Gold in SW Ghana

The Subika Gold Deposit, Sefwi Belt, Ghana

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Introduction

The world-class 8 million ounce Subika gold deposit in Ghana (Fig. 1) is currently owned and mined by Newmont Ghana. The Subika deposit is located on the western margin of the Paleoproterozoic Sefwi-Bibiani Greenstone belt of the Paleo-Proterozoic Man Shield, West Africa (Fig. 1). The most common host rocks for gold mineralisation within the belt are volcaniclastic units intercalated with volcanic units. The Subika deposit is a brittle fracture controlled ore body which is the largest in the Sefwi-Bibiani Greenstone belt (Fig. 2). The deposit is atypical because it is completely hosted within a granitoid, and is not located on a major regional shear or fault zone. The possible genetic role of the granitoids in gold mineralisation, and the control on the location of the deposit within the granitoid are not constrained. What is lacking is systematic documentation of the structural and alteration paragenesis of major deposits within the context of the evolution of the host terrane. This article undertakes such a study and presents a new structural model, integrated with alteration, for the evolution of the Subika deposit. This work was part of a Masters thesis by research and course work completed by Emmanuel Baah-Danso (Baah-Danso, 2011). The project aimed to aid both near mine and regional exploration targeting by placing this

Figure 1. Regional geology of southwest Ghana. Subika Mine is shown (modified after Allibone et al., 2002a).

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From the Director

Searching the Deep Earth

Looking at economic forecasts both at home and abroad, there appears to be a wave of demand for discovery of new resources that has yet to break over our industry. This message was brought home by forecasts of metal demand versus supply presented at the world’s premier mining conference PDAC in Toronto in March, which predicted undersupply for almost every commodity. Although many people focus on extraction technology to get more out of our existing resources and make marginal deposits economic, this is unlikely to meet future demand needs. In fact, this approach may be operating under a false economy as increasing costs of material, human and energy resources erode any incremental gains. The focus needs to be on quality resources, and in particular the discovery and delineation of new high quality resources to ensure supply security.

Thought leaders in the nation appear to be responding to this challenge: in August 2010 the Australian Academy of Science convened a Theo Murphy Think Tank on Searching the Deep Earth. The premise was to engage the top young minds in the nation on the challenge of what science needed to be undertaken to enable the discovery of future mineral resources. I am happy to report that CET was extremely well represented at this, with 6 CET staff of ca. 60 in attendance.

The result of the think tank was a document on Searching the Deep Earth: The Future of Australian Resource Discovery and Utilisation (full document available at www.science.org.au/events/thinktank/thinktank2010/index.html). In this document, six key initiatives are outlined: (1) a national cover map, (2) a national map of the deep crust and upper mantle, (3) a national distal footprints program, (4) a national 4D metallogenic map, (5) a national exploration research network, and (6) an education and technology transfer program. This document has been endorsed at the highest level by Federal Minister for Resources and Energy the Honourable Mr. Martin Ferguson AM MP, who stated, “From my perspective, as Minister for Resources and Energy, the Academy could not have chosen a more timely or important subject as the ninth topic in the Think Tank series than the future of resource discovery and utilisation in Australia.”

“The proposed road map you have put together is ambitious and a welcome contribution in terms of future policy direction and development.”

CET has a business and research model perfectly aligned with these research initiatives. These range from fundamental research in our national Centre of Excellence for Core to Crust Fluid Systems (initiative 2), to our mine- to camp-scale research projects on the footprints of gold and iron and NiS deposits (initiative 3), to our terrane-scale 4D modelling and mineral prospectivity mapping projects undertaken within Australia and around the world (initiative 4).

The other key aspect of the road map is collaboration for scientific breakthrough. No longer can one individual research group or centre provide all of the skill sets required to provide the scientific solutions the exploration industry requires. Therefore, CET has adopted a philosophy of identifying and engaging with thought leaders from around the planet and from a variety of subdisciplines…bringing the A-team to bear on solving your issues.

The final aspect of the new roadmap is technology transfer. In this regard, the CET, through its collaboration through the Minerals Council of Australia, Curtin University, James Cook University, The University of Tasmania and the University of Western Australia is an active participant in the National Mineral Geoscience Honours and Mineral Geoscience Masters Programs. As Chairman for the implementation committee for the National Mineral Geosciences Masters program, I can assure you that this program incorporates the latest in research results applied to the mineral industry, is well accepted by participants, and is focussed on training the leaders of tomorrow’s minerals industry. Our vision is to have this program perceived as the Harvard Business School equivalent in the global mineral resources industry in terms of training and research.

The CET is a lead organisation in a working committee looking at implementation of the Think Tank outcomes. I hope that all of our Corporate Members and research partners also will embrace this vision, and help us to achieve it.

Professor T. Campbell McCuaig
Director
granitoid hosted deposit into structural context with other greenstone and sediment hosted deposits within the Sefwi Belt.

**Regional Geological Context**

Ghana is located in the West African sub-region, and is predominantly underlain by Paleo-Proterozoic rocks (Birimian, ca. 2.2-2.1 Ga) of the Man Shield of the West African Craton, and a much younger over-lying sedimentary basin (the Volta Basin; Fig. 1). It is the Birimian rocks which are very well endowed with gold, with >170 Moz endowment discovered to date within Ghana. The most extensive and important units that occur in the Birimian of SW Ghana comprise: 1) volcanic rocks of the Paleo-Proterozoic Birimian Supergroup and, 2) fluvial sediments termed the Tarkwaian rocks (Leube et al., 1990). The Birimian Supergroup within Ghana is divided into two lithostratigraphic divisions (Leube et al., 1990): 1)‘basins’ which are regionally extensive metamorphosed sedimentary rocks dominated by thick turbidite packages, carbonaceous shales and rare chert, and 2)‘belts’, which are comprised of metamorphosed basaltic and andesitic lavas, felsic volcanics and rare rhyolitic and dacitic lavas (Leube et al., 1990). Six metavolcanic belts have been identified within the Birimian of Ghana. These are named the Kibi-Winneba, Ashanti, Sefwi-Bibiani, Bui, Bole-Navrongo and Lawra Belts. These belts are separated from each other by the intervening sedimentary basins (Leube et al., 1990; Fig. 1).
The Tarkwaian rocks consist of coarse clastic sedimentary rocks that include conglomerates, quartzites, sandstones and subordinate shale (e.g., Tunks et al., 2004). They are spatially restricted to the belts where they unconformably overlie volcanic rocks of the Birimian (Davis et al., 1994). Dating completed by Davis et al. (1994), and more recent work by Pigois et al. (2003), has constrained the maximum age of sedimentation of the Tarkwaian to 2133±4 Ma.

Two distinct granitic suites have intruded the Birimian Supergroup: the Dixcove and Cape Coast suites. The Dixcove granitoids comprise granodiorite to monzonite and syenite, predominantly intrude the belts, and are dated at 2172±1.4 Ma in the Ashanti Belt (Hirdes et al., 1992). The Cape Coast-type granitoids are dominantly granodiorites that have predominantly intruded the basins and are dated between 2104±2 and 2123±3 Ma in the Kumasi Basin (Oberthur et al., 1998).

Three key tectonic events have been described in Ghana (e.g. Milesi et al., 1991). The rocks have undergone regional metamorphism up to amphibolite grade in the sedimentary and volcano-sedimentary units. The majority of the world class deposits in Ghana are located along major regional fault zones (e.g. Obuasi; Allibone et al., 2002a). A generalised event history that follows Allibone et al., (2002a,b) and Feybesse et al., (2006) has three major contractional or strike-slip events (although slight variations in sub-divisions occur between different workers). The first is a NW-SE shortening event (termed D1 compression), that produced a penetrative foliation S1 and metamorphism. A second event (D2), related to NW-SE shortening, produced northeast-striking thrust faults and is related to the main gold mineralisation phase within the belt with sinistral-slip kinematics linked to lode development (e.g., Allibone et al., 2002a). These early events were overprinted by D3 dextral strike-slip faulting.

**Local Geological Context**

The Subika deposit is located in the Sefwi-Bibiani belt, which comprises several narrow north-east trending volcanic and volcaniclastic rocks, and is bounded to the northwest by the Sunyani Basin and to the southeast by the Kumasi Basin (Hirdes et al., 1992; Fig. 1). The known deposits are considered to be typical of mesothermal vein-style, or orogenic-style gold deposits (Groves et al., 2003). The gold mineralisation is hosted along a regional thrust fault, the Kenyase Thrust, interpreted from aeromagnetic data and juxtaposition of lithologies. This thrust has a NE-strike and spans the entire stretch of the Sefwi-Bibiani belt (Fig 1), separating rocks of the Sunyani sedimentary basin to the west, and rocks of the Sefwi volcanic belt to the east. The belt margin was intruded by granitoids that form elongated bodies parallel to the regional strike of the fault. In many

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**Figure 4.** Pit map showing relationship between Gabbro, MFZ and cross cutting Fault (Victor Fault). Note apparent sinistral (left-lateral) off set of MFZ across Victor Fault.

