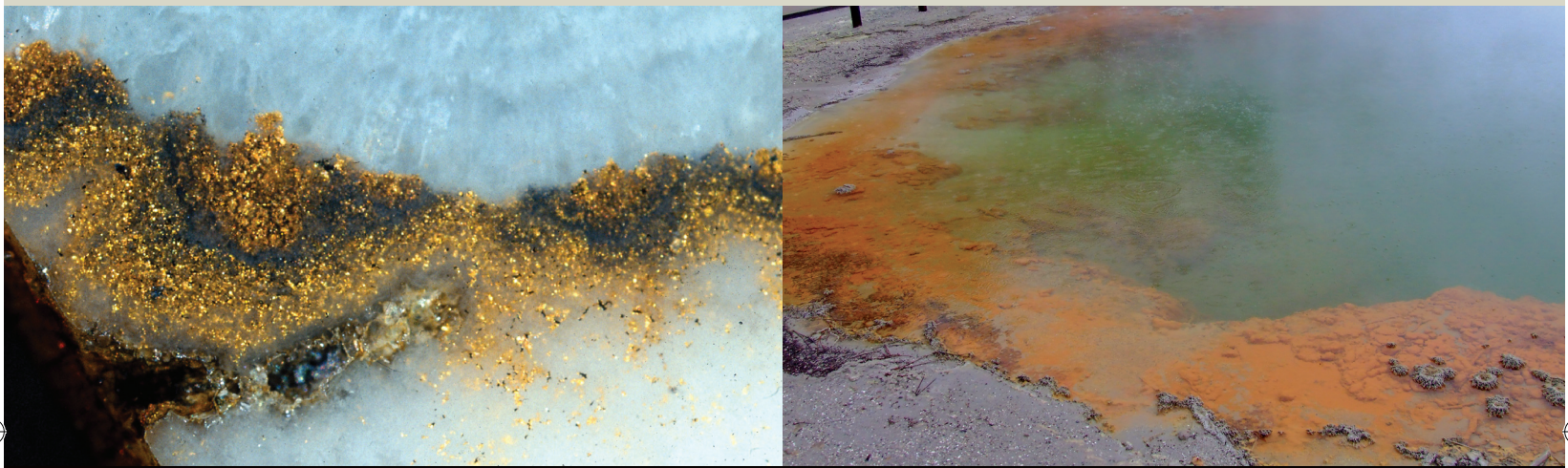


Fermor 2011

Ore Deposits in an Evolving Earth

7 - 9 September 2011



Abstract Book

CONVENORS

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CONTENTS

Sponsor acknowledgement	Page 2
Programme	Pages 3-7
Oral abstracts (In programme order)	Pages 8-38
Poster abstracts (In programme order)	Pages 39-65
Sponsor information	Pages 66-68
Fire safety information	Pages 69-70
Map to the Royal Society	Page 71
Note pages	Pages 72-74

We gratefully acknowledge the support of the sponsors for making this meeting possible.



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Programme

Wednesday 7 September 2011	
12.30	Arrival & registration & lunch
Student session - sponsored by Gnomic Resources, Goldfields & the SEG	
13.40	Opening comments Gawen Jenkin, University of Leicester
13.45	Modern mineral exploration – more than just geology Barry Stoffell, Rio Tinto
14.30	CPD and Chartership in the mining and exploration industry Bill Gaskarth, Geological Society & Jim Coppard, Anglo American
15.00	Tea & coffee & student posters
16.15	Keynote: Introduction to exploration and mining finance Philip Crowson, University of Dundee
17.15	Discussion & closing remarks
17.30	Icebreaker reception – sponsored by Carbine Resources
Thursday 8 September 2011	
08.00	Arrival & registration
08.40	Opening comments & welcome Gawen Jenkin, University of Leicester, Chair MDSG
Session – Super-Giant Mineral Deposits – sponsored by Anglo American	
08.45	Keynote: The Carbon Leader Reef in the Witwatersrand Basin; Why is it such a unique Supergiant Gold Deposit? Ross Large, University of Tasmania
09.30	Understanding ore controls at the Navidad silver deposit, Chubut, Patagonia Warren Pratt, Specialized Geological Mapping Ltd
Session – Evolution of the Earth and ore deposits – sponsored by Anglo American	
09.45	Keynote: Temporal relations between mineral deposits and global tectonic cycles – a generational archive or preservation bias? Peter Cawood, University of St Andrews
10.30	Assembly and breakup of Earth's first supercontinent <i>Nuna</i>: its impact on formation and preservation of Paleo-Mesoproterozoic mineral deposits Sally Pehrsson, Geological Survey of Canada
10.45	Tea & coffee – sponsored by Scotgold
11.15	BIF-hosted Iron Ore: The Archean versus Paleoproterozoic hypogene records in Western Australia Thomas Angerer, University of Western Australia

11.30	Bedded martite/microplaty-hematite ore genesis: environmental evolution in the Paleoproterozoic era Desmond Lascelles, University of Western Australia
11.45	Poly-orogenic tectonic and chronologic setting of gold mineralization in Nigeria, West Africa Laurence Robb, University of Oxford
12.00	Komatiite volcanism: Lithospheric controls on the Earth's hottest melts and implications for associated Ni-Cu-PGE deposits David Mole, University of Western Australia
Session – Microbe-Mineral Interactions in Ore Processes	
12.15	Keynote: Economic Geomicrobiology Gordon Southam, University of Western Ontario
13.00	Lunch – sponsored by Helio Resources
14.00	Invited talk: The life and times of an Irish-type Zn+Pb ore deposit Adrian Boyce, Scottish Universities Environmental Research Centre
Session – Ore Genesis	
14.30	Multiple Sulfur and Iron Isotope Composition of Magmatic Ni-Cu-(PGE) Sulfide Mineralization from Eastern Botswana Marco Fiorentini, University of Western Australia
14.45	High temperature deformation in magmatic chromites from the Merensky Reef (Bushveld Complex, South Africa) Zoja Vukmanovic, University of Western Australia
15.00	New Gold Occurrences in the Scottish Dalradian, UK – Nature and Constraints on Genesis Nyree Hill, University of Leicester
15.15	Tea & coffee & poster session – sponsored by Micromine
16.00	Micromine demonstration in the Lecture Theatre (optional activity)
18.00	Close of day
19.00	Conference dinner at the Royal Society – sponsored by Rio Tinto
Friday 9 September 2011	
08.00	Arrival & registration
Session – Fluids from the Core to the Ore	
08.45	Keynote: The role of magmatic sulfides and low-density fluids in the formation of porphyry-type ore deposits Andreas Audétat, University of Bayreuth (talk sponsored by the Geochemistry Group)
09.30	Evidence that barely-contained nearly-explosive venting of large volumes of magmatic volatiles initiated porphyry Cu formation Lawrence Cathles, Cornell University

09.45	Ore Genesis of The Estrela Copper Deposit, Brazil: Evidence From Geology, Mineral Paragenesis, and Fluid Inclusion and Stable Isotope Studies Karen Volp, CSA Global (UK) Ltd
10.00	Keynote: Metamorphic Fluids: do they contribute to ore systems? Bruce Yardley, University of Leeds <i>(talk sponsored by the Metamorphic Studies Group)</i>
10.45	Orogenic Gold Mineralisation in the Birimian of West Africa: is it as simple as it seems? Peter Treloar, Kingston University
11.00	Tea & coffee
Session – Ore Genesis	
11.25	A Metallogenic model for mineral deposition of carbonate hosted Mississippi Valley type Pb-Zn-Sr-Br Ain Allega and El Aguiba ore deposits (Northern Tunisia) Riadh Abidi, Faculté des sciences de Bizerte, Tunisia
Session – The Future: Limits to Availability of Mineral Commodities	
11.40	Session introduction Gus Gunn, British Geological Survey
11.45	Keynote: The moral case for mining – is it a question the industry can answer? Mike Harris, Rio Tinto
12.30	Lunch – sponsored by Volta Resources
13.30	Keynote: Meeting the resources challenge on an increasing specialised and populated planet Lawrence Cathles, Cornell University, SEG Distinguished Lecturer for 2011 <i>(talk sponsored by the Society of Economic Geologists)</i>
14.15	Keynote: Tectonic Diffusion Estimates of Global Mineral Resources Steven Kesler, University of Michigan
15.00	Opportunities and challenges in the future supply of rare earths; developing metrics for responsible sourcing Francis Wall, University of Exeter
15.15	Resource mapping using multi-scale mineral-spectroscopy Carsten Laukamp, WA Centre of Excellence for 3D Mineral Mapping
15.30	Tea & coffee – sponsored by Glasmin
16.00	Keynote: The Cycles and Criticality of Metals Thomas Graedel, Yale University <i>(talk sponsored by the Applied Mineralogy Group)</i>
16.45	Closing discussion
17.00	Close of conference

Poster Programme

Arthur Holmes Room

Session - Evolution of the Earth and ore deposits
Mapping the intra-cratonic framework of an Archean Craton: implications for camp-scale mineralisation David Mole, University of Western Australia
Continental evolution and the tectonic setting of IOCG mineralisation Martin Smith, University of Brighton
Abundant sulphate in the Neoproterozoic ocean: implications of $\delta^{34}\text{S}$ and $\delta^{18}\text{O}$ analyses of sedex barite deposits in the Scottish Dalradian Norman Moles, University of Brighton
The Congo craton: an evolving giant iron ore province Melvin Nforba, University of Yaounde I
A Classic Geological Argument Origin of Archaen Pyritic Conglomerates and Witwatersrand Gold Reefs Are they Hydrothermal or Sedimentary? Graham Oram
3D Structural Model of Southwest Turkey Reveals Lithosphere-Scale Control on Hydrothermal Fluid Flow Klaus Gessner, University of Western Australia
Session – Fluids from the Core to the Ore
Is fluid exsolution depth the key to molybdenum porphyries? Daniel Smith, University of Leicester
Session – The Future: Limits to Availability of Mineral Commodities
Critical metal resources in Tertiary epithermal and porphyry systems at NE Greece Nikolaos Skarpelis, University of Athens
Session – Ore Genesis
The Kago Low-Sulfidation Au/Ag Deposit: an affiliated Nansatsu deposit, microthermometry and Ar/Ar age determinations Tom Tindell, Kyushu University
Iron sulphide from the Boulder Conglomerate of the Navan Zn-Pb Deposit, Co. Meath, Ireland: composition and origin Gareth Barker, University College Dublin
“Layered” Mineralisation at the Navan Zn-Pb Mine, Ireland – A story of sedimentation Craig Barrie, Scottish Universities Environmental Research Centre
Genetic constraints for the Lupa Goldfield, SW Tanzania: Implications from Rhenium-Osmium pyrite and molybdenite geochronology Christopher Lawley, Durham University
Ore-forming Condition of the Keisen No. 3-1 Vein in the Hishikari Gold Deposit, Kagoshima, Japan Takuma Suga, Kyushu University
Occurrences and Chemical Compositions of Ore Minerals, and Their Implications for Epithermal Gold Mineralization at the Victoria Gold Deposit, Northern Luzon, Philippines Takahiro Tanaka, Kyushu University

Origin and Serpentinization of Siruka peridotites, Southeastern Choiseul, Solomon Islands

Christopher Vehe, Kyushu University

The analysis and interpretation of trace element geochemistry in sulfide minerals and mercury isotopes for the purpose of deposit exploration

Matthew Murphy, University of Western Australia

Microstructural characterization of natural gold alloys

Angela Halfpenny, CSIRO

Geometallurgy of Iron Ores from Liberia and Cameroon

Kelvin Anderson, Camborne School of Mines

Multiple phases of fenitisation and REE-enrichment in fenites around carbonatites – implications for future exploration targets

Emma Dowman, Kingston University

Tectonic setting of volcanic rocks hosting high sulphidation style gold mineralisation in Sibutad, Zamboanga del Norte (Philippines): clues from petrochemistry and $^{40}\text{Ar}/^{39}\text{Ar}$ dating

Jillian Aira S. Gabo, Kyushu University

ORAL ABSTRACTS

Demand, supply and prices: The horse, cart and driver of the mineral industries

Philip Crowson

University of Dundee

The rationale for mining is to create wealth through the provision of necessary raw materials to meet demands for goods and services of all types. Without potential markets for any minerals discovered exploration would have little economic justification. Minerals are seldom, if ever, demanded for their intrinsic characteristics but for their properties in use, and demand for them is derived from the demand for the products in which they are used. Most materials are substitutable in many uses with varying degrees of effectiveness, and end users are largely indifferent about which mineral products, if any, are incorporated in their purchases. Demand is influenced by a wide range of factors whose importance varies over time and between countries. The changing location of demand has always been a strong influence. Minerals usage is heavily biased towards construction, capital expenditure of all types, and consumer durables, all of which are more cyclically volatile than other types of expenditure.

Supply ultimately depends on the adequacy and accessibility of known resources and on investment in mines and processing facilities for their extraction. Historically the known reserves of most minerals have grown at least as fast as, and often much faster than demand. Exploration expenditure has been important in that regard, but technological change in extraction and processing and in end use markets has also contributed very strongly. Once they have been developed mines will tend to produce as long as prices cover their avoidable costs, but investors prospectively require much higher prices in order to justify new projects. Their expectations are not always realised. Many mines produce ore containing several marketable products, sometimes with undesirable by-products. Costs are governed by a wide range of geological and geographic influences as well as economic factors like energy prices and exchange rates. Companies have increasingly exploited the economies of scale in order to hold down costs, but at the expense of reduced flexibility of response to changing market conditions.

Supply is typically much less volatile than demand, with prices taking the strain. Price is the equilibrating force that keeps the system in dynamic balance, often working through technological change, and affecting both demand and supply. When markets move out of balance prices invariably overshoot their equilibrium level, in either direction. This overshoot sets in train the necessary corrective actions, some of which may be quick acting, whereas others may have lengthy gestation periods. The equilibrium level is not constant, but itself shifts in response to the fundamental forces acting on marginal supply and demand. The paper concludes with a discussion of some topical issues against this context.

The Carbon Leader Reef in the Witwatersrand Basin; Why is it such a Unique Supergiant Gold Deposit?

Ross R Large¹, Leonard Danyushevsky¹, Sebastien Meffre¹, Rob Burnett², Stuart Bull¹ and Sarah Gilbert¹

1. CODES, ARC Centre of Excellence in Ore Deposits, University of Tasmania, Hobart, Tasmania, Australia, 7001

2. AngloGold Ashanti Ltd., Geoscience Technical Office, Johannesburg, South Africa

For over 80 years the origin of gold in the Carbon Leader or Main Reef of the Witwatersrand Basin, the worlds greatest gold deposit, has been hotly debated. Proponents of the current two models; stratigraphic controlled modified placer and structurally controlled hydrothermal deposition, have provided specific lines of evidence that are convincing for their favoured model. The economic geology community has been split on the issue, with the modified placer model gaining more support in recent times.

As part of a collaborative AMIRA International research project, with specific support from AngloGold Ashanti we have applied the recently developed LA-ICPMS trace element mapping technique to study a series of Carbon Leader Reef (CLR) samples, from the Tautona Mine, West Wits. The results demonstrate that a two-stage process was the key to the phenomenal gold concentration in the CLR; involving an early stage 1 of detrital gold, arsenian pyrite (with invisible gold), uraninite and organic matter concentration in a quartz pebble conglomerate layer on the unconformity surface, followed hundreds of millions of years later by a second stage hydrothermal upgrading during regional metamorphism. The laser ablation ICP-MS mapping of trace elements shows that porous and sooty forms of detrital pyrite in the CLR are enriched in invisible gold up to 7.5 ppm Au, 1700 ppm As, 1200 ppm Ni, 850 ppm U, 70 ppm Te and 15 ppm Mo. These represent the stage 1, syn-sedimentary (detrital), phase of gold enrichment in the reef, which most likely was sourced by erosion of pyritic carbonaceous shale packages lower in the Witwatersrand basin. The laser mapping also shows that most of the detrital pyrites in the CLR, have arsenian pyrite rims from 10 to 60 microns thick that are of metamorphic-hydrothermal origin (stage 2), and enriched in invisible gold (up to 6.5 ppm), micro particles of free gold, brannerite, NiAs-sulfides and a range of trace elements, including; Co, Ni, Cr, Mn, Pb, Ag, Bi, Te and Sb. Fractured and brecciated pyrite along bedding parallel micro fracture zones in the reef, also show partial replacement of detrital pyrite by hydrothermal pyrite with the same trace element signature as the hydrothermal pyrite rims. This stage 2 hydrothermal upgrading of the gold in pyrite provides support for a widespread hydrothermal event focused on the Carbon Leader Reef.

Without this two stage process of early synsedimentary gold, pyrite, uranninite enrichment, involving continued reworking on unconformity surfaces during basin development, followed by the second stage hydrothermal upgrading of gold and uranium during metamorphism, accompanying basin inversion, it is doubtful that the Wits Carbon Leader Reef would have developed into the worlds all time supergiant gold deposit.

Understanding ore controls at the Navidad silver deposit, Chubut, Patagonia

Warren Pratt

Specialized Geological Mapping Ltd, Station Rd, Urquhart, Moray IV30 8LQ.

The Navidad silver project (Pan American Silver Corp) occurs in Patagonia, Argentina. It is one of the largest undeveloped silver deposits in the world, with published resources of about 750 Moz of silver. Localized on a mega crustal shear zone, it is hosted within a Jurassic non-marine Rift basin. Shortly after widespread ignimbrite and andesite volcanism, the basin suffered extreme extension. This created isolated and rotated listric fault blocks that subsequently controlled sedimentation and mineralization. Some sub-basins were filled by coarse clastics (sandstones and debris flow deposits); others by relatively sediment-starved black calcareous siltstones, stromatolitic bituminous limestones, and strontium-rich evaporites. Angular unconformities are common. The bituminous sequence contrasts strongly with the mostly oxidised lavas beneath and forms a major regional Redox boundary.

Mineralization is unusual and has both high-level epithermal, and syngenetic, features. Most ore occurs as veins or open space-fillings within a fractured and autobrecciated lava flow. There is evidence of boiling fluids, such as bladed calcite, in veins and open spaces within the tilted lava blocks. However, most silver was deposited higher, immediately beneath the Redox boundary. This implies that rising oxidised and metal-bearing fluids were reduced, thereby dumping out silver. Possible exhalative rock, resembling travertine, occurs immediately above some major veins, implying that mineralization was accompanied by venting of hot springs into an alkaline lake. Local massive sulphide occurs at favourable structural sites, particularly where permeable fractured lava is brought into faulted contact with organic-rich siltstones and coals. Elsewhere, silver ore is mostly remarkably sulphide-poor and includes native silver.

Temporal relations between mineral deposits and global tectonic cycles – a generational archive or preservational bias?

P.A. Cawood¹, C.J. Hawkesworth¹ and B. Dhuime^{1,2}

¹*Department of Earth Sciences, University of St. Andrews, North Street, St. Andrews KY16 9AL, UK*

²*Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, UK*

The rock record, including that of mineral deposits, displays a heterogeneous spatial and temporal distribution. This is generally considered to reflect secular and episodic processes of rock generation in an evolving Earth system, including the cyclic aggregation and breakup of supercontinents. We argue that this distribution does not represent a global episodicity in the processes responsible for magmatism and mineralization, but instead is a consequence of the greater preservation potential of rocks and mineral deposits enveloped within collisional belts. The record is therefore biased by the construction of supercontinents. Peaks and troughs of ages in the rock record reflect the balance between the volumes of rocks generated during the three stages of supercontinent evolution (convergence, collision and breakup) and the respective preservation potential of magmas generated in each of these stages. Convergent plate margins are sites of major continental growth and of certain mineral deposit types, for example porphyry Cu ± Au, epithermal Au-Ag, and orogenic gold, but the overall preservation potential of deposits in such settings is low unless the deposits are young or formed during the latter stages of plate convergence and enveloped within the protective sheath of an aggregated supercontinent. The correlation of mineral deposits formed in extensional settings (e.g. VMS, sediment-hosted Pb-Zn deposits) with phases of supercontinent aggradation is also a function of preservation potential rather than specific processes of their generation. Intra-continental deposits (e.g. diamonds) have a high preservation potential due to the inherent stability of the ancient cratons in which they occur.

