West African mineral systems (gold & structural focus)

1John Miller*, 2Yan Bourassa, 3Kim Hein, 1James Davis, 1Denis Fougerouse, 1Vanessa Markwitz, 4Elodie Le Mignot, 5Luc Siebenaller, 5Didier Béziat, 5Stefano Salvi, 4Anne-Sylvie André-Mayer, 5Lenka Baratoux, 1Vasek Metelka, 5Sylvain Block, 1Mark Jessell, 6Stephane Perrouty, 1Nicolas Thébaud, 1Campbell McCuaig, 7Stanislav Ulrich

Please note: This work, in part or as a whole, cannot be used without approval of the authors

1Centre for Exploration Targeting, University of Western Australia
2Golden Star Resources Ltd, Toronto
3School of Geosciences, University of the Witwatersrand, South Africa
4GeoRessources, Université de Lorraine-CNRS-CREGU, France
5IRD, Université Toulouse III, Toulouse, France
6Earth Sciences, Western University, Canada
7Anglogold Ashanti, Australia

* Now at CSIRO (Commonwealth Scientific and Industrial Research Organisation)
Birimian volcano-sedimentary belts with associated granitoids (2250 to 1960 Ma)
Late sedimentary sequence (2010-2000 Ma)
WAXI2 New 1:200,000 maps

- Sadiola Deposit
- Guinea-Mali
- Ghana
- Kalana, Syama, Tabakoroni, Morila deposits
- Ashanti Belt Deposits

WAXI2 Workshop Perth May 2015
WAXI2 Stratigraphic Synthesis

Tarkwa Fm

Kumasi Fm

Tarkwa-like Basin Formation

Senegal Provisional Stratigraphic Column, Hein 2013 (Unpub)
Mali Provisional Stratigraphic Column, Davis 2012 (Unpub)
South West Burkina Faso Stratigraphic Columns, modified from Baratoux et al., 2011
N. Ghana Stratigraphy Sylvain et al., 2013
Ghana Stratigraphy Perrouy et al., 2012

MAX DEPOSITIONAL AGE (Ma)

Kki
Yanfolia Belt (Inc Siguiiri)
Syama Belt
Banfora Belt (Katola - Marabi)
Hounde West (Quango - Fitini)
Hounde East (Tehini)
Boromo West
Boromo East
Bole - Nangodi Belt
Ashanti Belt

2700 Ma
2100 Ma
2120 Ma
2150 Ma
2160 Ma
2180 Ma
2200 Ma
2240 Ma
2270 Ma
2400 Ma
2800 Ma
3000 Ma

Oceanic island arc-backarc ocean floor
SAG
UNCONFORMITY

Neo Archean
Meso Archean

Unclassified Birimian
Tarkwalan
Birimian Series Sediments
Sandstone, arkose
Conglomerate
Birimian sediment, volcano-sediments
Pyroclastics, volcanioclastics

Unpublished: West African Exploration Initiative
IKDA: L’Initiative d’Exploration Ouest Africaine
Original framework used for the interpretations in Mali, Guinea and Ghana

Baratoux et al., 2011, PreCambrian Research 191, 18-45
1) **Ni deposits and Platinoid occurrences** are along Archean Craton Margin and ultramafic intrusions

2) **Base metal and copper-gold systems.** The Boromo Belt in Burkina Faso has VMS deposits (Zn-rich Perkoa deposit) and Cu-Au porphyry systems with calc-alkaline volcanic rocks (Gaoua).

The restricted nature of the distribution of these systems compared to the gold-only systems, is inferred to reflect the distinct tectonic settings that these deposits form in.
Major focus on gold-only systems – note broad geographic spread
Projets en Afrique

Mana ~ 2 million ounces
Burkina Faso

Morila, Mali (~7 million ounce)

Syama, Mali (~5 million ounce)

Siguiri, Guinea (~7 million ounce)

Komana, Mali

Sadiola, Mali (~5 million ounce)

Bogoso, Ghana (~5 million ounces)

Obuasi, Ghana (~50 million ounces)

Kiniero, Guinea (~1 million ounces)
High profile and cited model for Ghana - Feybesse et al., (2006)