**Figure 5.** Top figure. Cross section view showing main faults and also alteration types. Note normal offset of the MFZ on the cross-cutting faults. Lower figure. Long section of the MFZ with the gold (modelled in Leapfrog software). Red is 3g/t Green is 0.5g/t. The intersections of the cross cutting faults are yellow dashed lines. The intersection of the main Gabbro body is also marked (solid purple line).
areas, the contact between the Sunyani sedimentary basin and granitoids delineates the Kenyase Thrust, with the granitoid occurring in the hangingwall of the thrust at several gold deposits (e.g., Apensu and Awonsu).

The intrusive rocks that host the Subika deposit, and are the locally preferred host rock for mineralisation within the Kenyase Thrust (e.g. Apensu, Awonsu and Amoma deposits), have a large range in composition. At Subika, the intrusions are dominantly diorite ± gabbro. At the thrust margin, intrusions hosting the Apensu, Awonsu and Amoma mineralization are more felsic granodiorite to monzonitic in composition. These host rocks are inferred to be part of the Dixcove Suite. The geometry of the intrusive rocks ranges from 1 km to greater than 8 kms in diameter, and they contain locally large relict blocks or xenoliths of Birimian mafic volcanic and volcano-sedimentary rocks. The last magmatic phases include cream-coloured aplite dykes that are up to 50 cm wide.

**Geometry and Character of Mineralisation at the Subika Deposit**

The Subika ore body is hosted entirely within a diorite intrusion which has been intruded by gabbro dykes and deformed. The ore body has two main structural features. The NE-trending SE-dipping Magic Fracture Zone (MFZ), which is the main gold lode, is a 5 to 40 metre wide mineralised brittle fracture zone marked by a stockwork of quartz-carbonate veinlets (Fig. 3, 4, 5). A secondary structural control is a set of NE-trending and shallowly to moderately dipping faults, with moderate to minor mineralisation, which cross cuts and offsets the MFZ (The Victor, Kalbaas, and Hatch Faults; Fig. 4, 5).

Hydrothermal alteration at the Subika Deposit has been characterised and logged as weak (Alt 1), moderate (Alt 2), or strong (Alt 3), and is spatially related to the structural features described above (Figs. 4, 5).

Figure 6. Summary of stereonet plots of structural data used to constrain structural model. Stereonets are equal area projection. Reading in brackets is the mean structural orientation.

Figure 7. Early foliation within intrusive rocks. a) Early S1 foliation defined by flattened mafic clasts. b) Early S1 foliation defined by alignment of plagioclase and mica. c) Shearing along NE-trending dyke - this is associated with a localised S2 cleavage. Early S1 foliation is also shown.
Alteration 1 comprises chlorite (replacing hornblende) and sericite (replacing plagioclase) occurring as a broad halo around the MFZ and extending out into the cross cutting Victor and Kalbaas Faults (Fig. 5). Alteration 2 is identified by the first appearance of massive silica, albite and sericite patches spatially associated with small brittle shears and narrow quartz + iron carbonate veinlets, generally containing >15% pyrite and >2 g/t Au. Remnant chlorite is locally present, but the majority is altered to white mica. (Fig. 5). Alteration 3 consists of pervasive iron carbonate and quartz veinlets with quartz-carbonate-albite-pyrite selvages completely replacing the primary host rock mineralogy, is restricted to the MFZ, and normally carries >2 g/t gold mineralisation.

Field analysis of the Subika Deposit

Geometry of Intrusive Units

The intrusive body at Subika is mainly dioritic in composition, with cross-cutting gabbro intrusions within the diorite which generally have a east-west trend (070/75S; Fig. 4, 6). The gabbro is cross cut by the Subika mineralization (MFZ). However, there is a close spatial association with the location of the gabbro units and high grade mineralisation along the MFZ structure (Long section, Fig. 5). The diorite-gabbro contact shows a strong sub-vertical magmatic foliation striking 070, and in the mapping areas this cleavage is parallel to the intrusive contacts of the gabbro. This foliation is defined by the preferred orientation of mafic minerals (hornblende) and plagioclase feldspars.

Aplite dykes and pre-mineralization veins up to 50 cm wide occur throughout the diorite - the timing between these dykes and the gabbro intrusives was not constrained. The boundaries of these features are sharp, but have no observable alteration minerals around them. The pre-mineralization veins comprise mainly quartz and are widespread within the mapped area. These features act as marker layers for determining kinematics of later deformation associated with mineralisation.

The pre-mineralisation veins clearly over print the aplite dykes, but have the same trend as the dykes (Fig. 6). Field measurements of the pre-mineralization veins show a dominant E- to ENE-trend with a steep dip towards the south (075/86S; Fig. 6), similar to the dominant orientation of the dykes (074/82S). Aside from the general trend of the dykes, a few dyke sets have a distinct trend (040-050) which is parallel to the MFZ.

Pre-mineralization foliations

Apart from the magmatic foliation parallel to the gabbros, two sets of foliation are observed in the host intrusions, defined by deformed plagioclase phenocrysts or flattened mafic enclaves (Figs. 7a,b): (1) a low angle foliation termed S1, and (2) a steeper dipping foliation, which over prints the S1 foliation, termed S2. The S1 is penetrative (Fig. 7a, 7b) throughout the region, and has been recognised at both the Subika and Apensu deposits. The S1 foliation over prints the pre-mineralization veins and dykes and has a mean orientation of 137/22W (Fig. 6). In many areas, mafic enclaves are elongate parallel to S1(Fig. 7a). The S2 foliation has a NE-SW.
trend with a steep dip towards the west (224/79W). The S2 fabric is strongly developed along aplite dyke margins which trend NE-SW (040-050) (Fig. 7c).

**Early ductile shearing and low grade Au mineralisation**

The Victor and Kalbaas Faults are strong ductile shears with a NE/SW to almost E-W trend with moderate to shallow dips towards the south (Fig. 6). These faults show a cross cutting relationship to the MFZ in a left-lateral sense in map view and a normal displacement in section (Figs. 4, 5). The Victor Fault's strike length covers the entire deposit (1 km) and has a mapped width of 4 to 6 m.

A stretching lineation is consistently developed within the shear zones, identified by chlorite mineral growth along fault planes and/or chlorite forming pressure shadows around clasts of plagioclase minerals, with a shallow plunge towards the SSE (Fig. 6). S-C fabrics and fault drag within the faults show clear evidence for reverse movement (lineations indicate top-to-the-NNW, Fig. 9). However, in contrast to this, dyke offsets below the Kalbaas Fault show evidence for normal displacement of pre-mineralization veins (see blue kinematic markers in Fig. 9), indicating multiple movement events on the faults.

Gold related alteration minerals observed on these faults are mainly pyrite-chlorite-carbonate, generally associated with weak mineralization (0.5-1.0 g/t), which is predominantly type 1 and 2 alteration defining the ductile fabrics. However, in some areas there are brittle shears along these faults with strong sericite-pyrite-carbonate-quartz alteration (high grade type 3 alteration). This over prints the alteration associated with the ductile shears, and is associated with the event discussed below.

**Brittle deformation and high grade Au mineralization**

The main shear zone that hosts the Subika mineralization is a steeply dipping, NE-SW trending (044/61SE) brittle shear termed the Magic Fracture Zone (MFZ) (Figs. 3, 4, 5). The MFZ occurs parallel to a NE-trending dyke that has a trend distinct to the dominant ENE-trend for this aplitic dyke set (Fig. 6, 10). The mineralisation occurs as stacked vein arrays within the MFZ, comprising quartz-carbonate veins varying from 5 mm to 20 mm in width with type 3 sericite-pyrite-carbonate-quartz alteration. These veins are present as single veins, branching veins and as vein networks, commonly with large euhedral quartz textures and lacking in fibrous vein textures. The bulk of the mineralised
veins are spatially confined to the MFZ and grade into strongly mineralised breccia bodies (Fig. 10). The mean vein orientation within the MFZ is north-easterly with a south dip (052/58) (Fig 6). These mineralized veins are sub-parallel to the MFZ. Dilational jogs and quartz breccias within the MFZ indicate a dextral-normal movement sense (Fig. 11). The mineralized veins also offset pre-mineralization veins that give a normal to dextral-normal movement sense (Fig. 11). Gabbro-diorite contacts are reactivated with normal movement senses during high grade mineralisation (Fig. 12).