Assembly and breakup of Earth's first supercontinent *Nuna*: its impact on formation and preservation of Paleo-Mesoproterozoic mineral deposits

Pehrsson, S.J. *, Eglington, B.E. ^, Evans, D.A.D. ¹, and Huston, D. ²

*Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8 (presenter)

^University of Saskatchewan; ¹Yale University; ²Geoscience Australia

The early Proterozoic is marked by confluence of two major geodynamic events: oxygenation of the atmosphere and assembly of Earth's first true supercontinent, *Nuna*. This confluence profoundly influenced the formation and preservation of world-class metallotects associated with distinct phases of *Nuna*'s evolution: 1) TransHudsonian VMS; Homestake, Tanami and Pine Creek Gold; Circum-Superior- Baltic Ni-Cu-PGE associated with assembly; 2) Athabasca-Kombolgie unconformity-hosted U associated with stability and 3) BrokenHill, Mt Isa and Sullivan Pb-Zn and Olympic Dam IOCG associated with protracted break-up. New appropriately scaled reconstructions of *Nuna* can now be used to evaluate the influence of supercontinent formation on its contained mineral endowment.

Nuna was formed by closure of the Manikewan ocean between 2.1 and 1.8 Ga, during which nine Archean cratons and eight ribbon microcontinents were amalgamated along with seven newly assembled cratonic blocks. Orogens and contraction-related ore deposits (VHMS and orogenic lode gold) of *Nuna* show a lateral age progression reflecting diachronous closure of the Manikewan interior ocean and related seas. Magmatic nickel deposits formed in diverse, broadly back-arc settings immediately following early periods of accretion. Younger 1.7-1.6 Ga VMS (Jerome-Bagdad) formed above or inboard of a subduction zone on *Nuna*'s periphery that initiated following termination of assembly-related convergence. Unconformity-U deposits contemporaneously formed in intracontinental basins that underwent alternating transpressive tectonism and subsidence linked to changes in coupling of this long-lived peripheral orogen. A major triple junction between Siberia-Laurentia-Proto-Australia rifted ca. 1.67-1.4 Ga, forming basins (Broken Hill) and a seaway (Sullivan) that hosted major Pb-Zn districts. Its failed northern arm preserved the greater Laurentia configuration, influencing subsequent Rodinia paleogeography.

The difference in assembly between *Nuna* (introversion) and Rodinia (extroversion) profoundly influenced the character of bounding orogens and their metallogeny and may partially explain the underwhelming mineral endowment of the later, even when scaled for its presently preserved deeper crustal level. Introversion with its younger oceanic lithosphere, abundant pericratonic arcs and minimal subduction erosion allowed rapid obduction, trapping newly formed submarine VMS deposits before they could be consumed. Extroversion with its subduction of older oceanic lithosphere and often strong subduction erosion doomed Rodinia's VMS endowment. With nearly double the number of assembled plates and cratons than *Rodinia*, *Nuna* preserves a distinctly Archean-esque series of contraction-related metallotects. Importantly the switch to peripheral orogenesis late in *Nuna*'s history favoured formation of IOCG and unconformity U metallotects where older 'introverted' accretionary structures were intruded, crosslapped or reactivated and ultimately preserved.

BIF-hosted Iron Ore: The Archean versus Paleoproterozoic hypogene records in Western Australia

T. Angerer and S.G. Hagemann

Centre for Exploration Targeting, School of Earth and Environmental Science, M006, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009,
Contact: thomas.angerer@uwa.edu.au

Many significant banded iron formation (BIF) hosted iron ore deposits are complex systems of deep-seated magnetite- and/or hematite ore with halos of hydrothermally altered BIF, and deep-weathered crusts hosting “direct shipping” goethite-martite or microplaty hematite ore with 58 - 69 wt.% Fe and low Si, Mn, P, and S contamination. BIF (~35% Fe) is abundant in both, Archean greenstone belts and Paleoproterozoic basins, and therefore understanding on style and control of hypogene alteration and mineralization processes in both realms non only contributes to the knowledge of early Earth mineral systems, it is significant for robust exploration models. The Hamersley basin is the prime producer of high-grade iron ore (~16 Bt resource), but deposits are also located in Paleo- to Mesoarchean greenstone belts in the Yilgarn craton accounting for a ~1.2 Bt of resource.

For the studied hypogene-supergene microplaty hematite deposits in the Hamersley basin (e.g. Mt. Tom Price, Paraburdoo), a common theme for high-grade ore genesis is the presence of early Fe-rich carbonate±magnetite caused by basinal brines originating from underlying dolomite strata and ascending through Meso-Proterozoic low-angle extensional faults (Thorne et al. 2008, and references within). Subsequently, microplaty hematite replaced carbonate minerals due to deep convection of meteoric water. Important BIF hosted iron ore deposits in the Yilgarn craton show similar hypogene ore-forming stages, but controlling structures are compressive Meso- to late-Archean shear and fold zones (Angerer and Hagemann 2010; Duuring and Hagemann 2010). New geochemistry and stable isotope data suggest that metamorphic devolatilization of mafic country rocks and interaction with magmatic hydrothermal fluids from granitoids surrounding the belts, played a significant role in the hydrothermal alteration.

One crucial process for all hypogene-influenced iron ore deposit appears to be (Fe-) Mg-Ca-Mn metasomatism leading to carbonate and/or Fe-Mg-silicate alteration in BIF (Dalstra and Guedes 2004). The structural control and types of fluids involved in the metasomatic reactions are, however, variable and changed during the evolution of a BIF hosted iron ore deposit. A revised model, integrating distinct hydrothermal fluids (magmatic, metamorphic, basinal, and meteoric water) involved in the hypogene iron ore systems, discriminates between the hypogene altering systems and reveals two main genetic BIF iron ore systems: (1) the metamorphic/magmatic to meteoric, and (2) the basinal brines to meteoric iron systems. The first is common in both, Paleoproterozoic or Archean, settings, whereas the basin brines are absent in Archean deposits, which is related to the secular evolution of carbonate basins in the Proterozoic.

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Thorne WS, Hagemann SG, Webb A, Clout J (2008) Banded Iron Formation-related Iron Ore Deposits of the Hamersley Province, Western Australia In: Hagemann SG, Rosière CA, Gutzmer J, Beukes NJ (eds) *Banded Iron Formation-related High-grade Iron Ore*. pp 197-222.

Bedded martite/microplaty-hematite ore genesis: environmental evolution in the Paleoproterozoic era

Desmond F. Lascelles

Centre for Exploration Targeting, Department of Geology and Geophysics, University of Western Australia, Crawley, W.A. 6009

Email, dlascell@geol.uwa.edu.au

The term martite-microplaty hematite ore was used (Morris, 1985) to describe the premium high-grade low-phosphorous ore of the Hamersley Province in Western Australia and similar hematite ore on the northern margins of the Pilbara (Podmore, 1990) and Yilgarn cratons (Lascelles, 2009). However, close examination of this ore type reveals that not only is martite typically absent but the individual hematite grains are acicular to prismatic isotropic pseudomorphs.

The northern margin of the Yilgarn craton was uplifted and eroded to a deeply weathered low-lying peneplain on sub-vertical strata of the Joyner's Find greenstone belt (JFG) and the enclosing granite. Hematite pseudomorphs of iron-bearing minerals and bright red jasper were formed during this weathering cycle which spans the period from uplift of the Yilgarn Craton at ca 2.5-2.6 Ga to ca 1.95-2.2 Ga (Ferdinando, 2002). The proportions of minerals in unweathered BIF vary greatly both in thickness and composition and in addition to the typical magnetite and microquartz layers with accessory iron silicates and carbonate the latter may form monomineralic layers as well as mixed layers. Unweathered ore differs only in the absence of microquartz layers.

The early Paleoproterozoic weathering cycle concluded with the erosion of a wave-cut platform across the JFG and the unconformable deposition of epeirogenic sediments of the Yerrida Group. A second weathering period followed uplift and erosion of the Yerrida Group but goethite pseudomorphs of iron-bearing minerals (including magnetite pseudomorphs of hematite) were formed instead of hematite together with abundant secondary goethite but no red jasper.

A third weathering cycle followed unconformable deposition of the Earraheedy Group at ca 1.8-1.9 Ga and subsequent uplift and erosion exposed 4km of the second wave-cut platform and 12km of the earlier wave-cut platform (Fig. 1).

In all cases the microplaty hematite association with unconformably overlying Paleoproterozoic conglomerates, containing microplaty hematite BIF and ore clasts but no trace of martite or goethite, is clear or can be reasonably postulated. Under modern weathering conditions goethite is typically the stable chemical weathering product forming pseudomorphs of iron-bearing minerals, however, in the hot arid red centre of Australia the stable product is hematite and the regolith is bright red in colour instead of reddish-brown. This temporal restriction of microplaty hematite suggests that the microplaty hematite and the red jasper are primary weathering products associated with a hot arid environment similar to that present in Central Australia and that the later Paleoproterozoic formation of goethite pseudomorphs signals a change to a more humid weathering environment.

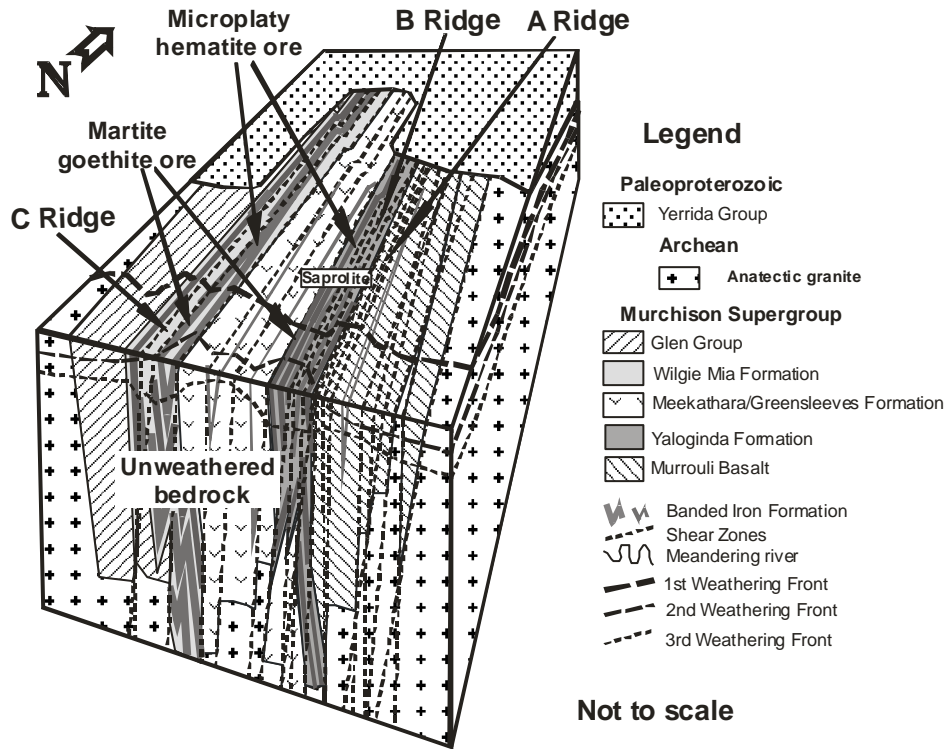


Figure 1. Block diagram of the northern part of the Joyner's Find greenstone Belt.

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Poly-orogenic tectonic and chronologic setting of gold mineralization in Nigeria, West Africa

Laurence Robb¹, Andrew Bullimore¹ and Martin Whitehouse²

1. Department of Earth Sciences, University of Oxford, Oxford, UK

2. NORDSIMS, Swedish Museum of Natural History, Stockholm, Sweden

On a continental scale, West Africa boasts a gold endowment second only to the Witwatersrand Basin in South Africa. Nigeria is located to the east of a prolific West African domain that is underlain by the Archaean Man Craton and the Palaeoproterozoic Birimian orogenic terrane, and yet is virtually unknown as a producer of gold. Whether the reasons for this are socio-political or geological remains a pertinent question.

The western half of Nigeria is underlain by sub-parallel, NNE trending, meta-volcanosedimentary schist belts that are intercalated with granitoid gneiss and collectively intruded by a variety of younger granite bodies. Our U-Pb zircon ion-probe study suggests a complex, poly-orogenic history for the Nigerian basement complex (Ferré et al., 1996), even at the scale of single samples. The existence of Archaean crustal remnants (Kroner et al., 2001) is confirmed from the Kaduna district where zircons from migmatitic gneiss record an age of 3394 ± 33 Ma, some of which contain rims with ages of 626-724 Ma. Other migmatitic gneisses from the Kushaka schist belt comprise palaeosomes, yielding an age of 2133 ± 51 Ma, and neosomes, containing a variety of zircon populations yielding 967 ± 36 Ma, 786 ± 5 Ma, 635 ± 36 Ma and 575 ± 28 Ma. Younger intrusive granites from Tgina and Laka provide ages of 587 ± 10 Ma and 590 ± 11 Ma respectively. These data confirm that the Nigerian basement comprises essentially 3 elements:-

1. Palaeoarchaeon remnants, the geographic extent of which is essentially unknown;
2. Metavolcano-sedimentary arcs with intercalated migmatitic gneiss (mainly in western Nigeria), the latter recording Palaeoproterozoic ages coeval with Eburnian/Birimian orogenies elsewhere on the Continent; and
3. A long-lived Neoproterozoic orogenic overprint extending over 400my (ca. 950-550 Ma) - this Pan-African event is accompanied by widespread granitoid intrusion emplaced largely between 620-580 Ma.

The tectonic setting and structural evolution of western Nigeria is little studied, but the authors' observations suggest that schist belts preserve early (Eburnean), syn-metamorphic, bedding-parallel, ductile shear zones that are cut by later (Pan-African), more brittle, often bedding-discordant, structures. Primary gold mineralization in Nigeria is orogenic in character. Prevailing models (Garba, 1996) favour a Pan-African timing for the formation of most of the gold occurrences in the region. Recent work at the Paimasa prospect (Niger State) and the old Bin Yauri gold mine (Kebbi State) show that gold mineralization is associated with quartz-tourmaline-sulphide vein sets that are discordant, have formed in a brittle regime and are spatially linked to, or cut, Pan-African granites (such as the 590 Ma Laka granite intrusion at Bin Yauri).

Recent exploration in the Kushaka schist belt (Kaduna State) suggests that an earlier episode of gold mineralization also exists. The Kushaka prospects, for example, are associated with a bedding-parallel ductile shear zone comprising thin, dismembered, anastomosing vein sets cutting graphitic metasediments along the contact with Palaeoproterozoic gneisses. It is suggested that gold mineralization in Nigeria is also, therefore, polyorogenic in origin and that a probable Eburnian event created early shear zone-hosted mineralization that was remobilized into brittle structures formed during the ubiquitous Pan-African overprint. The lack of gold exploration in this region appears, therefore, to have its roots in the socio-political history of Nigeria, and not to geological non-prospectivity.

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Komatiite volcanism: Lithospheric controls on the Earth's hottest melts and implications for associated Ni-Cu-PGE deposits

D. R. MOLE^{1,*}, M. FIORENTINI¹, N. THEBAUD¹, T. C. MCCUAIG¹, K. F. CASSIDY², C. KIRKLAND³, S. ROMANO³, M. DOUBLIER³, E. A. BELOUSOVA⁴ & S. J. BARNES⁵

¹Centre for Exploration Targeting, University of Western Australia, Stirling Hwy, Crawley 6009, Perth, Western Australia

²Bare Rock Geological Services, PO BOX 1633, Fremantle WA 6160, Australia

³Geological Survey of Western Australia, 100 Plain Street, East Perth 6004, Western Australia

⁴Centre for Geochemical Evolution and Metallogeny of Continents (GEMOC), Macquarie University, Macquarie, NSW2109, Australia

⁵CSIRO Earth Science & Resource Engineering, 26 Dick Perry Ave, Kensington 6151, Western Australia

Komatiite-hosted nickel deposits of the Yilgarn Craton form within two regions during two distinct periods. The oldest known deposits (3.0-2.8 Ga; Wang *et al.* (1998); Witt (1999)) occur in the south of the Southern Cross Domain (SCD). The youngest (~2.7 Ga; Kositsin *et al.* (2008)) are found in the Norseman-Wiluna belt of the Kalgoorlie Terrane (KT). This study aims to investigate whether variations in lithospheric architecture can explain the location and timing of komatiite magmatism and by proxy associated nickel sulphide formation (Begg *et al.*, 2010). An integrated program of U-Pb and Lu-Hf analyses were performed on granitoids and felsic volcanics from the south-central Yilgarn Craton, Western Australia. These data have been plotted as time-resolved Lu-Hf maps which record the changing architecture of the craton in space and time.

The 3.1-2.8 Ga Lu-Hf time-slice shows that the south-central Yilgarn lithosphere (encompassing the Forrestania, Lake Johnston and Ravensthorpe greenstone belts) was relatively juvenile ($\epsilon_{\text{Hf}} > 0$) at this time. The region to the north (central SCD), encompassing the Marda greenstone belt, shows an evolved signature ($\epsilon_{\text{Hf}} < 0$). The greenstone belts formed over juvenile crust contain thick komatiite sequences which comprise high Mg lavas, thick cumulate zones and channelized flows, indicative of rapid, voluminous emplacement of extremely primitive magma (Barnes 2006a, 2006b). As a result a number of nickel sulphide deposits occur in this region (Flying Fox, RAV-8, Maggie Hays). In contrast, the Marda greenstones are dominated by a thick, mafic succession, with minimal komatiite (Chen *et al.*, 2003). No known nickel sulphide deposits occur in this region.

The younger, 2.8-2.6 Ga time-slice indicates that the west Yilgarn has cratonised into a more homogenous, evolved terrane (Youanmi Terrane; YT), whereas the KT has a juvenile signature. This contrast forms an isotopic discontinuity (paleo-craton margin?) between the two terranes, and results in a ~700 km, N-S trending belt of komatiites on the juvenile (KT) side of the isotopic boundary. These komatiites represent some of the hottest magmas ever erupted on Earth (F_{O_2} 92-94; Barnes (2006a)) and host a number of world-class nickel camps such as Kambalda, Mt Keith and Leinster. In contrast, there is no known coeval mafic-ultramafic volcanism in the YT. These results not only explain the timing and location of major komatiite eruptions but also why some regions do not have significant komatiite sequences at all. They also indicate that the evolution of the lithosphere and its subsequent architecture form a major control on volcanism, particularly komatiites, and as a result their ability to form nickel sulphide deposits.

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Economic Geomicrobiology

Gordon Southam

University of Western Ontario

Bacteria play an important role in catalyzing a wide array of biogeochemical processes that affect the dissolution of minerals, the aqueous geochemistry of their surroundings and secondary mineral formation. Processes occurring at the bacteria-mineral interface can occur on the scale of nanoenvironments and will normally extend to microenvironments or even, to macroscopic scales where active growth of bacteria over geological time can produce km-scale features. However, in any bacterially influenced system, we need to focus at the scale of the bacteria themselves to appreciate the actual chemistry of their surroundings and the kinds of reactions that they can catalyse.