- **D1 (2.13 to 2.105 Ga)** = The D1 thrust tectonism, crustal thickening
- **Tarkwaian Basin** contemporaneous with this D1, infill continued during D2 tectonism.
- **D2–3 events (2.095 to 1.98 Ga)** = strike-slip movement. Peak D2 was sinistral to reverse-sinistral shearing.
- Structures active in D2 channelled and trapped gold-bearing hydrothermal fluids
Gold deposit host rocks (2.2-2.1 Ga)

Host rock types range from;

• carbonate-hosted (Sadiola)
• sediment-hosted (Siguiri, Obuasi)
• sediment and granitoid hosted (Kalana)
• mafic intrusive hosted (e.g., Syama)
• mafic volcanic hosted (e.g. Kiniero)
• granitoid hosted (e.g. Banfora, Subika)
• placer deposits in quartz-pebble conglomerates (Tarkwa).
Deposit styles/ models

- Intrusion-related (e.g. ~8 Moz Morila deposit; McFarlane et al., 2011)
- Classic fault-valve orogenic gold models (e.g. > 5 Moz Damang deposit; Tunks et al., 2004) with regional fluid flow focussed into low stress domains (Feybesse et al., 2006)
- Paleoplacer systems (e.g. >28 Moz Tarkwa deposit; Pigois et al. 2003) age ca. 2100 to 2110 Ma
- Cryptic early poly-deformed deposits (e.g., ~5 Moz Wassa deposit; Bourassa, 2003).
- Ductile shear zones (Wassa), fault-vein arrays (Kalana, Damang), and Low-T brittle high level breccias (Syama).
Syama: low –T breccia (mafic intrusive)

Wassa: folded ductile shear zone (mafic volc.)