The high-grade type 3 Alteration over prints the type 1 alteration associated with chlorite (Fig. 13). There is also extensive development of high grade gold related alteration along the early low angle S1 foliation (Fig. 13).

**Subika ore shoot controls**

The grade distribution within the MFZ structure has been visualized as a surface produced by making a wire frame of the mid-point of the Alteration 3 envelop. This highlights key features relating to the ore shoot geometry and grade distribution and has been presented as a long section (Fig. 5).

The ore shoot geometry shows a spatial relationship of gold grades to the spacing of the cross-cutting faults with a left-lateral (sinistral) movement (in plane-view) and normal offsets of ore blocks (in section view). This movement sense is an important feature in ore shoot targeting. Whilst gold mineralisation occurs along these cross faults (note extensive alteration type 1 in Fig 5), in many cases these faults actually correlate with lower grade mineralisation on the long section (e.g. Hatch Fault; Fig. 5).

One marked feature is that a large component of the grade has a lower angle plunge (black arrows in Fig. 5) than the intersection of the cross faults. The only mappable feature in the deposit that correlates with this trend is the intersection direction of the MFZ structure and the early S1 foliation planes. This suggests that the early S1 foliation may be a control on ore shoot development within the deposit.

Localised strike changes have also been observed along the MFZ structure. These strike changes occur at the intersection of the gabbroic intrusive and the MFZ structure, and correspond to high-grade gold and localized damage zones possibly related to dilation. The steeply ENE plunging intersection of the MFZ structure and the gabbroic enclaves (stereonet and purple line on long section, Fig. 5) may have been reactivated during the dextral-slip event synchronous with the main mineralising event. Significant gold grades do occur at the contacts of these intersections.

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**Figure 11.** Magic Fracture Zone (MFZ) at the northern end of Subika Pit. Middle photograph show layer-like zone of mineralized veins emerging from the MFZ with strike length and down dip continuity into the wall rocks. Note dextral-normal offset of pre-mineralization veins along MFZ parallel brittle shears.

**Figure 12.** Dilation jog with mineralized veins along gabbro-diorite contact indicating normal movement during high-grade gold mineralisation with type 3 alteration. (note offset dykes and dilational jog).
However, within the MFZ, the gabbro appears as a dead zone (as indicated on Fig. 5). This is because the gabbro is a poor host rock type.

Discussion

Based upon observed field relationships and kinematic indicators, the mineralization process at the Subika deposit can be summarized into four main stages (Fig. 14).

Stage one is the development of the E-W trending, gabbros (Fig. 14a), pre-mineralization veins and aplite dykes within the intrusive unit (i.e. the main granitoid) as a result of NW-SE extension (Fig. 14b). A few dykes have a distinct trend 040-050, which is similar to the trend of the MFZ, and may imply the structure upon which the Subika mineralization formed at this stage (termed the proto-MFZ in Fig. 14a, 14b). The gabbro intrusives are inferred to delineate a zone of earlier architecture that may have been a zone that focussed later hydrothermal fluids (Fig. 14a). The cross cutting relationship of the pre-mineralization veins and dykes implies a younger generation of the pre-mineralization veins to the dykes. However, their similar structural orientation suggests that they were formed under the same event. This event probably corresponds to the Eburnean I orogeny as described by Allibone et al., (2002a, b), which is responsible for the belt architecture due to a regional NW-SE extension within the basin.

Stage two is the development of an early, shallow SW-dipping foliation (Fig. 14c). This fabric over prints the aplite dykes and pre-mineralisation veins (Fig. 8) and it predates the NW-SE compression that dominates regional SW Ghana.

The steeper dipping S2 foliations (Fig. 14c) developed under the effect of almost WNW-ESE compression. The effect is also seen in the buckling of the pre-mineralisation vein and dykes observed during mapping.

The next stage in the mineralisation process is the development of the ductile cross cutting faults (Fig. 14d). The S-C fabrics and structures in the ductile shears indicate these are thrust faults and developed under the effect of NW-SE shortening. Some movement and/or reactivation of the MFZ is believed to have occurred during this stage. This is inferred to have focussed along the mylonitic S2 fabric developed along the 040-050 trending. This phase is only associated with weak gold (0.5-1.0 g/t) related alteration (commonly pyrite-chlorite-carbonate), which is typical of the ductile shears observed at Subika deposit. These ductile shears trend NE to almost E-W with shallow to moderate dips towards the south.

Finally, syn- to post-mineralization deformation (Fig. 14e) is characterized deformation and associated alteration during NNW-SSE extension and ENE-WSW compression. This is marked by quartz-carbonate breccia, dilational jogs, and normal to dextral-normal offsets of pre-mineralization veins within the belt.
The high-grade mineralised veins are sub-parallel to the MFZ, and are not sub-horizontal veins typical of fault-valve systems, such as those described for orogenic gold systems like those in the Lachlan Fold Belt in Central Victoria-Australia (Cox et al., 1991; Cox, 1995), the Revenge gold mine, Western Australia (Nguyen et al., 1998) and that of Damang gold mine, Ghana (Tunks et al., 2004). Furthermore, the lack of evidence for crack-seal veining and micro-textures, such as fibrous and laminated quartz, suggests that the Subika deposit was not formed under multiple fluid pulses (or at least not multiple fracture events to make each vein), rather a single event is inferred to be related to the formation of the lode gold as evident in the micro-fracturing textures described for quartz. This indicates the Subika deposit style is different in some aspects to other orogenic gold deposits (cf. Cox, 1995 and Nguyen et al., 1998).

The development of high grade ore shoots at zones of strike changes in the orientation of the MFZ is interpreted to be controlled by gabbric intrusive units intersecting the MFZ (this gabbro unit is mapped in Fig. 4; and its projection is marked on the long section in Fig. 5). This is inferred to have created localised zones for dilational jogs producing a discrete zone of mineralisation along the MFZ (the structure projects out of the pit in both directions but is not strongly mineralized). These intersection zones may have increased the permeability of the host rock by providing large surface areas and by increasing fracture density in a localized area to provide a zone where fluids of slightly different temperature, density, pressure and chemistry may mix. This phenomenon may be used in predicting other sites for gold mineralization within the granitoids in the area, i.e. the Subika deposit is located at the intersection of the gabbro trends with the MFZ.

Whilst not covered in this paper, similar kinematic indicators and textural observations have been made at the Apensu deposit (Baah-Danso, 2011) and indicate that the structural timing is coeval at the two deposits and other deposits alike in the region. The main high-grade gold event at Apensu is linked to brittle deformation under NNW-SSE extension, with an initial phase of NW-SE compression resulting in ductile shearing and thrusting (e.g. thrust movement on the Kenyase Thrust) (Baah-Danso, 2011).

Figure 14. Model for Subika gold mineralization. (a) Emplacement of Gabbro intrusives. (b) Emplacement of pre-mineralization veins and dykes within the intrusive due to NW-SE extension, belt architecture. (c) E-W compression producing early foliation (S2 fabrics) and micro-folds. The timing of the S1 foliation prior to this is is poorly constrained. (d) Development of thrust faulting with pyrite-chlorite-carbonate type 1 alteration (low grade gold) associated with NW-SE shortening. (e) Main mineralising event, NNW-SSE extension and ENE-WSW compression with pyrite-carbonate-quartz type 3 alteration and associated dextral-normal breccias along MFZ. Cross cutting faults (e.g., Victor Fault) and gabbro-diorite contacts are reactivated as normal faults.

MFZ. Pre-existing S1 and S2 foliations are inferred to have acted as permeability pathways allowing the infiltration of gold-bearing fluids into the wall rock within the MFZ. The dextral component to the movement along NE-trending structures (i.e. the MFZ) is distinct to other gold deposits in Ghana with the dominant phase of gold linked to sinistral-oblique slip (e.g. Bogoso; Allibone et al., 2002b).

The mineralisation during NNW-SSE extension and ENE-WSW compression is inferred to have been synchronous with normal reactivation of the cross faults (e.g. Kalbaas and Victor Faults) producing the observed normal offsets of the MFZ across these features (Fig. 5). This interpretation explains the contradiction of thrust-related S-C fabrics associated with the cross faults, but with marker units preserving normal offsets (Fig. 10). Gold related alteration observed around the veins is pyrite-carbonate-quartz, which corresponds to high-grade ore (>5 g/t) in the deposit.
Conclusions

The conclusions of this study are:

— Four main stages of deformation history are recognised for the mineralisation process at the Subika deposit based upon field relationships.

— Two mineralisation events can be clearly mapped within the deposit, an early low-grade mineralisation associated with ductile deformation, thrusting and NE-SW compression, followed by brittle stockwork veining associated with dextral wrench tectonics under approximately ENE-WSW shortening.