The colonisation of mineral substrates depends on the physico-chemistry of the mineral surface, which will be influenced on the presence (or absence) of secondary mineral phases and on the ability of the mineral substrate to contribute to redox, i.e., energy generating, processes. For example, the growth of thiobacilli on metal sulphide surfaces at or near the Earth's surface begins under bulk chemical conditions that do not reflect the presence of acidic microenvironments occurring at the bacteria-mineral interface. Continued growth of thiobacilli in a supergene environment can produce a world-class copper deposit (Morenci, AZ). Weathering of metal sulfides is also important to the mobility of gold. The biogeochemistry of gold has been examined under controlled conditions in order to understand the origins of secondary gold, and the effect of complex organic/inorganic reactions on the mobility of gold and in the formation of gold nanoparticles, which should have application in exploration geochemistry and mineralogy, i.e., tracking the origin(s) of gold deposits.

Dissimilatory sulphate reducing bacteria (SRB) represent the only process by which sulfate can be reduced to sulfide at low temperature. SRB are being employed for the bioremediation of metal pollution, typically forming amorphous metal sulphide precipitates, and (again) with geologic time, could lead to economic accumulations of base metals. Recent work examining SRB responses to elevated nickel resulted in elevated hydrogenase formation, potentially leading to biotechnologically efficient hydrogen production.

Hard rock mine wastes that are rich in magnesium silicate minerals have an inherent but untapped capacity to absorb and trap the GHG, carbon dioxide. Weathering of ultramafic materials releases magnesium, which can then be utilized in carbonate precipitation reactions which can be mediated by both physical and biological processes, thereby trapping carbon from DIC in stable carbonate minerals and potentially valuable biomass.

The life and times of an Irish-type Zn+ Pb ore deposit

Adrian J. Boyce and Craig D. Barrie

NERC Isotope Community Support Facility, Scottish Universities Environmental Research Centre, Rankine Avenue, East Kilbride, Glasgow, G75 0QF, UK

adrian.boyce@glasgow.ac.uk

It is well established that the Irish Orefield represents the most concentrated Zn anomaly in the world – an order of magnitude greater than any other region. What is less well known is that it is also likely to be the largest concentration of precipitated bacteriogenic sulfide in the world. Fallick et al (2003) established that not less than 90% of ore sulfide in the Navan deposit – by far Europe's leading producer of Zn, and one of the world's largest underground Zn mines – was produced by the bacterial reduction of Carboniferous seawater sulfate. Using only today's ore tonnages, 120Mt at 8%Zn and 2%Pb, that represents **3.1Mt of bacteriogenic sulfide**. Without the activity of sulfate reducing bacteria there would be no economic ore deposits in Ireland at today's prices.

But how do we know that these bacteria were active at the time, since there has been no physical identification of the bacteria in any Irish ore deposit to date? The key is the S isotopic composition, which has a distinctively low $\delta^{34}\text{S}$ value – much removed from the ranges of $\delta^{34}\text{S}$ in the mineralizing fluid. By using these isotopic compositions, not only are we able to quantify the bacterial contribution, but we are also able to examine the dynamics of the mineralizing system. Barrie et al (2009; this volume – see poster) have begun to highlight the complexity and rapidity of the mineralizing process at the millimeter scale, and this and more recent studies are establishing that the process is pulsed, incredibly dynamic rather than a slow relentless style. Our data also suggest that when the hydrothermal tap was switched on, it may have given rise to a distinctive bacterial network, resulting in distinctive isotopic signatures during ore deposition.

Since the seminal work of Rickard (1973), who established that normal sulfate reducing bacteria (SRB) could produce enough sulfide to allow an ore deposit to develop, much work has been done on bacterial networks related to seafloor sites under the influence of hydrothermal activity. Using the new data (e.g. Weber and Jørgensen, 2002), it is ever more clear that SRB will certainly not be the rate limiting step to the development of ore deposits in the sedimentary environment. Indeed, in a hydrothermally-influenced seafloor environment, it is possible to produce enough sulfide to form Navan ore in less than a year. Whilst that may be unrealistic in practice, it reinforces the potential of SRB to develop ores. But, how long did it take to form Navan? There is now no doubt that these systems switch on and off, and so there is a reasonable distinction to be made between the actual timescale of the mineralization – the length of time of ore deposition – versus the lifetime of the mineralizing system. Our calculations show that timescale for total mineralisation at Navan could have been completed in ~26,000yrs; but that time may be cut to around **500yrs**, if we use the metal concentrations determined from Wilkinson's (2009) 'supercharged' ore fluids.

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Multiple Sulfur and Iron Isotope Composition of Magmatic Ni-Cu-(PGE) Sulfide Mineralization from Eastern Botswana

Marco L. Fiorentini¹, Andrey Bekker², Olivier Rouxel³, Boswell A. Wing⁴, Wolfgang Maier⁵, Douglas Rumble⁶

¹Centre for Exploration Targeting, University of Western Australia, Crawley 6009, Australia

²Department of Geological Sciences, University of Manitoba, Winnipeg, MB, R3T 2N2, Canada

³European Institute for Marine Studies, Technopôle Brest-Iroise, France

⁴Department of Earth & Planetary Sciences, McGill University, 3450 University St., Montreal, Quebec, Canada H3A 2A7

⁵Department of Geology, University of Oulu, Linnanmaa, 90014 Oulu, Finland

⁶Geophysical Laboratory, Carnegie Institution, Washington, USA

We report here high-precision multiple sulfur and iron isotope compositions for a series of mineralized samples from Ni-Cu-(PGE) sulfide deposits in the Archean Tati greenstone belt and the Phikwe Complex of eastern Botswana. Mineralized samples from the Phoenix and Selkirk Ni-Cu-(PGE) deposits in the Tati greenstone belt display slightly positive $\delta^{34}\text{S}$ isotope values, ranging from 0.2‰ to 0.8‰ V-CDT. $\Delta^{33}\text{S}$ values of sulfides at Phoenix and Selkirk are -0.01‰ to -0.08‰ V-CDT, suggesting either a dominantly mantle sulfur source or effective eradication of a crustal $\square^{33}\text{S}$ anomaly through equilibration with large amounts of silicate melt. In the Selebi-Phikwe belt, a granite-gneiss terrane with abundant amphibolite lenses of either volcanic and/or intrusive nature, mineralized lower-grade samples from the Phikwe, Phokoje, and Dikoloti Ni-Cu-(PGE) deposits have more variable $\delta^{34}\text{S}$ values ranging from -3.1 to +0.3‰ and display significant mass independent anomalies ($\Delta^{33}\text{S}$ values ranging from -0.89 to -0.27‰), suggesting that barren sulfides associated with distal or low-temperature seafloor hydrothermal activity contributed sulfur to these deposits. Iron isotopes of sulfides from these deposits show a relatively small range of negative $\square^{56}\text{Fe}$ values (-0.29 to -0.04‰), consistent with high-temperature fractionations in magmatic systems, with the exception of one sample from the Dikoloti Ni-Cu-(PGE) deposit of the Selebi-Phikwe greenstone belt, which shows a more negative $\delta^{56}\text{Fe}$ value of -0.61‰, consistent with assimilation of sedimentary or hydrothermal sulfides rather than fractionations in high-temperature magmatic systems. Data from this study highlight the complexity and variability that characterize ore-forming processes in magmatic systems. We suggest that the presence of sulfur-bearing lithologies in host rocks of mafic and ultramafic intrusions may not be essential towards the assessment of the prospectivity of a province to host orthomagmatic nickel sulfides. Geological settings without any or little sulfur in the stratigraphy, which have been traditionally neglected in terms of their prospectivity, should thus be revisited and possibly reassessed considering the potential importance of external source of sulfur to generate ore deposits.

Keywords

Multiple S isotopes, sulfur incorporation, nickel-sulfides, orthomagmatic deposit, Tati belt

High temperature deformation in magmatic chromites from the Merensky Reef (Bushveld Complex, South Africa)

Vukmanovic, Z.^{1,2}, Barnes S. J.¹, Reddy, S. M.³, Godel, B.¹ and Fiorentini, M. L.²

¹ Australian Commonwealth Scientific and Research Organization (CSIRO), Kensington WA 6151, Australia

² University of Western Australia, Centre of Exploration and Targeting, Crawley WA 6009, Australia

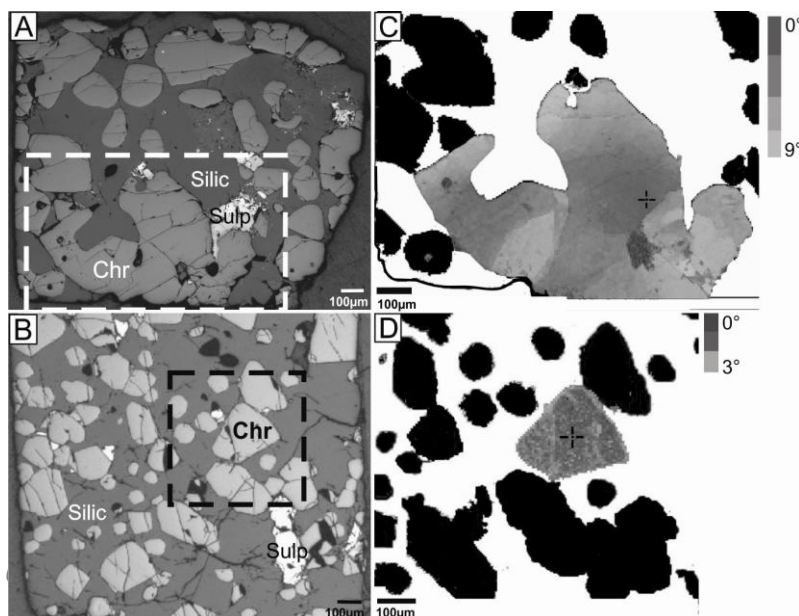
³ Curtin University of Technology, Bentley, WA 6102, Australia
vukmaz01@student.uwa.edu.au

The Merensky Reef, located in the Upper Critical Zone of the Bushveld Complex (South Africa), hosts about 22 percent of the world's platinum reserves. At Rustenburg, the Merensky Reef overlies an anorthosite and it comprises a lower chromitite layer (0.7-1 cm), a coarse-grained melanorite (~10 cm), an upper chromitite (~1 cm) and an overlying melanorite. The two chromitite layers are morphologically distinct (Fig. 1). The origin of these two layers has previously been attributed to multiple magma injections (Cawthorn and Boerst, 2006; Godel et al., 2007).

Electron backscatter diffraction analysis (EBSD) was used to reveal internal microstructures within chromites and base-metal sulphides (pyrrhotite, pentlandite and chalcopyrite). None of the layers show crystallographic preferred orientation of the chromite grains. The upper chromitite layer (Fig 1B & 1D) is characterized by idiomorphic inclusion-free chromite grains whereas chromite grains in the lower chromitite show “amoeboidal” morphologies and common silicate inclusions. EBSD showed that amoeboidal chromites exhibit signs of deformation caused by dislocation glide while idiomorphic chromites from both lower and upper chromitites remain mostly undeformed (Fig 1C&D). In the lower chromitites, all sulphides record crystallo-plastic deformation.

Dislocation creep is generally assigned to high temperature conditions (Passchier and Trouw, 2005). Regional geology of the Bushveld Complex as well as previous microstructural study done by Barnes and Maier (2002) at Impala support the idea that dislocation glide in chromites is caused by compaction during the cooling of the overlying magmatic column.

The chromites from the upper chromitite crystallised above the “mushy” melanorite. The absence of deformation in the upper chromitite is explained by the upper chromitite being formed by a second injection of magma while the melanorite was still a partially crystalline mush (Cawthorn and Boerst 2006). In the lower chromitite, the rigid interface between solid accumulate anorthosite and the overlying melanorite localized the deformation in the early crystallized “amoeboidal” chromites.



High resolution EBSD maps were also made on grains of cooperite ((Pt,Pd,Ni)S) and laurite (Ru(Ir,Os)S₂) located at the boundary between chromite, sulphide and silicate. Neither platinum-group mineral grain shows any evidence of deformation. The absence of deformation in PGMs can be due either to post compaction crystallisation, or due to their morphology and common occurrence with idiomorphic undeformed chromites.

Figure 1: A) Photomicrograph (reflected light) of the lower chromitite layer from the Merensky Reef. Larger chromites show amoeboidal shape whereas finer grains have more idiomorphic habit. Sulphide (Sulph); Silicates (Silic). B) Photomicrograph of the upper chromitite layer from the Merensky Reef. Chromite grains are idiomorphic and octahedral. C) EBSD composite map of lower chromitite showing relative misorientation from the reference point (black cross). Light gray colour indicate maximum misorientation of 9° where as darker gray colour indicate 0 to 1° of misorientation. D) EBSD composite map of upper chromitite layer showing very mild to no variation in gray colours indicating the absence of the misorientation in the idiomorphic chromite.

New Gold Occurrences in the Scottish Dalradian, UK – Nature and Constraints on Genesis

N.J. Hill^{1}, G.R.T. Jenkin¹, D.A. Holwell¹, D. Catterall², A.J. Boyce³, D. Mark³, J. Naden⁴, G. Gunn⁴ and C.M. Rice⁵*

¹ *University of Leicester, LE1 7RH, UK*

² *Scotgold Resources Ltd, Tyndrum, FK20 8RY*

³ *Scottish Universities Environmental Research Centre, G75 0QF*

⁴ *British Geological Survey, NG12 5GG*

⁵ *University of Aberdeen, AB24 3UE*

**Corresponding Author: njh35@le.ac.uk*

The Dalradian Supergroup is known to host economic gold deposits. In Northern Ireland the Omagh mine is in production and Curraghinalt is currently in a pre-feasibility stage. The Cononish deposit in Tyndrum, Scotland, hosts a resource (estimated in accordance with the JORC code) of 31 koz Au at 17.9 g/t, 24 koz at 10.2 g/t and 108 koz at 10.8 g/t in the Measured, Indicated and Inferred categories respectively and is currently awaiting planning permission. In conjunction with Scotgold Resources a number of new gold occurrences have been identified near Cononish.

New gold occurrences are of two types; gold-bearing quartz veins and gold-bearing breccia pipes. In addition, the River Vein area of Glen Orchy is distinct; NNE trending fractures have alteration selvages containing molybdenite and pyrite, with a separate gold-bearing quartz vein phase present.

Characterisation of the new occurrences has shown gold occurring as electrum within sulphides. Pyrite dominates the sulphide assemblage, with sporadic galena, sphalerite, chalcopyrite and arsenopyrite. Quartz and carbonate gangue is observed. Electrum occurs as inclusions within pyrite and occasionally at boundaries between sulphides. A second stage of electrum is found in fractures within pyrite. Silver tellurides, largely hessite, are associated with a late Pb-Zn phase of mineralisation. This work indicates a complex system with at least two mineralising fluids throughout the area:

- Early Au-Ag-Fe-Pb bearing phase
- Late Ag-Pb-Zn-Te bearing phase re-mobilising electrum from the first phase of mineralisation.

Pyrite $\delta^{34}\text{S}$ values obtained for this study show a wide variation; from -2 to +12‰. The majority of gold-bearing quartz veins, including samples from River Vein area, have $\delta^{34}\text{S}$ values between +5 and +11‰. Beinn Udlaidh breccia pipes show lower values at +1 to +7‰. The mineralised vein pyrite $\delta^{34}\text{S}$ show variations related to vein location. The high $\delta^{34}\text{S}$ values support a sedimentary origin for the sulphur as advocated by Curtis et al. (1993), but the wide range of values within a small area suggest mixing of two sources in the system, with lowest values indicating a significant magmatic component. Molybdenite $\delta^{34}\text{S}$ values from the River Vein area also indicate significant crustal input with an average value of +6‰. This further supports a magmatic-sedimentary mixing system.

Further investigation is needed to define local sedimentary sulphide $\delta^{34}\text{S}$, as well as fluid sources through further stable isotope work and fluid inclusion microthermometry. Additional characterisation of the paragenesis is required to help constrain the nature of vein formation.

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The role of magmatic sulfides and low-density fluids in the formation of porphyry-type ore deposits

Andreas Audétat

Bayerisches Geoinstitut, Universität Bayreuth, 95440 Bayreuth, Germany

This lecture will address two topics.

Topic 1: Origin of metals in porphyry-type ore deposits

Over the past 15 years, a large amount of evidence has accumulated to suggest that mafic magmas played a crucial role in the formation of porphyry Cu (-Mo,-Au) deposits. Mafic input magmas typically were sulfide undersaturated, contained 100-300 ppm Cu, 1-2 ppm Mo, and 1000-6000 ppm S. During magma mixing and fractional crystallization, the Cu content of the residual melt decreased to <50 ppm, whereas Mo concentrations increased to up to 14 ppm.

Evidence for an involvement of mafic magmas in porphyry Mo systems is much more subtle, but present in almost every deposit. The mafic input magmas were sulfide saturated, but probably contained less sulfur than those associated with porphyry Cu deposits because they were less oxidized. Copper concentrations decreased from 200-800 ppm Cu in the most primitive melts to <20 ppm in the most evolved melts, while Mo concentrations increased from 2-4 ppm to up to 25 ppm Mo.

The high Cu content of mafic melts associated with porphyry Mo systems is unexpected, as Cu grades in these deposits are extremely low. A model is presented in which the Cu-mineralizing potential of a magma system depends on the depth of magmatic sulfide residence.

Topic 2: Vapor transport of Cu – a natural artifact?

Microanalysis of vapor and brine inclusions from porphyry deposits commonly reveal higher Cu concentrations in the vapor inclusions, a feature that has been interpreted to be due to the formation of stable sulfur-bearing Cu complexes in the vapor phase. However, efforts of several research groups worldwide to reproduce this phenomenon experimentally have failed so far. We have conducted re-equilibration experiments of quartz-hosted fluid inclusions at conditions simulating the fluid evolution in natural environments and found that vapor–brine assemblages with $D_{\text{Cu}}^{\text{vap/brine}} \ll 1$ can quickly turn into assemblages with $D_{\text{Cu}}^{\text{vap/brine}} \gg 1$ (and *vice versa*) by post-entrapmental diffusion of Cu through quartz. All that is required is the presence of a significant amount of sulfur in the vapor inclusions and a change in the pH of the surrounding fluid from ≤ 1 to a more basic value. The results imply that the role of low-density fluids in the formation of porphyry Cu deposits may have been severely overestimated, and that more attention should be paid to brines again.

Evidence that barely-contained nearly-explosive venting of large volumes of magmatic volatiles initiated porphyry Cu formation

L. M. CATHLES^{1,*} AND RACHEL SHANNON²

¹Cornell University, Ithaca, New York 14853 (lmc19@cornell.edu)

²S. S. Papadopoulos and Assoc. Inc., 7944 Wisconsin Avenue, Bethesda, MD 20814-3260
(rshannon@sspa.com)

Conversion of hornblende to biotite through the addition of K at high temperature is the earliest, most extensive alteration in porphyry copper deposits. In the Butte deposit in Montana a 7 x 4 x 2 km deep rock volume was altered by the addition of ~1 wt% K at ~600°C. The transition to fresh quartz monzonite occurs over a distance of only ~230 m. The pre-main stage porphyries and the main stage veins sit within a small portion of this K alteration.

The volume of magmatic volatiles vented is measured by the K-altered rock volume; the rate of volatile expulsion by the width of the transition zone. Division gives the duration of venting. The most likely parameter values at Butte indicates that the alteration occurred in ~900 years when ~100 x 10⁹ m³ of magmatic volatiles were expelled from an ~8.3 km diameter magma body. Uncertainties in matrix porosity, pore tortuosity, and fracture spacing and the fraction transmitting fluid at any one time suggest range of 1/3rd to ~50 times the 900 year estimate.

