indonesia	Oligocene andesite lavas & volcanoclastic rocks	Miocene multiple veins and breccia	illite-pyrite-adularia (proximal) chlorite-carbonate (distal) kaolinite-silica (surficial)	9.5 Mt @ 4.0 g/t Au, 102 g/t Ag 1.2 Moz Au	Wurst (2002) Simmons and Browne (1990)
Cerro Vanguardia, Argentina	Jurassic rhyolite ignimbrites	Jurassic multiple veins and stockwork	illite-quartz-adularia-chlorite (proximal) illite-smectite-quartz (distal) kaolinite (surficial)	15.9 Mt @ 8.3 g/t Au, 101 g/t Ag 4.3 Moz Au	Sharpe (2002) Sharpe et al. (2002)
Twin Hills, Australia	Devonian rhyodacite intrusive & breccias	Devonian disseminations and stockwork	quartz-illite-adularia-chlorite (proximal) chlorite-adularia-quartz (intermediate) albite-chlorite-calcite (distal)	8.3 Mt @ 2.1 g/t Au 0.6 Moz Au	Young (2001) Sennitt (1991)
Bimurra, Australia	Devonian rhyolite lavas & volcanoclastic rocks	Devonian veins and stockwork	quartz-illite(sericite)-adularia (proximal) illite-smectite-pyrite (intermediate) chlorite-smectite-calcite-pyrite (distal) alumite-kaolinite-silica (surficial)	1.6 Mt @ 1.4 g/t Au 0.07 Moz Au	Booth (2002) Tate (2001)

* resources as of 31/12/2002

Thallium

One of the new aspects of the interpretation of the whole-rock has been the relationship between K_2O and Tl. Thallium is an element that occurs in phyllosilicates (micas and clays), tectosilicates (feldspars) and sulfides (galena, pyrite and Tl-sulfides and Tl-sulfosalts) with concentrations generally are in the range of 1-10 ppm (Ikramuddin et al., 1983; Shah et al., 1994). Thallium has been noted as an element that is concentrated in altered rocks surrounding a variety of mineral deposit styles, for example VHMS (Large et al., 2001), mesothermal veins, uranium deposits, porphyry Cu-Mo deposits, and epithermal vein deposits (Shah et al., 1994). In our study, there is a distinctive positive correlation between K_2O and Tl for altered samples from both mafic-intermediate and felsic-hosted deposits, while there is little correlation between K_2O and S. Our research indicates that adularia, not sulfide or illite, contains the Tl in the altered rocks surrounding the low sulfidation epithermal deposits examined.

Mineral chemistry

Chlorite

A systematic zonation of chlorite chemistry is observed from the analysis of chlorites at Gosowong, Mt Muro and Cerro Vanguardia. Chlorite chemistry varies systematically with type of alteration and proximity to the deposit. Mg-rich chlorite occurs proximal to the vein in quartz-adularia-illite alteration, passing outwards Mg-Fe chlorite in illite-smectite zones to Fe-chlorite in the distal propylitic alteration zone.

Potassium feldspar

A new and novel method, laser ablation-ICPMS, for determining the mineral chemistry of hydrothermal potassium feldspar was pioneered in this project. At Cerro Vanguardia Ba, Sr, Rb, Li, Cs, Tl and Pb have elevated levels in both secondary K-feldspar and vein adularia. Both the secondary K-feldspar alteration and adularia grains at any given location have relatively constant trace element levels and are internally homogeneous. This study has identified Ba and Pb, and to a lesser extent Cs, as elements in adularia that vary systematically and can be used as vectors towards mineralisation at Cerro Vanguardia.

Pyrite

Laser ablation-ICPMS analyses of pyrite were also undertaken on pyrite from Cerro Vanguardia. Pyrite in the vein and stockwork has higher levels As, Ag, Cu and Au contents compared to pyrite in the wall rock. In comparison, pyrite in the wall rock has higher levels of Zn, Sb, Tl, Co, Pb and Bi, with lower Tl contents. Lead, Bi and Mo in pyrite have systematic increases towards a vein.

Exploration vectors

Deposit and district scale

A review of the data generated at each of the study sites has led to some general conclusions regarding deposit and district scale vectors for low sulfidation epithermal deposits. The most promising exploration vectors are:

- Alteration zonation. Proximal potassium feldspar adularia-quartz-illite to illite-smectite to distal chlorite-epidote-calcite-albite.
- Adularia distribution. Adularia is more abundant than generally recognised. Fertile structures have a greater abundance of adularia and a positive K_2O -Tl relationship compared to non-fertile structures. As the presence of adularia indicates both boiling of the hydrothermal fluids and, in general, proximity of gold mineralisation potassium feldspar staining should become a routine part of an exploration program.