— The main mineralizing phase is influenced by a single deformation event related to NNW-SSE extension and ENE-WSW compression at the Subika deposit.

— High-grade ore shoots are controlled via fluid infiltration along early low angle S1 foliations and by the intersections of the gabbro intrusives and the MFZ (that may reflect earlier magmatic architecture that focussed later hydrothermal fluids).

— Multiple gold events have been identified with different kinematics and alteration. This should be expected in Birimian deposits, and careful documentation of these will assist in local oreshoot delineation as well as regional mineral systems understanding for targeting.

Acknowledgements

We gratefully acknowledge Newmont Ghana Gold Limited for financial support in undertaking this study.

Emeritus Professor David Groves receives highest honour

CET is extremely proud to learn that the Winner of the 2011 SGA Newmont Gold medal is Emeritus Professor David Groves.

The SGA-Newmont Gold Medal is the highest honour bestowed by the Society for Geology Applied to Mineral Deposits (SGA), and recognises the career of the awardee involving unusually original work in the mineral deposit sector. Award of the Medal is based upon career accomplishments, including published scientific research; leadership, both in research and in industry; success in exploration or mining geology; and service to SGA and like organisations. The award covers all aspects of research applied to mineral deposits, from field geology and mineral exploration, through development of analytical techniques, ore system models and metallogeny, and to the management of research and exploration projects and institutions.

The SGA is one of the two premier global professional organisations for economic geologists and the minerals industry, the other being the SEG (Society of Economic Geologists).

The award of the SGA Newmont Gold Medal follows on from David’s receipt of the SEG Penrose Gold Medal, the highest honour bestowed by that organisation. David is thus the only person to have served as President of both of these societies, and the first to be awarded both of these Societies’ highest honours.

These accolades are a fitting tribute to David’s distinguished career, which has profoundly impacted on the science of Economic Geology and the Minerals Industry. This impact is seen not only in the large body of leading research he and collaborators have undertaken over 4 decades. It is, in my opinion, most profoundly seen in the long list of industry leaders that have been trained by David. It was David’s drive, vision and enthusiasm that saw the establishment of a leading and globally recognised Centre of Excellence in economic geology and minerals geoscience research at UWA, which now continues as the CET.

We offer our heartfelt congratulations to David for his receipt of this award, and our appreciation for his (continuing!) tireless commitment to the profession of economic geology.
This two-day, hands-on, Excel-based course focuses on the principles of Discounted Cash Flow (DCF) modelling and financial evaluation of investments in mining projects at the conceptual to pre-feasibility stage. Ideal for professionals in the mineral exploration, mining and securities industries.

**Course Overview**
This course provides an understanding of the fundamental principles and concepts of finance and project evaluation as applied to investment decisions in the resources sector.

It first considers the nature of financial accounting statements and their relationship to a firm's cash flows. Particular focus will be placed on the nature of the mining industry assets, their effective lives and depreciation and on how these affect the taxation of mining-derived income.

It then progresses from simple discounted cash flow (DCF) models constructed under assumption of certainty and 100% equity funding to the construction of the financial model of a more realistic mining project.

The course finally considers the role and related leverage benefits and risks of using debt in funding mineral projects and how to include borrowing in a DCF model.

**Who Should Attend**
This course is an ideal introduction to fundamental project modelling and financial evaluation methodologies for professionals in the mineral exploration, mining and securities industries, whose task is to evaluate investment opportunities in resources projects.

**Key Requirements**
At the end of the course participants will have gained some familiarity with:

- the nature of financial accounting statements and their relationship to a firm's cash flows.
- the difference between recurrent and capital expenditure, assets depreciation and related tax implications.
- how to construct the discounted cash flow (DCF) model of a mining project and evaluate it using traditional DCF criteria of value, i.e. net present value (NPV), internal rate of return (IRR), payback period etc.
- the nature and role of debt in funding resources projects.

**Registration**
The cost of the course is $1440 for two days per participant (GST included) with a 30% discount for CET Corporate Members. The venue is Robert Street Building UWA (Resource Room G03), Fairway Entrance 1, Crawley WA 6009.

For more information contact Cindi Dunjey, cindi.dunjey@uwa.edu.au or on 08 6488 2640.

EXPLORATION TARGETING

Minerals Geoscience Masters Course

This course focuses on identifying the challenges in predicting the location of mineralisation at a variety of scales using both empirical and conceptual techniques; how to translate an understanding of mineral systems into exploration targeting models; and how to collate and visualize available geoscience data sets to generate and rank targets from mine to regional scale using computer-based methods.

Topics include the business of exploration targeting; remote and proximal sensing; applied geophysics in exploration targeting; creating targeting models from mineral system models, generating and ranking of targets; an introduction to Geographic Information Systems (GIS-based prospectivity analysis) (creation of derived GIS layers to represent exploration criteria; spatial data analysis to quantitatively test exploration criteria; methods to combine data sets into mineral prospectivity maps weights of evidence, fuzzy logic and neural networks); creation of 3D models from the integration of numerous geoscience data sets and then use in targeting. This course is NOT a how-to-use software instruction but instead focuses on practical application of these technologies in mineral exploration. The participants will emerge with a solid understanding of exploration targeting and the advantages and pitfalls of the various technologies available. All industry (not for award) participants receive a Certificate of Participation.

PRESENTERS

Prof. T. Campbell McCuaig (CET-Director), Dr. Carsten Laukamp (CSIRO-C3DMM), Tom Cudahy (CSIRO-C3DMM), Dr. Arianne Ford (CET), Dr. Greg Partington (Kenex P/L), Mr. Matthew Hill (CET), Assoc. Prof. Alok Porwal (IITB), Mark Jessell (IRD-Toulouse-Gledden Fellow) and Mr. Peter Gleeson (SRK Consulting).

REGISTRATION

Modules can be undertaken individually or as part of a 10-day course.

For more information contact Cindi Dunjey, cindi.dunjey@uwa.edu.au or on 08 6488 2640.

To register for the Exploration Targeting Course 2011, please download the registration form at http://www.cet.uwa.edu.au/courses/short-courses/
MODULE ONE
4 & 5 July 2011
Exploration Targeting in a Business Context
Prof. T. Campbell McCuaig (CET/UWA)
This 2-day course provides an overview of exploration targeting from a business perspective, as well as building the confidence of participants in how to approach the technical challenges of targeting. This course is aimed at project geologist and exploration managers from junior through to Major companies, who are making technical decisions about ground selection, target generation, target ranking and target evaluation.

MODULE TWO**
6 & 7 July 2011
Applied Geophysics in Exploration Targeting
Mark Jessell (IRD Toulouse-Gledden Fellow)
This one day course will concentrate on how to make best use of geophysical datasets for the targeting of structures and lithologies. Participants will be shown the latest in advances in fusing, visualizing and interpreting geophysical and geological data sets at the regional scale, as applied to regolith and near surface geology.

MODULE THREE
8 July 2011
Interactive 3D Targeting
Peter Gleeson (SRK Consulting)
Participants on this day will be seeing the use of the GeoModeller program and its application in real world exploration targeting. Led by SRK consultants, attendees will be shown why there is a need for 3D modeling in geology and presenters will highlight the advances that have occurred in these areas in recent years.

MODULE FOUR**
11 & 12 July 2011
Hyperspectral Sensing for Mineral Exploration
Tom Cudahy and Carsten Laukamp
This two-day course is aimed at showing geoscientists how a range of spectral sensing technologies, from drill core logging to satellite imaging sensors, can be used to provide information about the composition of geological materials, especially its mineralogy and mineral physicochemistry.

MODULE FIVE**
13, 14 & 15 July 2011
GIS-Bases Mineral Prospectivity Mapping
Dr Arianne Ford, Dr Alok Porwal, Dr Greg Partington (Kenex P/L) & Matthew Hill
This 3 day course will introduce participants to GIS functionalities and show how to do simple model-based mineral prospectivity mapping in GIS through a series of exercises and case studies. Presenters will show how to implement knowledge-driven (fuzzy logic) models and data-driven (weights of evidence, neural networks) models for mineral prospectivity mapping. Additional methods will be presented if time permits.