The K-alteration requires 22 times the volatile volume needed to heat the rock to 600°C. Thus the Butte system started by heating a rock volume ~3 times larger than that potassically altered, and the K alteration occurred under isothermal conditions. The two pre-main stage porphyry deposits formed as the venting waned and the system cooled to ~450°C, allowing SO₂ to disproportionate to H₂SO₄ and H₂S. System life was ~500,000 years- the conductive cooling time of the heated volume. This is a reasonable estimate provided weak venting did not significantly prolong nor convection accelerate the cooling. The spectacular 3 m wide main stage chalcocite veins at Butte formed ~1.8 Ma after the pre-main stage as a consequence of a less-contained venting of volatiles from a second intrusion.

Porphyries are susceptible to explosive eruption (Mt Pinatubo, sector failure, pebble dikes). The evolution from rapid to slower, cooler venting with mineralization and acid attack matches geological observations. Rapid initial venting requires rapid magma crystalization and it is challenging to understand how this might occur.

Ore Genesis of The Estrela Copper Deposit, Brazil: Evidence From Geology, Mineral Paragenesis, and Fluid Inclusion and Stable Isotope Studies

KAREN M. VOLP

CSA Global (UK) Ltd, 2 Peel House, Barttelot Rd, Horsham, West Sussex, RH12 1DE, United Kingdom and Economic Geology Research Unit, James Cook University, Townsville, Qld 4811, Australia

The Estrela Cu deposit (230 Mt at 0.5% Cu) is located within the Carajás Mineral Province, Brazil, and hosted by a Proterozoic A-type granite, the Refugio granite, and its Archean country rocks.

A-type granites are associated with a variety of known mineralisation styles particularly rare metal, Iron Oxide Copper Gold (IOCG), and Sn-W-dominant intrusion related (IR) polymetallic deposits. The Refugio granite is an evolved granite, similar to the granite hosts of rare metal and IR polymetallic deposits having high volatile content, aplite and pegmatite, endogreisen and exogreisen, and miarolitic cavities and unidirectional solidification textures.

From a detailed study of the geology and mineral paragenesis the Estrela Cu deposit is interpreted to have formed by the superposition of at least two mineralising magmatic-hydrothermal systems: (1) weak Mo-Sn-Nb-Ta rare metal mineralisation localised in the plutons' apices, its dykes and pegmatite-hydrothermal veins; overprinted by (2) Cu-dominant polymetallic [Fe-Cu-Mo-(Ni-Pb)] mineralisation (chalcopyrite-pyrite-pyrrhotite-magnetite-molybdenite, in order of abundance) which also extended to country rock biotite-rich shears and fluorite crackle breccia.

Fluid inclusion and stable isotope studies indicated that each mineralising magmatic-hydrothermal system progressed from high temperature and high salinity NaCl-CaCl₂-H₂O magmatic-derived or equilibrated fluids to lower temperature and lower salinity fluids. This may have involved magmatic degassing and/ or phase separation and isotopic fractionation during convection cell fluid dynamics and interactions with potentially meteoric fluids.

The geological setting, mineral paragenesis and metal zonation, and fluid evolution for Estrela are similar to that of rare metal and IR polymetallic deposits, although Fe and Cu concentrations are higher and more extensive than previously reported. On that basis the Estrela Cu deposit is classified as a Cu-rich member of the IR polymetallic class of deposits.

The ore genesis of granite-hosted mineral deposits, including IR polymetallic deposits, is logically linked to the host granite. At Estrela, however, Cu and Fe concentrations are inconsistent with the low S solubility and base metal concentrations of A-type granites. Hypotheses which may permit the Refugio granite to be the source of base metals include: (i) discharge of SO₂ and chalcophile elements from an underlying melt or the injection of a mafic body into a felsic one; (ii) presence of immiscible phases at the magmatic-hydrothermal transition including metals in the form of an exotic sulphide melt or "clusters" co-existing with the silicate magma; (iii) an enriched magma source; and (iv) the partial melting of pre-existing IOCG mineral deposits.

Metamorphic Fluids: do they contribute to ore systems?

Bruce Yardley

School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

James Cleverley

CSIRO Earth Sci & Resource Engn, Bentley, WA 6102, Australia

Many hydrothermal ore deposits are hosted in metamorphic rocks, and so the possible involvement of metamorphic fluids in their formation has attracted interest for many years. Metamorphic petrologists have mainly concentrated on defining fluid compositions in terms of the solvent species, primarily CO₂ and H₂O, rather than the dissolved load, and have generally assumed that metamorphic fluids would be rather dilute because the water released from mineral breakdown will not carry large amounts of dissolved salts. A number of highly saline metamorphic fluids have now been documented however, and these can carry moderate base metal loads. Nevertheless, the main type of ore deposit which is commonly ascribed to metamorphic fluid activity is orogenic gold deposits, and these are associated with rather dilute fluids (c. seawater salinity). Interestingly, some gem emeralds are linked to metamorphic brines however.

A major drawback to a metamorphic model for ore deposits is that many hydrothermal deposits form very rapidly in geological terms, whereas endothermic metamorphic dehydration reactions produce small amounts of water very slowly. This constraint does not apply if the dehydration occurs during rapid uplift, when reaction can continue while driving temperature down, and some orogenic gold deposits fit such a model (Craw et al. 2010, *Mineralium Deposita* v.45, p. 631-646). Metamorphic rocks may also offer favoured sites for the precipitation of ores from fluids that are not themselves of metamorphic origin. Whether this is by interaction of the introduced fluid with metamorphic fluids or with the metamorphic host rock lithologies themselves is not always well defined, and resolving this issue would greatly enhance our understanding of fluid behaviour in crystalline rocks.

Three-dimensional analysis of grade data, lithology and structure at the Sunrise Dam gold mine, Western Australia, which is categorised as an orogenic gold deposit, demonstrates that high grades in steep breccia zones and composite vein structures are associated with cross cutting, moderate to gently dipping shear zones. This led Baker et al. (2010, *Econ. Geol.*, v.105, p.873-894) to suggest that periodic breaching of hydraulic seals led to changes in pressure that triggered mixing or un-mixing of fluids and drove gold deposition. Arsenic and gold variability at a range of scales point to complex interplays in fluid-fluid or fluid-rock interactions, while variations in ore related elements through the paragenesis (Au to Au-Ag-Te to Au-Ag-Te-base metals) also point to an evolving fluid or fluid mixtures. In base metal-rich gold-bearing assemblages the presence of phases such as Kolarite (PbTeCl₂) implies that hypersaline brines were a component of the fluid mix, while apatite that was deposited with gold provides a primitive mantle Sr-isotope signal (Cleverley et al., 2009, pmd**CRC Y4 report*). So while the rocks might broadly reflect metamorphic fluid processes overall, there are other fluid components present, at least in the high-grade parts of the system. Evidence will be presented to indicate that such major gold deposits were the focus of transient fluid migration from multiple reservoirs, possibly ranging from basin brines to magmatic in origin, through zones of extensive rock damage. However it appears likely that metamorphic fluids, as well as metamorphic rocks, played a role in driving gold mineralisation.

Orogenic Gold Mineralisation in the Birimian of West Africa: is it as simple as it seems?

Peter J. Treloar¹, Andrew H. Rankin¹, David M. Lawrence¹, Christina M. French¹, Adrian Boyce², Diamacour Senghor³, and Paul Harbidge³.

1. *Centre for Earth and Environmental Science Research, Kingston University, Surrey, KT1 2EE*
2. *SUERC, Rankine Avenue, Scottish Enterprise Technology Park, East Kilbride, G75 0QF*
3. *Randgold Resources Ltd, Halkett Street, St Helier, Jersey*

The orogenic gold model differentiates between epithermal, largely supra-subduction zone, porphyry related Au deposits and mesothermal gold deposits hosted in fault systems linked to some form of terrane accretion. The core of the model is that fluids that transport gold to deposition site are of metamorphic origin and that gold is carried in S complexes. Gold deposition is hosted in higher order faults developed in strike-slip fault systems during non-orthogonal crustal growth.

The Palaeoproterozoic was a period of crustal growth with the West African Birimian terrane a prime example. Models of ore generation during such periods should thus be informed by studies of Birimian terranes. The Ghanaian Ashanti gold belt sits on the eastern margin of the Birimian and isotopic systems there are consistent with metal stripping from host sediments during metamorphic de-watering. However, our new mineral paragenesis, fluid inclusion and isotope data from orogenic gold deposits in the western part of the Birimian terrane in Mali and Senegal suggest that metal transport in magmatically derived fluids is significantly more important than previously suggested.

The West Mali Loulo mining district hosts several ore-bodies with atypical orogenic orebody and alteration signatures. The Gara deposit has an Fe-rich paragenesis dominated by pyrite, REE phosphates and tungstates, and Ni-bearing sulphides including pentlandite and gersdorffite. Similar associations occur in neighbouring granitoids. The Yalea North lode has a similar paragenesis but elevated Co concentrations add cobaltite. Atypical orogenic gold parageneses, enriched in base metals including Pb, Ni, Co, Cu and Zn, occur in the hanging-wall ore-zone at Goukoto. Alteration at Gara and other Loulo orebodies is characterised by pervasive multi-stage tourmaline and pink albite alteration, both typical features of local felsic intrusions. A regional Boron anomaly extends 200 km along strike from Loulo. Galena, Co-bearing gersdorffite, cobaltite and zincian tetrahedrite are present at Massawa in eastern Senegal.

Fluid inclusion evidence for magmatic mineralisation comes from the presence of primary hypersaline (~40 wt.% NaCl equiv.), high temperature (>400 °C) metalliferous, H₂O-CO₂-NaCl-FeCl₂ inclusions in gold-bearing quartz veins at Gara. Ca-rich magmatic brines are also responsible for mineralisation in the Morila deposit in southern Mali. A magmatic fluid model is indicated by stable isotope data from Massawa ($\delta^{34}\text{S}$ 0 to +4.1 ‰), Morila (+2 - +7) and Gara ($\delta^{13}\text{C}$ -14.4 to -4.5 ‰).

Taken together these characteristics, atypical of “normal” orogenic gold deposits, suggest a strong influence on mineralisation of magmatically sourced fluids and should force a re-evaluation of the orogenic gold paradigm.

A Metallogenic model for mineral deposition of carbonate hosted Mississippi Valley type Pb-Zn-Sr-Br Ain Allega and El Aguiba ore deposits (Northern of Tunisia)

Riadh ABIDI ^{1,*}, Najet SLIM-SHIM², Nouri HATIRA ⁵, Christian MARGNAC^{3, 4}, Nouri HATIRA ⁵, Dominique GASQUET ⁶, Christophe RENAC ⁷.

^{1,*} Faculté des sciences de Bizerte, département de géologie, Jarzouna-Bizerte.7021. Tunisie.

☎ 00216 97031647

✉ abidi1riadh@yahoo.com

² Faculté des sciences mathématiques, physiques naturelles de Tunis. Campus Universitaire. 1060 Tunis. Tunisie.

³ Centre de Recherches Péetrographiques et Géo-chimiques (CNRS), BP 20-54501 Nancy, France

⁴ Ecole Nationale Supérieure des Mines de Nancy, Parc de Saurupt, 54042 Nancy, France.

⁵ Faculté des Sciences de Gabès Cité Erriadh 6072 Zrig Gabès Tunisie.

⁶ Université de Savoie – CISM Laboratoire EDYTEM Bâtiment Belledonne Campus de Technolac 73370 LE BOURGET DU LAC.

⁷ Département de Géologie de l'Université Jean Monnet UMR 6524 (équipe Transferts lithosphériques) 23, rue du Dr. P. Michelon 42023 St. Etienne France

Ain Allega and El Aguiba are among the largest barite-celestite deposits associated to the formation attributed to Triassic period in Tunisia. They are located in the flysch zone on the eastern edge of the Triassic diapir of Jebel Hamra (Abidi et al., 2010 and 2011; Abidi, 2011). The ore body consists of dolomite intently brecciated surrounded by (marls, clay, gypsum and dolomite) from formation attributed to Triassic, which forms the hanging wall of the deposit, and rimmed by the Paleocene marls. The ore minerals show a cap-rock type mineralization with various forms and types particularly impregnation in dolomite, breccia cement, replacement of carbonate cap-rock and open space filling in the dissolution cavities and fractures. Ore minerals include sphalerite, galena, marcasite and pyrite. Principal gangue minerals are composed of barite, celestite, calcite, dolomite and quartz (Abidi et al., 2010 and 2011; Abidi, 2011). The ore minerals are hosted by the Triassic carbonate rocks, which show hydrothermal alteration, dissolution and brecciation. large-scale replacement of carbonate by barite or sulfides. Slightly, the petrographic, geochemical, and isotopic data support a model in which early fine-grained barite and important sulfides formed at first hydrothermal stag. That's followed by hydrothermal barite caused by the introduction of ore-stage metal-rich of second stage of hydrothermal fluids. Metal-rich fluids reductively dissolved the preexisting barite to produce H₂S and induce sulfide mineral formation. With continued flow of hydrothermal fluids, progressive thermal alteration of carbonate host-rock. The hydrothermal activity processes resumed until late Miocene time.

The sulfur isotope analyses show a less variability for sphalerite (from 14.1 to 16.8 ‰), galena (from 12.2 to 16.6 ‰), barite and celestite (from 16.2 to 23‰). These values corresponding to reduction process by thermochemical sulfate reduction (TSR), for Messinian seawater evaporit, and Triassic sulfate. The fluid inclusions study showed two stages of hydrothermal ore depositions that are characterized respectively: fluid-I (T_h= 176±2°C; Salinity= 17±1 wt. % NaCl equivalent) fluid-II (T_h= 186°C; Salinity= 8.54 wt. % NaCl equivalent). The mixing of two hydrothermal fluids of distinct chemistry, but saturated with respect to carbonates, could account for porosity in carbonate rocks because of the intrinsic effects of chemical mixing (Figs. 1 and 2). Consequently, the generation of porosity and its filling at late with sulfides sulfate and carbonates. This corresponds to the textures commonly observed in MVT deposits. The mineralization ores are related to late Miocene dynamics correlated to late Alpine convergence (Abidi, 2011), the saliferous Triassic dipapir and igneous rocks emplacement, favored a thermally-driven fluid circulation origin for Ain Allega and El Aguiba Mississippi Valley-type (MVT) deposits.

The wall rock of ore deposits diffuses into the ore zone, reducing sulfate and precipitating the ore minerals. Equilibrium reactions show that reaction between organic carbon and calcium sulfate (gypsum and anhydrite) of Triassic formation in saline brine to precipitation of dolomite.

Keywords: hydrothermal mineralization, Mississippi Valley-type, carbonate dissolution, TSR, H₂S

The moral case for mining – is it a question the industry can answer?

Mike Harris

Rio Tinto

The mining business operates in an environment increasingly hungry for its products while more intolerant of accepting that the overwhelming percentage of the profits and benefits from the destruction of non-renewable resources and natural habitats go to distant stakeholders.

A recent PricewaterhouseCoopers survey¹ reported that the top 40 miners had 2010 revenues of \$453 billion and have announced plans to spend \$311 billion on new or expansion projects with \$120 billion in 2011 alone. It is little wonder that governments and many sectors of the public are questioning the right of miners to grow at such aggressive rates through depleting irreplaceable natural resources often in areas remote from their origins and their shareholders.

The rise in Chinese demand for most commodities makes this questioning even more relevant. Establishing the moral case for taking natural resources from one part of the world to benefit another with a preponderance of profits leaving the host country is becoming increasingly difficult. The same can be said about the often irreparable change to delicate ecosystems through mining - why should plants, animals and peoples suffer, often die, in one place to benefit development in another while dominantly enriching distant investors?

Most modern mining companies try their best to operate in an environmental and local community-friendly way making fleeting to real attempts to put a percentage of their profits back into sustainable development programmes intended to benefit the areas around their operations. In the end, mining companies are answerable to their shareholders and are regulated by governments; they generally fiercely resist increased taxation and any hint of “resource nationalism”.

The pressures or “business case” to continue expanding that faces particularly the larger miners is ever increasing. Global demand for the major industrial commodities has doubled roughly every 20 years with this pace of growth likely to continue. Global reserves and resources for most commodities are replaced as fast as they are mined with peak metal not on the horizon given buoyant demand.

Although grades are generally declining in existing mining districts, deeper discoveries are appearing as the industry explores around known deposits. Step-change technological innovation and higher prices will increasingly make mining these deep ore bodies and/or lower grade surface ores financially attractive.

Society needs to have an honest debate on the morality of mining in the context of the consumption of its products. The paper brings forward arguments to help frame this debate.

¹ Mine, June 2011, PricewaterhouseCoopers website
07-09 September 2011

Future Rx: Optimism, preparation, acceptance of risk

L. M. Cathles

Cornell University, Ithaca, New York 14853 (lmc19@cornell.edu)

The world population, presently at 7 billion, will rise to 10.5 billion in the next century, and all 10.5 billion will rightly expect at least a European living standard. Our great challenge is to provide the energy and mineral resources needed to meet this expectation. Can we? I believe we unquestionably can, provided we have optimism, preparation, and acceptance of risk. Considering the oceans, the world is a planet awash in energy and mineral resources. Raising energy consumption to the European level of 7 kW/p for the current population would require tripling our present total energy production from 15 TW to 45 TW, and accommodating a population growth to 10.5 bn would require 72 TWe. Growing from 15 to 72 TW over 100 years represents a modest compound growth rate of 1.6%/yr. With breeder technology, the 4.6×10^9 tonnes of U dissolved in the oceans (not to mention Th which is a better nuclear fuel) can sustain a 72 TW production for 78 centuries. My estimated seafloor Cu and Zn resources can sustain humanity for 50 and 140 centuries, respectively. Three percent of the Li dissolved in the oceans could provide $\frac{1}{4}$ of a hybrid car per person for 10.5 bn. Deep-sea muds contain a resource of the rare earth elements that is at least as abundant as that on land. The deep ocean could sustain the phosphate needs of world agriculture for 33 centuries. Thus if we tap the oceans, humanity has the resources needed for a sustainable future. Furthermore, the oceans offer more equitable access to these resources, and the mobility of the ocean mining infrastructure means these resources can be surgically mined and recovered with less environmental damage and greater safety than is possible on land. Risk remains, but we need to accept it with the confidence that we can fix any problems that arise and thereby become ever better at mitigating it. This approach is far less risky than trying to avoid all risk. To move forward we need to accelerate laying the knowledge foundation for recovering ocean resources in the most environmentally and ecologically acceptable way possible, and impress the next generation, not with the immensity of future pain, but the immensity of future gain: sustaining everyone at a European standard indefinitely with the huge increases in the scientific understanding of natural systems that meeting this challenge will provide.

Tectonic Diffusion Estimates of Global Mineral Resources

Stephen E. Kesler

Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109-1005 USA

Bruce H. Wilkinson

Department of Earth Sciences, Syracuse University, Syracuse, NY 13244-1070 USA

Estimates of global mineral resources are commonly based on geological or statistical extrapolation into the deeper crust of information about known deposits at and near the surface. This extrapolation is hampered by growing uncertainties with increasing depths, an important limitation in view of the general agreement that future mineral supplies will come largely from deeper levels in the crust.

The tectonic-diffusion method provides an estimate of the distribution of mineral deposits at all depths in the crust. It is based on the age-frequency distribution for deposits of a specific type, which is a direct function of their history of burial, uplift and erosion. This history can be simulated computationally by emplacing deposits into the crust at a known depth and allowing them to move up, down or sideways (stasis) randomly with the passage of time. The calculation continues until a best fit is attained, in terms of both number and age-frequency distribution, between known (actual) deposits and those at the computational surface. Results are calibrated using the average depth of formation of the deposit type of interest and are converted to metal content using the size of an average deposit.

