WEST AFRICAN OROGENIC GOLD DEPOSITS:
DO THEY FIT THE GLOBAL PARADIGM?

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WHAT ARE OROGENIC GOLD DEPOSITS?

• The most abundant producer of gold on Earth
• Mesothermal rather than epithermal epigenetic ore deposits
• Temporally linked to periods of crustal growth in accretionary or collisional orogens
• Struturally controlled, steeply dipping ore lodes commonly located in allochthonous terranes characterised by strike slip faults
• Regional first order strike-slip structures provide the main control of deposit distribution with greatest ore fluxes in higher order shears, faults, and folds
• Generated in metamorphic terrains and hosted in greenschist facies mafic rocks, volcanic or intrusive, or clastic sediments
• The standard model suggests that they form from deep seated low salinity \( \text{H}_2\text{O} - \text{CO}_2 + \text{CH}_4 + \text{N}_2 \) metamorphic fluids that carry \( \text{Au} - \text{Ag} + \text{As} + \text{B} + \text{Bi} + \text{Sb} + \text{Te} + \text{W} \) (low base metal)
Tectonic Settings of Epigenetic Gold Deposits

Herrington after Groves et al. (2003. Econ Geol)
QUESTIONS

1. Where have models for orogenic gold mineralisation taken us?
2. Are models that imply a metamorphic origin for orogenic gold fluids correct?
3. What are the potential roles of magmatic fluids in orogenic gold deposits?
Regional geology of the KKI

Legend
- Kakadian Batholith
- Basalts
- Andesites
- Volcaniclastic sed.
- TTG calc-alkaline plutons
- Falémé iron ore deposits
- Sediments
- Granites
- Cover sequences
- Hercynian belt

Regional geology:
- Diale-Dalema Series
- Falémé Series
- Kofi Series

Key locations:
- Yatela
- Sadiola
- Sabodala
- Massawa
- Loulo
- Segala
- Tabakoto
- Yatela
- Sadiola
- Sabodala
- Massawa
- Loulo
- Segala
- Tabakoto
Yalea Open Pit 2010
Gounkoto Open Pit - 2014
Loulo, West Mali: Gara stockwork in quartz-tourmaline rock
Quartz and carbonate veins with pyrite
MULTI-STAGE TOURMALINE GENERATION AT GARA

A

Py

Qtz-ank-py veins

E-stage tur

400 µm

B

M-stage tur

Ank

E-stage tur

200 µm

C

Py

L-stage tur

Ank

Qtz

150 µm

D

L-stage tur

Ank

Py

400 µm
MINERAL PARAGENESIS

Ni-Co sulphides at Yalea North
### Mineral Paragenesis at Gara

- **Pre-Cretaceous event**
  - Supergene
  - Limonitization
  - Gold
  - Chalcopyrite-I
  - Uraninite/Sayrite
  - Monazite
  - Scheelite
  - Asbestos
  - Pyrrhotite
  - Gersdorffite
  - Chalcopyrite-II
  - Pyrite
  - Ore-related phases

- **Main ore-stage**
  - Type I quartz
  - Type II quartz
  - Ankerite
  - Albite
  - Hematite
  - Rhodochrosite

- **E-stage tourmaline**
  - Vein material
  - Type I calcite
  - Type II ankerite

- **M-stage tourmaline**
  - Gangue
YALEA MINERAL PARAGENESIS

Albitic QR alteration

Ductile textures (rich in carbonate)
YALEA – KEY ORE MINERALOGY

Asp-I

Py-II

Asp-I

Py-II
LOULO, LOW SALINITY FLUID INCLUSIONS

Type 1
mono- or bi-phase CO$_2$ inclusions (60-90%)

Type 2
rare l+v H$_2$O inclusions (<5%)

Type 3
mixed CO$_2$-H$_2$O inclusions (5-12%)
LOW SALINITY FLUIDS

- This range of fluids is seen elsewhere in the Birimian
- Fluid immiscibility (Coulibaly et al., 2008) +/- post-entrapment modifications (e.g. Klemd et al., 1997)
- Low salinity H$_2$O-CO$_2$ fluids common for orogenic Au deposits and generally suggested to represent a metamorphic fluid source???
GARA HYPERSALINE FLUID INCLUSIONS
(LAWRENCE ET AL. 2013)