** Module two, four and five attendees who are not enrolled as students in the MSc student program will be required to provide their own laptops with licenced copies of ArcGIS and the Spatial Analyst toolbox installed to participate in this module. Those unable to provide their own copy of this software should contact Cindi Dunjey at least one (1) week prior to module commencement to arrange alternatives, if available.
CET PROJECTS
Global projects and research

- Au - prospectivity mapping in Wabigoon subprovince
- Au targeting in Pataz
- Au Pampeanas initiative
- Farallón Negro project
- Casposo Au project
- Sn-W project
- Jaspilite-hosted iron ore
- BIF-hosted iron ore
- Structural controls of Au in Iron Quadrangle
- Structural controls of Au in West Qinling
- Au targeting in Pataz
- Au-Sb-Pb-Zn Tibetan plateau project
- Andorinhas Au project
- Ni-Cu-(PGE) Pechenga Complex
- Ni-Cu-(PGE) genesis in Ivrea Zone
- Ni-Cu-(PGE) mineralization in SE Siberian Traps
- Au - prospectivity mapping in Wabigoon subprovince
- Kevitsa Ni-Cu-(PGE)
- Ni-Cu-(PGE) genesis in Ivrea Zone
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- Au - prospectivity mapping in Wabigoon subprovince
- Kevitsa Ni-Cu-(PGE)
- Ni-Cu-(PGE) genesis in Ivrea Zone
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- Kevitsa Ni-Cu-(PGE)
- Ni-Cu-(PGE) genesis in Ivrea Zone
- Ni-Cu-(PGE) mineralization in SE Siberian Traps

See map of
- Western Australia
- West Africa
Updated June 2011

See map of Western Australia
CET PROJECTS
Focus on CET Western Australian and West African projects and research

West Africa Projects and Research
AMIRA P934A WAXI-2 and ARC Linkage
4D evolution of crustal architecture and control on mineral systems

Geometric and genetic controls of Sadiola Au
4D evolution of Siguiri Au
Geometric and genetic controls of Morila Au
Geometric and genetic controls of Syama Au
Geometric and genetic controls of mineralization in the Yanfolila belt
Structural controls at Subika and surrounding Au mineral system
4D controls on geometry and genesis of Obuasi Au

Updated June 2011
Western Australian Projects and Research

- Ni-Cu-(PGE)
- Au/Au-Cu
- Fe

- MT lines
- Terrane-scale projects

Updated June 2011

**Project Highlights**

- **BIF-hosted iron ore in the Koolyanobbing greenstone belt**
- **Nebo-Babel Ni-Cu project**
- **Lithospheric architecture of W Musgraves**
- **Lithospheric architecture of SE Yilgarn margin**

**Projects and Research**

- **ARC Linkage - 4D evolution of crustal architecture and its control on mineral systems**
- **ARC Linkage - Tectonic evolution of Southern Cross - Au**
- **4D model and structural controls at Edna May**
- **4D evolution of Plutonic greenstone belt and Au**
- **BIF-hosted Wiluna iron ore project**
- **Structural controls at Jundee**
- **4D evolution of Agnew gold field**
- **Ni-Norseman-Wiluna GB**
- **4D model of the Tanami: Au mineral systems/prospectivity analysis**
- **Lithogeochemical prospectivity in the Musgraves**
- **4D model of the Telfer**
- **Ni-Cu-(PGE)**
- **Au/Au-Cu**
- **Fe**

**Map Details**

- **0 50 100 200 300 400 500 km**
- **Structural control / alteration of BIF-hosted iron ore at Paraburdoo and Mt Tom Price**
- **Newman EIS GSWA**
- **BIF-hosted iron ore in the Weld Range**
- **BIF-hosted iron ore in the Koolyanobbing greenstone belt**
- **4D model and structural controls at Edna May**
- **ARC Linkage - 4D evolution of crustal architecture and its control on mineral systems**
- **Nebo-Babel Ni-Cu project**
- **Lithospheric architecture of SE Yilgarn margin**
- **4D evolution of St Ives field**
- **ARC Linkage - multiscale modelling of ore systems**
- **ARC Linkage - controls on NiS camps**
- **MINERA M358 - Hydrothermal footprints of Ni deposits**
- **Lithospheric architecture of NE Yilgarn**
- **Mineral systems analysis at Sunrise Dam - Au**
- **Lithospheric architecture of W Musgraves**
- **ARC Linkage - multiscale modelling of ore systems**
- **ARC Linkage - controls on NiS camps**

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

Marco Fiorentini

Introduction

The role of external sulfur in the genesis of magmatic Ni-Cu-(PGE) sulfide deposits has been widely debated. Traditionally, ore genesis models emphasize crustal incorporation of sulfur as the key process that triggers sulfide liquid immiscibility in a magmatic system. However, the spectrum of mineralization styles that are represented in nature may reflect a diversity of ore-forming processes and, potentially, a diversity of S sources (Bekker et al., 2009; Penniston-Dorland et al., 2008; Seat et al., 2009).

Metallogenic models have had a critical impact on targeting and exploration. Consequently, the emphasis on external S addition as a major trigger for sulfide saturation in orthomagmatic systems has directed exploration towards areas with sulfide- or sulfate-bearing country rocks. However, even though crustal sulfur assimilation is crucial for some ore-forming processes, the potential of terranes, where sulfide- and sulfate-bearing country rocks are not known near mafic-ultramafic rocks should not be neglected. In fact, recent studies have shown that the location of sulfur assimilation and deposition may not necessarily be adjacent (Ding et al., 2011), because basaltic and komatiitic magmas are capable of transporting entrained sulfide blebs for great distances. Massive sulfides may also be transported for significant distances, as discussed in the earliest papers on Kambalda, in numerous papers on Sudbury offset ores, and in several papers on Voisey’s Bay.

Metallogenic models have traditionally emphasized addition of external sulfur as a key ore-forming mechanism, but without specifying the sulfur reservoir that has been most accessible to mafic-ultramafic magmas. Conversely, Bekker et al. (2009) argued that in the case of komatites, giant deposits form when ultramafic magma interacts with felsic volcanics-hosted hydrothermal massive sulfide lenses as opposed to sulfide-bearing shales. This interpretation, which is largely based on the application of multiple sulfur isotope data, provides new insight into the sulfur source for some Ni-Cu-(PGE) deposits.

In this study, we use multiple sulfur isotope data to investigate the sulfur source for magmatic Ni-Cu-(PGE) deposits in the Tati and Selebi-Phikwe greenstone belts of eastern Botswana. The deposits in these greenstone belts are hosted by magmatic rocks that have lithophile trace element similarities to arc basalts, however, they exhibit bimodal PGE characteristics, with some deposits being PGE-rich while others being PGE-poor (Maier et al. 2008). The sulfur source is poorly constrained for these deposits (Maier et al., 2008), but would help to elucidate how these geochemical characteristics developed. Our multiple sulfur data suggest that diverse mechanisms have led these Botswana magmatic systems to sulfide saturation. Our results thereby provide new insight on the prospectivity of magmatic provinces where the host rocks are sulfide-poor. The findings have thus the potential to broaden the scope of exploration targets for new Ni-Cu-(PGE) mineralized provinces.

Geological background

We investigated the multiple sulfur isotope signature of mineralized samples from selected intrusive Ni-Cu-(PGE) sulfide deposits in the Tati and Selebi-Phikwe belts of eastern Botswana (Figures 1 and 2). Several deposits in these belts are of considerable economic interest, including the Phoenix, Selebi-Phikwe, Tekwane, and Selkirk ore bodies. The deposits are of variable size ranging from 31 Mt of ore (1.36 % Ni, 1.12 % Cu) at Phikwe to 0.6 Mt of ore (1.2 % Ni, 0.6 % Cu) at Tekwane (Maier et al., 2008). Some of the deposits, notably Phoenix, contain significant concentrations of platinum-group elements (ca. 5-10 ppm Pt+Pd in sulfides).

The eastern Botswana Ni-Cu-(PGE) deposits may be subdivided into two groups. The first group of the deposits, hosted by the Phoenix, Selkirk and Tekwane intrusions occurs within and at the periphery of the Tati greenstone belt. The second group of deposits, comprising Phikwe, Dikoloti, Lentswe and Phokoje form part of the Selebi-Phikwe mafic-ultramafic belt of intrusions that occur within gneisses of the Limpopo metamorphic belt, some 200 km to the south of the Tati greenstone belt.
The Tati greenstone belt forms part of the Francistown Arc Complex, which is located along the southwestern margin of the Zimbabwe craton. Based on lithostratigraphic similarities, the volcanosedimentary rocks of the Francistown Arc Complex are correlated with the ca. 2.7 Ga upper Bulawayan greenstones in Zimbabwe. Correlation with the adjacent ca. 2.7 Ga Vumba and Matsitama greenstone belts further support this age for sedimentary and volcanic units of the Tati greenstone belt (Døssing et al., 2009). The Tati greenstone belt comprises lower greenschist to lower amphibolite facies volcanic and sedimentary rocks intruded by granitoids of unknown age. The volcanosedimentary succession has been subdivided into three formations. At the base is the 1400-1650m-thick Lady Mary Formation, which comprises altered komatiite and komatiitic basalts, and lesser amounts of quartzitic schist, calcitic marble, and iron formation. The overlying Penhalonga Formation is of variable thickness (~1 to > 10km) and comprises basaltic, andesitic and rhyolitic volcanics and volcaniclastic rocks, as well as phyllites, pyrite-bearing black shales, calcitic marbles, and jaspilites. The Penhalonga Formation is overlain by the up to several km-thick Selkirk Formation, which comprises dacitic and rhyolitic volcaniclastic rocks and minor amounts of mafic volcanic rocks, quartzites and quartz-sericite schists. The Selkirk Formation hosts the Phoenix, Selkirk and Tekwane meta-gabbronoritic intrusions and the Sikukwe meta-peridotite intrusion.