Morila: high T with partial melts

Damang: low angle veins

Folded gold lodes
WAXI2 Ore Deposit Synthesis – won’t cover today

<table>
<thead>
<tr>
<th>Type</th>
<th>Company</th>
<th>Deposit name</th>
<th>Host rock</th>
<th>Metam</th>
<th>Mode of occurrence</th>
<th>Deformation</th>
<th>Specific Alteration</th>
<th>Sulphides</th>
<th>Au Association</th>
<th>Apy T</th>
<th>Re-Os Dating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morilla-type</td>
<td>Voita</td>
<td>Kaika</td>
<td>Upper amphibolite</td>
<td>Late shear</td>
<td></td>
<td></td>
<td>Carb, chlor, pyrite, and pyrrhotite</td>
<td>Vg in shear-related fractures</td>
<td>Po + Py</td>
<td>&gt;450</td>
<td>Po + Py</td>
</tr>
<tr>
<td></td>
<td>Anglogold</td>
<td>Randgold</td>
<td>Upper amphibolite</td>
<td>Ductile (+veining), bi-foliation</td>
<td>Muscovite</td>
<td>Apy</td>
<td>Po, py, loell, Bi</td>
<td>Incl. in Apy in contact with loell</td>
<td>460-570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pamp-type</td>
<td>Avocet</td>
<td>Inata</td>
<td>Black shale, andesitic dykes</td>
<td>Greenschist</td>
<td>Veins in shear zone corridor, during D2-D3</td>
<td>Ab, carb, late musc + chl</td>
<td>Py, aspy</td>
<td>Gp, cp, ZnS</td>
<td>Inv Au in sulphides on vein edges, VG in fractured sulphides</td>
<td>&lt;300-420</td>
<td>Py</td>
</tr>
<tr>
<td></td>
<td>Tamgold</td>
<td>Kalana</td>
<td>Sandstone, volcano-sedimentary, diorite</td>
<td>Upper amphibolite</td>
<td>Qtz-carb + folds veins</td>
<td>Shear veins and tension gaps</td>
<td>Py, cpy, aspy, po</td>
<td>Sph, gn, bi, Te</td>
<td>Vg in sulphides; free in veins, &gt;Au in fine grained molybdenite in albit halos</td>
<td>&gt;350</td>
<td></td>
</tr>
<tr>
<td>Goldenstar</td>
<td>Pampe</td>
<td>Pampe</td>
<td>Black shale, mafic dykes</td>
<td>Greenschist</td>
<td>Veins in shale and dykes</td>
<td>Ab, carb, late musc + chl</td>
<td>Py, aspy</td>
<td>Gp, cp, ZnS</td>
<td>Inv Au in sulphides, VG in fractured sulphides</td>
<td>375</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Goldenstar</td>
<td>Bogoso</td>
<td>Black shale</td>
<td>Greenschist</td>
<td>Dissiminated and veins</td>
<td>Ductile/brittle</td>
<td>Carb, quartz, ab</td>
<td>Py, apy</td>
<td>Py, PblSb5, Te, Pd</td>
<td>In py as inc or in late fractures</td>
<td>365-380</td>
</tr>
<tr>
<td></td>
<td>Goldenstar</td>
<td>Buesichem</td>
<td>Black shale and mafic volcanics</td>
<td>Greenschist</td>
<td>Dissiminated and veins</td>
<td>Ductile (mylonite)</td>
<td>Carb, quartz, ab</td>
<td>Py, apy</td>
<td>Py, PblSb5, ZnS</td>
<td>In py as inc or in late fractures</td>
<td>375</td>
</tr>
<tr>
<td></td>
<td>Resolute</td>
<td>Tabakoroni</td>
<td>Sandstone, black shale and chert</td>
<td>Greenschist</td>
<td>Dissiminated and veins</td>
<td>Strong, shear zone</td>
<td>Carb</td>
<td>Apy</td>
<td>Py, CuSb5</td>
<td>In Apy as inc or in late fractures</td>
<td>320</td>
</tr>
<tr>
<td></td>
<td>Resolute</td>
<td>Syama</td>
<td>Lamprophyte/black shale</td>
<td>Greenschist</td>
<td>Dissiminated and veins</td>
<td>Ductile/brittle (several deformation stages)</td>
<td>Ab, carb, musc</td>
<td>Py</td>
<td>CoSb5, Apy</td>
<td>In py as inc or in late fractures</td>
<td>&lt;300</td>
</tr>
<tr>
<td>Nassara-type</td>
<td>Goldenstar</td>
<td>Benso</td>
<td>Diocline quartztite</td>
<td>Upper greenschist</td>
<td>Dissiminated and veins/shearbands</td>
<td>Localized sheara zone</td>
<td>Ab, chl, quartz</td>
<td>Py, PblSb5, Ccp</td>
<td>Associated to sulph, chl, and Pbl</td>
<td>&lt;300</td>
<td>Py</td>
</tr>
<tr>
<td></td>
<td>Nassara</td>
<td>Nassara</td>
<td>Shale, andesite, diorite</td>
<td>Lower greenschist</td>
<td>Dissiminated and veins</td>
<td>Ductile + brittle</td>
<td>Carb, chlor, py</td>
<td>Po, cp, gn, ZnS, Apy</td>
<td>In py as inc or in late fractures</td>
<td>&lt;300</td>
<td>Py</td>
</tr>
<tr>
<td></td>
<td>Volta</td>
<td>Gaoua, orogenic Au</td>
<td>Diorite, andesite</td>
<td>Greenschist</td>
<td>Shear areas deforming porphyry, c-qtz veins</td>
<td>Ductile shear zone</td>
<td>Carb</td>
<td>Py</td>
<td>Cp, PblTe, AgTe, CuSb5</td>
<td>In sulphides, chl, and in fractures</td>
<td>&lt;300</td>
</tr>
<tr>
<td>Wassa-type</td>
<td>Goldenstar</td>
<td>Wassa</td>
<td>Mafic Volcanics, felsic porphyry, mafic clastic horizons and very rare black shale</td>
<td>Greenschist</td>
<td>Dissiminated and veins</td>
<td>Ductile (lenticular py), folding of D1</td>
<td>Chlor, carbon, quartz, trm</td>
<td>Po, cpy, Apy, ZnS</td>
<td>Inv Au in py, inclusions in py</td>
<td>375</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tarkwa-type</td>
<td>Goldfield</td>
<td>Congl / microclastite</td>
<td>Greenschist</td>
<td>Placer and hydrothermal dissemination of Au and veins</td>
<td>Ductile/brittle</td>
<td>Carb, Trm, gr</td>
<td>Py -&gt; po</td>
<td>Cp</td>
<td>Linked to Trm and sulphides</td>
<td>&lt;300</td>
</tr>
</tbody>
</table>
Architectural/ regional structural controls