- Mineral chemistry. Chlorite becomes Mg-rich towards a deposit. Adularia shows an increase in Ba, Pb and to a lesser extent Cs towards a deposit. Lead, Bi and Mo increase in pyrite towards a deposit.
- High or increasing illite crystallinity (>1) towards deposit.
- Geochemical variations. The consistent geochemical indicators are:

Basalt-andesite hosted deposits

Surficial: increases in as, Hg, Tl, Sb and Mo (advanced argillic alteration)

Halo: increases in K₂O, S, Alt. index, S/Na₂O, Tl, As, Sb; decreases in Na₂O, CaO

Rhyolite-dacite hosted deposits

Surficial: increases in as, Hg, Tl, Sb and Mo (advanced argillic alteration)

Deposit: increases in Au, Ag, Sb, As, Tl, Te, Li, K₂O

Halo: Increases in K₂O, Tl, As, Rb, Ba, Cs

Distinguishing ore grade epithermal systems from barren or low grade systems

Our best information on low-grade to barren systems comes from portions of the Cerro Vanguardia district and Bimurra, both felsic-hosted systems. No low grade or barren systems hosted in mafic to intermediate rocks were studied. The conclusions presented below are based on research from the felsic-hosted systems with inferences drawn from our understanding of the systems hosted by mafic and intermediate rocks.

The most promising discriminators for distinguishing high-grade from low-grade or barren systems are;

- Alteration intensity. The alteration mineralogy and zonation is essentially the same between high and low-grade or barren systems, but the scale and intensity of alteration are much greater in the high grade systems.
- High or increasing illite crystallinity (>1) towards a deposit in high grade systems.
- Size of paleohydrothermal system. The high grade systems are larger in terms of structures, large dilatancy zones within structures, footprint of alteration and intensity of alteration.
- Fertile structures will have a greater proportion of adularia and a positive K₂O-Tl relationship compared to non-fertile structures.
- Vein textures. High grade systems have large structures with complex histories (i.e. repeated opening and fluid flow events). In general, higher grade systems have multiply generations of fluid pulses, as evidenced by complex colloform, crustiform, cockade and breccia textures.
- Presence of boiling (bladed calcite or pseudomorphs, two-phase fluid inclusions) is not a distinguishing feature. Many deposits with evidence of boiling do not have high grades.
- Geochemical variations. Research at Cerro Vanguardia has highlighted the differences between the alteration geochemistry surrounding high and low grade veins. Overall, higher grade Au-Ag veins tend to have wall rocks and veins that contain higher K₂O (>4%), Tl (>3 ppm), Rb (>150 ppm) and Ba (>300 ppm) contents than lower grade veins. The abundance of these trace elements reflects higher K₂O contents associated with intense K-feldspar alteration. Low grade to barren veins have low K₂O (<4%), Tl (<2 ppm), Rb (<150 ppm) with variable Ba contents.

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References

- Booth, J., 2002. Mineralization and alteration of the Bimurra prospect, Drummond basin, Queensland, Australia. Unpublished Honours thesis, University of Tasmania, 122p.
- Buchanan, L.J. 1981. Precious metal deposits associated with volcanic environment in the southwest. in *Relations of Tectonics to Ore Deposits in the Southern Cordillera*, Dickinson W.R. and Payne, W.D., eds, Arizona Geological Society Digest 14: 237-262.
- Carmen, G.D. 2003. Geology, mineralization, and hydrothermal evolution of the Ladolam gold deposit, Lihir Island, Papua New Guinea. *Economic Geology Special Publication* 10:247-284.
- Cater, G. 2002. Deep hydrothermal alteration at the Ladolam epithermal gold deposit, Lihir Island, Papua New Guinea. Unpublished Masters thesis. University of Auckland, 126p.
- Cooke, D.R. and Simmons, S.F. 2000. Characteristics and genesis of epithermal gold deposits. *Reviews in Economic Geology* 13: 245-278.
- Gemmell, J.B. 2002. Hydrothermal alteration associated with the Gosowong low sulfidation epithermal Au-Ag vein deposit. ARC-AMIRA P588 Final Report 2: 1.1-1.11.
- Heald, P., Foley, N.K. and Hayba, D.O. 1987. Comparative anatomy of volcanic hosted epithermal deposits: acid-sulfate and adularia-sericite types. *Economic Geology* 82: 1-26.
- Hedenquist, J.W., Arribas, A. and Gonzalez-Urien, E. 2000. Exploration for epithermal gold deposits. *Reviews in Economic Geology* 13: 221-244.
- Herrmann, W. 2002. Ladolam gold deposit, Lihir Island, PNG. ARC-AMIRA P588 Final Report 2: 4.1-4.10.
- Ikramuddin, M., Asmeron, Y., Nodstrom, P.M., Kinart, K.P., Martin, W.M., Digby, S.J.M., Elder, D.D., Nijak, W.F. and Afemari, A.A. 1983. Thallium: a potential guide to mineral deposits. *Journal of Geochemical Exploration* 19: 465-490.
- Ishikawa, Y., Sawaguchi, T., Iwaya, S. and Horiuchi, M. 1976. Delineation of prospecting targets for Kuroko deposits based on modes of volcanism of underlying dacite and alteration halos. *Mining Geology* 26: 105-117
- Large, R.R., McPhie, J., Gemmell, J.B., Herrmann, W. and Davidson, G. 2001. The spectrum of ore deposit types, volcanic environments, alteration halos and related exploration vectors in submarine volcanic belts: some examples from Australia. *Economic Geology* 96: 913-938.
- Olberg, D.J. 2001. Ore shoot targeting in the Gosowong vein zone, Halmahera, Indonesia. Unpublished Masters thesis, University of Tasmania, 227p.
- Olberg, D.J., Rayner, J., Langmead, R. P. and Coote, J.A.R. 1999. Geology of the Gosowong Epithermal Gold Deposit, Halmahera, Indonesia. *Australasian Institute of Mining and Metallurgy Publication* 4/99: 179-186.
- Reyes, A.G. 1990. Petrology of Philippines geothermal systems and the application of alteration mineralogy to their assessment. *Journal of Volcanology and Geothermal Resources* 43: 279-309.
- Sennitt, C.M. 1991. Aspects of epithermal gold mineralization, Twin Hills, Queensland. Unpublished Masters thesis, James Cook University, 234p.
- Shah, M.T., Ikamuddin, M. and Shervais, J.W. 1994. Behaviour of Tl relative to K, Rb, Sr and Ba in mineralized and unmineralized metavolcanics from the Dir area, northern Pakistan. *Mineralium Deposita* 29: 422-426.