The Selebi-Phikwe area forms part of the Limpopo belt, an Archean to early Paleoproterozoic granulite-facies metamorphic belt situated between the Kaapvaal and Zimbabwe cratons. The Limpopo belt comprises several terranes with different ages ranging from ca. 3.2 to 2.6 Ga and tectono-metamorphic histories. These terranes have been accreted onto the Zimbabwe and Kaapvaal cratons over a period of ca. 700 Ma and are separated by wide, steeply dipping shear zones (Barton et al., 2006). The major terranes comprise the Central Zone, Southern Marginal Zone and Northern Marginal Zone. The Phikwe Complex is located within the Central Zone and largely consists of Archean hornblende-bearing and quartzofeldspathic tonalitic and trondhjemitic gneisses, which host the mafic-ultramafic intrusions of the Selebi-Phikwe belt. Most of the host rocks for the Selebi-Phikwe belt contain <200 ppm S, but sedimentary rocks with higher S contents reaching several 1000 ppm may locally occur (Brown, 1988).

**Results**

Vein-hosted and massive sulfide samples from the Phoenix and Selkirk Ni-Cu-(PGE) deposits in the Tati greenstone belt display δ34S values that are only slightly δ34S-enriched (0.2 to 0.8‰ VCDT) with respect to Cañon Diablo meteorite, which is assumed to reflect the average Earth and mantle composition (Farquhar et al., 2002). The ∆33S values of Phoenix and Selkirk sulfides are also similar to those of Cañon Diablo meteorite, with a small range from -0.08‰ to -0.01‰. δ56Fe data show a small range of negative iron isotope values from -0.29 to -0.09‰.

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Figure 1: Schematic map of the Limpopo belt and adjacent cratons, showing the location of the Tati and Selebi-Phikwe greenstone belts. Figure modified from Maier et al. (2008).
In the Selebi-Phikwe greenstone belt, vein-hosted and basal massive sulfide samples from the Phikwe, Phokoje and Dikoloti Ni-Cu-(PGE) deposits display sulfur isotope values with a small but significantly larger range of $\delta^{34}S$ values (-3.1 to +0.3‰) than that displayed by sulfides from the Tati greenstone belt. In addition, $\Delta^{33}S$ values show a significant mass-independent anomaly with respect to the mantle reservoir ranging from -0.89 to -0.27‰. Iron isotope data also show a larger range of negative iron isotope values from -0.61 to -0.04‰. All results are shown in Figure 3.

**Discussion**

Analysis of multiple sulfur isotopes permits testing of crustal assimilation models and identification of crustal sulfur reservoirs that contributed to ore genesis. Results from this study on ore samples from various deposits in the greenstone belts of eastern Botswana indicate that magmas can reach sulfide saturation through multiple processes. Accordingly, tenor and mineralization style might be affected by the process through which sulfide saturation was attained. According to Maier et al. (2008), the Ni-Cu-
(PGE) deposits in the Tati and Selebi-Phikwe belts show important compositional differences as far as the former are relatively PGE-rich, whereas the latter are relatively PGE-poor. In addition, there is also significant difference in their size. The deposits of the Tati greenstone belt are relatively small (~4.5 Mt of ore at 2.05% Ni and 0.85% Cu) and have a high Ni tenor, whereas the deposits of the Selebi-Phikwe greenstone belt are much larger (up to 31 Mt of ore grade) but have lower tenors. The question arises whether these compositional and size differences could be due, at least in part, to different processes involved in reaching sulfur saturation.

**Deposits in the Tati greenstone belt**

Sulfur and iron isotope data from this study indicate that the magmas from which the deposits in the Tati greenstone belt crystallized either did not assimilate any significant crustal S upon emplacement and crystallization or derived S from a large crustal reservoir that was thoroughly homogenized to erase mass-independent fractionation in sulfur isotopes. The range of mass-independent fractionation in sulfur isotopes is dramatically smaller in sediments deposited between 2.7 and 3.2 Ga with respect to a much larger range in sediments deposited between 2.5 and 2.7 Ga (Ohmoto et al., 2006). Poor geochronological constraints allow for sediments of the Tati greenstone belt to be in an older age group. However, even if the 2.7-3.2 Ga sediments with a small mass-independent fractionation of sulfur isotopes are inferred as the main sulfur source for ultramafic intrusions in the Tati greenstone belt, a larger range of $\Delta^{33}S$ values than the measured range would be expected.

Furthermore, black shales of the Manjeri Formation from the Belingwe greenstone belt, Zimbabwe that are lithostratigraphically and geochronologically broadly correlative with sediments from the Tati greenstone belt show a large range in $\Delta^{33}S$ values with negative $\Delta^{33}S$ anomalies, largely restricted to early diagenetic pyrite nodules, and highly positive $\Delta^{33}S$ values typical for disseminated sulfides (Bekker et al., 2009). Therefore, the lack of $\Delta^{33}S$ anomaly at the Phoenix and Selkirk deposits rules out significant S contribution from the pyrite-bearing black shales, which are the only sulfur-bearing rocks that appear in the stratigraphy of the Tati greenstone belt. The small negative range in iron isotope values of ~0.2‰ of Ni-Fe sulfide minerals is consistent with high-temperature magmatic fractionation processes although a small-scale assimilation of iron from sedimentary rocks in the footwall cannot be ruled out.

Another possible alternative calls for a large-scale assimilation of crustal rocks, which would homogenize sulfur to the original, close to the mantle sulfur isotope composition. In this case, other geochemical and geological proxies should also suggest significant crustal contamination. However, the relatively small size and high tenor of these deposits is inconsistent with a large-scale crustal homogenization required by this model. Our preferred interpretation is that the parental magma for these intrusions did not experience significant crustal contamination. This interpretation is consistent with the conclusion of Maier et al. (2008), who postulated mainly on the basis of trace element geochemistry and field observations that magmas remained S-undersaturated before emplacement and were not significantly contaminated by crustal materials.

**Deposits in the Selebi-Phikwe greenstone belt**

Sulfur isotopic data for mineralized samples of the Selebi-Phikwe greenstone belt are notably different from those of the Tati greenstone belt. Despite a small range of $\delta^{34}S$ values from -3.1 to +0.3‰, which could be explained by mass-dependent processes affecting mantle-derived S, sulfides...
from the Selebi-Phikwe greenstone belt display a significant negative $\Delta^{34}$S anomaly, which reflects input from a crustal reservoir. As a result, the sulfur isotope signature of mineralized samples from the Selebi-Phikwe greenstone belt is consistent with an ore-forming process that incorporated external (crustal) $S$ into the mafic magmas. The negative $\Delta^{34}$S anomaly suggests that sulfur may have been assimilated from massive sulfide lenses, either barren or mineralized, associated with felsic rocks or black shales with early diagenetic pyrite nodules. Iron isotope data show a larger range of negative $\delta^{56}$Fe values down to -0.6‰ well beyond an expected range of high temperature magmatic fractionations. These values are consistent with iron assimilation from either hydrothermal sulfide deposits or pyrite nodules in organic matter-rich shales, which generally display negative $\delta^{56}$Fe values (Rouxel et al., 2008). However, Brown (1988) indicated that in the footwall of the deposits in the Selebi-Phikwe greenstone belt, the only lithologies that contain elevated $S$ contents are hornblende-bearing gneisses bearing up to 9400 ppm $S$ and quartzites with up to 47000 ppm $S$.

Sulfur and iron isotope data from this study support the conclusion of Maier et al. (2008), who inferred on the basis of trace element geochemistry that magmas from which the Ni-Cu-(PGE) sulfide deposits at Phikwe, Phokoje and Dikoloti formed likely assimilated a significant external sulfur component upon emplacement.