Fig. 3. (Cont.)
GARA
CRACKED
HYPSERSALINE
FLUID
INCLUSIONS
<table>
<thead>
<tr>
<th>GARA</th>
<th>YALEA</th>
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</thead>
<tbody>
<tr>
<td>Gara</td>
<td>Yalea</td>
</tr>
<tr>
<td>• Tourmaline rich</td>
<td>• Tourmaline poor</td>
</tr>
<tr>
<td>• Fe-REE-As-Ni-Co-Au+Cu+W</td>
<td>• Fe-As-Cu-W-Pb-Sb-Au-Ag</td>
</tr>
<tr>
<td>• Pyrite dominant sulfide</td>
<td>• Pyrite-arsenopyrite rich</td>
</tr>
<tr>
<td>• Aspy, cpy, gersdorffite, pentlandite, pyrrotite, cobaltite, monazite, xenotime, scheelite</td>
<td>• Asp + py + scheelite + late Cu minerals + Pb minerals (absence of tourmaline, REE and Ni-Co sulphides)</td>
</tr>
<tr>
<td>• Qtz-cc veins</td>
<td>• Carb – phyllic alteration</td>
</tr>
<tr>
<td>• Abundant High salinity fluid inclusions</td>
<td>• No high salinity fluid inclusions</td>
</tr>
</tbody>
</table>
**MIXING OF FLUID 1 & 2**
- changes in T, fO₂, & pH
- unmixing due to "salting out effect"
- Gare-style deposits

**SOURCE 1**
Magmatic fluid
H₂O-NaCl-FeCl₂-CO₂

- ~45-55 wt.% NaCl equiv.;
- < 5 mol.% CO₂
- High T fluid (400-500 °C) released from
  a HM-buffered, Fe-B-rich, granitic
  magma at >2 kbar

**TRAP 1**
Migration via seismic pumping with
some degree of conductive cooling by
interaction with country rock, some
loss of CO₂, exchange of Na, K + Fe

Metals (e.g. Na, Fe, Cu,
Ni, W, Pb, Zn + Au) transported
as chloride complexes

Au + other metals carried
as bi-sulphide complexes

**OXIDISING**

**ZONE OF MINERALISATION**

**UNMIXING OF FLUID 2**
- caused by decreases in P, T
  & fO₂ leading to loss of H₂S
- Ylea-style deposits

**SOURCE 2**
Metamorphic fluid
CO₂-N₂-H₂O-NaCl

- <10 wt.% NaCl equiv.;
- > 5 mol.% CO₂-N₂
- Lower T (300-350 °C), QFM-
  buffered fluid released during
  regional greenschist facies
  metamorphism at 2-3 kbar

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**Figure 14**
Massawa deposit is hosted in:

A. Volcaniclastic agglomerate
B. Greywackes
C. Graphitic schists
D. Gabbro
E. Feldspar Porphyrys some mineralised and some not
F. Ductile, carbonate-sericite-quartz alteration zone
Three mineralising events

1. Ore stage 1 (replacive qtz, ser, ank, pyr, aspyr, Au)
2. Barren qz- molybdenite veins
3. Ore stage 2 (quartz-stibnite-Au)
Main Ore Phase Stage 1:

A: Ankerite-sericite-quarz alteration; B: Asp after Pyr; C: Pyr after Asp; E: Asp after Pyr; F: Au in Asp; H: Au in qtz.
MINERAL PARAGENESIS

Qtz-Molybenite veining at Massawa: Stage 2
A: Qtz intergrown with stibnite; B: stibnite-chalcostibite-quartz; C: stibnite associated with aurostibite and native gold; D: Stibnite intergrown with sphalerite, gold and zinkerite
Dominant fluid inclusions in both qtz-stibnite veins (A and C) and quartz associated with stage one ore (B) are:
Type 1 CO$_2$-CH$_4$ and Type 2 H$_2$O-NaCl
NB

Typical Metamorphic Fluids

Type 1.

Ore stage 1
15 – 33% Mol% CH₄

Ore Stage 2
10 – 15% Mol% CH₄

Type 2
2 – 8% NaCl
Sulphur Isotope data overlap for all stages.
(NB diagenetic sulfides in the KKI have $\delta^{34}S$ values of 6 – 15 ‰)
Morila Sulphur Isotope Data

Interpreted as a Reduced Intrusion Related Gold System (RIRGS)

McFarlane et al. 2011
STABLE ISOTOPES
Variation in sulfide S isotope compositions in sediment hosted orogenic gold deposits through time and seawater sulfate curve (Chang, 2008, Geology)
SMSZ - BORON SOIL CHEMISTRY
Figure 8.11: Histogram of $\delta^{11}\text{B}$ data from hydrothermal and magmatic tourmaline in the Kofi Series and the Falémé Volcanic Belt (n=100).
CONCLUSIONS

• West African Orogenic Gold deposits do not have a one size fits all model – different mineralogies, fluid chemistries and isotope signatures

• Hypersaline fluids can be derived from metamorphic reactions

• Boron does not necessarily mean magmatic

• Not all orogenic gold deposits are sourced from metamorphic fluids
  • The Gara and Yalea deposits at Loulo (bizarrely given the B and Cl levels) are likely sourced from metamorphic fluids
  • S isotope data at Massawa, together with field relations, speak of magmatic fluids
  • Morila is a RIRGS