- Gold-only deposits formed at different geological times and have markedly host rocks and different deposit styles defined by observable structural, metamorphic and alteration.
- At the belt and regional scale architectural controls appear to be a key control on the gold deposit locations.
- This could be an effective targeting tool within a prospective greenstone belt.
- Similar observations made for the Western Australian Goldfields.
Major variations between individual deposits. Belt scale architectural controls appear to be a control on deposit location.

Intersections, ENE- & N-trending architecture (dykes map these)
Guinea and Mali (interpretation with gravity data)
Kinematics and timing

- Multiple phases of gold mineralization with different kinematics and alteration occurred, in some cases within the same belt.
- Regionally a dominant late-stage gold D4 event at ca. 2100 - 2070 Ma, which is commonly associated with NW-SE shortening, sinistral slip and high arsenic e.g., Obuasi (Allibone et al., 2002; Feybesse et al., 2006).
- Also later stage D5 brittle reverse/dextral stage (Syama and Damang).
- World class ca. 2100-2110 Ma Tarkwa Formation Paleoplacers in the Ashanti belt predate the D4 gold event – this requires an older pre-Tarkwa deposition gold event to have acted as a source.
- Evidence for early D1/D2 gold systems that pre-date Tarkwa deposition groups deposits is strong (in comparison for example to early gold models in the Archean Yilgarn craton of Australia).
WAXI2 Space-Time Correlation Chart Major D4 gold event highlighted

<table>
<thead>
<tr>
<th>SENEegal</th>
<th>MALI</th>
<th>SW BURKINA FASO</th>
<th>NE BURKINA FASO</th>
<th>GHANA</th>
</tr>
</thead>
</table>

Detailed look at Ashanti Belt
Ghana

Feybesse et al., (2006)
D2–3 events (2.095 to 1.98 Ga) = sinistral strike-slip movement & gold (D4 in WAXI history)
Ashanti Belt (Ghana) – critical study area
Major deformation events and phases of gold

• Poorly defined early events
• Early D1 gold at Wassa – this is pre-deposition of Tarkwa unit
• Deposition of ca. 2100 to 2110 Ma Tarkwa paleoplacers
• Major D3 NW-SE shortening linked to regional folding of all sedimentary sequences (including Tarkwa Fm) and shear development
• D3 Gold related to horizontal stretching and NW-SE shortening
• Regional D4 event linked to a major phase of gold mineralisation with cross cutting D4 crenulation cleavages/foliation, sinistral slip linked to NNW-SSE shortening (=D3,D4 and D5 of Allibone et al., 2002)
• D5 NE-SW to ENE-WSW shortening linked to low angle veins and associated gold mineralisation within the Tarkwa units at Damang
• Early N-trending and ENE-trending architecture is a probable control on deposits (combined with fault intersections)
Ashanti Belt history (deposit by deposit) – linked to WAXI2 event history

NOTE: major late-stage orogenic gold = most common observation in the literature

Local events versus WAXI2 event history = will use WAXI2 regional events

Peak Gold described by Feybesse et al., (2006)

Tarkwa Paleoplacer gold ca. 2100-2110 Ma
Wassa deposit ~ 5 million ounces gold (Early Gold, D1 deposit with overprints)

Perrouty et al., 2015

Folded gold lodes
Transposed layering
Wassa (Early Gold, interpreted D1, strongly over printed deposit)

- Texturally early gold
- Grade control data suggests lodes are folded
- Re-Os ages of sulphides from the Wassa deposit produced two ages $2164 \pm 22$ Ma and $2054 \pm 11$ Ma (Le Mignot et al., in review).
Tarkwa Unit Paleoplacer (Tarkwa) ca. 2100 – 2110 Ma

Paleoplacer with hydrothermal overprint (Damang)

Repe T1 Conglomerate

> 28 million ounces of gold

Akontansi T3 Cross Bedding

Banket Series

Huni Phyllite s/s
Banket HW
Guider Cong.
Middling s/s
Malta Cong.
Middling s/s
Star Cong.
Banket FW s/s
Kaware Cong.