Results of these calculations indicate that mineral deposits in the crust contain approximately 3×10^{11} tonnes of copper and 1.4×10^7 tonnes of gold, that <1% of crustal copper and gold has been concentrated into deposits through time, and that at least two-thirds of these deposits have been recycled by erosion. Only deposits at relatively shallow crustal depths will be amenable to exploration and mining in the foreseeable future. For instance, global deposits to a depth of 1 km contain an estimated 1.1×10^{10} tonnes of copper and 1.4×10^6 tonnes of gold, amounts that compare favorably to U.S. Geological Survey estimates for the upper 1 km of the United States. Global deposits to a depth of 3 km contain about 8×10^{10} tonnes of copper and 5×10^6 tonnes of gold. If we can find and mine about half of these, global metal supplies are probably sufficient to supply current and probable future world mine production for only one or two thousand years, suggesting that humans are well into the second half of the period during which they can produce metals from mineral deposits on Earth.

Opportunities and challenges in the future supply of rare earths; developing metrics for responsible sourcing

F. Wall¹, P. Mitchell², T. Buckle¹, T. Lee¹, S. Stanley¹

¹Camborne School of Mines, University of Exeter Cornwall Campus, Penryn, TR10 9EZ, UK

²Green Horizons Environmental Consultants Ltd, Tregony, Cornwall TR2 5RN, UK

Rare earth (REE) prices have risen sharply over the last year, driven by increasing demand for REE in various new and green technologies, coupled with a supply crisis created by China cutting its export quotas. This has led to a rapid increase in exploration activity.

There is no shortage of REE in the Earth. Crustal abundances of the light REE are as high as copper and the long range extractable geological resource in the top 1 km has been estimated as 6700 Mt REE (Graedel *et al.*, 2011). Much of this is probably held in carbonatites and alkaline rocks but REE are also distributed in other rock types. World reserves are estimated at 110 Mt REO (USGS) whereas predictions of demand for REE in a few years time are generally around 200 000 tpa.

So there are certainly opportunities to develop sources of REE outside of China. However, moving from exploration to production is a laborious process and only a small percentage of exploration targets will eventually become viable operating mines. For REE deposits the need to develop beneficiation and extraction processes for new varieties of ore minerals is a particular challenge.

Another constraint may be the increasing demand for 'responsibly sourced' mineral commodities. Given their role in green technologies it seems likely that REE will be as, if not more, exposed to this trend than other metals.

The main environmental challenge for REE production is the association with the radioactive elements, thorium and uranium, which may be incorporated in the lattice of the REE minerals or occur as separate but associated thorium-bearing minerals. Carbonatite deposits, weathered deposits and REE-bearing ocean floor muds are lower in thorium and uranium than granite-derived deposits.

Energy is also likely to be a particular challenge. Deposits that require minimal comminution are likely to be the lowest consumers of energy. For example, small scale mineral sands workings are particularly energy efficient, using 500 times less energy per tonne REO than a hard rock carbonatite deposit but this must then be balanced against the content of radioactive elements. This paper explores some preliminary metrics for comparing the environmental and social footprint of mining and processing associated with different REE deposits. This is the first step in developing a tool to forecast the environmental footprint of a deposit using mineralogical data available during exploration, and thus integrating 'responsible sourcing' considerations at the earliest stages of the decision-making process.

Graedel, T. et al. 2011 Estimating Long-Run Geological Stocks of Metals, UNEP International Panel on Sustainable Resource Management, Working Group on Geological Stocks of Metals, Working Paper, April 6, 2011

USGS Mineral Commodity Summaries 2011
<http://minerals.usgs.gov/minerals/pubs/mcs/2011/mcs2011.pdf>, accessed 14.7.11

Resource mapping using multi-scale mineral-spectroscopy

Carsten Laukamp¹, Tom Cudahy¹, Mike Caccetta¹, Maarten Haest¹, Ian Lau¹, Cindy Ong¹, Andrew Rodger¹, Joanne Chia² and Simon Collings²

¹CSIRO Earth Science and Resource Engineering, WA Centre of Excellence for 3D Mineral Mapping, Kensington, Australia

²CSIRO Mathematics and Information Sciences, WA Centre of Excellence for 3D Mineral Mapping, Kensington, Australia

Ensuring global mineral security for a developing world that coexists with a sustainable Earth environment is one of the fundamental challenges of our time. New technologies that can non-invasively and accurately map the composition of the Earth's surface and top 1 km will be critical for the future discovery, exploitation and environmental management of mineral resources. Amongst this new suite of technologies is "hyperspectral" sensing from satellite, aircraft, field and drill core logging systems, which provide quantitative mineral information sensed from the top few microns of the target materials. From this increasing operational array of hyperspectral systems, 3D mineral maps of the upper Earth's surface can now be generated from the continent- to the deposit-scales.

Capturing this 3D mineral mapping opportunity for the Australian resources industry is the aim of the Western Australian Centre of Excellence for 3D Mineral Mapping (<http://c3dmm.csiro.au/>). C3DMM is building capabilities that calibrate and transform the raw sensor signals into, publicly accessible, validated, traceable accurate 3D mineral maps. The 2020 vision is to create a publicly accessible, 3D digital mineral map of the Australian continent in collaboration with the government geoscience agencies across Australia.

One major step to achieving this vision is the generation of an ASTER satellite geoscience map of Australia (~18 products), which provides mineral group information of value for mapping the regolith, primary geology as well as superimposed metamorphic and metasomatic alteration affects. This involves ~4000 ASTER multi-spectral (14 bands) scenes collected between 2000 and 2008 provided by NASA/ERSDAC/USGS. Specific applications of these maps include: (1) more accurate mapping of transported versus in situ materials to improve drill hole planning; (2) recognition of mineral vectors to ore systems; and (3) baseline environmental mapping prior to resource development.

Current airborne and drill core logging systems (<http://nvcl.csiro.au>) as well as future hyperspectral (>100 bands) satellites (www.isiswq.org) provide much more specific mineral information, including the abundances and physicochemistries (crystal chemistry and crystallinity) of individual minerals. This enables the tracking of mineral-chemical gradients, such as changes in composition of white micas and chlorites, which are important alteration minerals in base and precious metal systems.

This paper will show how multi-scale (spatially and dimensions) mineral mapping information can be used to create accurate 3D mineral maps of different deposit styles, including channel iron ore and IOCG. Armed with this information, cost and environmental efficiencies are delivered, especially through more accurate targeting of subsequent drilling operations.

The Cycles and Criticality of Metals

Thomas E. Graedel

Center for Industrial Ecology, Yale University

Today's technology employs virtually the entire periodic table. The stocks and flows of the major metals, essentially unknown a decade ago, are now reasonably well quantified. Those cycles can be used to generate an overview of societal metal use. A key issue is whether scarcity implies long-term shortages or unavailability. To address this issue, a detailed methodology for generating a reliable assessment of the criticality of metals has been completed, making extensive use of peer-reviewed datasets and analytical approaches from the fields of geology, international trade, political science, and international policy, among others. This criticality evaluation has three components – Supply Risk, Environmental Implications, and Vulnerability to Supply Restriction, each of which is itself the composite of several metrics. The initial results of applying this methodology to several widely used metals will be presented and the results discussed in some detail. The products of this research are expected to provide guidance for materials choice in product design and development, recycling potential, and the consideration of substitute materials in modern technology.

POSTER ABSTRACTS

Mapping the intra-cratonic framework of an Archean Craton: implications for camp-scale mineralisation

D. R. MOLE^{1,*}, M. FIORENTINI¹, N. THEBAUD¹, T. C. MCCUAIG¹, K. F. CASSIDY², C. KIRKLAND³, S. ROMANO³, M. DOUBLIER³, E. A. BELOUSOVA⁴ & S. J. BARNES⁵

¹Centre for Exploration Targeting, University of Western Australia, Stirling Hwy, Crawley 6009, Perth, Western Australia

²Bare Rock Geological Services, PO BOX 1633, Fremantle WA 6160, Australia

³Geological Survey of Western Australia, 100 Plain Street, East Perth 6004, Western Australia

⁴Centre for Geochemical Evolution and Metallogeny of Continents (GEMOC), Macquarie University, Macquarie, NSW2109, Australia

⁵CSIRO Earth Science & Resource Engineering, 26 Dick Perry Ave, Kensington 6151, Western Australia

It is widely accepted that lithospheric architecture controls the location of many post-Archean mineral deposits (Begg *et al.* 2009; Begg *et al.* 2010). However, there is clearly huge potential for camp-scale mineralisation *within* Archean Cratons as demonstrated by the multitude of world-class gold, nickel, and iron deposits known from the Superior and Yilgarn Cratons alone (Barnes 2006; Groves *et al.* 1995; Sims 1976). These mineral systems are controlled by an intra-cratonic framework of 'micro-continents' each with their own geochemical, physical and litho-stratigraphic properties. This intra-cratonic lithospheric architecture controlled a multitude of Archean geological systems, including: melt generation, hydrothermal systems, major structural regimes, location/type of volcanism and potentially geodynamics (Griffin *et al.* 2008).

This work, based on a craton-scale study of the Yilgarn Craton of Western Australia, maps the lithosphere using Sm-Nd isotopes from granitoids (Champion & Cassidy 2007). These data allow the source, history and composition of a region to be assessed in space and time, enabling the identification of different crustal blocks. The isotopic affinity of the various terranes, particularly the boundaries between blocks of differing history, show a striking correlation with the location of major gold, nickel and iron belts/camps.

Gold deposits typically follow boundaries between juvenile ($\epsilon\text{Nd}>0$) and evolved ($\epsilon\text{Nd}<0$) regions. These 'boundaries' potentially represent paleo-craton margins between old micro-continents, although these variations could also be due to different processes of melt generation and/or geodynamics. The localisation of gold mineralisation in these areas is likely related to the concentration of deep-seated magmatism and lithospheric discontinuities at these isotopic interfaces. Iron deposits also prefer the isotopic interface between juvenile and evolved regions; however, they appear to prefer the evolved side of the margin and are also found *within* the evolved blocks away from margins. These correlations may be due to facies variations observed in banded iron formations (Lascelles 2007) between juvenile and evolved areas, as well as the stable tectonic regime inferred for older, evolved blocks. Komatiite-hosted nickel deposits also appear to be controlled by the location of major isotopic boundaries, with the major komatiite sequences and associated nickel deposits found on the juvenile side of a margin. This is believed to be due to plume focus into the more juvenile (thinner) region.

This work is a prime example of how understanding the origin and evolution of the lithosphere can lead to significant discoveries that can advance our knowledge of Earth evolution and have direct consequences for the way large-scale mineral systems are targeted.

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Continental evolution and the tectonic setting of IOCG mineralization

Martin P. Smith¹ and Craig D. Storey²

¹School of Environment and Technology, University of Brighton, BN2 4GJ

(martin.smith@brighton.ac.uk)

²School of Earth and Environmental Sciences, University of Portsmouth, PO1 3QL, UK

(craig.storey@port.ac.uk)

The formation of mineral deposits has been linked to global tectonic cycles by a number of authors. Periods of large scale mineral deposition have been linked to virtually all active tectonic settings and their timings have been related to the supercontinent cycle (Groves and Beirlein, 2007). The IOCG class of deposits is extremely diverse, but the major Proterozoic examples, including the associated Kiruna type Fe oxide-apatite (Fe-Ap) deposits, have been related to the margins of Archaean cratons, and suggested to be linked to periods of anorogenic magmatism related to plume-induced partial melting of metasomatised sub-continental lithospheric mantle (Groves and Beirlein, 2007; Groves et al., 2005b). Here we examine this hypothesis in general, and in relation to the Kiruna district Fe oxide-apatite and IOCG mineralisation in particular. Correlation between the direct dating record of IOCG and Fe-Ap deposits and the record of continental crustal growth from U-Pb analyses of zircon indicates mineralisation during periods of supercontinent formation. Detailed analysis of data from the Kiruna district indicates Fe-Ap mineralisation alongside the generation of subduction related granitoids (sourced from the melting of igneous crust around 1.90-1.85Ga), whilst IOCG type mineralisation occurred in this period and synchronously with post-orogenic magmatism (melting of upper crust during orogenic collapse around 1.80-1.75Ga). The results of Nd isotope analyses of titanite from both deposit types indicate metal sources from the subduction related granitoids and mafic crust of the Karelian Kiruna Greenstone Group. The Greenstones of northern Fennoscandia have been suggested to have been formed in the period 2.1-2.0Ga in a potentially plume-related extensional setting. The most Cu-rich deposits show the highest ^{143/144}Nd, and therefore probably the largest component of metal from mafic sources. Previous studies of halogen geochemistry suggest input of both magmatic and external fluids to the mineralising systems. The results overall imply that fertile mafic crust was incubated under and on the margins of the Archaean craton in the early Palaeoproterozoic, but mineralisation did not occur until an arc was initiated at the margin and hence provided a heat and fluid source for mobilisation and concentration of the metals. The conclusions on tectonic setting may apply to some Phanerozoic IOCG examples as well, but may not reflect the setting of major deposits in the Cloncurry District and Gawler Craton, Australia.

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Abundant sulphate in the Neoproterozoic ocean: implications of $\delta^{34}\text{S}$ and $\delta^{18}\text{O}$ analyses of sedex barite deposits in the Scottish Dalradian

Moles, N.R.¹, Boyce, A.J.², Fallick, A.E.²

¹ School of Environment and Technology, Cockcroft Building, University of Brighton, Lewes Road, Brighton BN2 4GJ, UK

² Scottish Universities Environmental Research Centre, East Kilbride, Glasgow, Scotland G75 0QU, UK

Currently debate surrounds oxygenation of the oceans which is estimated using various proxies in the geological record. One proxy is the isotopic composition of marine sulphate in evaporates (rare in the Precambrian) and carbonate-associated sulphate (relatively common). Proterozoic CAS-sulphur isotope datasets often show marked variations over small stratigraphic intervals (e.g. 20‰ over 300m) from which it is inferred that oceanic sulphate concentrations were much lower than modern values (e.g. Bottrell & Newton, 2006; Hurtgen *et al.*, 2002).

A large accumulation of Neoproterozoic sulphate (>8 million tons SO_4 preserved) is located in the Grampian Highlands of Scotland. The Aberfeldy barite deposits are hosted by pelitic, graphitic and calcareous metasediments of the Dalradian Easdale Subgroup deposited around the time of the Marinoan glaciation (640 \pm 10 Ma). Barite rock of hydrothermal exhalative origin forms laterally extensive beds up to several metres in thickness. Multiple beds of barite occur through a >300m thick sedimentary sequence deposited in a syn-/post-glacial environment.

The barite has retained primary isotopic compositions through regional metamorphism. Pronounced $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$ variations near the top and bottom edges of thicker beds are attributed to diagenetic alteration. This aside, barite from throughout the deposits shows a narrow range in $\delta^{34}\text{S}$ with a mean of 36.0 \pm 2‰. Barite $\delta^{18}\text{O}$ ratios show considerable scatter with a mean of 13.5 \pm 5‰. We infer that these represent the isotopic ratio of contemporaneous seawater sulphate, and that $\delta^{34}\text{S}_{\text{seawater}}$ was constant during deposition of a considerable stratigraphical thickness. Uniformity of $\delta^{34}\text{S}_{\text{seawater}}$ during barite precipitation, even in thick (>10m) beds, implies that a large reservoir of seawater sulphate was readily available during the short-lived hydrothermal exhalative events.

Enrichment in the heavy isotope ^{34}S is a distinctive feature reported in other studies of sulphate in marine sediments formed after 'snowball Earth' episodes. This enrichment has been attributed to deposition within anoxic marine sediments of much of the sulphur reservoir as sulphides that preferentially incorporate ^{32}S . Although graphitic and sulphidic sediments host the Aberfeldy deposits, this theory is difficult to reconcile with the stratigraphically uniform $\delta^{34}\text{S}_{\text{barite}}$ values.

Our data suggest an abundance and constancy of ocean sulphate which contrasts with the shifting nature of the exosphere suggested by others whose techniques may be more open to alteration (e.g. CAS). By comparison our data represent an anchor point. Work in progress aims to precisely date the base and top of the Aberfeldy barite stratigraphy to enable its use as a global marker of $\delta^{34}\text{S}_{\text{seawater}}$.

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The Congo craton: an evolving giant iron ore province

^{*1,2}Nforba, M.T., ³Kamga Kabeyene, V., and ⁴Suh, C.E

1. Department of Earth Science, Faculty of Science, University of Yaounde I, P.O. Box 3412 Messa, Yaounde, Cameroon.

2. Cameroon Iron Ore Company, B.P. 33059, Bastos, Yaounde, Cameroon.

3. Higher Teacher's Training College (ENS), University of Yaounde I, B.P. 8127 Yaounde, Cameroon.

4. Economic Geology Unit, Department of Geology and Environmental Science, University of Buea, P.O. Box 63 Buea, Cameroon.

*Corresponding author: nforbamel@gmail.com

Banded iron formations (BIF) have long been an object of interest because, apart from being the major source of iron ore, they are particularly important for the understanding of atmospheric evolution, the chemical composition of the oceans, and the appearance of life on Earth. Iron ore is the primary mineral resource that feeds the world's iron and steel industries. Approximately 1 billion tons of steel is being produced per year, requiring a production of 1.3 billion tons of iron ore per annum. As such, iron ore is one of the most important mineral resources, not only in volume but also in value (USGS, 1999).

At present about 90% of the iron ore mined in the world comes from high-grade hematite (60-70 wt %) deposits (Cairncross et al., 1997) hosted by Precambrian BIF. Production comes mainly from Brazil, Australia, India and South Africa (Fig. 1). The iron ore deposits of the Congo craton are less known due to the fact that no major exploration or mining work has been done in this area. Increase in the iron ore of this area gathered momentum in the early 2000 when the over 200mt Mbalam iron ore deposit was discovered by Sundance Resources Ltd.

The iron prospects in northern Congo are hosted by Archaean rocks (older than 2500 million years) that form part of the Congo craton in Central Africa. This craton extends from northern Angola through the Republics of Congo and Cameroon with a significant part exposed in the Democratic Republic of Congo and Gabon. The iron formations of the Republics of Congo and Cameroon are an extension of the BIF formations in Brazil following a pre-Mesozoic reconstruction of Africa and South America.

The cluster of known BIF deposits on the Archean Congo Craton in Cameroon, Congo Republic and Gabon (Figure 1). Iron ore deposits in Cameroon are located at Mbalam, Nkout, Ngovayang and Les Marmelles. Contiguous and across the frontier to the south in the Congo Republic are a number of known BIF occurrences at Avima, Nabeba, Bamegod/Elogo, Youkou, Zanaga, Mayoko-Mousondji, Badondo and Letioukbalala. The southern part of the Congo Craton Iron Province is located in Gabon centred on Belinga, Batouala, Boka-Boka, Minkebe, Mela, Kango, Mebanga-N'gama and Tchbanga Mouteli.

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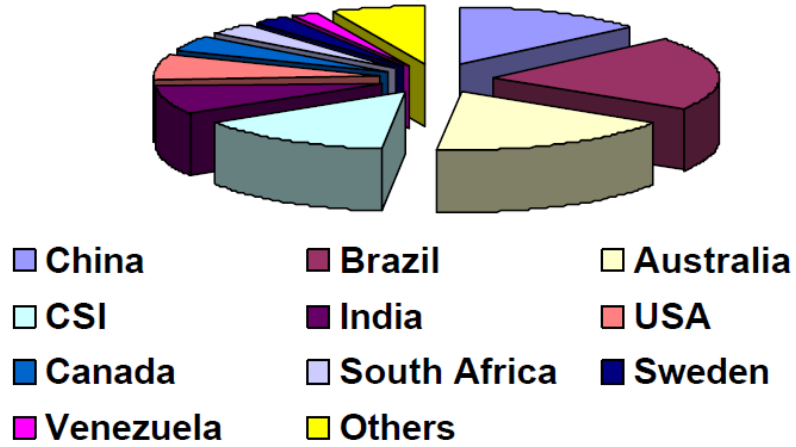


Figure 1: World production of iron ore in 1998 (USGS, 1999).