**Conclusive remarks**

Results from this study show that sulfur in deposits situated within and along the Tati greenstone belt in Botswana may have been largely derived from the mantle. This implies that incorporation of crustal $S$ was not an important mechanism in triggering sulfide saturation in these magmas, but that other processes including fractional crystallization, assimilation of silicates, and changes in pressure and temperature may have been critical for the mineralization process to form these relatively small, PGE-rich deposits. Similar conclusions have also been reached in studies of other large magmatic sulfide deposits based on $\delta^{34}$S values alone (e.g., the Proterozoic Nebo-Babel deposit in the Musgrave Complex of Western Australia; Seat et al., 2009) or based on both $\delta^{34}$S and $\Delta^{33}$S values (the Platreef deposit of the Bushveld Complex, South Africa; Penniston-Dorland et al., 2008).

Conversely, magmas that formed the deposits of the Selebi-Phikwe greenstone belt underwent significant crustal contamination during crystallization and assimilated significant amounts of crustal sulfur during this process. An analog setting may be represented by the Eagle Ni-Cu-(PGE) deposit in USA, where recent multiple $S$ isotope study indicates a complex history of sulfur assimilation and interaction between mafic magma and both Archean and Proterozoic country rocks (Ding et al., 2011). Although the specific source of $S$ in the Selebi-Phikwe greenstone belt remains undetermined, this study suggests that $\Delta^{33}$S measurements, even in cases of $S$-poor terranes hosting mineralization, may unveil the significant contributions of crustal sulfur that were necessary to saturate the magma. In this light, it is interesting to note that most of the granitic and gneissic rocks in the Limpopo Belt are extremely $S$-poor (< ~200 ppm sulfur; cf. Brown (1988)), and a crustal assimilation model would traditionally not be applied to the deposits of the Selebi-Phikwe greenstone belt. It may be that the gneisses lost most of their sulfur during high-grade metamorphism after mineralization formed, thereby creating the appearance that these lithologies could not contribute significant amounts of sulfur to drive the mafic-ultramafic magma to sulfide saturation. There is little outcrop in the belt, and so the apparent paucity of sulfur may be misleading.

In magmatic systems, near-zero $\delta^{34}$S or $\Delta^{33}$S values permit a mantle source, but do not prove it if the complexity of homogeneization processes is considered. However, non-zero $\delta^{34}$S or $\Delta^{33}$S values prove a non-mantle source. In conclusion, data from this study highlight the complexity and variability that characterize ore-forming processes in magmatic systems. The presence of sulfur-bearing lithologies in the footwall hosting mafic and ultramafic intrusions should not be considered as essential towards the assessment of the prospectivity of a province. Geological provinces without any or with little sulfur in the footwall stratigraphy, which have been traditionally neglected in terms of their prospectivity, should be revisited and possibly reassessed.

**Acknowledgements**

This short article summarizes a more comprehensive study, which has been accepted for publication in Economic Geology (in press in late 2011). The coauthors of this study are acknowledged: Andrey Bekker, Olivier Rouxel, Boswell A. Wing, Wolfgang D. Maier and Douglas Rumble. We thank Tati Nickel for facilitating sampling of the Phoenix and Selkirk deposits. WDM acknowledges funding by the Centre for Research on Magmatic Ore Deposits at the University of Pretoria. Marco Fiorentini acknowledges support from AMIRA and the Australian Research...
Although exploited over more than 100 years, the structural and metamorphic evolution, as well as the associated mineralisation style and timing of deformation, remains widely unconstrained in the Southern Cross district. An ongoing project co-sponsored by the Geological Survey of Western Australia (GSWA) and the Australian Research Council (ARC) aims to resolve these outstanding issues by adopting a multidisciplinary approach combining down-to-earth field investigation including structural geology, geochronology, metamorphic petrology, and cutting edge 3D modeling techniques.

A recent project review was organized in the field by Nicolas Thébaud (CET) and Michael Doublier (GSWA) in order to present the results to date. The team included Nicolas Thébaud, Cam McCuaig, Klaus Gessner from CET, Eric Tohver from the School of Earth and Environment from UWA and Michael Doublier, Sandra Romano, Stephen Wyche and Michael Wingate from GSWA. Specifically this field forum was the opportunity to discuss “on the rocks” the stratigraphic, structural and mineralisation characteristics of the Southern Cross district and preliminary result of the current study.

In the short future, the leaders of the project aim to organize an industry-focused field forum with the aim to transfer the large knowledge base acquired on the South Eastern Youamni Terrane over the past 3 years.

References

The References for this article can be accessed using the following link:

http://www.cet.uwa.edu.au/__data/assets/pdf_file/0011/1693244/
Financial Risk Analysis and Real Option Valuation of Mining Projects

This two-day, hands-on, Excel-based course focuses on the principles of risk and decision analyses and Real Option Valuation (ROV) as applied to investments in mining projects from the exploration to the feasibility stage. Ideal for professionals in the mineral exploration, mining and securities industries.

Course Overview
This course provides a basic understanding of the fundamental principles and concepts of risk and decision analyses and risk management as applied to investment in exploration and mining projects. The course will:

— Evolve from risk-neutral decisions based on expected value to risk-averse decisions incorporating investor’s attitude and tolerance to risk.
— Enable participants to identify and quantify risk using sensitivity and scenario analyses and Monte Carlo simulation.
— Bring participants up to date on recent developments in project modeling and evaluation using financial risk management principles, Modern Asset Pricing (MAP) and Real Options Valuation (ROV) techniques.

This course is a very good complement to CET’s “Discounted Cash Flow (DCF) Modelling & Financial Evaluation of Mining Projects”.

Who Should Attend
This course is an ideal introduction to risk analysis and real option valuation methodologies for professionals in the mineral exploration, mining and securities industries, who are familiar with how to construct a discounted cash flow (DCF) model of a mining project in Excel and who wish to update and broaden their project evaluation skills.

Key Benefits
At the end of the course participants will:

— Appreciate that static expected DCF NPV does not measure the whole value of a project.
— Have greater familiarity with how different attitudes to risk influence decisions under uncertainty and with the use of decision trees.
— Discover that project values often include significant real option value. This is the value of managerial flexibility to adjust their course of action to take full advantage of positive events and to avoid or minimise the potential impact of adverse ones by learning from emerging information and circumstances as they progressively dispel uncertainty.
— Have acquired the skills to identify, model and evaluate simple real options common in mining projects.
— Have a solid springboard to expand their skills in this exciting field, both at an individual and corporate level.

Registration
The cost of the course is $1440 for two days per participant (GST included) with a 30% discount for CET Corporate Members.
The venue is Robert Street Building UWA (Resource Room G03), Fairway Entrance 1, Crawley WA 6009.
For more information contact Cindi Dunjey, cindi.dunjey@uwa.edu.au or on 08 6488 2640.
To register for the Advances in Ore Deposit Geology Course 2011, please download the registration form from http://www.cet.uwa.edu.au/courses/short-courses.

11 & 12 August 2011
Presented by Professor Pietro Guj
DAY 1

Review of Discounted Cash Flow (DCF) Analysis
— Constructing a basic DCF model of a mining project

Introduction to uncertainty and risk
— Fundamentals of probability, uncertainty and risk

Risk-neutral decisions
— Expected value (EV), binomial probability distributions and risk of gambler’s ruin

Decision trees and conditional (bayesian) probabilities
— EV of an exploration program, and
— Measuring the contribution of an exploration survey to improving the probability of discovery

Risk-adverse decisions
— Risk attitudes and profiles
— From EV to the related certainty equivalent (CE) and the price of risky projects, and
— Risk-spreading and risk management by joint venturing

Risk analysis
— Sensitivity and scenario analyses, spider and tornado diagrams

Monte Carlo Simulation
— The “expected” base case
— Probability distributions of inputs, and
— Resultant distribution of possible output values and their interpretation

DAY 2

Recent developments in project evaluation
— Overcoming the limitations and bias of discounted cash flow (DCF) analysis, and
— An introduction to real options valuations (ROV)

Modern Asset Pricing (MAP)
— Hedging commodity price risk
— Constructing a MAP model of a mining project, and
— Comparing a MAP and a corresponding DCF model determining the related time-and-risk-adjusted rate of discount

Real Options Valuations (ROV) Methods
— General principles
— Closed-form equations
— Binomial lattices
— Binomial decision trees
— Risk neutralisation and
— Single, multiple, sequential and compound options

Application of the Black and Scholes (B-S) Formula
— Evaluating a gold future
— Evaluating a marginal mining project
— Limitations of the application of the B-S formula to real options

Application of the Binomial Lattice and Decision Tree Methods
— Valuing a risky asset under various possible future states of nature
— “Risk-neutral” probabilities and the roll-back process to value a real option in the present
— Evaluating a mine expansion project

More Complex ROV Applications
— Consideration of the versatility and ease of use of the binomial lattice and decision tree methods in evaluating multiple and sequential / compound real options
Staff Profiles

Tony Kemp

Tony Kemp arrives at UWA to commence an ARC Future Fellowship. This represents the culmination of a clockwise global loop that has taken him from PhD studies in Canberra to postdoctoral research positions at the University of Bristol (UK), Niigata University (Japan) and James Cook University, Townsville. Despite a penchant for playing with fancy instruments, like ion microprobes, laser ablation systems and multi-collector plasma ionization mass spectrometers, igneous and metamorphic rocks are Tony’s real scientific passion.