2.48 g/t

DRC-1767
49594-4960cm
82 g/t
Star Conglomerate

DRC-1767
5053055.68m
95 g/t
Hydrothermal Lode (Banket Footwall s/s)

Wall rock alteration

Vein
D2/D3 graphitic shears (Obuasi and Bogoso)

Work by A. Allibone
Obuasi deposit = > 50 million ounces
Gold at Obuasi prior to the “classic” D4 gold event
Late D3 = NE-SW directed stretching and NW-SE shortening linked to gold (overprinted by D4 foliation)

(pressure shadows folded/ cross cut by D4 foliation).

Junner 1932 noted same relationships.

D4 foliation

Fougerouse et al., (in press)

Junner 1932
Ashanti Belt history (deposit by deposit) – linked to WAXI2 event history

**NOTE:** major late-stage orogenic gold = most common observation in the literature

### Local events versus WAXI2 event history

**D4 Peak Gold - described by Feybesse et al., (2006)**
Obuasi - Major gold control from D4 foliation (Allibone et al., 2002)
Regional gold-associated D4 cleavage/foliation

Obuasi – D4

Bogoso

Cut side

Uncut side

Wassa

Vein with visible Au
D4 gold mineralisation (gabbro and mafic dyke hosted)

Adoikrom

Salvi et al., (2015)
Ashanti Belt – linked to WAXI2 event history

NOTE: major late-stage orogenic gold = most common observation in the literature

Local events versus WAXI2 event history
D5 Damang deposit

- 5 million ounces gold
- NE-SW compression
D5 Damang deposit (& late D5 veins at Anyankyerim)

Anyankyerim

Regional low angle D5 veins

NE-SW compression
Ashanti Belt – linked to WAXI2 event history

NOTE: major late-stage orogenic gold = most common observation in the literature

Local events versus WAXI2 event history

D4 Peak Gold - described by Feybesse et al., (2006)
Tarkwa Paleoplacer gold ca. 2100-2110 Ma
High profile and cited model for Ghana - Feybesse et al., (2006) = Late-kinematic orogenic gold deposits

Circulation of gold-bearing fluids favoured by late-orogenic events that increased crustal permeability caused by;

- change in tectonic style from D1 thrusting to D2 sinistral shearing.
- uplift and erosion to a shallow crustal position enabling D2 brittle behaviour
- period of reduced tectonic activity (= stress quiescence)

Two key take home points from today’s talk;
1) Main stage or “gold peak” post Tarkwa deposition is very complex
2) Pre-Tarkwaian basin gold events linked to world class deposits exist
SUMMARY

• Gold deposits have a broad geographic extent and structural styles ranging from early ductile shear zones (Wassa), High-T (Morila), fault-vein arrays (Kalana, Damang), and brittle high level low-T breccias (Syama).

• Host rock types for the gold deposits range from sediment-hosted (Siguiri), sediment and granitoid hosted (Kalana), volcanic and mafic intrusive hosted (Syama)

• Multiple (3) phases of gold mineralization with different kinematics and alteration occurred post deposition of the Tarkwa Formation (D3, D4, D5)

• There is a dominant D4 gold event, commonly associated with high arsenic mineralization and sinistral-slip kinematics linked to NW-SE shortening.

• Some phases of gold predate the deposition of the Tarkwa units (D1 Wassa deposit). These deposits could be potential analogues of the source for the world-class palaeo-placer deposits occurring within the Tarkwa Formation in Ghana. MORE FOCUS ON THESE SYSTEMS IS REQUIRED TO UNDERSTAND CONTROLS ON DEPOSIT LOCATION

• Architectural controls and causes of localisation of early gold deposits versus possible placer systems should be assessed