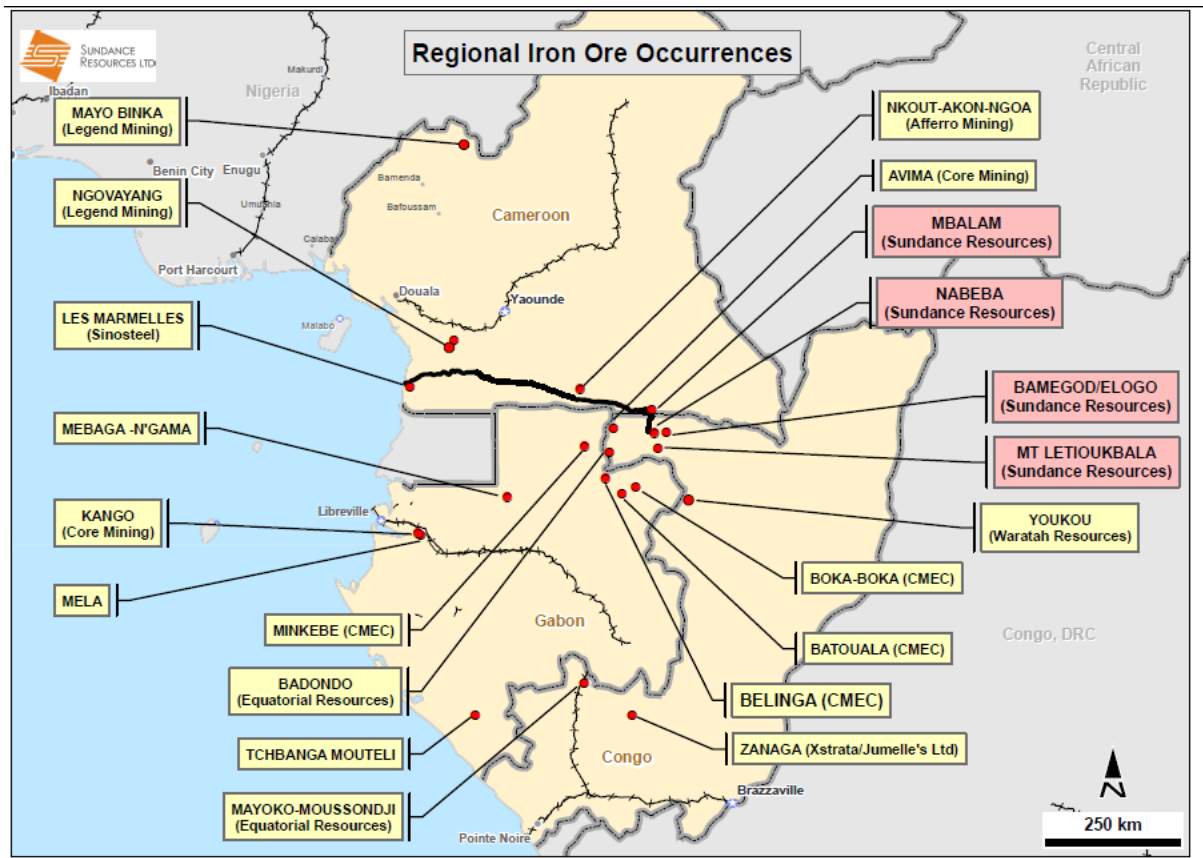


Figure 2: Regional iron ore occurrences within the Congo craton (an emerging iron ore province). Major iron ore exploration companies are shown in brackets.

A Classic Geological Argument Origin of Archaen Pyritic Conglomerates and Witwatersrand Gold Reefs Are they Hydrothermal or Sedimentary ?

Graham Oram

The poster presents three new pictures and some old observations of this major gold deposit from the Archaen Eon and asks the reader to decide if the gold in these ore deposits is of hydrothermal or sedimentary origin.

One picture is of the edge of a sedimentary channel exposed in a Basal Reef stope on President Steyn Mine. This picture shows alteration of the footwall quartzite. The hand specimen is of Leader Reef from President Brand Mine and very unusually shows pebble and pyrite grain surfaces. The smoky quartz rim of one white quartz pebble among several unaltered quartz pebbles shows recycling from an older uranium rich reef. A photomicrograph (x8) of the Leader Reef specimen (taken at the ANU) shows fractured round pyrite grains in more detail. These grains of amorphous accumulations of tiny pyrite needles were broken during compaction.

Written descriptions of Archaen Pyritic Conglomerates (APC), the Witwatersrand basin, a typical "Reef" and some of the mineralogy and sedimentology of this deposit are included. The academics, led by A Barnicoat, argue for a hydrothermal origin whereas the mine geologists, led by W.E.L. Minter, have always favoured a sedimentary origin. The age of the gold is 3.1Ga. (Arizona University;) the gold is older than the sediments and should be irrefutable evidence for a sedimentary origin.

The academics maintain pyrite cannot be a detrital mineral in a mature conglomerate. Gold and carbon are hydro-dynamic opposites. The mine geologists know the ore grade controls are all sedimentary. All the evidence says sedimentary but the implications of this conclusion are unacceptable to many geologists. However, astronomers accept the conclusions from a sedimentary origin as consistent with their proposal for the origin of the atmosphere.

If this deposit is hydrothermal then the Witwatersrand is unique. If it is sedimentary then the physics and chemistry of these APCs describes an Archaen environment that was very different from today; the air contained hydrogen sulphide. This conclusion raises many questions relating to the source of the gold, the origin of the atmosphere and when, why and how it changed. Answers to these questions provide an answer to, "Where can I find another Witwatersrand? But perhaps more importantly these conclusions illuminate the Archaen environment and begin a better understanding of the history of the Earth.

3D Structural Model of Southwest Turkey Reveals Lithosphere-Scale Control on Hydrothermal Fluid Flow

Klaus Gessner

Centre for Exploration Targeting, and Western Australian Geothermal Centre of Excellence, School of Earth and Environment, The University of Western Australia M006, 35 Stirling Highway, Crawley WA 6008, Australia, klaus.gessner@uwa.edu.au

Luis Gallardo, Vanessa Markwitz

Centre for Exploration Targeting, School of Earth and Environment, The University of Western Australia M006, 35 Stirling Highway, Crawley WA 6008, Australia

It is well known that geological processes along plate boundaries have the potential to generate the energy flux required to drive large hydrothermal mineralizing systems. Many world-class mineral provinces in the Archaean (e.g. Superior province and Yilgarn craton) and the Proterozoic (e.g. Gawler and North Australian Craton), however, appear to be controlled by linear features within continental lithosphere. One question that can be asked in the light of the 'Lyellian hypothesis' that the study of current Earth systems can help unravel questions of deposit formation through geological time, is, if such mineralized second order discontinuities in the continents have modern analogues.

Here we present results from a study that integrates geophysical and geological data to better understand the structural control on Miocene to Recent hydrothermal activity in the Menderes Massif in western Turkey. The Menderes Massif is mainly explored for epithermal gold and porphyry copper-gold, and hosts a number of large-scale high-enthalpy geothermal reservoirs.

The Menderes Massif exposes the deepest tectonic units of the Tethyan orogen in western Turkey, a composite nappe stack comprising Precambrian and Phanerozoic tectonic units that were assembled during Eocene to Oligocene crustal shortening to form the western Anatolide part of the Tethyan orogen. Only parts of the upper tectonic units within the Menderes Massif can be correlated along strike into the Hellenide part of the Tethyan orogen in the Aegean Sea. The along-strike differences between the Anatolides and the Hellenides, however, are not limited to the Alpine shortening structures, but are also obvious in different kinematics during crustal extension.

We propose that a NE-trending sinistral wrench zone has been a defining structural feature in southwest Turkey since the Miocene. While this wrench zone has a subtle surface expression and has only recently been identified in the crustal architecture, it can be imaged from datasets such as satellite gravity, seismic tomography, the distribution of earthquake locations, and the distribution of Miocene to Recent hydrothermal fluid flow systems.

We argue that after Alpine crustal shortening, the wrench zone stretched, exhumed, denuded and fragmented the Menderes Massif in a kinematic framework that is consistent with a tear in the slab, and partial delamination of the lithosphere.

Our hypothesis addresses some of the open geodynamic and tectonic questions in the regional geology, but also provides an explanation how lithosphere discontinuities that are not at the scale of plate boundaries can control the location and mineral systems in Earth's crust.

Is fluid exsolution depth the key to molybdenum porphyries?

D.J. Smith

Department of Geology, University of Leicester, Leicester, LE1 7RH, djs40@le.ac.uk

Recent studies ^[1] have suggested that the emplacement depth of porphyry stocks controls the metal tenor of related mineralisation, with deeper intrusions favouring molybdenum ore formation. Whilst deeper deposits do tend towards greater Mo grades, shallower deposits can also exhibit significant molybdenum mineralisation. It is suggested that rather than emplacement depth, it is the depth at which aqueous fluid exsolves that controls Mo extraction from the magma, and thus availability for ore formation.

Hydrous intermediate magmas can begin exsolving an aqueous phase at considerably higher pressures and depths than they begin crystallising ^[2, 3]. For magmas with high initial water contents (e.g. Questa Mo-porphyry, New Mexico, the parent melt had ~10 wt % H₂O ^[4]) the water saturation / magma liquidus relationship is such that they must exsolve an aqueous phase prior to crystallisation. The lack of a crystal record of early or deep fluid production may mean that it is poorly recognised and reported, particularly in heavily altered systems. Nonetheless, there are mineralised systems with early, deep, fluid formation implied (e.g. Butte Cu-Mo, Montana, deep emplacement depth ^[5]) or directly evidenced (e.g. aqueous–melt emulsions, Río Blanco Cu-Mo, Chile ^[6]). Indeed, the generic model for porphyry formation has the intrusive stock being a focus for fluids and volatiles from a deeper magma ^[7]. Mineralising fluids are therefore decoupled from the porphyry stock, and can be exsolved at a much greater depth and pressure than the emplacement depth of the stock indicates.

Experimental work on the hydrothermal transport of molybdenum suggests that it is mobilised from magma to aqueous fluid as a molybdate species ^[8], rather than a chloride or sulphide complex (c.f. Cu and Au). The distribution of Mo between melt and aqueous fluid increasingly favours the aqueous fluid at higher pressures ^[8, 9]; exsolution of an aqueous phase at higher pressures therefore improves the extraction of Mo from the melt.

Pressure itself is not a significant control on the solubility of Mo in aqueous fluids ^[10]. An Mo-enriched fluid may decouple from the parental magma and ascend to higher levels, and generate mineralisation at much shallower depths than it originally formed. Thus, deeply emplaced deposits (e.g. Butte) tend towards high Mo grade as they logically must have exsolved fluid at high pressure; decoupling means that shallow emplaced systems can display a range of Mo contents.

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Critical metal resources in Tertiary epithermal and porphyry systems at NE Greece

Nikolaos Skarpelis

*Department of Geology and Geoenvironment, University of Athens, GREECE;
e-mail address: skarpelis@geol.uoa.gr*

In nowadays it is indispensable to look for new sources of critical metals. Northeastern Greece is a favorable terrain for exploration for conventional and critical metal resources. Tertiary volcano-sedimentary sequences at the borders of Rhopope polymetamorphic belt are the hosts of epithermal Au (\pm Ag, Cu), epithermal base metals+Ag veins and porphyry Mo-Re mineralization. Two IS-HS epithermal Au deposits are in the process of permit for mine development. The first modern geochemical bulk ore analyses carried-out by ICP-OES and ICP-MS addressing distribution of critical metals (Te, In, Ga, Ge, Cd, Re) in the district are presented. Mineral concentrates and metal rich samples were analysed.

Te distribution is highly varied in epithermal Au-Ag mineralization, and individual assays range from <1g/tn to nearly 150g/t. On average the content of Te is 32g/t, indicating the ore would not be an economic source of Te in its own right.

Sphalerite-wurtzite concentrates from epithermal base metal+Ag veins are enriched in In (up to 1090ppm, mean 170ppm), Cd (up to 5390ppm, mean 3230ppm) and Ga (up to 1088ppm, mean 556ppm). They contain up to 91ppm Ge (mean 26ppm). Mineral chemistry and geochemical correlations indicate association of Ag with galena and Cu-sulfosalts (tennantite). Cu-rich concentrates show elevated Sn values (up to 0.35 wt% Sn), with levyclaudite, stannite and k esterite as minor Sn minerals. In, Cd, Ga, Ge (\pm Sn) concentrations in base metal veins may indicate an influence of fluids expelled from magmas during emplacement of post-collisional rhyolitic dikes. Recent reconnaissance sampling of a Mo porphyry prospect (Kirki) made clear the pattern of hydrothermal alteration of a dacite porphyry (potassic+silicic zone highly overprinted or overlain by sericitic and argillic alteration). The distribution of molybdenum shows local anomalies related mostly to stockwork and sheeted quartz-sulfide and sulfide veining within the potassic zone. Bulk samples of mineralized porphyry are low in Mo and anomalous in Re. Mo and Re show a tendency to concentrate into the potassic zone, whereas grades are distinctly low in the sericitic zone (MoS₂ max 0.03% in the potassic zone compared to MoS₂ max 0.008% into the sericitic zone). The correlation coefficient between Mo and Re is R= 0.66, possibly as a result of the occurrence of Re in the structure of rheniite. For a better understanding of the mineral intensity of the porphyry system and assessment of economic viability of the prospect, a next stage of geochemical rock sampling program is suggested to minimize exploration risks for locating a blind economic Mo-Re system.

The Kago Low-Sulfidation Au/Ag Deposit: an affiliated Nansatsu deposit, microthermometry and Ar/Ar age determinations

*Thomas TINDELL, Koichiro WATANABE, ¹Ryohei TAKAHASHI, ¹Akira IMAI, ²Adrian BOYCE, ³Anders SCHERSTEN and ³Laurence PAGE

Department of Earth Resources Engineering, Kyushu University, Japan

¹*Department of Earth Science and Technology, Akita University, Japan*

²*Scottish Universities Environmental Research Centre, UK*

³*Department of Earth and Ecosystem Science, Lund University, Sweden*

The Kago low sulfidation deposit, which lies prominently along the Northern margin of the Nansatsu District, Japan, has been exploited over a 400-year period for Ag and Au (grades ranging 4.1-13.3g/t Au and 2.6-6.6g/t Ag). In contrast to Kago, Nansatsu deposits comprise high-sulfidation Au/Cu disseminated types, such as Kasuga, Iwato and Akeshi, which range in age from 4.4 Ma, 4.3 Ma and 3.7 Ma, respectively, and are characterised by the presence of enargite, luzonite and native gold. We seek to answer a key genetic and exploration question: what is the relationship of Kago to the Nansatsu system?

Kago consists of a series of veins striking NE-SW, and dipping at 60-70° N, hosted in sandstones and mudstones of the Shimanto-Supergroup, which are dated 83.3Ma. There are 3 vein groups the central vein group (CVG), in which much of the underground mining explored. Veins are typically 4-20 cm wide and composed of electrum, polybasite, pyrite and quartz, chalcedony gangue. Silicification is common surrounding the CVG and is accompanied by a low temperature argillic alteration assemblage. The CVG is considered to extend for approximately 1km along strike. The southern vein group (SVG) are thin veins (1-3cm width) composed mainly of pyrite and chalcedony. The northern vein group (NVG) has not been explored due to poor exposure.

Preliminary fluid inclusions from the SVG show homogenisation temperatures in bi-phase (liquid/vapour) inclusions in the range 210-220°C, and salinities around 0.8 NaCl eq. wt%. These data point towards a predominantly meteoric source for the fluids, likely shallowly circulating fluids heated from a distal magmatic source. This differs with the Nansatsu high-sulfidation deposits, which are typically of a higher temperature and salinity (250-270°C and 2-5 NaCl eq. wt%).

Ar/Ar age determinations were performed on two veins located within the CVG. Adularia, from two samples in a thin band of colloform banded quartz, and a hydrothermal breccia (associated with disseminated pyrite) gave ages of 4.23 ± 0.09 Ma and 4.07 ± 0.04 Ma respectively. These ages fall within the age range of the regional Nansatsu high-sulfidation deposits.

Stable isotopic signatures of the vein groups are currently being undertaken to the explore further sources of sulfur and fluid histories in Kago versus Nansatsu, now that age dating reveals a coincidence of mineralizing events.

*Corresponding Author: tindell-tom@mine.kyushu-u.ac.jp

Iron sulphide from the Boulder Conglomerate of the Navan Zn-Pb Deposit, Co. Meath, Ireland: composition and origin.

Gareth J. Barker and Julian F. Menuge

School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland

Iron sulphide-rich ore-grade mineralization termed Conglomerate Group Ore (CGO) accounts for ~3% of the 105 Mt carbonate-hosted Zn-Pb Navan deposit, Co. Meath, Ireland. CGO is the stratigraphically highest lens hosted by a sequence of fault talus and debris known locally as Boulder Conglomerate (BC). Immediately below BC a Chadian erosion surface, considered the product of submarine gravitational instability caused by extensional faulting, truncates the main Navan orebody.

Drill core samples of BC were collected southeast of the main orebody within 100 m south of the C fault, the interpreted ore fluid conduit. Sulphide textures include massive replacement, cavity infill, massive framboidal pyrite and dislocated clasts of earlier ore. Iron sulphide paragenesis includes multiple episodes of precipitation. Pyrite displays framboidal, colloform and euhedral morphology. Marcasite assumes botryoidal, colloform and euhedral morphology. Unlike the other sampled textures, sampled massive framboidal pyrite is not associated with ore grade CGO and originated at the highest stratigraphic level of the BC most distal from the feeder fault.

Texturally different iron sulphide samples were selected for electron probe microanalysis of minor elements. Pyrite and marcasite both deviate from ideal FeS_2 , typically containing As, Zn, Pb, Ni, Mn and Cd. Notably, most samples are "arsenian", containing up to 8.8 wt. % As. Botryoidal and massive framboidal samples contain the lowest total abundances of minor elements, averaging 0.56 wt.% and 0.70 wt.%, respectively. A positive correlation between Pb and Sb suggests that boulangerite ($\text{Pb}_5\text{Sb}_4\text{S}_{11}$) may be present as undetected inclusions. Variation in trace element composition correlates with spatial location, mineralogy, morphology and inferred precipitation process.

Fe isotopic analysis by MC-ICP-MS was carried out on sub-milligram iron sulphide samples microdrilled from thick sections and chemically purified using anion-exchange resin. Substantial Fe isotopic variation exists between massive framboidal pyrite and other iron sulphide morphologies, with massive framboids having the heaviest $\delta^{56}\text{Fe}$ (-0.28 ‰) and other morphologies the lightest (-1.40 to -2.01 ‰) $\delta^{56}\text{Fe}$.

Comparison with unpublished sphalerite Fe and S isotope data for the main Navan orebody (Gagnevin et al.) suggests that BC framboidal pyrite was precipitated from surface-derived fluid rich in bacterially reduced sulphide, and that other BC Fe sulphides were precipitated from hydrothermal fluid enriched in sulphide derived from the Lower Palaeozoic basement.