He continues to indulge this passion though a range of ongoing projects, including studies of Miocene granulites from Japan, Paleozoic granites from eastern Australia, Paleoproterozoic igneous rocks from Mount Isa and the Halls Creek orogen, the Lewisian granulites of Scotland and the Eoarchaen I tsaq gneisses of southern West Greenland. The common thread uniting these studies is geochronology, geochemistry and isotope geochemistry, focusing on the isotope and trace element systematics of accessory minerals like zircon, and driven partly by a compulsion to drill tiny holes in things. Recently, Tony has also taken tentative steps down the path to enlightenment in Economic Geology, with projects investigating porphyry-style Cu-Au-Mo mineralization and Sn-W mineralization.

His Future Fellowship is aimed at charting the earliest growth history of the Australian continent by studying the formation of ancient rocks in the Yilgarn and Pilbara cratons. Tony will also be heavily involved in the newly funded ARC Linkage project on the four-dimensional lithospheric and metallogenic evolution of West Africa and the Northern Australian Craton being lead by Cam McCuaig.

Geoff Batt

Geoff Batt brings to the CET a passionate curiosity about the natural world, and a distinguished background in the late-stage evolution and exhumation of structural systems.

Geoff’s interests in structural dynamics extend back to his formative years in the active landscape of southern New Zealand. He completed an honours degree in Geology at Otago University, and (despite a brief flirtation with paleontology and stratigraphy) went on to pursue a Ph.D. on orogenic evolution at the ANU. His research there blazed an early trail in the integration of isotopic ages with structural evolution through numerical models of crustal deformation.

He pursued the development of thermally and structurally sensitive isotopic chronometers as a window on late- and post-orogenic history as a post-doctoral fellow at Yale University, and subsequently spent 8 years at Royal Holloway University of London as a Lecturer. Focused initially in metamorphic petrology and field geology, Geoff’s portfolio of teaching diversified to encompass remote sensing, tectonics, communication skills, and science philosophy.

Geoff fulfilled a long-held ambition of moving back to Australia in 2008, initially based in the John de Laeter Centre for Mass Spectrometry, where he has initiated dating programmes in northwestern China, and undertaken a pioneering investigation of exhumation history as a contributor to gold endowment variability in the Yilgarn.

Geoff is now moving over into the CET, bringing his experience in dynamic systems analysis and 4-D reconstruction to bear on an exciting project supported by Newcrest Mining. His focus over the next two years will be to develop an understanding of the evolution of Newcrest’s gold-copper deposit at Telfer, and its fit within the context of the Paterson Province of northern WA. Together with the work of PhD student Christian Schindler, we hope to deliver a new integrated understanding of the mineralization history and wider prospectivity of this region.
Luis Parra Avila

Luis A. Parra, born in Caracas, Venezuela, is a PhD student that joined the CET last March. He decided to study abroad in 2004 and moved to the Midwestern United States to start his geology career. In the process, he swapped the chaos and stress of Caracas for the extensive farm fields of more rural Missouri. After earning his Bachelor’s degree in 2007 he then moved to the neighbouring state of Illinois to work on his Masters’ degree, which he earned in 2010. His Masters’ thesis involved Co-Ni enriched Mississippi Valley-type deposits in southeast Missouri. For the project, Luis had the support of the “The Doe Run Co.”, which allowed him access to their mines and supported his research through a geology summer internship. Luis also received two grants from the Society of Economic Geologist (SEG). Before completing his Masters’ he was selected to attend the student dedicated field trip sponsored by SEG in 2009. That year the trip covered the northern Nevada gold deposits. After the trip he became interested in continuing his education and decided that Western Australia was the best fit for his interest and goals, plus it would allow him to fulfil the childhood dream of visiting Australia.

Luis’s project at the CET focuses on the 4D modelling of the Paleoproterozoic development of the West African Craton. The project is funded through the ARC linkage program and is part of the AMIRA West Africa Exploration Program. The main objective of the project is to establish the crustal tectonic history of the craton across Burkina Faso, Ghana, Mali, Ivory Coast and Guinea and link this development to the identification of potential targeting areas for Ni exploration.

Before leaving the big city and becoming a geologist, Luis participated in the organization of the Caracas International Theatre festival, and spend as much of his free time in the water as possible. He was a lifeguard for the local fire department, gave swimming lessons for local children and participated in a masters swimming team attending several national master swimming meetings.

Margaux Le Vaillant

Ms Margaux Le Vaillant, born in Paris, is a PhD student who joined the CET last February on prestigious SIRF scholarship. After four years of study in France, both in Paris and Nancy, she decided to experience the cold and the darkness of northern Sweden, and went to study at the University of Technology of Lulea. She attended the second year of the “Environment and Mining Exploration” Masters and did her thesis in partnership with INMET Mining Corporation at the Pyhäsalmi mine in Finland. In her project she constructed an integrated geological and geophysical 3D model of the Mullikkörame deposit which was subsequently used to identify new drilling targets. Out of the six identified targets, two were prioritised and included in the exploration program of the year 2010-2011. In September 2010, she graduated from both the department of “Matières Premières Minerals” (Mineral Resources) of the ENSG (French National School of Geology in Nancy) with an Engineer Diploma and from the University of Technology of Lulea in Sweden with a Masters’ degree in Environment and Mining Exploration.

Before starting her PhD at UWA, Margaux went back to Finland for 3 months to do some drilling supervising and logging for the drill holes related to her master thesis project. She arrived in Perth in February 2011 to start her PhD project at the CET on Nickel sulphide exploration. She is supervised by Dr Marco Fiorentini (UWA/CET) and Dr Steve Barnes (CSIRO).

Margaux’s PhD project focuses on the study of geochemical haloes around Nickel Sulphide deposits with a focus on the Agnew Wiluna Belt and the Kambalda/Widgiemooltha domes of Western Australia. This is a MERIWA project (M413), which involves the key participation of three exploration companies: BHP Billiton, Mincor and First Quantum Minerals. The aim of the project is to enlarge the detectable footprint of altered and deformed nickel sulphide ore bodies, with a focus on the application of geochemical and geophysical techniques used by mining exploration companies. Most Nickel sulphide magmatic deposits have been extensively altered and modified as a result of interaction with post magmatic hydrothermal and metamorphic fluids, and hence left a deposit-scale “stain” in the surrounding rocks. The goal of the project is to identify secondary haloes and 3D vectors around deposits to help the exploration for Nickel sulphide deposits.
CET would like to thank its Corporate Members for their continued support in 2011.

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CET Research Themes and Leaders

The Centre is aimed squarely at the mineral industry’s need to increase the discovery of new mineral deposits. Its six research themes reflect the belief that more effective targeting, coupled with independent action to reduce the risks of value destruction, will deliver outcomes that can significantly improve the risk : reward ratio.

Each theme has a leader and is responsible for a portfolio of projects. Researchers within the CET are often engaged across several project portfolios.

Theme leader contact details are available at http://www.cet.uwa.edu.au/contact/staff

MSc Ore Deposit Geology and Evaluation

The course work Masters program is designed for geoscientists who want to gain up to date knowledge and skills in economic geology and mineral exploration. The course at UWA is part of the national Minerals Geoscience Masters program and is supported by the Minerals Council of Australia. The program is run jointly between the Centre for Exploration Targeting (UWA), CODES (UTAS), EGRU (JCU) and Curtin University of Technology (CUT).

The Masters course can be completed in three ways:

Option 1 - (8 course work units) Eight units of course work: at least two of which must be undertaken at UWA. The other units are done at UWA or at the other participating universities.

Option 2 - (6 course work units + dissertation) Six units of course work and a dissertation (25% of overall assessment). Two of the units must be completed at UWA.

Option 3 - (3 course work units + thesis) Three course work units and a thesis which accounts for 62.5% of the overall assessment. The thesis is similar to an honours project in scope.

Courses offered by the CET:
— Exploration Targeting, 4-15 July 2011
— Advanced Ore Deposits, 7-18 November 2011
— Applied Structural & Field Geology, July 2012
— Ore Deposits Field Excursion, September 2012

Contact Information

If you would like to find out more about the Centre for Exploration Targeting, its Corporate Membership program, Applied Research opportunities or Training possibilities, please contact:

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