- Sharpe, R. 2002. Low sulfidation epithermal veins of the Cerro Vanguardia district, Patagonia, Argentina: integration of stratigraphic, alteration and geochemical constraints to define exploration vectors and discriminate high and low grade veins. ARC-AMIRA P588 Final Report 2: 5.1-5.19.
- Sharpe, R., Riveros, C. and Scavuzzo, V. 2002. Stratigraphy of the Chon Aike Formation ignimbrite sequence at Cerro Vanguardia Au-Ag epithermal vein district. In *Actas del XV Congreso Geológico Argentino CD-ROM*, Cabaleri N., Cingolani, C.A., Linares, E., López de Luchi, M.G., Osters, H.A. and Panarello, H.O., eds, Artículo N° 232 6p.
- Sillitoe, R.H. 1993. Epithermal models: genetic types, geometric controls and shallow features. In *Mineral Exploration Modelling*, Kirkham, R.V., Sinclair, W.D., Thorpe, R.I. and Duke, J.M. eds, Geological Association of Canada Special Paper 40: 403-417.
- Sillitoe, R.H. 1997. Characteristics and controls of the largest porphyry copper-gold and epithermal gold deposits in the circum-Pacific region. *Australian Journal of Earth Science* 44: 373-388.
- Simmons, S. F. and Browne, P.R.L. 1990. Mineralogic, alteration and fluid inclusion studies of epithermal gold-bearing veins at the Mt. Muro prospect, Central Kalimantan (Borneo), Indonesia. *Journal of Geochemical Exploration* 35: 63-104.
- Simmons, S.F., White, N.C. and John, D.A. 2005, Geologic characteristics of epithermal precious and base metal deposits. *Economic Geology* 100th Anniversary Volume: 485-522.
- Tate, N.M. 2001. Geology of the Bimurra prospect MDL 22. Unpublished report for Delta Gold Ltd.
- White, N.C., Leake, M.J., McCaughey, S.N. and Paris, B.W. 1995. Epithermal gold deposits of the southwest Pacific. *Journal of Geochemical Exploration* 54: 87-136.
- White, N.C. and Hedenquist, J.W. 1990. Epithermal environments and styles of mineralization: variations and their causes, and guidelines for exploration. *Journal of Geochemical Exploration* 35: 445-474.
- White, N.C. and Hedenquist, J.W. 1995. Epithermal gold deposits: styles, characteristics and exploration. *Society of Economic Geologists Newsletter* 23: 1, 9-13.
- Wurst, A. 2002. Au-Ag low sulfidation epithermal vein and breccia systems, Mt Muro, Kalimantan, Indonesia. ARC-AMIRA P588 Final Report 2: 2.1-2.17.
- Young, B., 2001, A mineralogical and geochemical study of the Lone Sister epithermal gold deposit, Queensland, Australia, Unpub, Masters thesis, University of Auckland, 81p.

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