“Layered” Mineralisation at the Navan Zn-Pb Mine, Ireland – A story of sedimentationCraig D. Barrie^{1*}, Adrian J. Boyce¹, Alan P. Boyle², Damien Gagnevin³ and Robert Blakeman⁴¹NERC Isotope Community Support Facility, Scottish Universities Environmental Research Centre, Rankine Avenue, East Kilbride, Glasgow, G75 0QF, UK²School of Environmental Sciences, Department of Earth and Ocean Sciences, University of Liverpool, Liverpool, L69 3GP, UK³UCD School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland⁴Boliden Tara Mines Limited, Navan, County Meath, Ireland*craig.barrie@glasgow.ac.uk

Previous work on layered ‘colloform’ sphalerite textures has revealed a complex tale of changing crystal orientations, trace element chemistry and S isotope signatures, across only a few centimeters of ore (Barrie et al., 2009). These ‘layered’ textures precipitate via growth of interlocking crystals, a nature which gives rise to a number of unique features, including the preservation of *growth-parallel* crystal orientations indicative of *in-situ* precipitation. However, the majority of ‘layered’ textures at Navan are not ‘colloform’ and are almost certainly unrelated to *in-situ* mineralization. Instead these ‘layered’ textures consist of packages of sphalerite grains, sometimes preserving delicate internal structures such as *planar and trough cross-stratification*. Anderson et al. (1998) previously reported the presence of these textures, suggesting they represented ‘*rapid nucleation within the ore fluid and subsequent deposition out of suspension*’. In this study we have collected a suite of ‘layered’ textures, both ‘colloform’ and ‘non-colloform’, from various ore zones at the Navan Zn-Pb Mine, Ireland. These samples were investigated through petrographic, crystallographic and isotopic analyses to determine how and if their natures differ and whether there is evidence for a pseudo-sedimentary formation process for the ‘non-colloform’ textures. As with the work of Barrie et al. (2009) the ‘colloform’ layering all preserve strong *growth-parallel* crystal orientations. In contrast all of the ‘non-colloform’ layering preserves weak *layer-parallel* or statistically random crystal orientations. This layer parallel orientation of sphalerite grains, coupled with the texture of the sphalerite within the layered packages, indicate that these layers have not formed via *in-situ* mineral growth but, either represent ‘mechanical flow’ or later ‘replacement’ mineralization processes. The cross-cutting relationships preserved in samples showing more than one of these textural types plus, the presence of interstitial carbonate suggests that at least some, if not all of these ‘non-colloform’ textures represent pseudo-sedimentary flow, as hinted at by Anderson et al. (1998).

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Genetic constraints for the Lupa Goldfield, SW Tanzania: Implications from Rhenium-Osmium pyrite and molybdenite geochronology

C.J.M. Lawley^{1}, D. Selby¹, and C. MacKenzie²*

¹*Department of Earth Sciences, Durham University, Science Labs, Durham, DH1 3LE, UK*

²*Helio Resource Corp., 580-625 Howe Street, Vancouver, British Columbia, V6C 2T6, Canada*

*Corresponding Author: c.j.lawley@durham.ac.uk

The temporal distribution of orogenic gold deposits is closely correlated with periods of supercontinent formation, globally-dominant convergent margin tectonics, and crustal growth. Paleoproterozoic-aged (i.e., 2.5–1.6 Ga) orogenic gold deposits are found globally, however the absolute timing of gold deposition in relation to the absolute timing of tectonic and magmatic activity remains poorly constrained for many of these goldfields. The Lupa goldfield, SW Tanzania is one such example. Herein we present Re-Os pyrite and molybdenite ages from the Kenge, Porcupine, and Konokono mineral systems within the Lupa goldfield. Gold within these ore zones occurs as free gold and intergrowths with pyrite. As a result, Re-Os pyrite ages are interpreted to constrain the timing of gold mineralization. Molybdenite forms an accessory sulphide phase to gold at the Porcupine and Kenge systems although the timing relationship between gold and molybdenite is difficult to interpret. At Porcupine, simple gold- and molybdenite-bearing quartz vein textures suggest molybdenite and gold were coeval. Gold- and molybdenite-bearing quartz vein textures at Kenge are more complex. These veins are typically deformed and mantled by pyrite- and gold-bearing mylonitic rocks. Petrographic evidence suggests pyrite crystallized during mylonitization and is interpreted to constrain the timing of mylonite development and gold deposition. Preliminary pyrite Re-Os data from gold-bearing mylonitic rocks at Kenge suggest gold mineralization occurred at ca. 1880 Ma. This age from Re-Os pyrite analyses is younger than previously-reported molybdenite Re-Os ages of ca. 1940 Ma. The difference in Re-Os molybdenite and pyrite ages may suggest an early molybdenite mineralizing event followed by a gold mineralizing event that was contemporaneous with mylonitization.

The preliminary Re-Os pyrite age of 1880 Ma is identical to molybdenite Re-Os ages at the Porcupine deposit (ca. 1880 Ma) and preliminary Re-Os pyrite ages at the Konokono ore zone (ca. 1890 Ma). The concordant Re-Os pyrite and molybdenite ages from Kenge, Porcupine, and Konokono ore zones suggest a large-scale gold mineralizing event occurred at ca. 1880 Ma. This interpreted gold mineralizing event is also broadly contemporaneous with magmatic activity within the Lupa goldfield and tectonic activity elsewhere within the Ubendian Belt.

Ore-forming Condition of the Keisen No. 3-1 Vein in the Hishikari Gold Deposit, Kagoshima, Japan

T. SUGA¹, S. NISHIMURA¹, A. IMAI², R. TAKAHASHI², T. TANAKA¹, K. YONEZU¹, Y. OKAUE³ and K. WATANABE¹

¹Department of Earth Resources Engineering, Kyushu University, Japan

²Department of Earth Resources and Technology, Akita University, Japan

³Sumitomo Metal Mining CO., LTD

Hishikari gold mine is located in the northern part of Kagoshima Prefecture, Japan. The deposit is classified as a low-sulfidation and/or adularia-sericite type epithermal gold deposit, consisting of the Honko, Sanjin and Yamada vein deposits. Gold reserves, including past production, is estimated to be over 300 metric tonnes, with an average gold grade is approximately 40 g/t. This study aimed to reveal the ore-forming conditions of the Keisen No. 3-1 vein +25mL and +40mL by microscopic observation, XRD, XRF, SEM-EDS analysis and fluid inclusion micro thermometry.

Ore minerals such as electrum, sphalerite, hessite, Se-bearing galena and pyrite were observed in the Keisen No. 3-1 vein. Quartz, adularia, calcite, prehnite and clay minerals were also observed as gangue minerals. Electrum is coexistent with sphalerite in quartz and smectite at +25mL. Adularia and prehnite occur in the gold mineralization bands. Electrum and hessite are found in quartz and truscottite at +40mL. Host rocks have suffered from chlorite and chlorite-smectite alterations. These conditions suggest the hydrothermal solution was neutral pH, further the temperature of hydrothermal solution was >200°C.

SEM-EDS analysis indicates electrum mineralization between the early stage and late stage exhibits a decrease in Ag content, towards the late stage. The average Au content in electrum increases from 57 to 62 at% and the average diameter also increases from the margin to the center of the vein; from 10µm to 14µm.

Quartz was the most abundant mineral in all of the bands, particularly in the early stage, associated with adularia, prehnite and a small amount of calcite at +25mL. The presence of truscottite and xonotlite increases in the late stage. The stable condition of the mineral assemblage truscottite, xonotlite and quartz is recognized to be >200 °C. On the basis of these facts, the hydrothermal solutions contained abundant Ca.

Homogenization temperature ranges of fluid inclusions in quartz were dominantly from 210 to 230 °C at +25mL and +40mL. The salinities of almost all samples ranged from 0.2 to 0.8 NaCl eq. wt%. On the other hand, a sample at +40mL ranged from 1.5 to 5.1 NaCl eq. wt%. It is considered that 1) mixing of deep hydrothermal solutions and meteoric water, or 2) loss of vapour and concentration of saline solutions caused by boiling, may explain this phenomena.

*E-mail: suga-takuma@mine.kyushu-u.ac.jp

Occurrences and Chemical Compositions of Ore Minerals, and Their Implications for Epithermal Gold Mineralization at the Victoria Gold Deposit, Northern Luzon, Philippines

Takahiro TANAKA¹, Akira IMAI² and Koichiro WATANABE¹

¹*Department of Earth Resources Engineering, Kyushu University, Japan*

²*Department of Earth Resources and Technology, Akita University, Japan*

The Victoria epithermal gold deposit is located in the Mankayan mineral district in northern Luzon, Philippines. The Mankayan mineral district is known as a porphyry copper-gold deposit bearing magmatic-hydrothermal system. The Victoria deposit consists of several sheeted veins which show a horsetail pattern. The Victoria gold deposit has been recognized as a carbonate-base metal type low-sulfidation epithermal deposit (Cuison et al., 1998; Claveria, 2001; Sajona et al., 2002). However, this study revealed that the Victoria deposit has intermediate- to high-sulfidation assemblages including enargite, luzonite-famatinite, colusite-nekrasovite and covellite. Luzonite is observed almost all over the Victoria deposit, however, other high-sulfidation state minerals are mainly recognized at the shallower and eastern part of the Victoria deposit. Further, telluride and tin, bismuth-containing minerals are also recognized at the shallower and eastern part of the Victoria gold deposit.

In this study, the veins of the Victoria gold deposit are categorized into four vein types by mineral assemblages and characteristics: (1) quartz vein containing base metal-sulfides and often with a small amount of luzonite; (2) quartz vein containing yellow sphalerite and silver-sulfosalt, further, high-sulfidation state minerals are not recognized; (3) quartz vein mainly containing tetrahedrite group minerals, tellurides and high-sulfidation state minerals; (4) pyritic sulfide vein often containing quartz. These are categorized as follows; vein type 1 is base metal type, 2 is base metal-Ag type, 3 and 4 are polymetallic type gold mineralizations. Type 3 and 4 veins are mainly found at the shallower and eastern portion, exhibiting a similar mineral assemblage, containing high-sulfidation state minerals, tellurides and tin, bismuth-containing minerals, however, gold-containing tellurides, altaite and kawazulite are not recognized in the vein type 4. Hessite, petzite, sylvanite, stützite, altaite, tellurobismuthite, kawazulite and tetradymite are recognized as telluride, while native tellurium also occurs in the vein type 3 and 4. Tellurium-bearing tetrahedrite group minerals are dominant in the vein type 3 and 4. A large number of these are categorized as goldfieldite. Ag content range in native gold and electrum and FeS content range in sphalerite are 16.1-36.4 and 0-1.6 mole % (vein type 1), 18.7-35.7 and 0.2-0.8 mole % (vein type 2), 4.0-27.6 and 0.2-0.8 mole % (vein type 3) and 0-18.0 and 0.2-1.6 mole % (vein type 4), respectively. The silver content in native gold and electrum decreases from the vein types 1 and 2 to 3 and 4, which is controlled by increasing of sulfur and tellurium fugacity.

*E-mail: takahiro-tanaka@mine.kyushu-u.ac.jp

Origin and Serpentinization of Siruka peridotites, Southeastern Choiseul, Solomon Islands

Christopher V SAGAPOA¹, Akira IMAI², Takeyuki OGATA³, Yonezu KOTARO¹, Koichiro WATANABE¹

¹Department of Earth Resources Engineering, Kyushu University, Japan

²Department of Earth Science and Technology, Akita University, Japan

³International Centre for Research and Education on Mineral and Energy Resources, Akita University

The Solomon Islands form an archipelago situated between longitudes 156° to 170°E, and latitudes 5° to 12°S (Fig 1). In order to unravel the tectonic record and serpentinization processes of the Siruka peridotites from Choiseul, Solomon Islands detailed petrologic and mineralogical analysis was conducted. The original rock of it is mainly harzburgite, dunite and less commonly lherzolite. Common primary constituent minerals of the Siruka peridotites are olivine, pyroxene and spinel. Secondary assemblages are essentially tremolite, magnesio-hornblende, chlorite and serpentine (chrysotile and lizardite) with subordinate amounts of magnetite, talc, brucite, magnesite and trevorite. In this work we use olivine, pyroxene and spinel elemental composition of the peridotite to construe the possible origin of the studied peridotite. Petrography, mineralogy and geochemical characteristics of the Siruka peridotites illustrate a residual mantle origin typified by its depleted peridotites affinity. Using textural and geochemical evidences, we interpret these peridotites as residual abyssal mantle (with 10 to 18% fractional melting), interpreted as portion of a mantle material controlled by major tectonic processes, probably when the unified lithosphere in the southwest pacific had mid-ocean ridge basalt (MORB) characteristic and the mantle an abyssal peridotite composition. Siruka peridotite textural features also indicate deformation in a regime under lithospheric physical conditions presumably below solidus temperature. TiO₂ versus Cr# plot of spinel in Siruka peridotites reveal an abyssal peridotite origin. Combining mineral chemistry and mineral phase relationship, we suggested that the occurrence of talc is associated with breakdown process of pyroxene at potentially low temperature environment associated with low grade metamorphism. Metamorphism grade is estimated following close association of talc with amphibole and chlorite in Siruka peridotites. Compared with other serpentinites, the peridotites from Siruka are characterized by the presence of magnetite and talc. Serpentinization process in Siruka is not so pervasive and broad in extent.

Key words: Siruka peridotite, mantle, abyssal peridotite, serpentinization, Choiseul, Solomon Islands

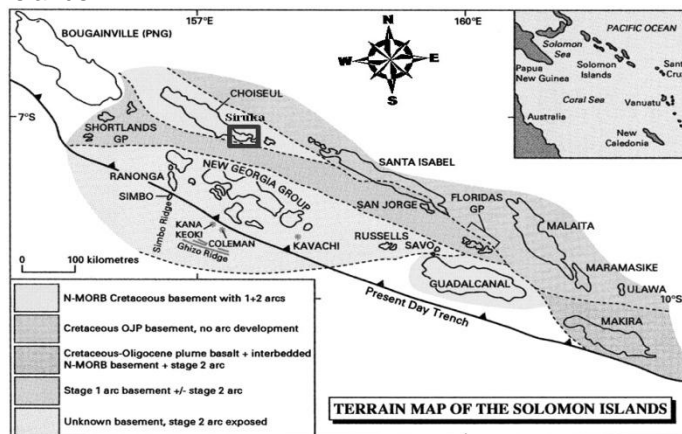


Figure 1: Modified geological terrain model (after Petterson et al., 1999). Inset is a simplified map of the geographical location of Solomon Islands in the southwest pacific. Denoted with an open square is the study area.

REFERENCE:

07-09 September 2011

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The analysis and interpretation of trace element geochemistry in arsenopyrite for the purpose of gold and base metal deposit exploration

Matthew Murphy¹, Prof R. John Watling² and James I. Stewart³

1) PhD Student, University of Western Australia, Centre for Forensic Science

2) Winthrop Professor, University of Western Australia, Centre for Forensic Science

3) Director-Consultant, Golden Archer Resources, Australia

New discovery occurrences of buried gold and base metal mineralization with obvious surface expression are becoming increasingly rare, and as a result of this it is becoming increasingly more difficult and costly to use traditional geochemical techniques to locate new ore bodies. Consequently, new and more sensitive geochemical exploration protocols must be developed. This study details the use of trace element association patterns in arsenopyrite to indicate the presence of gold or base metal mineralization and to assist in endowment estimation of the potential deposit.

Analysis of the trace element assemblages in arsenopyrite, using Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS), provides potentially valuable information on the chemistry of the hydrothermal fluid forming the arsenopyrite and which can be used to develop geochemical exploration protocols to discover gold or base metal ore bodies.

Arsenopyrite trace element assemblages can be used to distinguish between arsenopyrite formed in hydrothermal gold mineralized events and arsenopyrite formed in magmatic hydrothermal base metal systems. Initial indications are that arsenopyrite formed by events unrelated to gold or base metal mineralizing events can be differentiated from arsenopyrite formed in mineralizing systems. Within the gold mineralizing systems from Australia; Archean, Proterozoic and Phanerozoic mineralizing systems can be differentiated from one another based upon trace element chemistry of the arsenopyrite contained within the deposit. Furthermore, the trace element assemblages contained in arsenopyrite provide an insight into the development of Archean gold deposits that may be used to estimate the endowment of the deposit. For Archean gold deposits the relationship between Ni and Bi can be used as a predictive tool to estimate a gold deposit endowment which is independent of grade.

There is a significant difference between the trace element assemblages in gold and the New England magmatic hydrothermal systems (Fig. 1) which, in the latter case, may be able to be used as indicators of the style of mineralization as well as potential orebody composition.

Currently the interaction and evolution of trace elements in arsenopyrite is being analysed to determine how these interactions may be used in geochemical exploration regimes to locate an orebody from the surface in a more efficient and less costly fashion. Initial data indicates that the host rock and the distance from ore zones have significant impacts on the trace element chemistry of arsenopyrite and consequently changes in these relationships may be positively used in the exploration protocols for buried and blind ore bodies.

Microstructural characterization of natural gold alloys

Angela Halfpenny¹ and Robert M. Hough¹

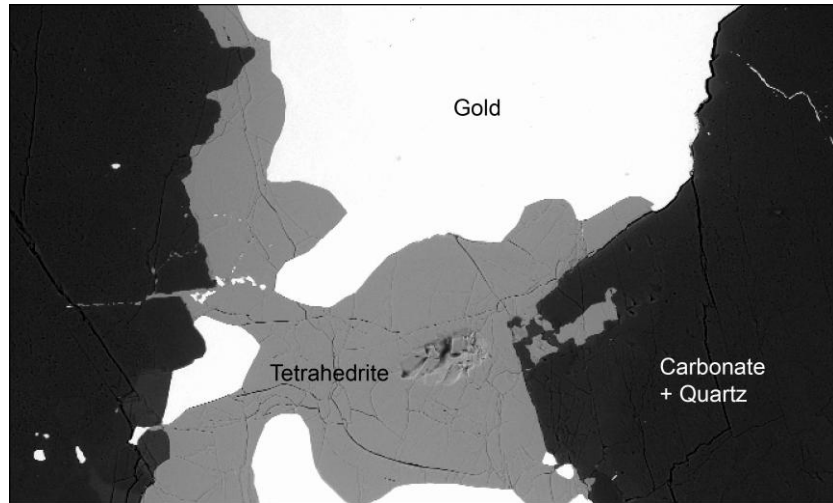
¹ Earth Science and Resource Engineering, CSIRO, Kensington, Western Australia
Angela.halfpenny@csiro.au

Gold, due to its economic significance and variable properties is an important metal to understand. Most geological research on gold has been performed to constrain the location and timing of gold deposition, relatively few studies have focused upon the gold itself. This research focuses upon characterizing the microstructures of natural gold alloys by quantifying the crystallography and composition of the visible gold, with the aim of improving our understanding of how gold nucleates, crystallizes and deforms. Another aim of the research is defining the mechanisms involved in gold modification after crystallization.

We have studied visible gold hosted by quartz carbonate veins from lode gold deposits in Western Australia. The samples vary in structural style from weak breccias to discrete veins hosted in shear zones. The visible gold in the breccia veins occurs as aggregates of subhedral grains which vary in grain size from tens of microns to hundreds of microns in size and are located in the carbonate dominated vein material between the breccias clasts. Whereas the visible gold in the shear hosted veins occurs mostly as centimeter long veinlets with the occasional large aggregate. When large aggregates form they are intimately associated with tetrahedrite. The boundaries between the gold and tetrahedrite are extremely undulatory and the gold appears to be replacing the tetrahedrite or in filling a void which has been left by tetrahedrite dissolution (see figure).

The full crystallographic orientation of each gold crystal was measured using electron backscatter diffraction (EBSD) and chemical variations were measured using (EDS), both are scanning electron microscope (SEM) based techniques. The gold crystals contain $\Sigma 3$ twin boundaries, which are not always planar and exhibit weakly curved grain boundaries. The gold grains also exhibit a weak misorientation of the crystal lattice. Possible causes for this lattice misorientation could be due to deformation or replacement of Au atoms (Cu is ~ 12% smaller in atomic size, which leads to distortions in the crystal lattice when it replaces Au) or thermal alteration.

Measurements of the gold's composition by EDS show that there are no significant variations across each gold crystal at the 1% detection limit; this could indicate that the lattice variations are not due to significant substitution of Au atoms. The composition of the crystals has been measured at an average of 98% Au and 2% Ag. A thermally annealed microstructure would be characterised by straight grain boundaries and $\Sigma 3$ twins, which is not the case here, therefore we conclude that the original microstructure may have been representative of thermal annealing but has since been modified by plastic deformation.



Geometallurgy of Iron Ores from Liberia and Cameroon

Anderson, K.F., Wall, F., Moon, C., Rollinson, G.

Camborne School of Mines, University of Exeter, Cornwall Campus, Penryn, Cornwall, TR10 9EZ, UK, Email: kfea201@exeter.ac.uk

Africa is a growing region for the development and production of iron ore and it is becoming important as a future major supplier to Europe and China, being strategically located closer to these markets than other iron ore suppliers such as for example to Brazil or Australia. Falling shipping prices in addition to the evolution of markets towards more magnetite concentrates for pelletization are also making projects in the region more competitive. This study focuses on fresh magnetite deposits with weathered/oxidised haematite caps from Liberia and Cameroon which are parts of emerging iron ore provinces in West and Central Africa. These ores are primarily itabirites such as those in Brazil. An understanding of how the geology of the deposits correlates with the metallurgical characteristics (geometallurgy) is crucial to their successful development. A particular feature of these deposits is progressive weathering and alteration of the magnetite banded iron formations to maghemite, goethite and hematite assemblages and also strong stratigraphic and structural controls on the mineralization. It is also important to understand the elemental compositions and mineralogical relationships of the iron rich minerals with respect to deleterious elements such as phosphorus, aluminium, and silicon. Results from SEM/EDS, EPMA and XRD show no evidence of any iron silicate or carbonate minerals. The gangue minerals are quartz, apatite, calcite, epidote, alkali feldspar, pyroxene, amphibole and mica. Hematite and goethite in particular are interlocked with kaolinite, gibbsite and quartz; phosphorus is found in goethite. Kaolinite, gibbsite and micas are the main Al bearing phases whilst apatite and calcite are the main P and Ca bearing minerals. Field work is now planned to collect samples which are representative of the variability in the deposits and to map structural features. Stratigraphic controls based on a drill core database will also be studied. A protocol for quantitative mineral analysis using QEMSCAN® is being developed to generate the high volume of mineral data required for statistical validity and in conjunction with geochemical data and further physical lab tests, will aid production of a geometallurgical model for these deposits. The approach developed will help to improve characterisation and iron recovery, thereby adding value to the product and could be applicable to other similar deposits.

Multiple phases of fenitisation and REE-enrichment in fenites around carbonatites – implications for future exploration targets

Dowman, E^{1,3}, Wall, F.², Rankin, A.H.¹, Treloar., P¹

¹*Kingston University, Penryn Road, Kingston upon Thames, Surrey KT1 2EE*

²*Camborne School of Mines, University of Exeter, Cornwall Campus, Penryn, Cornwall, TR10 9EZ*

³*Department of Mineralogy, Natural History Museum, Cromwell Road, London SW7 5BD*

Carbonatites frequently host substantial concentrations of light rare earth elements (LREE) and most of the world's production of LREE minerals is currently extracted from carbonatite-related complexes, notably Bayan Obo. The REE are generally considered to be poorly mobile under many geochemical conditions and concentrations would therefore not be expected to be elevated in the alkali metasomatic aureoles, known as fenites, which commonly surround carbonatites.

A study of fenite rocks at two contrasting carbonatite complexes in Malawi, the world-class REE deposit at Kangankunde Hill and the apatite-pyrochlore (P-Nb) carbonatite at Chilwa Island, has investigated the spatial distribution of REE and associated elements in fenite.

Whole rock compositions were determined for three groups of fenite representing different degrees of alteration: a) brecciated rocks (most altered), b) syenite fenites and c) quartz fenites (least altered). The results show that REE are present throughout the fenitised zone at concentrations up to 1700 ppm.

At Kangankunde, the breccias show the highest level of REE. However, the distinction between syenite fenite and quartz fenite was not reflected in their REE profiles. Instead, two profiles with differing La:Nd ratios were revealed.

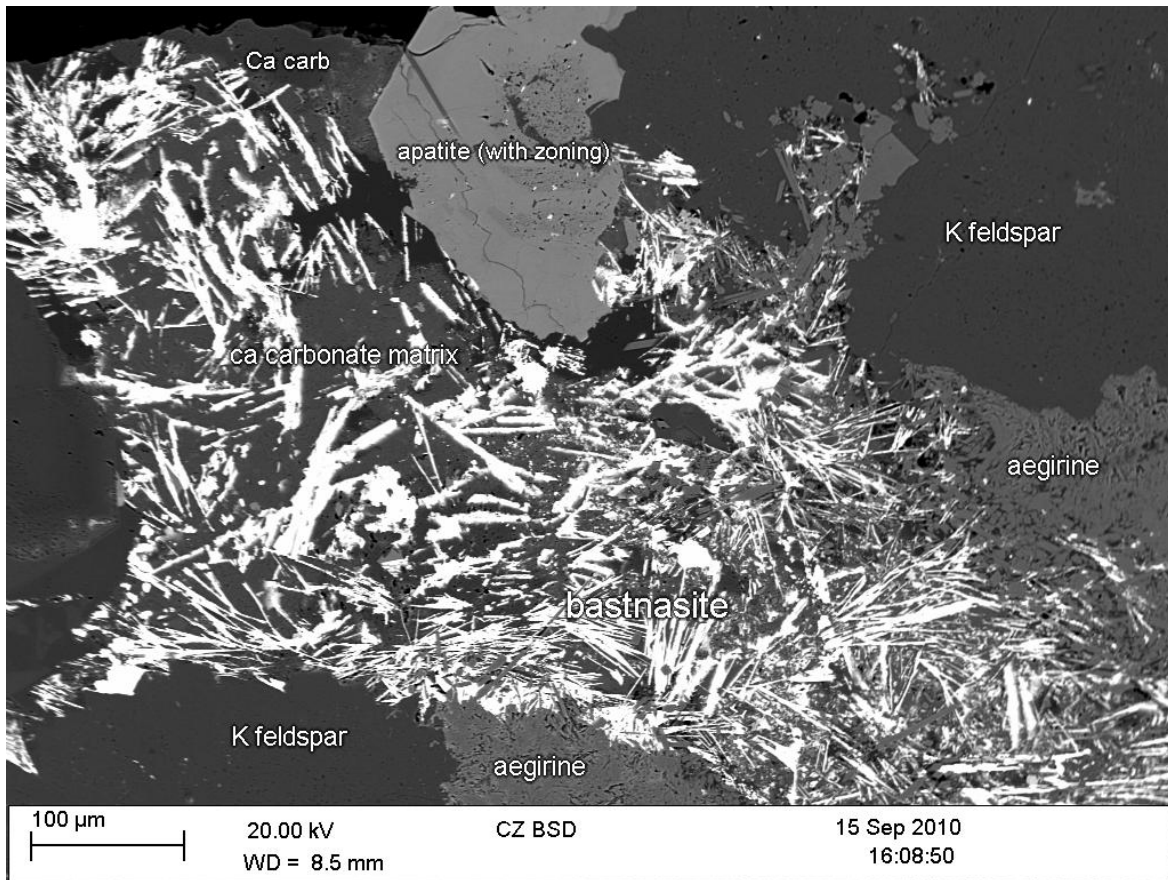


Figure 2 Backscatter image of REE mineralisation in quartz fenite at Kangankunde. *Bastnäs*ite-(Ce) and calcite are associated with an earlier fenite assemblage of apatite and aegirine.

Mineralogical and fluid inclusions studies show at least three phases of fenitising fluids. Apatite was formed in the first phase and subsequently resorbed by later fluids richer in REE. These fluids also invaded the separate potassic fenitisation phase. The fluid inclusion population is heterogeneous throughout the fenite rock, with inclusions rich in CO₂, water, daughter minerals, such as nahcolite and, occasionally, the REE-carbonate burbankite.

At Chilwa, levels of REEs are much lower. Syenite fenite and quartz fenite have similar REE profiles. A second group is composed of three of the least altered quartz fenites. The breccias have a REE profile totally dissimilar to that at Kangankunde, and a further rock, composed mainly of recrystallised quartz has the highest level of REE in the fenite.

Apatite at Chilwa is usually zoned and often contains grains of the REE- phosphate monazite, either within the apatite or as a bead-like formation around its rim. Resorbed apatite is present but less abundant than at Kangankunde. Fluid inclusions, as at Kangankunde, show highly heterogeneous compositions.

Even though the carbonatite complexes are small, the REEs are shown to be extensively mobilised into the fenite aureole up to a distance of at least 1 km, highlighting the importance of these aureoles as future exploration targets for low-grade, large-tonnage REE deposits.

This study highlights the importance of fenite aureoles surrounding REE-enriched alkali-carbonatite complexes as future exploration targets for low-grade, large-tonnage REE ore deposits.

Tectonic Setting of volcanic rocks hosting high sulfidation style gold mineralization in Sibutad, Zamboanga del Norte (Philippines) :Clues from Petrochemistry and $^{40}\text{Ar}/^{39}\text{Ar}$ dating

Jillian Aira S. Gabo¹, Akira Ima², Koichiro Watanabe¹, Anders Schersten³ and Laurence Page³

¹ *Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Fukuoka 819-0395, Japan*

² *Department of Earth Science and Technology, Faculty of Engineering and Resource Science, Akita University, 1-1 Tegata-gakuen, Akita, Japan*

³ *Department of Earth and Ecosystem Sciences, Lund University, Solvegatan 12, Lund 223 62, Sweden*

The Sibutad epithermal gold deposit in Zamboanga del Norte, Mindanao Island is a structurally-controlled mineralization that is hosted by a sequence of volcanic rocks. The mineralization occurs as hydrothermal breccia bodies in quartz veins. These veins that trend NW-SE and NNE-SSW are observed in flow deposits of aphanitic andesite and porphyritic andesite. These andesitic units are interstratified with tuff and tuff breccias that overlie a thick sequence of volcanoclastic rocks. Both volcanic sequences are intruded by dikes of andesite porphyry, which possibly caused the brecciation that led to mineralization. The surface exposures at or near the identified gold prospects in Sibutad exhibit pervasive hydrothermal alteration and silicification.

Representative samples of the host volcanic rocks were analysed for mineralogy (petrography) major and trace element geochemistry (X-ray fluorescence analysis and inductively-coupled plasma mass spectrometry), and geochronology ($^{40}\text{Ar}/^{39}\text{Ar}$ dating). Results of the $^{40}\text{Ar}/^{39}\text{Ar}$ dating revealed for the first time the age of magmatism in Sibutad as Late Miocene, and not Pliocene to Recent as was previously assumed. The whole-rock composition of representative samples indicated that they consistently show a high-K calc-alkaline signature and exhibit an affinity to an island arc tectonic setting. Furthermore, the trace element composition of the volcanic rocks point to a subduction-related setting. Results of the study indicate that the volcanic rocks in Sibutad were formed from the subduction of the Negros Trench during the Miocene. The volcanic host rocks in Sibutad can be considered as the southern terminus of the Miocene Negros calc-alkaline volcanic arc.

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With over 12,000 clients in more than 90 countries and 20 offices located in the world's major mineral producing capitals, MICROMINE is the leading provider of intuitive software solutions that deliver operational efficiencies through every step of the mining and exploration process. MICROMINE provides you with local support and services in your language and your time zone.

Mineral Deposits Studies Group

www.geolsoc.org.uk/mdsg

The purpose of the group is to study mineral deposits, mineralization processes and other geological topics related to mineralization. It does this by arranging meetings, and by organising visits to sites of scientific interest to its members.

Rio Tinto

www.riotinto.com

Scotgold Resources Limited

www.scotgoldresources.com.au

Society of Economic Geologists

www.segweb.org

Volta Resources

www.voltaresources.com

Burlington House Fire Safety Information

If you hear the Alarm

Alarm Bells are situated throughout the building and will ring continuously for an evacuation. Do not stop to collect your personal belongings.

Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshall on that floor.

Fire Exits from the Geological Society Conference Rooms

Lower Library:

Exit via main reception onto Piccadilly, or via staff entrance onto the courtyard.

Lecture Theatre

Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the staff entrance.

Main Piccadilly Entrance

Straight out door and walk around to the Courtyard.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS.**

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid

All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

Facilities

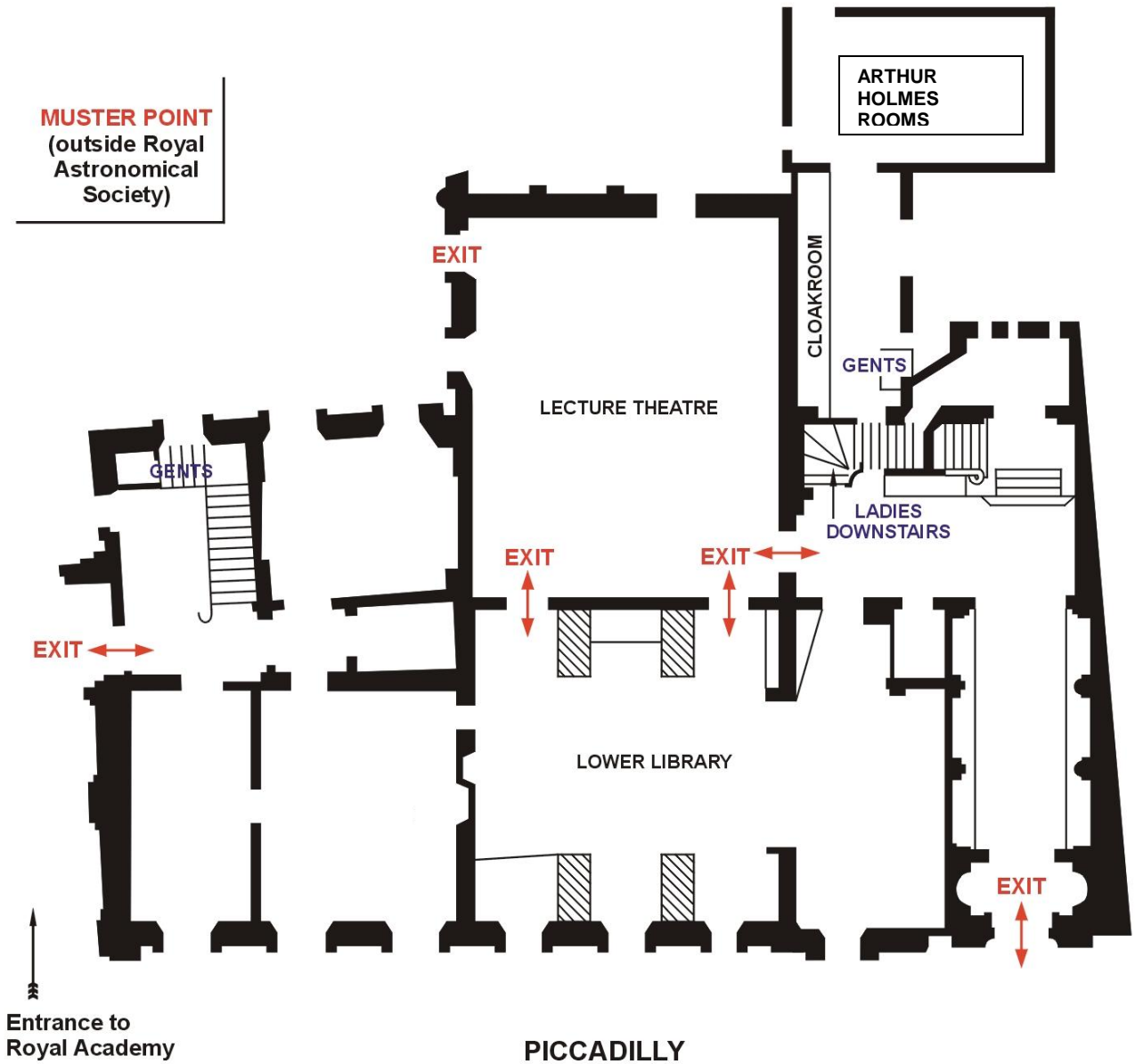
The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.

Ground Floor Plan of the Geological Society, Burlington House, Piccadilly

ROYAL ACADEMY
COURTYARD



Map to the Royal Society

Address

6-9 Carlton House Terrace
London SW1Y 5AG

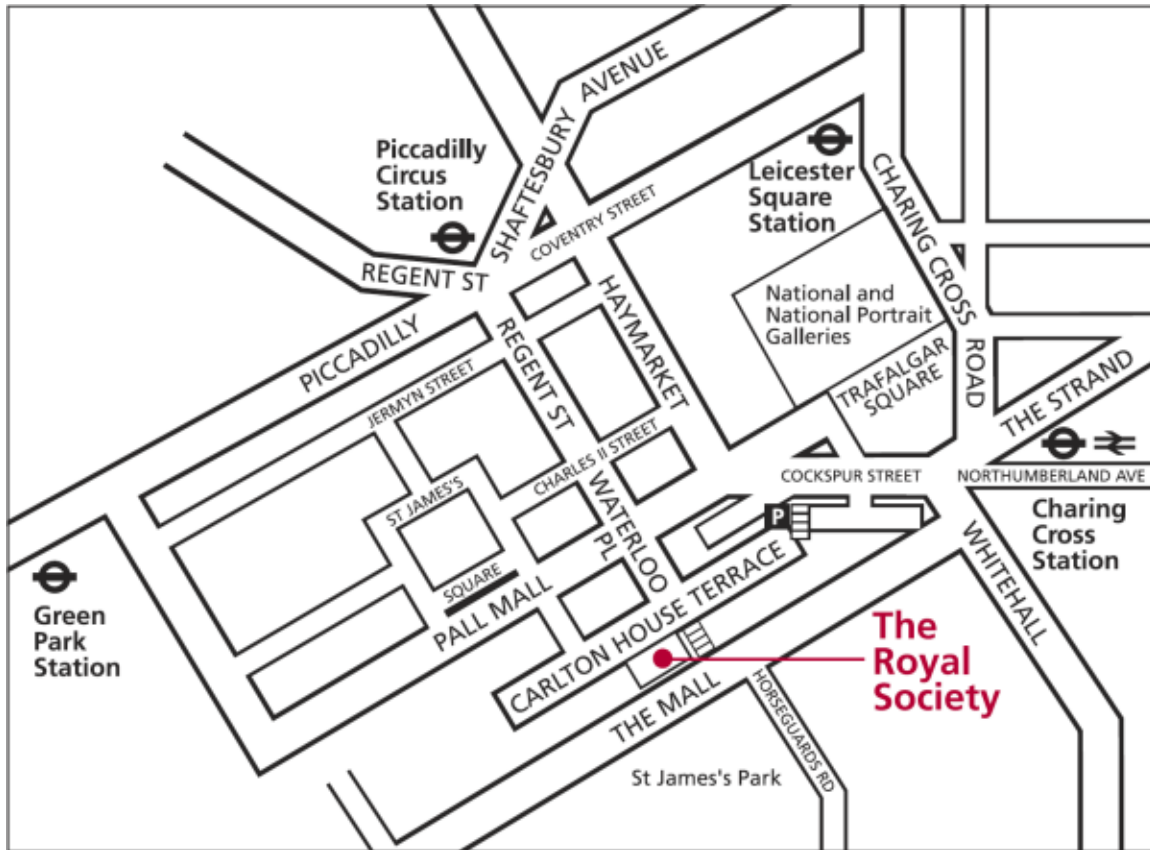
Telephone

020 7451 2500

Directions

Our main offices are located on Carlton House Terrace, just off Waterloo Place, between Pall Mall and The Mall.

It is five minutes walk to Piccadilly Circus underground station and ten minutes to Charing Cross mainline and underground stations, or 20 minutes through St James's Park to Victoria. Trafalgar Square, and all bus services through it, are also very close.



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